AN ABSTRACT OF THE THESIS OF

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Title: STRATIGRAPHY, SEDIMENTOLOGY, AND STRUCTURE OF THE LATE CRETACEOUS NANAIMO GROUP, HORNBY ISLAND, BRITISH COLUMBIA, CANADA

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The five upper formations of the Late Cretaceous Nanaimo Group underlie Hornby Island, British Columbia, Canada. These are in order of decreasing age: 1) De Courcy Formation (sandstone), 2) Northumberland Formation (mudstone-turbidite), 3) Geoffrey Formation (sandstone-conglomerate), 4) Spray Formation (mudstone-turbidite), and 5) Gabriola Formation (sandstone-conglomerate). This represents a 3,000 foot section consisting of two complete and one incomplete cycles of upward coarsening. Internal structures, lithology, fossils, and facies relationships suggests that these rocks represent fluvial, nearshore marine, and offshore facies that can be interpreted as delta plain, delta front, and prodelta environments.

Thin-section study of grain textures and lithologies indicate that these rocks were derived from a rugged high-

relief terrain subject to intense chemical and mechanical weathering. Erosion and transport were rapid and deposition and burial occurred without extensive reworking. Pebble lithologies indicate that the source area consisted primarily of andesite, basalt, igneous intrusives, chert, and metamorphic rocks.

Paleocurrent data indicates that detritus was shed from Vancouver Island and transported from southwest and southeast by highly competent streams and that during the total depositional sequence at least two major changes in the paleodispersal occurred because of distributary switching. This resulted in the progradation of delta lobes.

After deposition and burial, the rocks were uplifted and deformed into a broad southeast-plunging syncline with small displacement strike-slip and normal faulting trending northwest and northeast. Pleistocene glaciation has modified the topography.

Stratigraphy, Sedimentology, and Structure of the Late Cretaceous Nanaimo Group, Hornby Island, British Columbia, Canada

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INTRODUCTION

Location and Accessibility

Hornby Island lies at 124°40' west longitude and 49°33' north latitude off the northeast coast of Vancouver Island, British Columbia, Canada. The island is bounded on the northeast by the Strait of Georgia and is separated from Vancouver Island by Denman Island and the adjacent narrow waterways of Baynes Sound and Lambert Channel. By land, Hornby Island lies 55 miles north of the city of Nanaimo and 16 miles soth of Comox (Figure 1).

The study area consists of approximately 10 square miles and lies in what Richardson (1872) termed the Comox Basin (Figure 2). The clastic sedimentary sequence underlying Hornby Island is of Late Cretaceous age and consists of the upper five formations of the Nanaimo Group which, in order of decreasing age, are 1) DeCourcy Formation, 2) Northumberland Formation, 3) Geoffrey Formation, 4) Spray Formation, and 5) Gabriola Formation.

Transportation to Hornby Island consists of two small ferries which traverse Baynes Sound and Lambert Channel. During the summer months, these run on a regular hourly schedule. Travel on the island is facilitated by a network

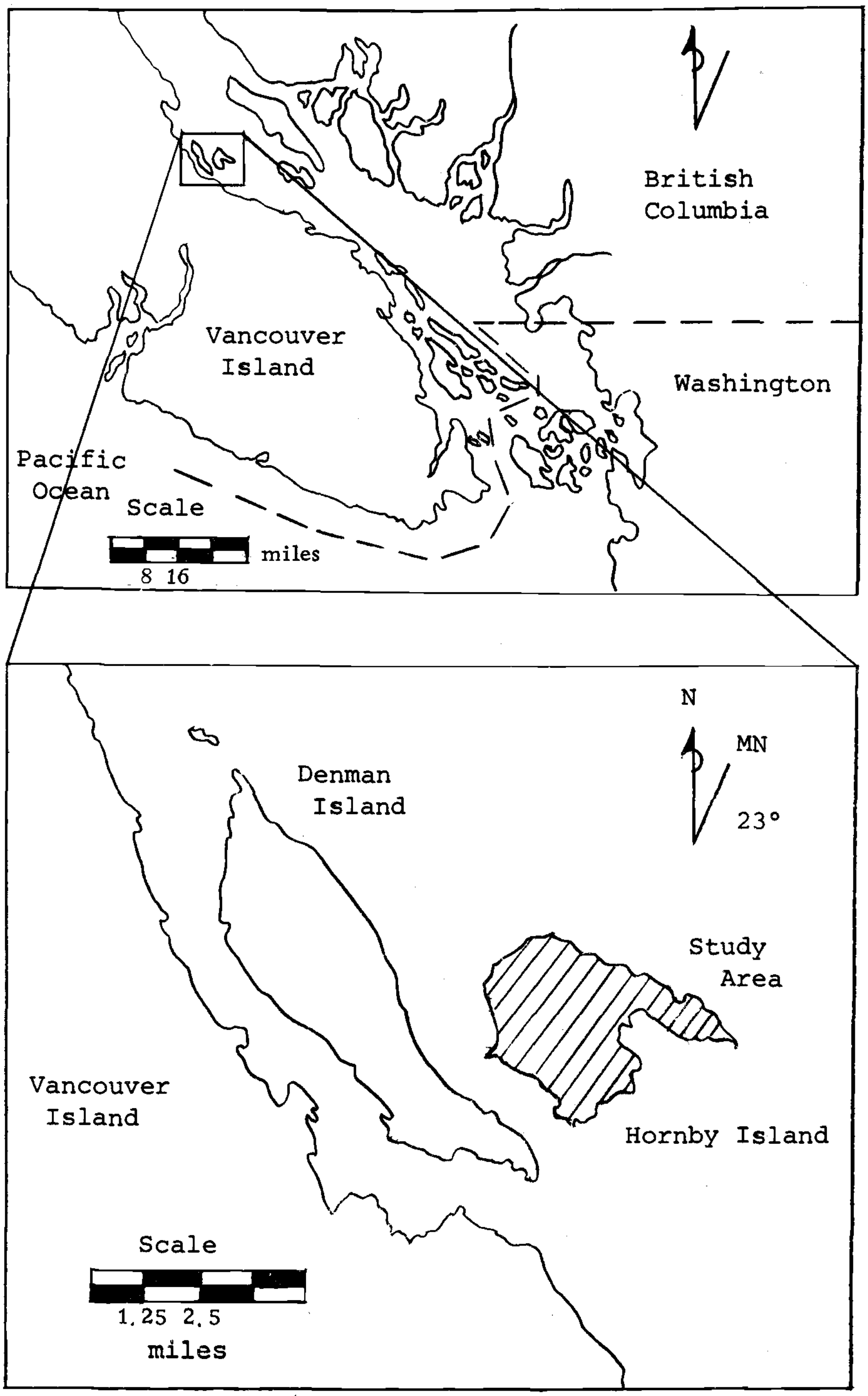


Figure 1. Study area locality map.

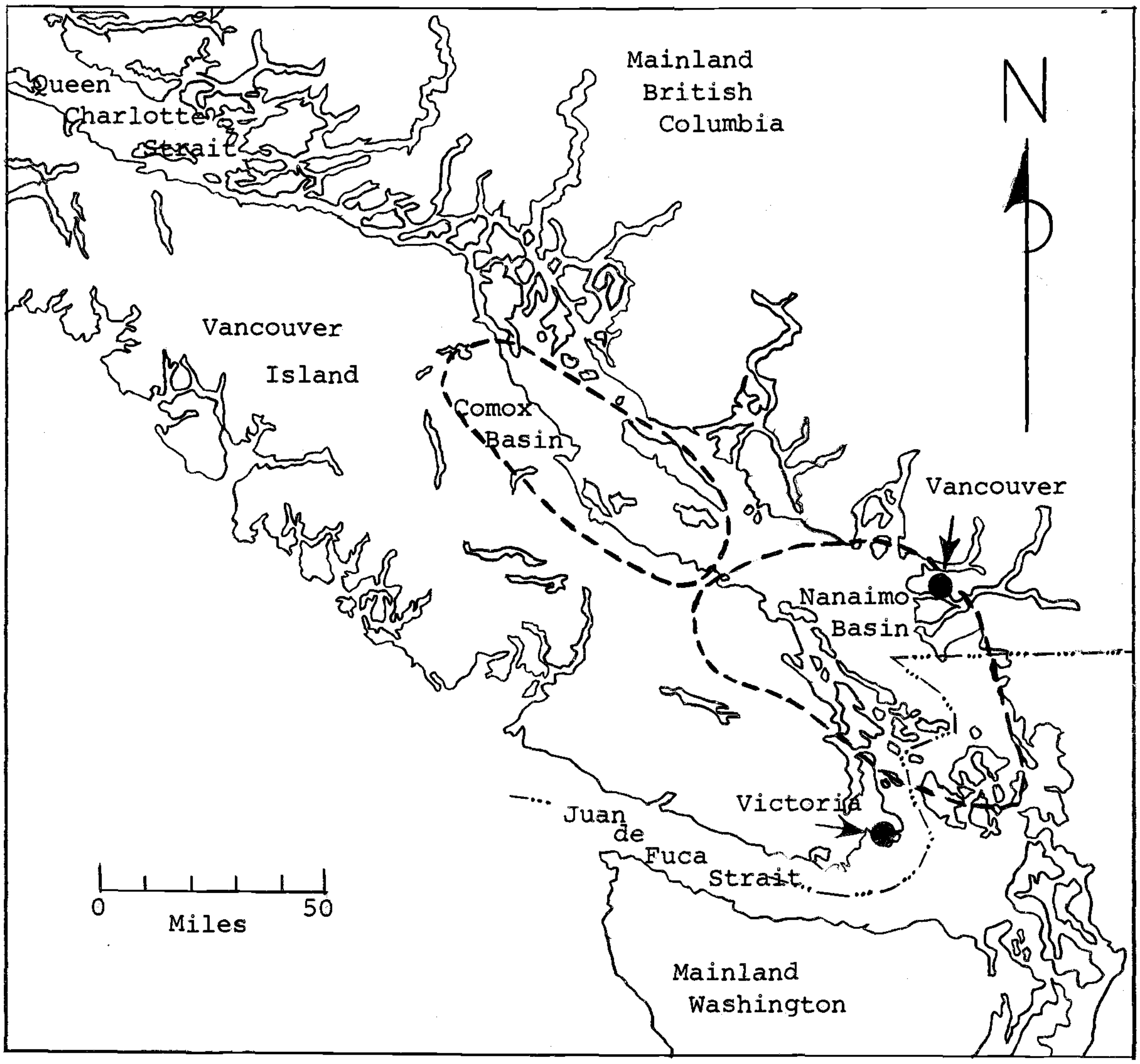


Figure 2. Approximate relative positions of Nanaimo and Comox Basins (modified after Richardson, 1872, 1878; McLellan, 1927; Usher, 1952; Geologic Map of Canada, 1962).

of semi-improved government and private roads. These encircle the perimeter of the island with inland access limited. The road shown on the enclosed geologic map (Plate 1), from Shingle Spit to Ford Cove, no longer exists.

Dense vegetation obscures most of the accessible inland outcrops except for very limited roadcuts, roadside ditches, and stream beds. Hence, the majority of the field work was completed utilizing the well exposed coastline consisting of wave-cut benches and sea cliffs. Less accessible outcrops occur along old logging roads and the western escarpment of Mt. Geoffrey, the anti-dip slope of a northeast dipping cuesta. However, because the 200 to 300 foot vertical cliffs limit geological inspection and impose a major physical risk, they were visited only briefly.

Purpose

The objectives of this study were:

1. to complete detailed mapping of the stratigraphy and structure of the Late Cretaceous Nanaimo Group found on Hornby Island, noting in particular the facies relationships and vertical succession of the formations;
2. to interpret the rocks of the Nanaimo Group with respect to source areas, paleoslopes, paleodispersal patterns, and environments of deposition and evaluate

these findings in light of the present interpretations of other studies from the Comox and Nanaimo Basins;

3. to consider such parameters as rock porosity and permeability, source rock and reservoir qualities in relation to the petroleum production potential of the Nanaimo Group found on Hornby Island.

Investigative Methods

In the Field

Actual mapping was done on aerial photographic stereographic pairs (scale 1:20,114), purchased from the British Columbia Lands Service, Surveys and Mapping Branch. Reconnaissance work was expedited by high altitude air photos to a scale of 1:64,000. Field stations, formational contacts, and structural features were plotted on acetate overlays and later transferred to a topographic base map of equal scale. This was prepared from two topographic sheets, the Horne Lake quad and the Comox quad at scale 1:50,000 and then reduced to the appropriate scale. Topographic sheets were obtained from the Canada Map Office, Dept. of Energy, Mines and Resources.

Bedding, fault plane, and current indicator attitudes were measured using a Brunton compass. Because of the gentle dip of the bedding, generally less than 10°, rotation of the current indicator attitudes to horizontal was not necessary.

Field descriptions of the lithologic units was facilitated by the use of a 10x hand lens, dilute HCl (to test for carbonate cement), a Wentworth sand gauge (to standardize grain size description), and a Geological Society of America Rock-Color chart (to standardize description of rock colors). Bedding structures of the individual sedimentary units were defined using the McKee and Weir (1953) classification.

Samples were taken at selected stations following the sampling techniques suggested by Compton (1962). Conglomerate samples were obtained by selecting a weathered outcrop and randomly collecting 100 to 200 pebbles from an area three feet by three feet. To insure the randomness of the sample, pebbles were selected in large handfuls without visual inspection.

One hundred foot representative sections of each formation were measured using a Jacob's staff and mounted Abney level following the techniques suggested by Compton (1962). Reliable formation thicknesses were extrapolated from the base map. This could be accomplished because of the homoclinal dip of the beds and the lack of severe structural deformation. Thicknesses obtained compare favorably with those of previous workers.

In the Laboratory

Analyses of the sandstone samples collected include petrographic modal analyses of thin-sections to determine composition, facilitate classification, and aid in the interpretation of depositional environments and post-depositional history. Billets were impregnated with Fiber-lay #416 resin to reduce grain plucking experienced in thin-section preparation. At least two thin-sections from each formation were counted using standard point counting procedures. To achieve statistical accuracy, 400 to 600 points per slide were counted. An estimation of plagio-clase composition was determined using the Michel-Levy method. Quartz was distinguished from potassium feldspar by staining techniques suggested by Laniz, Stevens, and Norman (1964). Billets were point counted using a grid system and binocular microscope, again counting 400 to 600 points. The results were incorporated into the thin-section modal analyses. Sandstones were classified using the classification scheme proposed by Gilbert (in Williams and others, 1954).

Pebble lithologies were obtained by inspection with a binocular microscope. These were used for the determination of provenance and comparison of the conglomeratic units.

Mudstones were tested for live hydrocarbons using the Turner #110 Fluorometer and using the methods suggested by the Shell Research Laboratories. This was done to test for potential source rocks in the area.

Geomorphology

Landforms

The most striking and prominent topographic feature found on Hornby Island is Mt. Geoffrey which rises 919 feet above sea level. The mountain is bounded on the west by a boomerang-shaped cliff that trends across the center of the island (Figure 3). Consisting of resistant conglomerate and sandstone, Mt. Geoffrey is part of a huge cuesta which dips gently to the northeast.

Tribune Bay, located on the southern shore of the island, is a lithologically controlled feature. Thick mudstone units of the Spray Formation have been eroded by wave action leaving two large embayments separated by a more resistant, thick-bedded sandstone that makes up Spray Point.

To the east of Tribune Bay, is a peninsula which culminates at St. John Point. This salient consists of the more resistant conglomerates and thick-bedded sandstones of the Gabriola Formation and forms a cuesta which dips to the northeast.

Wherever intercalated sandstones and mudstones are exposed to the sea, wave-cut benches form. Such features are prominent at Collishaw Point, Phipps Point, and Downes

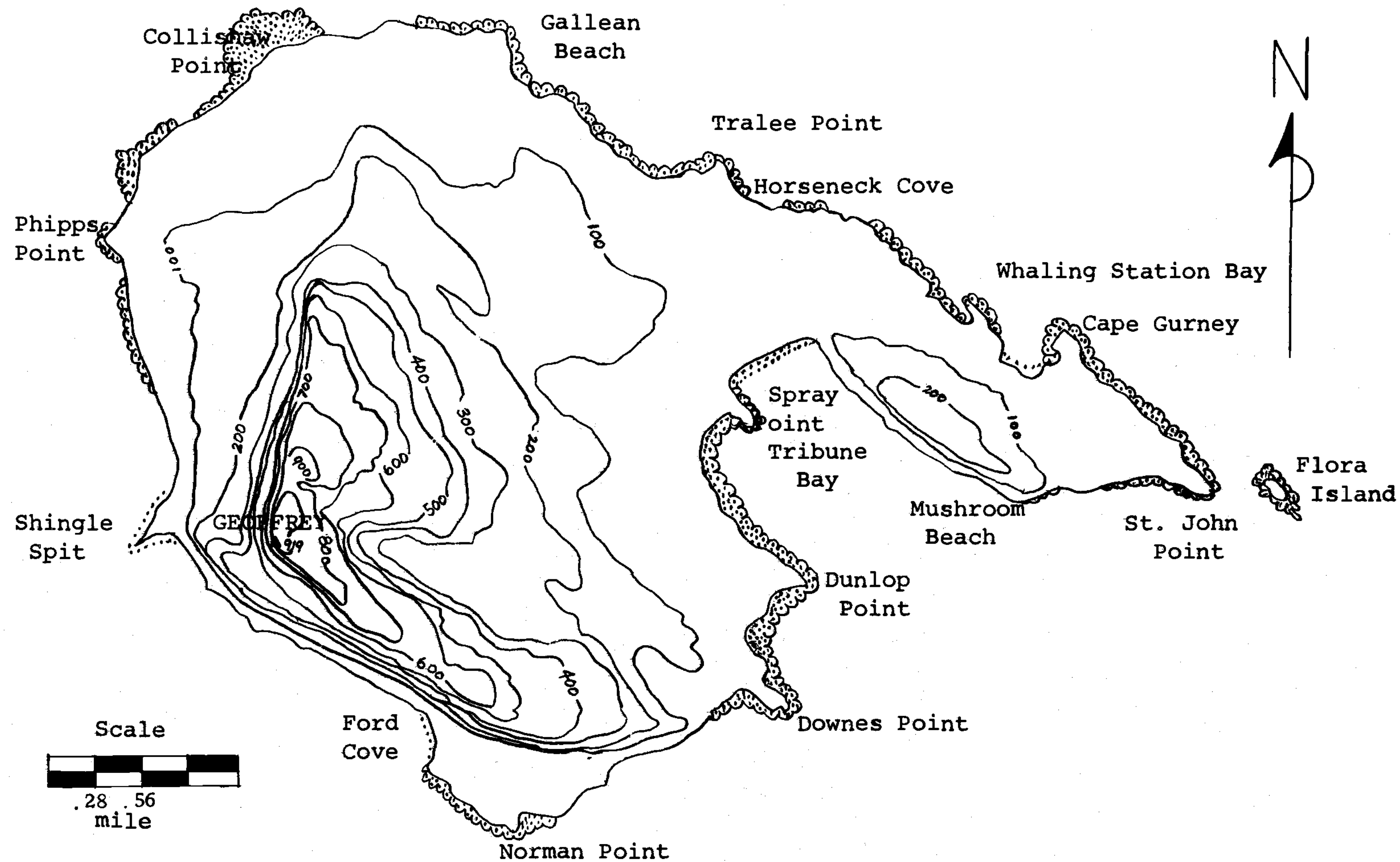


Figure 3. Geographic localities of Hornby Island.

Point (Figure 4a). These benches extend seaward as much as 300 yards and commonly are mantled with glacial erratics (Figure 4b).

Processes

Wave Action. The dominant erosive process presently affecting the rocks of Hornby Island is wave activity which is much influenced by the rock lithologies and structure of the island in forming the various coastal landforms. Well indurated rocks such as sandstones and conglomerates are more resistant and form the protruding points and sea cliffs found at Downes Point, Dunlop Point, Spray Point, and St. John Point. Softer, less resistant rock types such as mudstones have been deeply eroded forming wave-cut benches, bays and reentrants with sandy beaches such as those found at Tribune Bay and Whaling Station Bay.

Soft rock units of mudstone and siltstone with low erosive resistance crop out on the western and northwestern shore, from Shingle Spit to Collishaw Point. Here the rocks form wave-cut benches instead of the deeply eroded embayments because the rocks are protected from the major effects of the winter storms. The strike of the beds is parallel to the channel and the waves hitting the shoreline obliquely cannot expend their full force against the rocks.

Shingle Spit is an interesting feature on the western shore of Hornby Island. It extends approximately 200 to

Figure 4a. Wave-cut bench between Downes Point and Dunlop Point, Spray Formation, looking southeast

Figure 4b. Glacial erratics mantling wave-cut bench at Collishaw Point, Northumberland Formation, facing northeast. Hammer for scale.

300 yards out into Lambert Channel and consists of unconsolidated clean sand which was deposited by longshore drift processes.

Secondary features resulting from wave action and salt spray are beehive and honeycomb and gallery structures (Figures 5 and 6). The beehive structures are formed by the differential erosion of thick-bedded sandstones and are probably related to inhomogeneities in cementation. The honeycomb weathering texture, forming on the beehive structures, is caused by the differential weathering of the more resistant carbonate-filled cracks and the less resistant surrounding sandstones (Muller and Jeletzky, 1970). These structures invariably form within the spray zone on the dip-slope of the sandstone beds. They are best developed on the northern shore at Gallean Beach and 0.5 miles east of Tralee Point, but also occur at Norman Point on the southern shore.

Gallery structures in the DeCourcy and Gabriola Formations are best developed on the anti-dip slopes of thick-bedded sandstones. These are wave-cut notches with over-hanging sandstone roofs that have been etched into the more friable units (Muller and Jeletzky, 1970). On the other hand, Stickney (1976) attributes the formation of this type of structure to the rapid erosion of sandstones surrounding more resistant concretions. This permits the concretions to fall away, leaving sizeable depressions. These

Figure 5. Beehive and honeycomb erosional structures in the Gabriola Formation, Horseneck Cove, facing northeast.

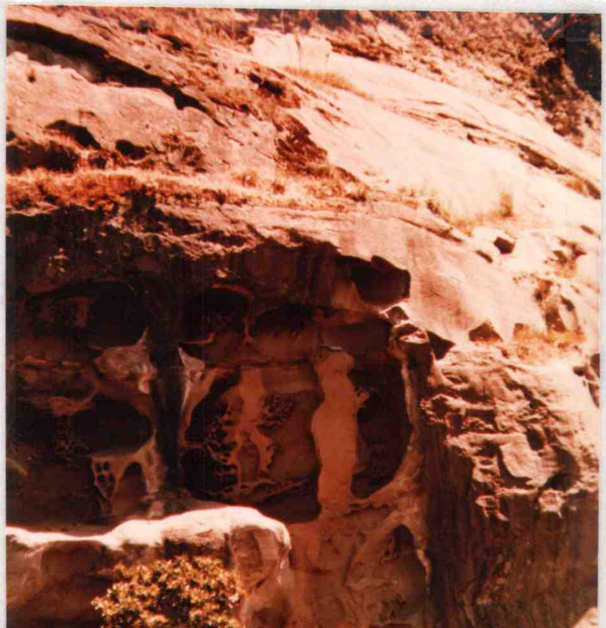


Figure 6. Gallery structure formed in the lower sandstone unit of the Gabriola Formation, northeast side of Tribune Bay.

depressions are then enlarged by hydraulic processes. It was noticed that these concretions often follow crude bedding and I feel that as the above process progresses, the enlarging depressions coalesce to form the gallery structure. However, both processes are probably valid and active.

Glaciation. The importance of glaciation as a factor in the sculpturing of physiographic features on Vancouver Island and the adjacent islands was recognized as early as 1890 by Dawson. He suggested that many of the channels and straits separating the Queen Charlotte Islands were not structural but directly related to glacial outwash and glacial scour. McLellan (1927) observed that in many instances the directional indicators (e.g.: striations, and groove markings) found at the bottom and the top of glacially carved valleys and channels in the San Juan Islands had anomalous attitudes. From this he surmised that the lower part of the glacier was guided by pre-existing topography while the overriding ice sheet was free to deviate. Easterbrook (1963) observed similar phenomena and stated that the general flow of ice was towards the southeast following the general trend of Vancouver Island.

This fact is indeed interesting when evaluating the geomorphology of Hornby Island. As mentioned previously, Hornby Island is separated from Vancouver Island by Baynes Sound and Lambert Channel. Following Dawson's suggestion, these two bodies of water could have been ancient river channels which drained a glacial mass to the north. The presence of imbricated outwash gravels on Hornby Island and Denman Island would tend to lend some credence to this hypothesis.

Glacial erratics can be found on the summit of Mt. Geoffrey, elevation 919 feet, indicating that glacial ice once covered Hornby Island. The dip slope of Mt. Geoffrey is characterized by low relief, irregular, hummocky topography. Several commercial gravel pits visited in this area consist of glacial till and stratified glacial outwash gravels. It is my contention that the physiographic features on the dip slope of Mt. Geoffrey were formed either by glacial scour or glacial deposits.

Glacial outwash gravels with pebble imbrications indicating a southeast current flow are found in a government owned gravel pit located in the NW¼ of Sec. 11 north of the main road. This evidence coupled with glacial erratics and till and the southeasterly trend of Lambert Channel indicate that glacial scour and glacial outwash scour were dominant modifying factors of Hornby Island topography. The fact that Lambert Channel and Baynes Sound parallel the strike of the rocks may indicate that the direction of flow of the ancient rivers was governed largely by the structure and stratigraphy.

Mass Wasting. Large areas of Hornby Island have been slumped. The area between Ford Cove and Shingle Spit has had a block of Geoffrey conglomerate, approximately 300 to 400 feet thick and a mile in length, slump down to sea level. House-sized blocks have broken loose from the cliff face of Mt. Geoffrey and now occupy positions at the base of the mountain. Blocks of the Gabriola conglomerate have fallen from the cuesta scarp located on the northeastern side of Tribune Bay as a result of undercutting of the more friable lower sandstone unit by wave action.

Stream Erosion. Stream erosion is extremely minor since most of the running water on the island is intermittent. During the summer months, stream drainage located on the dip slope of Mt. Geoffrey is nearly dry. The amount of downcutting by these streams has been negligible, rarely exceeding 20 feet.

Climate

Because Hornby Island lies in the rain shadow of the Beaufort Range on Vancouver Island, it is blessed with a moderate climate much like that of western Oregon. The last climatological data for Hornby Island were collected in 1969. The annual mean temperature was 49°F with a mean monthly temperature for January of 30°F and an extreme low temperature of 12°F. The monthly mean temperature for June was 64°F with an extreme high temperature of 94°F.

The annual precipitation for the island is approximately 39 inches. The majority of this falls during the winter and spring months, averaging more than four inches per month for the months of November to March. The summer months of June to September are characterized by very low rainfall which causes drought conditions to prevail during this time interval.

Vegetation

The major influence of the climate on Hornby Island geomorphology is that it enhances the growth of dense vegetation which in turn inhibits soil erosion, creep, and slumping. Thus, the features formed by other processes are preserved in their original state. The interior of the island hosts a thick forest consisting of Douglas fir, arbutus, western red cedar, red alder, and the coastal variety of lodgepole pine. Beneath the forest canopy, foot travel is very difficult because of thick growths of salal and ferns. Open areas are covered with lush grasses and mosses. Where drainage is good and soil is sparse, as on conglomerate bedrock, prickly pear cactus is abundant.

There appears to be a distinct geographic separation for the various species of trees mentioned above. Douglas fir, red cedar, and lodgepole pine are most abundant on the dip slope of Mt. Geoffrey and St. John Point. Arbutus and western red alder are the predominant species of the lowland areas such as Phipps Point and Collishaw Point. This separation may be the result of stratigraphic control. Mt. Geoffrey and St. John Point are underlain by mudstone units of the Spray and Northumberland Formations. This suggests that rock type and consequent permeability may directly influence the drainage and the soil cover and dictate the type of growth found there.

Previous Investigations

The discovery of coal on Vancouver Island in 1835 provided the impetus for many geologic investigations of what is now known as the Late Cretaceous Nanaimo Group. Usher (1952), Muller and Jeletzky (1970), Hanson (1976), and Stickney (1976), have all done commendable jobs in citing these previous studies. Therefore, to minimize redundancy, this section will capsulize only those studies that concern the general nature of the Nanaimo Group and in particular those studies in the Comox Basin.

J. S. Newberry, in 1857, first realized that the coal-bearing rocks found on the eastern coast of Vancouver Island were Cretaceous in age. He based his observation on the macrofossil assemblage he collected (Usher, 1952).

James Richardson was the first geologist to study extensively the Cretaceous rocks of Vancouver Island for the Geological Survey of Canada. He defined and named the Cowichan, Nanaimo, and Comox Basins based on stratigraphic relationships (Richardson, 1872). On Hornby Island he recognized a Middle Shale on the southwestern and western sides, an overlying Middle Conglomerate occupying the central part of the island, and an Upper Shale and Upper Conglomerate unit cropping out on the eastern side of the island (Richardson, 1878).

George M. Dawson (1890), studying the Cretaceous sequence of northern Vancouver Island, first proposed the name Nanaimo Group. He speculated on the fluvio-marine, transgressive-regressive nature of these rocks and noted that they displayed limited vertical and lateral continuity.

From 1909 to 1917, C. H. Clapp worked extensively in the Nanaimo Basin. However he also did reconnaissance work in the Comox Basin and proposed the names Comox Formation and Trent River Formation for the two oldest Cretaceous units found there. He provided formational names for 11 lithostratigraphic units in the Nanaimo Basin and recognized abrupt, lateral facies changes ascribed in part to pre-Cretaceous basement topography. Later workers would extend many of his formational names northward into the Comox Basin (Clapp, 1912, 1917; Usher, 1952).

A. F. Buckham (1947), proferred depositional and tectonic models for the Nanaimo Group. He suggested that rapidly fluctuating fluvio-marine processes were caused by alternating periods of uplift in the source area and submergence in the depositional area and periods of quiescence. He suggested a northward migration of the strand line through time.

J. L. Usher (1952), studied the ammonite faunas from the Comox and Nanaimo Basins. He established a Santonian through Maastrichtian age and four distinct faunizones that could be used for interbasin correlation. His work included faunal collections from the western shore of Hornby Island.

W. A. Bell (1957), suggested a warm temperate to tropical climate during Nanaimo Group deposition based on plant fossils.

E. W. B. Hoen (1958), studied the molluscan fauna of Hornby Island for a Master of Science thesis and concurred with Usher's findings. His interpretation of the stratigraphy and structure of the island was consistent with Richardson's (1878).

A. McGugan (1962, 1964) studied the foraminifera from the Comox and Nanaimo Basins. He suggested that the major coal seams of the two basins are not correlative, indicating that the basal formations in the Comox Basin are younger than the basal formations in the Nanaimo Basin. His Campanian-Maastrichtian boundary concurred with that of Usher. Five of microfaunal sections are located on Hornby Island.

C. H. Crickmay and S. A. J. Pocock (1968), correlated the continental Burrard Formation with the Cretaceous rocks of Vancouver Island. Microfloral analysis suggests an early Cenozoic age for the Cascade orogenic event which destroyed the Late Cretaceous-Paleocene depositional basin and ended Nanaimo Group sedimentation.

J. E. Muller and J. A. Jeletzky studied the Nanaimo Group from 1963 to 1970. They interpret the Nanaimo Group as representing a series of four transgressive cycles which show an upward fining progression from fluvial to offshore marine. They have standardized the formational names of the Nanaimo and Comox Basins. Jeletzky's biochronologic zones, based on Inoceramus fauna, concur with McGugan's microfaunal work. Two faunal sections are located on Hornby Island (Muller and Jeletzky, 1970).

W. V. Sliter (1975) proposed five concurrent-range zones based on foraminiferal faunal assemblages which can be used for local and European correlation. Bathymetric estimations indicate that deposition of the mudstone units occurred at depths ranging widely from 150 to 1000 meters.

Oregon State University graduate students under the supervision of Professor K. F. Oles, have mapped the stratigraphy and interpreted the paleoenvironments of the Nanaimo Group in the Nanaimo Basin (Packard, 197; Rinne, 1971; Simmons, 1972; Hudson, 1974; Sturdavant, 1975; Hanson, 1976; Stickney, 1976; Carter, 1976).

Pre-Cretaceous Geology

Vancouver Island, British Columbia, represents the southernmost extension of the Insular Belt, a tectono-lithologic belt on the west coast of Canada. The oldest rocks of Early Devonian or older age are highly metamorphosed argillites and wackes. They have been intruded by the Tyee Intrusions, a quartz porphyry metamorphosed to a quartz-augen schist. This intrusive complex has been dated at 390 m.y. or very early Devonian and is correlative to the Turtleback Complex in the San Juan Islands (Muller, 1976).

The late Paleozoic Sicker Group and early Mesozoic Vancouver Group overlie the early Paleozoic metamorphic complex and form the backbone of Vancouver Island. The basal member of the Sicker Group is the Youbou Formation, consisting of metavolcanics and clastic sedimentary rocks. The metavolcanics include andesite flows, breccias and pyroclastics, all of which have been altered to greenstones (Yole, 1969). The overlying clastic sedimentary rocks are predominantly wackes, argillites, conglomerates, and subordinate tuff beds that have undergone minor metamorphism. Fusilinids found within this sequence indicate a Middle Pennsylvanian age or older (Yole, 1969).

The middle unit of the Sicker Group is the Buttle Lake Formation. The rocks are medium- to coarse-grained, sparsely fossiliferous limestone with subordinate amounts of bedded chert. Fossil assemblages of brachiopods and bryozoans indicate an early Permian age (Muller and Carson, 1969).

Conformably overlying the Buttle Lake Formation is a unit consisting of argillite and mudstone which has been termed the "Unnamed Unit" (Yole, 1969). The age of the member is uncertain, but is inferred as Middle Permian to Early Triassic because of the Middle to Late Triassic age of the overlying Karmutsen Formation (Yole, 1969).

Rocks of the Vancouver Group have the greatest areal extent and thickness of any rock group on Vancouver Island. The basal Karmutsen Formation consists of 18,000 feet of amygdaloidal and finely prophyritic basalt flows, pillow lavas, and flow breccias. It has been suggested that most of the formation is of subaqueous character and that only the upper part of the formation indicates subaerial deposition (Surdam, 1968). Ammonites collected from an upper intervolcanic limestome bed indicate a Late Triassic age. Based on estimated rates of accumulation of the Karmutsen Formation, a Middle Permian to Early Triassic age is suggested for the basal volcanics (Surdam, 1968).

The Quatsino Formation overlies the Karmutsen volcanics and consists predominantly of 2,000 feet of thick-bedded, fine-grained to microcrystalline limestone with minor amounts of interbedded mudstone. Ammonites within the mudstones indicate an early Late Triassic age (Muller and Jeletzky, 1970).

The upper Vancouver Group rocks consist of a sedimentary and a volcanic sequence. The Parson Bay Formation of latest Triassic age consists of calcareous siltstone and shale, limestome, and tuffaceous beds with a total maximum thickness of 2,000 feet (Muller and others, 1974). Overlying the Parson Bay Formation are the Bonanza Volcanics comprising a total section of approximately 8,000 feet. The lithology of the Bonanza Volcanics is heterogeneous with compositions ranging from basaltic andesite to rhyodacite. These rocks occur as lava flows, breccias, and tuffs. Muller and others (1974) equate the Bonanza Volcanics to the volcaniclastic Harbledown Formation of the Queen Charlotte Islands. Based on this, they date the volcanic sequence as Early Jurassic in age.

Intrusive bodies are exposed along the entire length of Vancouver Island. In the easter part of the island the intrusives are of granodioritic composition. Quartz diorites are concentrated in the axial zone and rocks ranging from periodotitic to granitic composition occur in the western part of the island. The oldest plutonic rocks were emplaced during late Early to middle Late Jurassic time, approximately 145 to 179 m.y.b.p. (Carson, 1973). This corresponds to the latter part of the most prominent period of regional deformation and metamorphism (Surdam, 1973).

GENERAL STRATIGRAPHY OF THE LATE CRETACEOUS NANAIMO GROUP

General Statement

The sedimentary sequence which makes up the Nanaimo Group is exposed for 150 miles along the northeastern coast of Vancouver Island and the adjacent Gulf Islands. The northernmost exposure occurs at Campbell River and the southernmost exposure occurs on Orcas Island, Washington. This narrow belt varies in width from two to 20 miles in what is known as the Comox and Nanaimo Basins. These two basins are separated by a ridge of crystalline basement rock known as the Nanoose Ridge. Thickness of the Nanaimo Group in the southern Nanaimo Basin has been measured at 13,500 feet while total thickness in the Comox Basin has been recorded at 6,000 feet (Muller and Jeletzky, 1970). Outside of these two main basins, the Nanaimo Group is exposed in the lesser Alberni and Cowichan Basins located to the west of the Nanaimo and Comox Basins. Small outliers occur to the east on Texada and Lasqueti Islands (Muller and Jeletzky, 1970; Dawson, 1890).

The conditions under which the Nanaimo Group was deposited were first speculated upon by Dawson (1890). He wrote:

> The Cretaceous rocks constituted parts of a shore deposit which progressively overlapped the older rocks during a period of subsidence, and that the

> coal deposits of these rocks have been formed at times during which the deposition was in excess of the subsidence, or when the subsidence had temporarily ceased, allowing the formation and continued existance of land areas.

Later studies found that the Nanaimo Group was deposited on an irregular basement topography with a relief of at least 440 feet (MacKenzie, 1923; Buckham, 1947). Also suggested was a northward migration of the strand line through time to explain the variation in sequence thickness in the Nanaimo and Comox Basins (Buckham, 1947; Usher, 1952; Muller and Jeletzky, 1970).

As a result of their extensive work on the Nanaimo Group, Muller and Jeletzky interpret the rocks as representing four cycles of transgression. Each cycle consists of fluvial-deltaic sandstones, siltstones, and conglomerates which grade upward into offshore marine mudstones and turbidites. They have described five distinct sedimentary facies which in ascending order, may be found in each cycle. These are:

Benson-type facies: fluvial, poorly-bedded fanglomerates and wackes of lenticular and wedge-shaped geometries.

Extension-type facies: deltaic, interbedded conglomerate, pebbly sandstone, and arkosic sandstone.

Comox-type facies: lagoonal, quartzofeldspathic sandstone with numerous intercalations of carbonaceous shale and coal seams.

Haslam-type facies: nearshore marine, thick, poorly-bedded sandy shale and shaly sandstone.

Cedar District-type facies: offshore marine, thick sequences of graded beds of turbidite origin and thick structureless beds of mudstone.

Presently, nine formations can be delineated on the basis of lithological sequence and biostratigraphic correlation (Muller and Jeletzky, 1970). This nomenclature will be followed in this paper and is listed in Table 1, in terms of depositional cycle, formation name, predominant sedimentary facies, and dominant lithologic type found on Hornby Island. Unlike Muller and Jeletzky's upward fining transgressive model, I propose an upward coarsening regressive model for the sedimentary history of the upper Nanaimo Group found on Hornby Island (Table 1).

Muller and Jeletzky (1970) imply that source area uplift and/or basin subsidence is directly associated with the deposition of the deltaic Extension-type facies. The uplift of the source region would supply great quantities of sediment and create a progradational delta where sedimentation rates surpass the basin subsidence rate (Dott, 1964). As tectonic uplift waned, sediment supply would decrease and transgressive marine sedimentation would predominante. Such a model would produce repetitious couplets displaying a fining upwards character (Coleman and Gagliano, 1964).

Table 1. Upward coarsening sequence of the five upper formations of the Late Cretaceous Nanaimo Group found on Hornby Island, British Columbia.

FIFTH CYCLE

Gabriola Formation: Extension-type deltaic facies, conglomerate and thick-bedded sandstone.

Spray Formation: Cedar District-type offshore marine facies, turbidities and thick mudstone units.

FOURTH CYCLE

Geoffrey Formation: Extension-type deltaic facies, conglomerates and thick-bedded sandstones.

Northumberland Formation: Cedar District-type offshore marine facies, turbidities and thick mudstone units.

THIRD CYCLE

De Courcy Formation: Extension-type deltaic facies, conglomerates and thick-bedded sandstones.

This would infer continued basin subsidence or a rise in sea level or both.

Oregon State University graduate students have ascribed to a deltaic progradation-marine transgressive model for the stratigraphic sequence of the Nanaimo Group in the Nanaimo Basin (Hudson, 1975; Hanson, 1976; Stickney, 1976). In contrast to Muller and Jeletzky (1970), they interpret the depositional cycles as upward coarsening, a characteristic of delta-lobe progradation which precludes the necessity for periodic uplifts.

The choice as to which approach is correct is problematical and depends upon the choice of the datum line. Muller and Jeletzky feel that the basal contacts of conglomeratic units are unconformities or disconformaties. Indeed, many of the subsequent workers have described erosional or scour contacts between fine-grained mudstone units and overlying conglomeratic units (Hanson, 1976; Stickney, 1976). Muller and Jeletzky use this contact for the datum line which necessarily makes the overlying rocks an upward fining sequence. However, consider the progradational delta model. This could just as easily form erosional or scour contacts while displaying an upward coarsening sequence. This could be accomplished by discontinuing the deposition of a delta lobe at one locality and switching deposition to another part of the delta. This would result in coarse clastic material being deposited on fine-grained prodelta deposits as the delta lobe prograded seaward (Coleman and Gagliano, 1964). The mechanism for delta-lobe switching can be determined by studying modern deltas. Such studies indicate that delta construction consists of progradational lobes which change position relative to the delta front as the main tributary changes channels as a result of flooding, crevassing, or channel piracy (Coleman and Wright, 1975). This model necessarily results in an upward coarsening sequence.

The interpretation of ancient sedimentary environments depends upon close scrutiny of all available data. This data consists of facies relationships, vertical succession, internal and external sedimentary structures, paleontological observations, lithological observations, and rock unit geometry. These characteristics integrate as a response to certain depositional processes and because of this, detailed study may reveal characteristics peculiar to specific depositional environments. The detailed studies of previous Oregon State University graduate students in the Nanaimo Basin have strongly suggested the progradational delta-lobe model (Hanson, 1976; Stickney, 1976; Carter, 1976).

Local Stratigraphy

The Late Cretaceous stratigraphic sequence exposed on Hornby Island consists in part of the upper five formations of the Nanaimo Group. These are in order of their increasing age: the lower part of the Gabriola Formation; the Spray Formation; the Geoffrey Formation; the Northumberland Formation; and the upper part of the De Courcy Formation. The total maximum thickness is approximately 3,000 feet.

The Gabriola, Geoffrey and De Courcy formations all display Extension-Protection facies characteristics. These formations are predominantly conglomerate and thick-bedded sandstones with interbeds of siltstone characterized by abundant organic debris and coal stringers. The conglomerates of the Gabriola and Geoffrey occur in beds ranging from five to thirty feet in thickness. Scour channels are common especially at Gallean Beach and St. John Point. Individual units display normal grading and commonly a crude imbrication. The pebble and cobble clasts are well rounded to rounded. Compositionally the conglomerates consist of andesitic, basalt, granitic, quartzite, and chert clasts in a strongly cemented matrix of sand.

The thick-bedded sandstones of these formations occur in beds from two to fifteen feet in thickness. These sandstones are characterized by large scale planar cross-bedding, festoon cross-bedding, and scour channels. The sand grains are generally medium- to coarse-grained and consist of plagioclase, potassic feldspar, quartz, lithic fragments, and micaceous minerals.

The Northumberland and Spray Formations display Cedar District-type facies characteristics. The dominant lithologies are thick-bedded mudstones and turbidite sequences, the former being more prevalent in the Northumberland Formation. Bedding is laterally continuous for relatively large distances, as can be seen in good exposures in sea cliffs and on wave-cut benches.

The Northumberland Formation as defined in this study includes those rocks which crop out from Shingle Spit to Collishaw Point as well as those exposed at Ford Cove and Norman Point. This interpretation concurs with the interpretations of Usher (1952) and McGugan (1962, 1964). This is in contrast to Muller and Jeletzky (1970) who interpret the rocks exposed from Shingle Spit to Collishaw Point as Spray Formation and correlative to the rocks exposed at Tribune Bay. The reasons for my interpretation are: 1) the complex structure called upon by Muller and Jeletzky was not observed in the field, 2) the amount of displacement needed for the Muller and Jeletzky model is contradictory to the local faulting style, 3) they base the correlation between the two rock sequences on lithological similarities not on paleontological similarities, and 4) McGugan (1964) dates the Spray Formation exposed at Tribune Bay as younger than the rocks exposed between Shingle Spit and Collishaw Point. Table 2 is a partial schematic representation of the historic development of the Nanaimo Group nomenclature and correlations.

De Courcy Formation

The name De Courcy Formation was first proposed by Clapp (1912) for the gray, coarse-grained, thick-bedded sandstone overlying the "shales" of the Cedar District Formation. The type locality is found on a small group of islands known as the De Courcy Islands located southeast of the city of Nanaimo. The stratigraphic equivalent in the Comox Basin at one time was the Denman Formation (MacKenzie, 1923) but Muller and Jeletzky (1970) have extended the use

Richardson, 1873	MacKenzie & Williams 1924	Buckham, 1947 and Usher, 1952			McGugan, 1962 Williams-Burk, 1964			Muller and Jeletzky, 1970			This paper, 1977		
Comox Basin	Comox Basin	Nanaimo Basin		Comox Basin	Nanaimo Basin		Comox Basin	Nanaimo and Comox Basins			Comox Basin		
U. Conglomerate	St. John	Maastrichtian	Gabriola	Hornby	Maastrichtian	Gabriola	Hornby	Maastr.	Gabriola	Non Mar.	Tert.?	Gabriola	Fifth Cycle
Upper Shale	Tribune		North-umber-land	Spray			Spray	Late Campanian	Spray	Fourth Cycle	Maastr.	Spray	
Middle Congl.	Hornby			Geoffrey			Geoffrey		Geoffrey			Geoffrey	Fourth Cycle
Middle Shales	Lambert			Lambert	Late Campanian	North-umberl.	U. Lamb. L. Lamb.		North-umberland	Third Cycle	Late Campanian	North-umberland	
Lower Congl.	Denman	Late Campanian	De Courcy	Denman		De Courcy	Denman		De Courcy			De Courcy	Third Cycle

Table 2. Partial schematic representation of the historic development ofthe Nanaimo Group nomenclature and correlations (modified from Muller and Jeletzky, 1970).

of the De Courcy into the Comox Basin and have abandoned the Denman nomenclature.

Areal Extent, Thickness and Contact Relations. The lower part of the De Courcy Formation crops out on Denman Island. There the De Courcy forms the backbone of the island and consists of resistant, cuesta-forming, thick-bedded sandstones and conglomerates. Although only briefly visited during early reconnaissance work, the De Courcy crops out in road cuts and cuesta scarps the entire length of the island. The middle and upper parts of the De Courcy are covered by the waters of Lambert Channel. Earlier workers have treated Lambert Channel as an erosional feature parallel to strike rather than a structural feature such as a fault zone (Usher, 1952; Muller and Jeletzky, 1970). This precedence will be followed in this study. Therefore, the total thickness of the De Courcy Formation underlying Denman Island, Lambert Channel, and Hornby Island is approximately 1,100 feet. This was obtained using map extrapolations and assuming a homoclinal dip of 7° to the northeast. The thickness stated above corresponds to the thicknesses obtained by previous workers (Usher, 1952; Muller and Jeletzky, 1970).

The uppermost 220 feet of the De Courcy crop out on Hornby Island from Ford Cove to Norman Point. Here the De Courcy forms resistant sea cliffs and wave-cut benches which produce continuous outcrop for a two mile interval.

Inland from the coast however, outcrops are non-existent and contact relations have to be interpreted from air photos.

The contact between the Cedar District Formation and the overlying De Courcy occurs on Denman Island outside of the study area. This was not observed. Hanson (1976) describes this contact on Saltspring Island in the Nanaimo Basin as gradational. There, the upper Cedar District consists of intercalated sandstones and siltstones which grade upward into thick-bedded sandstones of the De Courcy. Upper Cedar District rocks on Denman Island are similar to those described on Saltspring Island. Because of this and the similar character of the lower De Courcy sandstone of Saltspring and Denman Islands, a gradational lower contact is inferred.

The contact between the De Courcy and the overlying Northumberland Formation is gradational (through 50 feet) and is best exposed 0.25 mile northeast of Norman Point. It is defined by the last occurrence of thick-bedded sandstone that is overlain by the unevenly laminated, thick mudstones of the Northumberland.

Lithology and Stratification. The predominant rock types of the De Courcy Formation exposed on Hornby Island is displayed in the sea cliffs between Ford Cove and Norman Point. These are thick- to very thick-bedded sandstones that weather to light olive gray (5Y 6/1) and yellowish gray (5Y 7/2). Fresh surfaces are medium gray (N5). The sandstones are coarse- to medium-grained and contain rare pebbles up to two inches in diameter. The individual sand grains are angular to subangular and consist primarily of plagioclase, potassium feldspar, quartz, lithic fragments, and large biotite and muscovite flakes tightly cemented with calcium carbonate.

Internal structures of the thick-bedded sandstones commonly are masked by weathering, staining, and compositional and textural homogeneity. But despite their overall homogeneous appearance, these sandstones locally contain an abundance of internal structures. The basal contact of the individual sandstone beds is sharp and undulatory with mudstone rip-ups and pebbly sandstone lenses (to four feet across) common within the bottom two feet of the bed (Figure 7). Scour channels are indicated by pebble conglomerate lenses and associated festoon cross-bedding. Pebble trains accentuate this feature in many instances. Etched surfaces, such as those at Ford Cove, display low-angle planar cross-beds, the most common structures of these sandstones (Figure 8).

Other internal features include rare shell and carbonized wood fragments, randomly occurring mudstone rip-ups, and ellipsoidal to spherical carbonate concretions ranging from six inches to four feet in diameter. These tend to parallel the overall bedding. Weathering structures include gallery and beehive and honeycomb features.

Figure 7. Scour channel filled with mudstone breccia, De Courcy Formation, Norman Point.

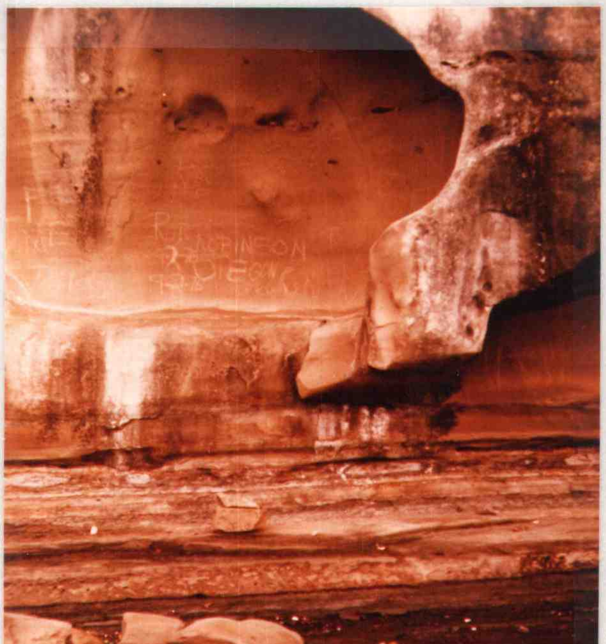


Figure 8. Low-angle planar cross-beds in thick-bedded De Courcy sandstone, Ford Cove. Note gallery structure.

Interbedded with the thick-bedded De Courcy sandstones are thin beds and partings of very fine-grained sandstones and micaceous siltstones. These weather light olive gray (5Y 6/1) to light gray (N8). Fresh surfaces are medium light gray (N6). These commonly display normal grading and thin parallel laminations which grade upward into ripple cross-laiminations. Flame structures, contorted bedding, abundant organic plant debris, coal stringers and intense bioturbation are also common. These beds pinch out laterally to the southeast.

Higher in the section, the characteristic lithology of the De Courcy changes. The change is gradational from the rocks just described to thin-bedded intercalated graded packets of fine-grained sandstone and siltstone. The sandstone beds range from four to 12 inches in thickness with the odd bed up to two feet in thickness. These are yellowish gray (5Y 7/2) weathering to a moderate olive brown (5Y 4/4). The sandstones are fine- to medium-grained and moderately sorted. The grains are angular to subangular and consist predominantly of plagioclase and quartz. These rocks are well indurated with a carbonate cement and a diagenetic clay matrix (see Petrography Section).

Internally, these thin-bedded sandstones display normal grading, and the BCDE and CDE units of the Bouma sequence. These are B) parallel laminations, C) ripple cross-laminations and convolute laminations, D) parallel laminations, and E) a pelitic interval (Reineck and Singh, 1973). Bottom surfaces are sharp and planar, sandstone grades upward into siltstone. The upper E unit of siltstone composition appears in many instances to be mottled and disrupted by intense bioturbation. No sole markings were found to indicate direction of flow. This was due to the fact that the beds are nearly flat lying, thus bottoms of beds are inadequately exposed. However, a large scale slump feature within this upper unit indicates a northeast-dipping paleoslope.

Paleoenvironmental Interpretation. When trying to interpret the depositional setting of the De Courcy Formation, one must keep in mind the character of the lower De Courcy rocks found on Denman Island. If this is not done, the possibility of a misinterpretation is increased. To interpret the De Courcy Formation on Hornby Island without consideration of lower De Courcy rocks would be like taking a phrase out of a paragraph. This phrase, taken out of context, may have a completely different meaning. Likewise, the upper De Courcy rocks when not viewed in light of the overall stratigraphic sequence may be interpreted wrongly. With this in mind, the De Courcy consists of basal thick-bedded sandstones overlain by thick-bedded conglomerates which display scour-and-fill channels and lensoid sandstone bodies. The rocks overlying the conglomerates are covered by the waters of Lambert Channel. The uppermost rocks of the De Courcy are thick-bedded sandstones overlain by intercalated sandstones and mudstones.

The general overall appearance of the Cedar District-De Courcy packet is an upward coarsening sequence, from thick mudstone and intercalated sandstone and siltstone units of the Cedar District to the thick-bedded sandstones and conglomerates of the De Courcy. This aspect has been widely noted in earlier studies and attributed to a regressional progradational delta lobe model (Simmons, 1973; Hanson, 1976; Stickney, 1976). Selley (1970) suggests that the main criteria for recognizing ancient deltas in the stratigraphic record are repeated cycles of upward-coarsening beginning with the marine shales of the prodelta region which pass upwards into coarser fluvial deposits of the delta plain. These fluvial deposits are best exemplified by the conglomerates of the De Courcy which are exposed on the southeastern shore of Denman Island. These display low-angle scour-and-fill channels and lensoid sandstone bodies which typify the deposits of braided streams and rivers (Selley, 1970).

If the De Courcy does in fact represent a progradational delta lobe, one can proceed to interpret those De Courcy rocks exposed on Hornby Island and relate them to the model. In doing so, it is extremely important to examine the data in light of modern and ancient analogues because sedimentary processes which form the sedimentary structures seed in modern deltas are applicable to ancient deltaic environments.

The data that I feel are important to the interpretation of the De Courcy rocks on Hornby Island are internal structures of the sandstones, deometry of the beds, facies relationships, and nature of the lithologies. The presence of low-angle planar cross-bedding is suggestive of beach, longshore bar, and alluvial fan environments (Reineck and Singh, 1973). This type of internal structure is best developed at Ford Cove. Incorporated in the beds displaying this type of structure are shell fragments and matrix-supported pebbles. The presence of festoon cross-bedding, pebble trains, pebble conglomerate lenses, and scour channels indicates a unidirectional current. Reineck and Singh (1973) attribute these features to a fluvial or a distributary mouth bar type environment. The geometry of these thick-bedded sandstones is quite like that described by Weber (1971) for the sheet-sandstones of the Niger River Delta. Similar sandstones displaying similar internal structure were described by McBride, Weidie, and Wolleben (1975) from the Late Cretaceous Difunta Group in northeastern Mexico. They interpreted these as a deltaic complex where the sandstones represent a complex of beach-nearshore marine-and distributary mouth bar deposits.

The internal structures of the very fine-grained sandstone to siltstone interbeds suggest a quiet water, low energy depositional environment. These features are parallel laminations and ripple cross-laminations. Also, in association with these rocks are coal stringers, abundant plant remains, and intense bioturbation. These characteristics are highly suggestive of delta plain interchannel or lagoonal-type environments (Visher, 1965; Krumbein and Sloss, 1963). The facies relationships between the thick-bedded sandstones and the fine-grained sandstones and siltstones indicates that both were being deposited simultaneously. Paleocurrent data (see Paleogeography Section) indicates a southwest to northeast sediment transport and a northeast dipping paleoslope. If this is assumed to be true (an assumption is needed here because the paleocurrent data for the De Courcy may be invalid), then the finer-grained sediments were being deposited northwest of the coarser-grained sandstones parallel to depositional strike. Such a situation can be explained in terms of interchannel delta plain or tidal flat deposits. Certainly the fine-grained size, the intense bioturbation, and abundant organic debris and coal stringers, and the internal structures would suggest this. However, the presence of parallel and ripple-cross laminations and the lack of flaser and herringbone cross-bedding would tend to suggest an interchannel delta plain deposit (Krumbein and Sloss, 1963).

Overlying the delta plain-fluvial-nearshore marine deposits are the thin-bedded intercalated sandstones and siltstones. The internal structures previously mentioned in the preceding section are highly suggestive of turbidity current deposition (Reineck and Singh, 1973). Similar rocks of the Difunta Group in northeastern Mexico have been described and interpreted as prodelta deposits (McBride and others, 1973). Dott (1966) further refines this concept and suggests that turbidity current deposits occurring on the prodelta slope are indicative of steep-sloped delta fronts. Selley (1970) concurs with this interpretation.

In summary, the De Courcy Formation is the upper member of an upward coarsening cycle. This type of sedimentary packet has been attributed to deltaic sedimentation and more specifically to delta lobe progradation (McBride and others, 1975; Dott, 1966; Coleman and Cagliano, 1964). Although the data is not conclusive, the lithofacies relationships, geometry, and internal structures of the De Courcy sandstones on Hornby Island probably indicate a complex environment consisting of interchannel delta plain-fluvial or distributary mouth bar-beach-and offshore ingredients. The offshore facies marks an end to De Courcy fluvial-deltaic sedimentation and indicates the start of a marine transgression (Northumberland Formation). The marine transgression is probably the result of delta lobe switching much like that common to the Mississippi River Delta.

Northumberland Formation

The term Northumberland Formation was introduced by Clapp (1912) to define the shale unit overlying the De Courcy Formation exposed on the north coast of Gabriola Island in the Nanaimo Basin. His lithologic units included a basal shale member, middle coarse clastic member, and an upper shale member. In the Comox Basin, the correlative to this sequence was the Lambert Formation, Geoffrey Formation, and the Spray Formation. The term Lambert Formation has been abandoned in favor of the Northumberland Formation (Muller and Jeletzky, 1970). Likewise, the Geoffrey Formation and Spray Formation nomenclature has been extended southeast into the Nanaimo Basin and now defines the middle coarse clastic member and the upper shale member respectively of Clapp's Northumberland Formation (Muller and Jeletzky, 1970).

Areal Extent, Thickness, and Contact Relations. The Northumberland as defined in this study crops out at Ford Cove and 0.25 mile east of Norman Point between the underlying De Courcy and overlying Geoffrey Formation (see Plate 1). This study will follow the interpretations of Usher (1952) and McGugan (1962, 1964) and designate the rocks exposed on the west coast of Hornby Island between Shingle Spit and Collishaw Point as Northumberland. This is in contrast to the interpretation of Muller and Jeletzky

(1970). The reasons for the difference in interpretation will be discussed below because it is felt that it is necessary to cite the evidence since there is a difference in interpretation.

Usher (1952) was the first geologist to attempt to correlate the rocks of the Nanaimo and Comox Basins. Based on molluscan fossil assemblages from the Nanaimo Basin, he dated the Northumberland shales as entirely Maastrichtian in age. However, he remarked that in the Northumberland shales, only four species of ammonites were conclusively identified, the bulk of the assemblage being fragmented and crushed and too tentative for identification.

In the Comox Basin, Usher sampled the Lambert Formation extensively and postulated that the rocks exposed from Shingle Spit to Collishaw Point were correlative to the lower shales of the Northumberland in the Nanaimo Basin. He further speculated on the correlation between the unfossiliferous Spray Formation exposed at Tribune Bay and the upper shales of the Northumberland in the Nanaimo Basin.

McGugan (1962, 1964) was the first in this area to use foraminifera as a means for intrabasin correlation. His interpretation correlated all of the Northumberland Formation as defined by Clapp (1912) with the lower Lambert Formation exposed between Shingle Spit and Phipps Point on Hornby Island. He based this on the Campanian ages obtained for both formations. McGugan also sampled the Spray

Formation at Tribune Bay and found these rocks to be younger than the upper Lambert Formation of earliest Maastrichtian age.

Muller and Jeletzky (1970) equated the Spray Formation with the upper Lambert Formation because of lithologic similarities. Having assumed equivalence, Jeletzky dated the Spray as latest Campanian to earliest Maastrichtian age based on *Inoceramus* fossil assemblages. However, if their primary assumption is in error and the Spray Formation at Tribune Bay is not correlative to the rocks exposed on the western coast of Hornby Island, then the age for the Spray Formation exposed at Tribune Bay would be too old. Such an erroneous correlation would result in the necessity of mapping complex facies and structural relationships.

Other evidence suggests that the rocks exposed at Tribune Bay and the western and northwestern coast of Hornby Island are not correlative. Muller and Jeletzky (1970) interpret a fault trending northeast-southwest along the cuesta scarp of Mt. Geoffrey, with the northwestern side down. This would bring the Spray Formation down against the Geoffrey Formation. The displacement needed to achieve such a situation would necessarily be on the order of 1,000 feet. This is completely contradictory to the small displacement faulting style observed in the field. Also, no evidence for such large scale faulting -- shear zones, slickensides, or juxtaposed rock types -- can be found in the field. Therefore, I suggest that the correlation of the Lambert (e.g., Northumberland) rocks with those of the Spray Formation is in error and that these actually represent two distinct formations.

Such statements as those above should not be made unless an alternate model can be proposed to explain the data. Both User (1952) and McGugan (1962, 1964) suggest that formational contacts between the Nanaimo and Comox Basins are diachronous. The placement of the Campanian-Maastrichtian boundary at the top of the upper Northumberland shale in the Nanaimo Basin and in the middle of the upper Lambert Formation on Hornby Island is evidence for this (Figure 9). In such a model the lower Northumberland shale of Campanian age in the Nanaimo Basin would be correlative to the Lambert Formation of the Comox Basin of late Campanian to early Maastrichtian age. Likewise, the two upper members of Clapp's Northumberland Formation of late Campanian age are correlative with the early Maastrichtian Geoffrey and Spray Formations underlying Mt. Geoffrey and Tribune Bay.

Such a model as the one proposed above would necessitate sedimentation continuing later in the Comox Basin than in the Nanaimo Basin. Although there is no direct evidence to substantiate this, the model does fit the sedimentation model proposed by Buckham (1947) and Muller and Jeletzky (1970). In this model, the strand line migrated northward during the close of the Cretaceous period. In latest

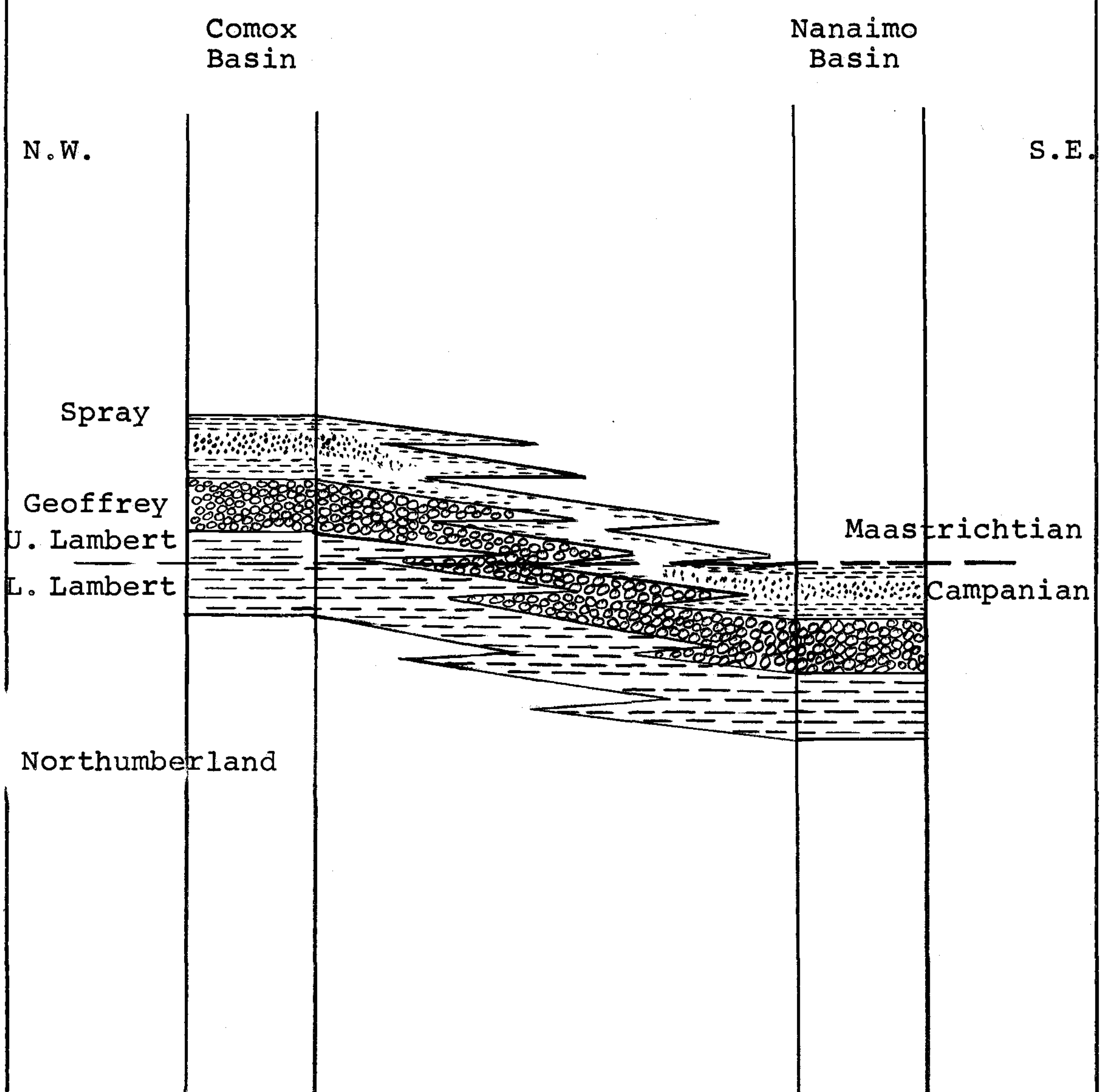


Figure 9. Proposed model for correlation of the Northumberland, Geoffrey and Spray Formations, Comox and Nanaimo Basins.

Cretaceous time, marine sedimentation was confined to the northern parts of the ancient Georgia Seaway.

As defined above, the Northumberland Formation would include those rocks which crop out at Ford Cove and Norman Point and lie between the underlying De Courcy Formation and the overlying Geoffrey Formation. Also included as part of the Northumberland are those rocks which crop out from Shingle Spit to Collishaw Point which were previously included in the Lambert Formation (Usher, 1952; McGugan, 1962, 1964).

The thickness of the Northumberland Formation northeast of Norman Point is at least 200 feet. This is an approximation because the contact with the overlying Geoffrey Formation is covered and placement of the contact is inferred. The coastline extending eastward from Norman Point is very rugged and covered by house-size blocks of conglomerate from the overlying Geoffrey. The steep slopes up to the conglomeratic cliffs, are covered by dense vegetation. However, at sea level, rare occurrences of mudstone similar to that exposed at Norman Point crops out. The last appearance of this mudstone occurs approximately 0.5 miles southwest of Downes Point and is considered part of the Northumberland Formation.

The Northumberland exposed from Shingle Spit to Collishaw Point has a thickness of approximately 750 feet (Muller and Jeletzky, 1970). This concurs with my figure obtained by map interpretation. The basal contact of the Northumberland occurs on the east coast of Denman Island and again at Norman Point on Hornby Island. At Norman Point the basal contact is gradational through 50 feet from the intercalated sandstones and siltstones of the upper De Courcy to the thick mudstone units of the Northumberland.

The upper contact with the overlying Geoffrey Formation is best exposed at the eastern extremity of Collishaw Point. Here thin-bedded intercalated sandstones and siltstones are abruptly overlain by the thick-bedded sandstones of the lower Geoffrey. There is some minor faulting at this location. The sandstones of the Geoffrey can be seen in fault contact with the Northumberland mudstones. However, the displacement is thought to be small (10 to 20 feet).

Lithology and Stratification. The general lithologic character of the Northumberland Formation can be summarized as thick units of unevenly laminated mudstone with rare thin beds of sandstone alternating with thick sequences of intercalated thin-bedded sandstone and siltstone. The thick mudstone units are best exposed lower in the formation between Shingle Spit and Phipps Point. Up section, between Phipps Point and Collishaw Point, thin-bedded intercalated sandstones and siltstones predominate.

The thick, unevenly laminated mudstone units are greenish black (5G 2/1) on fresh surface and weather to medium light gray (N6) and reddish brown (10 R 3/4).

Weathering produces a spheroidal to hackly appearance. The unit consists predominantly of clay-and silt-size particles with very fine-grained sand-sized quartz suspended in the finer material. Fine-grained crystalline pyrite in small (1-2 mm) localized clusters is dissiminated throughout the unit. These rocks are locally fossiliferous yielding many fine specimens of ammonites, pelecypods, and scaphopods. These are best preserved within the numerous calcareous concretions from five to twelve inches in diameter scattered throughout the formation, but are found to be particularly abundant in the thick mudstone units.

Thin interbeds and laminations of very fine-grained sandstones and siltstones from one to 12 inches thick occur here and there throughout the thick mudstone units. These are light gray (N7) on fresh surfaces and weather, to pale brown (5YR 5/2) and light olive gray (5Y 6/1). The bottom surfaces are sharp and undulatory whereas the upper contacts are gradational into the overlying mudstone. Internally these thin beds display thin parallel to cross-laminations. Sole markings are absent. These beds are characteristically deformed suggesting plastic deformation. The upper surfaces are covered with horizontal chevron burrows and fecal pellets. This type of burrow is characteristic of a low-energy, offshore environment with relatively low, continuous sedimentation rates. Recent analogies indicate that the sediment is organic-rich and deficient in oxygen several centimeters below the bedding surface (Howard, 1972).

Characteristic of the Northumberland, particularly between Shingle Spit and Phipps Point, are sandstone dikes which range from six inches to three feet in width (Figure 10). On fresh break these are grayish green (5G 5/2) and weather to dusky yellowish green (10GY 3/2). The dikes display poor sorting with grain sizes ranging from coarse to fine. The grains are angular to subangular and are tightly cemented with calcium carbonate. Grains are primarily quartz, plagioclase, orthoclase, biotite, and muscovite. These sandstone dikes appear structureless and contain abundant mudstone rip-ups presumed to originate from stoping.

The formation of the sandstone dikes is presumed to be a result of plastic deformation and sediment dewatering. It is not felt that the dikes followed any preconceived structure because the attitudes vary through 360° with no one direction being dominant. On the other hand, evidence for soft-sediment deformation is abundant in the surrounding mudstones and includes contorted bedding, slump structures, and bedding disruption.

Included within the thick mudstone units approximately 0.5 miles southeast of Phipps Point are large argillaceous limestone pods ranging from three to six feet in height and two to ten feet in length. These are concentrated in one

Figure 10. Sandstone dike in Northumberland Formation, 1/4 mile southeast of Phipps Point.

Figure 11. Argillaceous limestone pod in Northumberland Formation 1/2 mile southeast of Phipps Point.

area and are aligned perpendicular to the strike of the overall bedding which suggests that the individual pods occupy more than one stratigraphic horizon (Figure 11).

The fresh color of the limestone is dusky green (5BG 3/2) weathering to pale green (10GY 6/2). The pods appear to be structureless, however, the weathered pitted surfaces may obscure any internal structure. The limestone consists predominantly of micrite with subordinate sparry calcite of probable replacement origin. Shell fragments of ammonites, scaphopods, and pelecypods are common.

Phipps Point consists of thick- to very thick-bedded sandstones. These are grayish green (10GY 5/2) on fresh break and light olive brown (5Y 5/6) on weathered surfaces. Sorting is moderate with grain size ranging from medium to coarse. Angular to subangular grains predominate and consist of plagioclase, quartz, orthoclase, and volcanic fragments. These are tightly cemented with calcium carbonate.

Internal structures include planar, near horizontal bedding, festoon cross-bedding (?), and intense bioturbation. Interbedded siltstones with organic debris and coal stingers are abundant. This sequence (approximately 40 feet thick) represents an abandonment of the offshore sedimentation and a return to fluvial-nearshore sedimentation.

The predominant rock type 0.25 miles northeast of Phipps Point and again at Collishaw Point is thin-bedded intercalated sandstone and siltstone. These rocks are very similar to Cedar District rocks described by Hanson (1976) on Saltspring Island in the Nanaimo Basin. They are also similar to the Spray Formation underlying Tribune Bay on the southwestern shore of Hornby Island. However, the sand/shale ratio is much lower (approaching one) than in the Spray Formation. Fresh color of these sandstones is light gray (N7) to light bluish gray (5B 7/1), weathering to light gray (5Y 5/2). Overlying siltstone is medium gray (N4). The sandstones are moderately to poorly sorted and consist predominantly of angular to subangular grains of plagioclase and quartz of fine- to medium-grained size. Internally, the sandstones display CDE and DE units of the Bouma sequence. Less frequently, the BCDE Bouma sequence is found. The bottom surface is sharp and planar with very rare flute casts and plant debris orientations indicating a north to northwest transport direction. The upper surface is gradational into the overlying siltstones and is commonly bioturbated with horizontal and vertical burrows of Asterosoma and chevron affinities (Howard, 1972).

Paleoenvironmental Interpretation. Lithologic and paleontologic evidence that the Northumberland Formation was deposited in an offshore marine environment of Cedar District-type affinities. The water depth suggested by foraminifera studies ranges from 1,000 to 1,800 feet (Sliter, 1973). However, the argillaceous limestone pods could possibly be ancient shell banks. This would indicate a shallow water environment (Oles, 1977). Also indicative of shallow water is the regressive sequence from marine mudstone to fluvial-nearshore sandstones at Phipps Point. The contact between the sandstone and the mudstone is sharp which suggests rapid transition from marine to fluvial-nearshore sedimentation. Such a rapid transition could only be accomplished in shallow water.

Usher (1952) estimated water depths ranging from 30 to 500 feet based on the ammonite fauna found on Hornby Island. His figures are more conducive to the lithologic and stratigraphic relationships found in the field.

Much of the Northumberland consists of thick mudstone units that display little or no bedding, irregular laminations where present, and bioturbation. This type of deposit is representative of a low-energy marine environment where a steady "rain" of fine-grained detrital debris can settle out of suspension. Because of the abundant evidence for organic activity, the sedimentation rate would necessarily have been slow for the substrate to accommodate a large benthic community (Purdy, 1964).

Interspersed throughout the Northumberland are thick sequences of intercalated thin-bedded sandstones and siltstones. These are very much like those of the upper De Courcy Formation and because of the similarity are interpreted as turbidite deposits. The fine- to very fine-grained nature of the sandstones, the low sand/shale ratio (approaching one), and a predominance of CDE and DE Bouma units indicates either distal or interchannel turbidite deposits (Walker and Mutti, 1973). Rare flute marks and oriented organic plant remains indicate a north to northwest transport direction.

Thick mudstone units with similar lithologic, internal structure, paleontologic and facies characteristics have been described from the Pennsylvanian Canyon Group in north-central Texas. These rocks have been interpreted as a deltaic sequence with the thick mudstones representing prodelta deposits (Erxleben, 1975).

Thick sequences of distal or interchannel turbidites have been described from submarine fan deposits (Nelson and Kulm, 1973), from distal delta-front slope (Dott, 1963) and prodelta deposits (Selley, 1970). Any of these models could explain the sequence of rocks found within the Northumberland Formation. However, when viewed within the stratigraphic sequence of the entire Nanaimo Group, the submarine fan model quickly loses favor because there is no means in a fan model to explain the repetitious fluvio-marine sequences of the Nanaimo Group. Therefore, either the delta-front slope or the prodelta environment would seem the likely choice.

Geoffrey Formation

The Geoffrey Formation was named by Usher (1952) to define the thick-bedded sandstones and conglomerates of Mt. Geoffrey which overly the Northumberland (Lambert) Formation. Muller and Jeletzky (1970) have correlated this unit with Clapp's (1912) conglomeratic unit of the Northumberland Formation in the Nanaimo Basin.

Areal Extent, Thickness, and Contact Relations. The Geoffrey Formation crops out in a boomerang-shaped cuesta scarp which trends down the center of the island. This west-southwest facing escarpment is largely inaccessible with vertical cliffs rising 200 to 300 feet. Exposure on the northern shore from Collishaw Point to one mile east of Gallean Beach is excellent. Outcrops on the southern shore from Downes Point west are continuous but again steep slopes, dense vegetation, and vertical cliffs limit the amount of geologic work that can be accomplished.

Thicknesses obtained by Usher (1952) ranged from 700 feet on the northern and southern shores to 1,300 feet at Mt. Geoffrey. The greatest thickness is questionable because the exact placement of the Northumberland-Geoffrey contact is subject to interpretation. In my opinion the contact should be placed higher to coincide with contact relations observed near Downes Point. Because of this, I estimate the thickness of the Mt. Geoffrey section to be between 800 and 900 feet. Thicknesses obtained from the southern shore concur with that of Usher (1952). However, a thickness of 550 feet was obtained for the northern shore section. The difference again may be caused by interpretation of contact placement.

The contact between the Northumberland and Geoffrey exposed just east of Collishaw Point has been described previously. Muller and Jeletzky (1970) interpret the thick-bedded sandstones overlying the thin-bedded intercalated sandstones and siltstones as nearshore facies of the Northumberland. However, in my interpretation, these thick sandstones mark a definite lithologic change in the sedimentary record and as such are treated as the lowermost beds of the Geoffrey Formation.

The basal contact of the Geoffrey Formation was not observed on the southern shore because of dense vegetation. Usher (1952) remarks that here the contact is sharp and abrupt with Geoffrey conglomerates directly overlying Northumberland sandstones and mudstones.

The upper contact with the overlying Spray Formation is just as variable as the lower contact. On the southern shore the conglomerates that comprise the Downes Point salient are directly overlain by thin-bedded intercalated sandstones and siltstones of the Spray. On the northern shore the contact is more obscure. Two hundred yards southeast of Gallean Beach the Geoffrey lithology changes from predominantly conglomeratic to predominantly thick-bedded sandstone. The Spray Formation also changes from thin-bedded intercalated sandstone and siltstone at Tribune Bay to thick-bedded sandstone at Tralee Point. The placement of the contact is therefore open to interpretation. I have elected to place the contact at the highest occurrence of thick-bedded conglomerate which is overlain by a pebbly mudstone. This in my interpretation marks the end of fluvial deposition and the beginning of marine nearshore sedimentation.

Lithology and Stratification. The Geoffrey Formation exposed on Hornby Island is predominantly thick-bedded pebble to cobble conglomerates. This rock type is exposed on the northern shore at Gallean Beach, in the cuesta scarp of Mt. Geoffrey, and in the sea cliffs between Norman Point and Downes Point (Figure 12). The fresh color is grayish olive (10Y 4/2) and weathers to grayish brown (5YR 3/2). Sorting is poor with clast size ranging from 1/2 to 18 inches. Clasts are rounded to subrounded and are tightly packed in grain support. Clasts consist mainly of andesite, basalt, chert, metaquartzite, granitics, and dacite. Interstices are filled with a poorly sorted, medium- to coarse-grained sandstone with angular to subangular grains of quartz, plagioclase, and lithic fragments. Sandstone is tightly cemented with calcium

Figure 12a. Looking southeast at Cuesta scarp of Mt. Geoffrey consisting of channelized conglomerates and sandstones, Geoffrey Formation.

Figure 12b. Normal grading and pebble imbrication in Geoffrey conglomerate at Gallean Beach; facing northeast. Hammer for scale.

carbonate which also binds the larger clasts into a very resistant cliff-forming unit.

The highest occurrence of the Geoffrey conglomerate is 0.5 miles southeast of Gallean Beach. Here the textural and compositional characteristics are drastically changed. The pebble conglomerate is noticeably finer-grained with clast size ranging from 0.5 inch to a maximum of two inches. The clasts are angular to subrounded and consist predominantly of chert and quartzite.

Internally, the conglomeratic units of the Geoffrey display normal grading or an absence of grading, crude imbrication which is only locally developed, and pebble elongation (Figure 12b). These features are not always discernible. This may be the result of variability of depositional process, fluctuations in transport energy, or observation of sections parallel to depositional strike. Attitudes taken of pebble imbrications indicate a southwest to northeast transport. This would seem contradictory to the pebble elongation data which is predominantly east-west. However, this can be explained in terms of fluvial deposition variability (Reineck and Singh, 1973). The presence of large cobbles and small boulders indicate a highly competent fluvial transport.

Large scale features observed in the conglomeratic units are scour channels and lenticular sandstone bodies. These sandstone bodies are grayish green (5G 5/2) on freshly broken surfaces and weathers to moderate olive brown (5Y 4/4). They are poorly sorted, very coarse- to coarse-grained and consist of angular to subangular quartz, plagioclase, orthoclase, lithic fragments, and biotite. These are tightly cemented with calcium carbonate. Internally the sandstones are normally graded from pebbly sandstones to medium-grained sandstone. The basal parts of the sandstones commonly display parallel bedding accentuated by pebble trains. Higher in the unit the internal structure changes to small scale cross-bedding indicating a northeast flowing current. This sequence of internal structure indicates waning current energy (Harms and Fahnestock, 1969).

Thick-bedded conglomerates of the Geoffrey are sandwiched between thick-bedded sandstones which crop out west and east of Gallean Beach and 0.25 miles west of Downes Point. These are characterized by large spherical concretions up to four feet in diameter, beehive and honeycomb weathering texture, and thin interbeds of mudstone.

Colors of these sandstones on fresh surfaces are grayish green (10GY 5/2) weathering to light olive brown (5Y 5/6). Sorting is generally poor with grains ranging from small pebbles to medium- to fine-grained sand. The grains are angular to subangular and consist of plagioclase, quartz, lithic fragments, and micaceous minerals in a calcium carbonate cement. Internal structures include multiple scour-and-fill features, festoon cross-bedding, and mudstone rip-ups. The thin interbeds of siltstone are highly deformed with soft sediment deformation structures such as load casts, contorted bedding, and sandstone dikes very common.

Paleoenvironmental Interpretation. The deposition of the Geoffrey Formation completed the third cycle of upward coarsening deltaic sedimentation. The change from turbidity deposits of the underlying Northumberland Formation to thick-bedded sandstone deposits of the lower Geoffrey marks the transition from offshore facies to nearshore facies (Muller and Jeletzky, 1970).

The lower sandstones of the Geoffrey are interpreted in this study to have been deposited in a fluvio-marine transition zone. Evidence for such a presumption includes scour-and-fill structures common to fluvial environments and festoon cross-bedding which may indicate either fluvial or nearshore processes (Reineck and Singh, 1973). This facies is quite similar to those De Courcy sandstones cropping out at Ford Cove. Thin interbeds of mudstone and siltstone 0.5 miles west of Gallean Beach display parallel laminations, small scale ripple cross-bedding, interference ripple marks, coal stringers, bioturbation, and fecal pellets. This is suggestive of low-energy, shallow water deposition. The presence of *Inoceramus* fragments indicates a marine environment, possibly a tidal flat.

Features which are considered characteristic of braided stream deposits include fining upward sequence, erosional basal contacts and gradational upper contacts, scour-and-fill channels, pebble imbrication and elongation, a paucity of fine-grained deposits, and large scale cross-bedding (Reineck and Singh, 1973). All of these features were observed within the Geoffrey conglomerates with the exception of large scale cross-bedding. Because of the strong similarity between the Geoffrey conglomerates and modern analogues of braided streams, I believe that these conglomerates were deposited by highly competent braided streams. Muller and Jeletzky (1970) suggest that they were deposited as "delfaic fans issuing from separate streams onto a coastal conglomerates plain." The internal structures previously described are compatible with such a hypothesis.

Overlying the thick conglomeratic sequence found at Gallean Beach are thick-bedded sandstones much like those of the lower sandstone unit. Scour channels, pebbly sandstone lenses (one foot thick and four feet across); festoon cross bedding, and pebble trains are all common and are indicative of a fluvial type environment of high energy. Thin siltstone interbeds displaying contorted bedding are thought to represent nearshore deposition below wave base or delta plain deposition.

These rocks grade upward into a thick sequence of thin-bedded intercalated sandstones and siltstones similar to those of the upper Northumberland Formation. Like the Northumberland rocks, these display the CDE and DE units of the Bouma sequence, normal grading, and sharp planar bottom contacts. These are interpreted as delta slope deposits and may represent a small tongue of the Spray Formation.

The highest occurrence of the Geoffrey Formation is represented by thick-bedded sandstones and conglomerates. The total sequence is summarized as two upward coarsening sequences which may reflect two periods of progradation. Stickney (1976) observed similar sequences on Mayne Island in the Nanaimo Basin and attributed them to delta lobe switching. Such a model could certainly apply to the conglomerates and sandstones of the Geoffrey found on Hornby Island.

Spray Formation

The Spray Formation overlies the Geoffrey and represents a return to offshore marine sedimentation. The name was first applied to the rocks underlying Tribune Bay and is derived from Spray Point, a resistant sandstone salient protruding into Tribune Bay (Usher, 1952). Muller and Jeletzky (1970) have correlated this unit with the upper shale member of Clapp's (1912) Northumberland Formation in the Nanaimo Basin.

Areal Extent, Thickness, and Contact Relations. In my interpretation of the stratigraphy of Hornby Island, the Spray Formation crops out from the embayment directly northeast of Downes Point to the northeast side of Tribune Bay. This is the type section of the Spray. On the north side of the island, the Spray is less well defined by crops out from 0.5 miles west of Tralee Point to 0.25 miles east of Tralee Point. Thickness for the Spray exposed on the northern shore is approximately 700 feet whereas the type section at Tribune Bay is 950 feet thick.

The contact with the underlying Geoffrey on the south shore occurs in the embayment between Dunlop and Downes Point. The transition is abrupt with an inferred soft mudstone unit overlying Geoffrey conglomerate. On the northern shore, the lower contact is placed at the last occurrence of conglomerate and the overlying pebbly mudstone for reasons previously stated. This occurs approximately 0.5 miles northwest of Tralee Point.

The upper contact with the Gabriola Formation is covered by water on the northeast side of Tribune Bay. Here the thick-bedded sandstones of the lower Gabriola Formation form resistant vertical cliffs that reach 50 feet in height. The nature of the Spray Formation is unknown at this locality but is assumed to be thick mudstone because of the erosive nature of Tribune Bay. The contact is inferred to be very near the sea cliffs of the Gabriola at this locality.

The upper contact on the northern shore is located 0.25 miles east of Tralee Point on the eastern side of Horseneck Cove (see Figure 3), named by myself for the abundant horseneck clams found there. The nature of the contact is abrupt with thick bedded Gabriola sandstones overlying a presumed thick mudstone unit. The lithologic nature of the Spray at this locality is inferred from several samples taken inland from an ancient wave-cut bench.

Lithology and Stratification. The type locality for the Spray Formation occurs between Downes Point and the northeast side of Tribune Bay. Here the Spray is comprised of alternating thick sequences of thin-bedded intercalated sandstones and siltstones and inferred thick mudstone units similar to the Northumberland Formation. The lithology of the Spray on the northern shore is very different and consists of thick-bedded sandstones, thin-bedded intercalated sandstones and siltstones, and inferred thick mudstone units.

The predominant rock type from the basal contact to the southwest side of Tribune Bay is thin-bedded intercalated sandstone and siltstone (Fibure 4a). Fresh color of the sandstones is medium bluish gray (5B 5/1), pale blue green (5BG 7/2), and yellowish gray (5Y 7/2), weathering to olive gray (5Y 4/1), moderate yellowish brown (10YR 5/4), and moderate olive brown (5Y 4/4). Sorting is moderate to well sorted with fine-grained size predominating. Sandstones consist of angular to subangular grains of quartz, plagioclase, orthoclase, and micaceous minerals. Some of the sandstones are tightly cemented with calcium carbonate while others, concentrated lower in the section are tightly bound with a diagenetic clay matrix (see Petrography Section, Matrix).

These sandstones contain a plethora of internal structures. The most common are related to the Bouma sequence. Low in the section the sand/shale ratio is relatively high, approximately 4 or 5:1. The sandstone beds in this part of the Spray are characterized by the BCDE and CDE Bouma units. Bottom surfaces are sharp and planar and only rarely display sole markings. This lack of sole marks is thought to be the result of inadequate exposure, the beds being nearly flat lying. Parting lineations were observed and indicate a northeast-southwest current direction.

Higher in the section the sand/shale ratio approaches one with the sandstones beds becoming thinner and finer-grained. These sands display predominantly the CDE and DE Bouma units. The beds have sharp planar bottom surfaces and grade normally into overlying micaceous siltstone sand mudstone. Only three unidirectional indicators (flute casts) were found high in the section in the southwestern sea cliff of Tribune Bay. These indicate a N. 25° W transport direction.

Approximately 60 feet above the Geoffrey-Spray contact on the southern shore, the thin-bedded intercalated sandstones and siltstones grade laterally into a thick-bedded, coarse- to very-coarse-grained sandstone displaying a scour-and-fill bottom contact. The sandstone has an elongate geometric form and is oriented N. 48 E. Groove casts found on the bottom surface of this sandstone body indicate a N. 30° E.- S. 30° W. transport direction.

The thick-bedded sandstones of Spray Point are very different from those lower in the section. First, the beds range in thickness from one to four feet as compared to bedding thicknesses of .5 to 1.5 feet found lower in the section. Plagioclase, quartz, and volcanic rock fragments make up the majority of these medium- to coarse-grained sandstones which are tightly indurated by calcium carbonate cement and diagenetic matrix. These sandstones display large scale festoon cross-bedding, ripple drift cross laminations, mudstone rip-ups and mudstone breccia lenses, scour-and-fill features, controted bedding, and small coal stringers. Obviously this unit formed in a markedly different environment than did the underlying graded packets.

The basal rock unit of the Spray Formation on the northern shore is a pebbly mudstone (Figure 13). This unit directly overlies the last occurrence of the Geoffrey conglomerate. The pebbly mudstone consists of a sandy silt matrix with 0.5 to 5 inches well rounded pebbles of

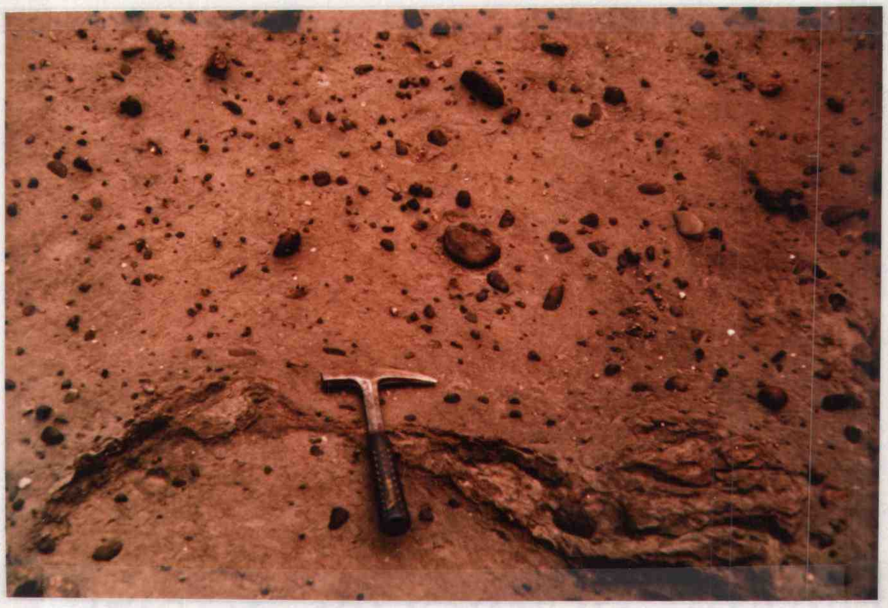


Figure 13. Pebbly mudstone of the basal Spray Formation 1/4 mile northeast of Tralee Point. Note contorted bedding under hammer.

predominantly andesite and basalt in matrix support. Bedding is indistinct but there is an indication of a greater percentage of sand and pebbles near the bottom of the bed. Large randomly oriented mudstone blocks one to five feet in length are abundant as is contorted bedding, and sandstone dike intrusion. Of particular interest is a diapiric clastic intrusion that may be related to marine mudstone dewatering and clastic dike intrusion.

The predominant rock type of the northern shore section is thick-bedded sandstone. The fresh color is grayish green (10GY 5/2) weathering to light olive brown (5Y 5/6). The sandstones are generally poorly sorted with grain sizes ranging from medium-grained sand to fine-pebbles. Sand grains are angular to subangular and are predominantly plagioclase, orthoclase, quartz, and lithic fragments. Mudstone rip-ups and lenses of pebbly sand and mudstone breccias are common. Scour-and-fill structures, large scale cross-bedding, and normal grading into thin-beds and laminations of micaceous siltstone characterize the internal structures. In general, the internal structures are very difficult to identify because the sandstone weathers to form irregular benches with cross section scarce.

Paleoenvironmental Interpretation. The rocks exposed from Downes Point to Spray Point are very similar to upper De Courcy and Northumberland rocks that have previously been interpreted as distal turbidite deposits. The evidence for these lower Spray rocks having been deposited by a similar mechanism is certainly convincing when viewed in light of internal structures, contacts, bedding geometry, and facies relationships.

The rocks exposed in the section from Downes Point to Spray Point display BCDE, CDE and DE Bouma units, repeated graded bedding, sharp planar bottom contacts and laterally continuous bedding with subtle thinning to the southeast. Flute casts are scarce but indicate a northwest current flow while parting lineations and groove casts indicate a northeast-southwest flow. Walker and Mutti (1973) suggest that this type of distal turbidite is characteristic of basin plain or submarine channel overbank deposition. The lateral gradation into a thick-bedded elongate sandstone body (described on page 71) and the thinning to the southeast away from the body strongly suggests that at least part of the Spray turbidite sequence was deposited as overbank flow. This would explain the discrepancy in the flow indicator directions previously mentioned.

The Spray rocks exposed on the northern shore are more reminiscent of the Geoffrey thick-bedded sandstones. The presence of scour-and-fill features, pebbly sandstone lenses, large scale cross-bedding, and mudstone rip-ups indicate a unidirectional current capable of erosive scour action and pebble transport. The normal grading indicates a waning current, and extreme bioturbation of siltstone interbeds indicates a very active bottom dwelling community. Internal structures such as these are interpreted by Reineck and Singh (1973) as forming in a nearshore environment or possibly a fluvio-marine transition zone like that interpreted for the thick-bedded sandstones of the De Courcy at Ford Cove.

The facies relationships are most interesting and tend to tie the northern shore and Tribune Bay depositional environments together. As seen at Downes Point, the thick-bedded conglomerates intertongue with thick-bedded sandstones which in turn are overlain by intercalated sandstones and siltstones. This type of sequence has been interpreted as fluvio-deltaic (conglomerates), delta front (thick-bedded sheet sands), and prodelta (thick turbidite sequences) (Selley, 1970; McBride, and others, 1975). The close similarities in lithologic type and facies relations of the Spray Formation with modern and ancient analogues is good evidence that the turbidite sequence of the Spray was deposited in a prodelta environment offshore from a fluvio-marine environment where the thick-bedded sandstones were being deposited.

Gabriola Formation

The name Gabriola Formation was first proposed by Clapp (1912) for the thick-bedded sandstone and conglomerate unit overlying his upper Northumberland shale unit.

The name is derived from Gabriola Island in the Nanaimo Basin where the type section is located. In the Comox Basin the Gabriola equivalent has been variously called "Upper Conglomerate" (Richardson, 1973), St. John Formation (William, 1924), and Hornby Formation (Usher, 1952). Seeking to standardize nomenclature between the Nanaimo and Comox Basins, Muller and Jeletzky (1970) have extended the use of Gabriola Formation into the Comox Basin and abandoned the use of the Hornby term.

Areal Extent, Thickness, and Contact Relations. The resistant cuesta-forming rocks of the Gabriola Formation underlie the St. John Point salient in its entirety. Anti-dip slopes on the southwest side of St. John Point take the form of vertical cliffs reaching a maximum height of 200 feet. The Gabriola rocks are exposed and easily accessible around the entire perimeter of St. John Point, especially at low tide.

Usher (1952) estimated the thickness of the Gabriola on Hornby Island to be between 600 and 800 feet. I obtained a value of 560 feet by trigonometric correction of map distance.

The basal contact with the underlying Spray Formation has previously been described. In short, this contact is located on the northeast side of Tribune Bay and 0.5 miles southeast of Tralee Point. In both instances the actual contact is covered either by water or sandy beach so that it cannot actually be observed. Packard (1972) states that the Spray-Gabriola contact on Gabriola Island in the Nanaimo Basin is concordant, sharp and planar. Carter (1976) found a similar relation on Galiano Island. Because the bedding attitudes do not change from the Spray to the Gabriola and a conformable contact has been reported from other areas, a similar contact relation is inferred for the Spray-Gabriola contact on Hornby Island.

The Gabriola represents the last known phase of Nanaimo Group sedimentation and as such has no known upper contact. It is conceivable however, that an overlying unit exists but remains covered by the waters of the Strait of Georgia.

Lithology and Stratification. Usher (1952) divided the Gabriola Formation of Hornby Island into three members: a basal very thick- to thick-bedded sandstone in the southwest-facing cliffs of St. John Point, a middle thick- to very thick-bedded conglomerate unit, and an upper thick- to very thick-bedded conglomerate and sandstone unit. Field observations indicate that while the distinction between the lower and middle members is very marked, the upper member is less well defined. There are some thick- to very thick-bedded sandstones that crop out in the unnamed point immediately northwest of Whaling Station Bay. However, the lateral extent of these beds is limited and not considered great enough for Usher's tri-division of the Gabriola.

Therefore, the Gabriola Formation will be treated in this study as consisting of two members: a basal thick- to very thick-bedded sandstone and an upper thick- to very thick-bedded conglomerate. The sandstones and mudstones at Whaling Station Bay are considered here to be part of a Spray marine tongue and are not included in the Gabriola.

The lower thick- to very thick-bedded sandstone member is best exposed on the southwest side of St. John Point. Here the vertical cliffs of a cuesta anti-dip slope reach a maximum height of 200 feet with the lower sandstone member attaining a thickness of approximately 100 feet. These weather to form gallery structures while the same unit on the northeast side of St. John Point 0.5 miles southeast of Tralee Point, forms beehive and honeycomb structures.

This lower sandstone member is thickly- to very thickly-bedded, the beds ranging from two to ten feet thick. The fresh color is dusky yellow (5Y 6/4) to light brown (5YR 6/4), weathering to light olive brown (5Y 5/6) and moderate brown (5YR 4/4). The sandstones are medium- to coarse-grained and poorly sorted with grains ranging from medium sand size to small pebble size. The sand grains are angular to subangular and consist of predominantly plagioclase, quartz, orthoclase and lithic fragments. The grains are tightly bound with a diagenetic clay matrix and subordinate amounts of calcium carbonate cement. These sandstones are considered arkosic wackes and arenites after Gilbert's

(1954) classification and compositionally and texturally immature using Folk's (1951) classification.

The lower Gabriola sandstones closely resemble those of the De Courcy Formation between Ford Cove and Norman Point. The internal features are masked by manganese oxide stain and erosional textures (e.g.: beehive and honeycomb textures). However, locally a wide range of internal features can be found. The sandstones appear to be normally graded with coarse sand and pebbly sandstone grading upward into a parallel and cross-laminated micaceous siltstone rich in organic debris, coal stringers, and burrows. The basal contacts of the sandstone beds are sharp and undulatory with scour channels (from four to ten feet across), very common. The latter are characterized by pebbly sandstones and mudstone breccias as backfilling. Mudstone rip-ups are common throughout. The lower part of the thick- to very-thick-bedded sandstone is parallel laminated which is replaced higher in the unit by large sacle cross-bedding (festoon?) and contorted bedding. Sole markings are absent but pebble trains indicate a northward current flow.

Laterally to the southeast, the lower sandstone member intertongues with repeated packets of very thin- to thin-bedded sandstone and siltstone (Figure 14a). The fresh color is pale yellowish green (10GY 7/2) and pale yellowish brown (10YR 6/2), weathering to dark yellowish green (10GY

Figure 14a. Tonguing between the lower Gabriola fluvial and the delta plain facies (flower for scale).

Figure 14b. Sandstone slab in the Gabriola conglomerates, Cape Gurney (hammer for scale). This has been interpreted as a channel bank relief.

4/4) and light brown (5YR 5/6). The sandstones are moderate to well sorted with grain sizes ranging from medium- to very fine-grained, and they grade upward into micaceous siltstone. Sand grains are angular to subangular and consist of plagioclase, quartz, and muscovite. Plant debris are common throughout these sandstones.

Internally these thin-bedded sandstones display the BCE and DE Bouma units. Contorted bedding, flame structures, coal stringers, carbonized wood and plant fragments, and intense bioturbation also characterize these sandstones.

Overlying the lower Gabriola sandstone unit is the upper conglomerate unit. The contact with the underlying sandstone member is sharp, irregular, and erosional. This contact is best observed at Mushroom Beach where vertical relief of the contact is on the order of 30 to 50 feet. On the northeast side of St. John Point, this contact is visible in the sea cliff approximately 3/4 mile southeast of Tralee Point. Again the overlying conglomerates are in scour contact with the lower sandstones but the amount of relief could not be determined.

The conglomerate unit is thick- to very thick-bedded with beds having a maximum thickness of 15 feet. The fresh color is moderate brown (5YR 4/4), and weathering to dark reddish brown (10YR 3/4). The conglomerates are poorly sorted and commonly display normal grading into overlying pebbly sandstone and sandstone bodies of lenticular geometry. Clasts range in size from 0.25 inches to 18 inches. There is a notable decrease in clast size to the northwest and also up section. Clasta are well-rounded to subrounded and consist predominantly of basalt, chert, quartzite, andesite, granite, and dacite (see Petrography Section). The clasts are in grain support with interstices filled with very coarse- to coarse-grained sandstone tightly cemented with calcium carbonate.

The internal structures of the Gabriola conglomerates include normal grading, channel scour-and-fill, pebble elongation, and pebble imbrication. These all suggest a unidirectional current of high competence. Normal grading is evident where beds are seen in cross-section, with cobble- to boulder-sized clasts grading upward into pebble-sized clasts. Imbrication and pebble elongation are best developed in the finer-grained parts of the conglomerate beds. Locally, large sandstone slabs up to 12 feet in length are supported in the pebbly matrix of the conglomerates. This is believed to be the result of channel bank undercutting (Figure 14b).

Paleoenvironmental Interpretation. The Gabriola Formation marks the last known episode of coarse clastic sedimentation in the Comox Basin. It also represents the coarse clastic member of the fourth and final cycle of upward coarsening. The deposition of Gabriola rocks is interpreted as a transitional change from offshore marine (Spray Formation) to fluvial-deltaic.

The lower sandstone member is very similar to the upper De Courcy sandstones between Ford Cove and Norman Point. Like the De Courcy, these sandstones display near horizontal bedding and laminations, cross-beds that may be festoon, normal grading, pebbly sandstone and mudstone breccia channel fills, pebble trains, and numerous mudstone rip-ups. All of these features, especially the pebble trains and internal bedding, are representative of tractive currents (Reineck and Singh, 1973). The presence of mudstone breccias, pebbly sandstone, and conglomerate channel fills, indicate that these sands were deposited by unidirectional, moderate to high competent flow. The fact that these thick- to very thick-bedded sandstones display scour channels and normal grading indicates that current energy waxed and waned, as would be expected in the fluvial environment.

These lower sandstones have a sheet-like geometry and extend along strike for approximately one mile. Very similar sands have been recorded in the studies of modern deltas. Several authors have interpreted the sands as delta front sheet sands which are made up of distributary mouth bar and fluvial channel sands (Oomkens, 1967; Van Straaten, 1959). Belemnoid fossils have been reported from this lower sandstone unit which attests to a marine nature

(Usher, 1952). Hence, it is very possible that these sands do represent delta front sheet sands.

Laterally, the thick-bedded sandstones of the lower Gabriola intertongue with thin-bedded, very fine-grained sandstones and siltstones. As previously mentioned, these display normal grading, the BCE and DE Bouma units, abundant coal stringers, and intense bioturbation. The lateral facies relationships with the delta front sheet sands indicate that the two depositional environments were in close proximity. The very fine-grained nature of these rocks along with the BCE and DE Bouma units suggests a very low-competency waning current (Harms and Fahnestock, 1965). The lack of scour structures also suggests low competency flow. The intense bioturbation both vertically and horizontally, suggest a very active bottom dwelling community. Such a community would be enhanced by abundant organic detritus and abundant oxygen (Purdy, 1964). The presence of many coal stringers suggests that plant material collected and concentrated in many isolated pockets. Similar rocks and deposits have been described as delta platform marsh or interdistributary basin deposits (Coleman and Gagliano, 1964; Beerbower, 1961). The close similarity of these Gabriola rocks with those described in the literature suggest a common delta platform depositional environment. The lateral facies change into delta front sheet sands to the northwest suggests a northwest delta progradation.

The conglomerates of the Gabriola display many of the same characteristics as those of the Geoffrey Formation. Because of the similarity, a similar braided river depositional environment is postulated. However, paleocurrent data reveals that the Gabriola was deposited by high competency fluvial processes from the southeast while the Geoffrey was deposited from the southwest. This type of switching has been widely attributed to stream channel avulsion which alters the pattern of sedimentation. Many examples of channel switching have been described in the recent literature on delta-lobe sedimentation (Frazier, 1967; Coleman and Gagliano, 1964).

PETROGRAPHY

Sandstones

A total of 35 thin-sections were studied and of these, 15 were point counted using a one millimeter grid and a petrographic microscope. Modal analyses of the point counted thin-sections are given in Appendix B. The following discussion relates to the framework grains, matrix, and cement of the sandstones studied.

Framework Grains

The sandstones of the five upper formations of the Nanaimo Group underlying Hornby Island contain five major types of framework grains. These are feldspar, quartz, lithic fragments, micas, and others.

Feldspar. The predominant framework constituent of the sandstones inspected are feldspars. The most common feldspar is plagioclase which ranges in abundance from 20.0 to 45.0 percent of the total rock. This is from three to five times more abundant than potassic feldspar. Relative abundances were obtained by point counting stained billets (Bailey and Stevens, 1960).

Maximum An content obtained for plagioclase was An_{38}, and the plagioclase ranged from oligoclase to andesine, as determined by the Michel-Levy method. Small variations in

An content were obtained from different formations, but these variations are probably caused by statistical error and are not attributed to actual formational variation.

The plagioclase in thin-section is predominantly untwinned. However, plagioclase with polysynthetic Carlsbad, Carlsbad-albite, and albite twinning can be found in all the sandstones. Zoned plagioclase is common in De Courcy, Northumberland, and Geoffrey medium- to coarse-grained sandstones. However, the Spray and Gabriola sandstones are devoid of this type of plagioclase -- a possible change in source rocks may be the cause.

In every sample, the plagioclase group includes examples of fresh to highly altered grains. The plagioclase has been altered to very fine-grained micaceous minerals of sericite affinity. Hanson (1976) suggests that this alteration includes the zeolite laumontite which replaces plagioclase grains and displays a reticulate pattern. This type of pattern was observed but the definite identification of such a fine-grained replacement mineral is beyond the scope of this study.

The predominant potassic feldspar is orthoclase. These are usually larger, more rounded and less altered than the plagioclase. The abundance of orthoclase ranges from 5.5 to 16.1 percent. The average orthoclase content (8.0%) is ubiquitous for all formations except the Spray which has a slightly higher average (10.0%). This is caused by sample 59H which has an anomalously high orthoclase content (16.1%). If this sample were rejected, the Spray orthoclase content would be similar to that of the other formations.

Microcline and sanidine are found in minor amounts in all sandstones. Microcline composes 2.0 to 3.0 percent in the Geoffrey, Spray, and Gabriola Formations but only trace amounts are found in the De Courcy and Northumberland Formations. This increase in microcline content up section corresponds to the decrease seen in zoned plagioclase abundance. Such data may reflect a gradual change in source rocks or statistical error. The maximum abundance (3.0%) of microcline is found in the medium- to coarse-grained sandstones of the Gabriola Formation. Trace amounts are found in the medium- to coarse-grained sandstones of the De Courcy and Northumberland Formations. Statistically, a three percent difference is not necessarily an indication of greater abundance or a change in source rocks. The corresponding up section decrease in zoned plagioclase abundance can also be treated as statistical error. However, when microcline abundance trends and zoned plagioclase abundance trends are viewed together, a gradual change in source rocks is indicated.

Besides the major constituents, myrmekitic, graphic, and perthitic intergrowths were found to be ubiquitous to the sandstones of Hornby Island. These are largely restricted to the coarser-grained units and reflect an intrusive granitic to dioritic parent rock as a source.

Quartz. Quartz is the second most abundant mineral constituent found in the sandstones of Hornby Island and ranges from 14 to 37 percent. Four species of quartz are recognized: 1) monocrystalline normal quartz, 2) monocrystalline undulatory quartz, 3) polycrystalline quartz, and 4) chert.

The distinction between normal and undulatory monocrystalline quartz is not necessary in this type of study. Both types can be found in igneous plutonic and metamorphic rocks and therefore are poor indicators of source rocks (Blatt and Christie, 1963). Undulose extinction can also form as a result of post-depositional compaction (Connally, 1965). Because of a lack of criteria to distinguish between the three environments -- igneous intrusive, metamorphic, and sedimentary -- normal and undulatory quartz are considered as one mineralic group without genetic implications.

Monocrystalline quartz composes 7.8 to 33.0 percent of the total sandstones. The quartz is clear and angular and commonly contains regular to acicular inclusions of apatitie, zircon, and rutile (?) (Keller and Littlefield, 1950). Monocrystalline quartz abundance is not found to be grain size dependent although normal quartz is more abundant in the finer-grained sandstones (visual estimation). This is because undulatory quartz is less resistant to abrasional mechanisms (Blatt and Christie, 1963).

Polycrystalline quartz is present in varying amounts from 1.6 to 4.2 percent. Connally (1965) found polycrystalline quartz to be less stable than monocrystalline quartz and as such it is concentrated in the coarser-grained sandstones typical of low to moderate abrasive energy. In the coarser-grained sandstone units of Hornby Island, polycrystalline quartz averages 3.0 percent but only 1.6 percent in the finer-grained sandstones.

There are two types of polycrystalline quartz present in the upper Nanaimo Group sandstones: metamorphic and vein quartz. The metamorphic polycrystalline quartz is characterized by elongate, sutured boundaries and aligned muscovite and chlorite flakes. Vein polycrystalline quartz is characterized by straight, non- to slightly sutured boundaries, an absence of aligned mica flakes, and equant to bladed grain shape. These two types are found to be equal in abundance in any one sample (visual estimation).

Chert fragments are in most cases subordinate to polycrystalline quartz and vary in abundance from trace amounts to 4.8 percent. Again, the coarser-grained sandstones contain the greater abundance. Chert is a stable constituent of the sandstones and as such is not abraded very rapidly. One possible reason for the grain dependent relation is that the chert being weathered out of the source area has an inherent large grain size that is carried over to the depositional environment. Much of the chert has formed as a result of the devirification of silicic volcanic glass. If this devitrification took place after deposition in the sedimentary environment, the resulting chert would be concentrated in the coarser-grained sizes because that is where the parent glass fragments would have been concentrated. This is because glass has a very low tolerance to abrasion and would break down easily with a resulting apparent concentration in the coarser-grained sizes.

Chert is characterized by a microcrystalline to cryptocrystalline texture,cross-cutting secondary quartz veinlets, plagioclase phenocrysts, and spherulites of coarser-grained radiating chalcedony interpreted as replaced microorganism tests (Niem, 1977). The textures indicate two modes of origin for the chert fragments: one by devitrification of silicic glass that preserved the relict phenocrysts, and another from marine organic siliceous ooze. Modern studies of the ocean basins indicate that chert is forming from the replacement crystallization of siliceous ooze derived from dissolved siliceous microorganism tests. The cherts displaying the spherulites are interpreted as having formed in this manner.

Lithic Fragments. In the coarser-grained sandstones, lithic fragments represent the third most abundant group of framework grains. These range in abundance from 4.0 to 30.0 percent. However, it is noted that the coarse-grained units characterized by a low lithic fragment content are also characterized by a high diagenetic matrix content that is attributable to alteration of the lithic fragments. As a result, the low values of some of the sandstone lithic fragment contents may be misleading.

Andesite and basalt fragments are the predominant lithologies in this group of framework grains. They compose 2.5 to 19.3 percent and average 9.0 percent of the total composition of the coarse-grained sandstones. Hyaloophitic, hyalophilitic, and pilotaxitic textures are common. The groundmass of the individual fragments is altered to a greenish and greenish brown amorphous to fibrous material. In many instances, this grades imperceptibly into the matrix of the sandstone.

Schistose fragments of muscovite-chlorite-biotite, quartz-biotite, and quartz-muscovite composition are less abundant than the volcanic fragments but like the volcanics are ubiquitous to the coarser-grained sandstones of Hornby Island. These occur as elongate grains with ragged terminations which often have been deformed as a result of compaction. Prehnite is a rare constituent but when it does occur is associated with the quartz-biotite schists.

Igneous intrusive fragments are common to all upper Nanaimo Group coarse-grained sandstones and especially to the De Courcy, Geoffrey, and Spray Formations in which the average abundance of 1.5 percent is approximately three times greater than that for the Gabriola. However, statistically, this may not be valid. Compositionally, the fragments consist of quartz, plagioclase, orthoclase, myrmekite, biotite, and muscovite. This would classify the intrusive fragments as approximately granodiorite (Williams and others, 1954).

Micas. Micas make up a minor amount of the sandstones but like the major framework constituents, are present in all samples. Abundances range from 2.6 to 9.4 percent. Biotite is the most abundant (average 4.0); muscovite is next (average 1.5). Chlorite ranges from trace amounts to 2.0 percent and is particularly abundant in the Gabriola Formation.

The micaceous minerals occur as single flakes or as small booklets. In either case, they are almost invariably crenulated and penetrated by surrounding framework grains as a result of compaction.

Others. Heavy minerals constitute a very minor amount of the total rock. These minerals were identified in thin-section with the aid of a petrographic microscope and reflected light. Grain mounts were not attempted because of the tightly indurated nature of the rocks.

As a group, the heavy minerals constitute from 1.0 to 7.0 percent of the total rock. They are common to all the sandstones but are more abundant in some of the finer-grained units (e.g.: A-3, 21H, 85H, Appendix B), and relatively less abundant in some of the coarser-grained units (73B, 76H, 20H, 27H, Appendix B). Rubey (1933) found that softer heavy minerals were concentrated in finer-grained sandstones because of impact abrasion energy. It is known that quartz grains abrade very little during transport (Krynine, 1950). However, because of their greater density and mass, heavy minerals abrade relatively quickly. This is because their mass provides the necessary inertia to effectively abrade upon impact.

Abrasion effectively reduces the size of soft heavy minerals by breaking the grains into smaller fragments. These smaller fragments, having a greater density than quartz grains of equal size, will be deposited along with quartz grains of equal settling velocity. In the case of the softer heavy minerals, this is usually quartz of fine- to medium-grained size. Because of their abrasionally inherited small size, these same heavy minerals will not be deposited with the larger grain sizes because their settling velocities are too low. Hence, the larger grained sandstones are deficient in heavy minerals. This can be applied to explain the paucity of heavy minerals in the coarser grained sandstones of Hornby Island.

Epidote, magnetite, and zircon are ubiquitous to the heavy mineral suites of these sandstones. Magnetite is the most common accessory mineral (average 1.3%) and is almost invariably associated with hematite as an alteration product. Epidote and zircon, while widespread, are only present in trace amounts to 0.5 percent. Other heavy minerals that are considered important from a provenance standpoint are clear garnet, tourmaline, and sphene which may indicate a metamorphic of an acid igneous intrucive source.

Finely disseminated pyrite is present in trace amounts and occurs in aggregates of small grains. This may represent syn- or post-depositional bacterial decay or organic matter resulting in a reducing microenvironment and the formation of pyrite (Niem, 1977).

Other framework constituents that occur in the sandstones of Hornby Island are carbonaceous material and shell fragments. The carbonaceous matter is largely restricted to finer-grained interbeds and occurs as carbonized debris and coal stringers. Shell fragments are very rare in the sandstone units but are important from a paleoenvironmental standpoint.

Matrix

The sandstones of the upper Nanaimo Group rocks on Hornby Island contain varying amounts of detrital and diagenetic matrix. Matrix contributes from 0.0 to 21.5

percent of the total rick and is especially noticeable in the Geoffrey and Gabriola Formations.

Detrital matrix consists of silt-sized angular particles of quartz, feldspars and micas and probably clay-sized particles although these could not be readily distinguished from the diagenetic matrix. The detrital matrix was deposited with the coarser framework grains as evidenced by aligned mica flakes.

All of the samples studied have varying amounts of diagenetic matrix. This consists of a greenish to greenish brown paste-like material of amorphous to radiating-fibrous crystalline form that is very similar to celadonite, an alternation product of basaltic glass. There is ample evidence that the celadonite aff. matrix is a result of post-depositional alteration and recrystallization of volcanic lithic fragments. It has been recorded that the appearance of abundant diagenetic matrix coincides with the first occurrence of abundant volcanic lithic fragments (Hanson, 1976). In the samples studied from Hornby Island, volcanic lithic fragments constitute a major part of the total composition of the sandstones. These volcanic fragments are present in varying degrees of freshness, from slightly altered with distinct grain boundaries and pyroxene phenocrysts to highly altered with obscure grain boundaries and highly altered groundmass and mafic phenocrysts. In the case of the highly altered volcanic fragments, the altered groundmass passes imperceptibly into the intersitial matrix of the framework grains. This is good evidence that the matrix of the Hornby Island sandstones is largely diagenetic (see Cement Paragenesis).

Cement

Many of the Hornby Island sandstones are tightly cemented with calcium carbonate. Amount of cementation ranges from 0.0 to 33.0 percent but follows no definite pattern. The De Courcy and Northumberland samples average 26.0 percent cement. The Geoffrey sandstones, with lithologies and textures much like those of the De Courcy sandstones, average only 1.1 percent cement. In the Spray Formation, the finer-grained units average 32.0 percent while the coarser-grained thick-bedded sandstones average 1.5 percent. Gabriola sandstones average 5.0 percent cement. In a very crude and general sense, the finer-grained sandstones contain more calcium carbonate cement than the coarser-grained sandstones.

Calcite cement occurs as pore fillings and fracture fillings where the predominant crystal form is sparry calcite and microcrystalline calcite that is finely disseminated throughout the matrix. Such a relationship suggests replacement of matrix minerals. Indeed, replacement seems to have been the primary form of calcite crystallization. Many of the calcic plagioclase grains have been almost totally replaced by calcite. In some samples, framework grains appear to be floating, suspended in the calcite cement. This has been used as evidence for a replacement crystallization origin for the calcite (Niem, 1977).

In other sandstones, notably of the Geoffrey and Gabriola Formations, calcite cement is of very little importance. There is evidence of replacement of plagioclase by calcite but most of the sparry calcite cement in these rocks occurs as interstitial pore fillings. This suggests an outside source for the calcium carbonate such as the underlying marine mudstones rich in foraminifera tests. This hypothesis would necessarily require calcium carbonate to dissolve and migrate into the overlying sandstones. This would have had to happen before the formation of the diagenetic matrix which effectively filled all interstitial spaces and greatly reduced the capacity for pore fluid migration.

In a few samples (27H, 81H, 61H, 76H, Appendix B), iron oxide is present in trace amounts and forms a cement. This includes yellowish-orange limonite and reddish-brown hematite. This occurs as pore fillings and individual grain coatings. The origin of the iron oxide cement is probably secondary as a result of alteration of iron-bearing minerals. Evidence that suggests this is the close association of partially altered magnetite displaying hematite coatings. The iron oxide extends outward from these iron-rich centers and concentrates along grain boundaries.

Paragenesis. The understanding of the cement paragenesis is essential in unravelling the post-depositional history of these Late Cretaceous sandstones. This can be accomplished by studying carefully the grain-grain and cement-grain boundaries and noting their relations.

At time of deposition, the framework grains were deposited along with a small amount of detrital matrix (5% or less, see Gabriola Formation, Classification Section). Based on recent studies, detrital matrix found in modern coarse-grained sands is less than 10 percent (Pettijohn and others, 1973), and may be as little as 2 to 5 percent in modern turbidite sands (Niem, 1977). So it may be valid to say that there was little detrital matrix deposited along with the framework grains. Indeed, in sample 61H of the Gabriola Formation the matrix content is 5.1 percent. This sample was taken from a calcareous concretion and displayed no evidence for diagenetic alteration of the volcanic lithic fragments. So it may safely be assumed that there was approximately 5.0 percent matrix of detrital origin deposited with the framework grains. Since this is a coarse-grained sandstone much like those of the DeCourcy, Geoffrey, and Spray, it is assumed that they too contained no more than 5.0 percent detrital matrix at time of deposition.

The partial alteration of magnetite to hematitie indicates that shortly after deposition or burial, an oxidizing environment was established. The hematite migrated through pore spaces and was deposited in pore spaces and on grain surfaces. The hematite coated grains are coated with either calcite cement or diagenetic matrix. This sequence indicates that the formation of the iron oxide cement came before the calcite cement and diagenetic matrix.

Pore fillings of calcite occur in the Geoffrey and Gabriola sandstones. The calcite probably precipitated before the formation of the diagenetic matrix. Sample 61H of the Gabriola Formation (calcareous concretion) has virtually no diagenetic matrix and abundant fresh volcanic lithic fragments. Samples 65H and 76H have an average of at least five percent diagenetic matrix and abundant highly altered volcanic lithic fragments. This relationship indicates that early precipitated calcite cement inhibited the later formation of diagenetic matrix. Calcite could not have precipitated from solution after the formation of the diagenetic matrix because the matrix probably closed the available pore space and inhibited the pore fluid migration.

The replacement calcite cement was probably the last phase of secondary alterations. In some samples (27H, 65H) the diagenetic matrix has been partially replaced by calcite. Also, plagioclase, in some instances, is almost totally replaced by micro and sparry calcite.

Textural Aspects

The textural aspects considered here are grain size, sorting, and rounding. The grain size was determined by direct measurement in thin-section and applying the values to the Wentworth scale. Visual estimation and comparison with Folk's (1968) sorting chart were used to estimate sorting. Grain roundness was determined by visual comparison with Powers' (1953) roundness chart. These textural parameters are listed in Appendix D.

Grain Size. The thick-bedded sandstones of Hornby Island are moderately to poorly sorted and display a range of grain sizes from very fine- to very coarse-grained (Wentworth, 1922). However, the sandstones of the Northumberland and Spray Formations are predominantly fine- to medium-grained.

Sorting. Most of the sandstones found on Hornby Island are moderately to poorly sorted. However, some of the thin-bedded sandstones of the upper De Courcy, Northumberland, and Spray Formations are well sorted to very well sorted.

Roundness. All of the sandstones are angular to subangular with respect to quartz. Less resistant grains such as feldspars and lithic fragments are subangular to well rounded.

<u>Textural Maturity</u>. Textural maturity as defined by Folk (1951) involves the degree of sorting, the degree of rounding, and detrital clay content. His classification is a genetic one. He sees supermature sandstones as having undergone extensive mechanical energy to round, sort, and winnow the grains. Mechanical energy influences immature sandstones very little as they are characterized by clay-sized particles in excess of five percent, poor sorting, and unrounded grains. His submature and mature classes have undergone intermediate amounts of mechanical energy.

The thick-bedded submature sandstones of Hornby Island have undergone moderate amounts of mechanical energy. They are moderately to poorly sorted and in my interpretation contain less than five percent detrital clay-sized matrix. Rounding of grains is restricted only to those of low resistance to abrasion such as lithic fragments and orthoclase. Quartz is almost invariably angular to subangular and displays no quartz overgrowths. Plagioclase feldspars are angular to subangular that is probably a reflection of grain size and cleavage.

The thin-bedded intercalated sandstones of the Spray and Northumberland Formations display strikingly different textural characteristics from the thick-bedded sandstones of the De Courcy, Geoffrey, and Gabriola Formation. Sandstones are fine- to medium-grained, well- to very-well sorted and have less than five percent detrital clay-sized particles. The quartz grains are angular to subangular. These textural characteristics are indicative of mature sands that have undergone moderate to high mechanical energy. However, these sandstones are interpreted as distal turbidities. At first this seems contradictory because turbidites are generally thought of as being poorly sorted. However, in turbidite sedimentation, the coarser material is deposited first while the finer material is kept in turbulent suspension (Middleton and Hampton, 1973). The farther the turbidity current travels, the finer the material being deposited. Logically, somewhere in the distal areas fine-grained sand-sized material should be deposited with few larger grains present. I propose this type of mechanism to explain these thin-bedded texturally mature sandstones.

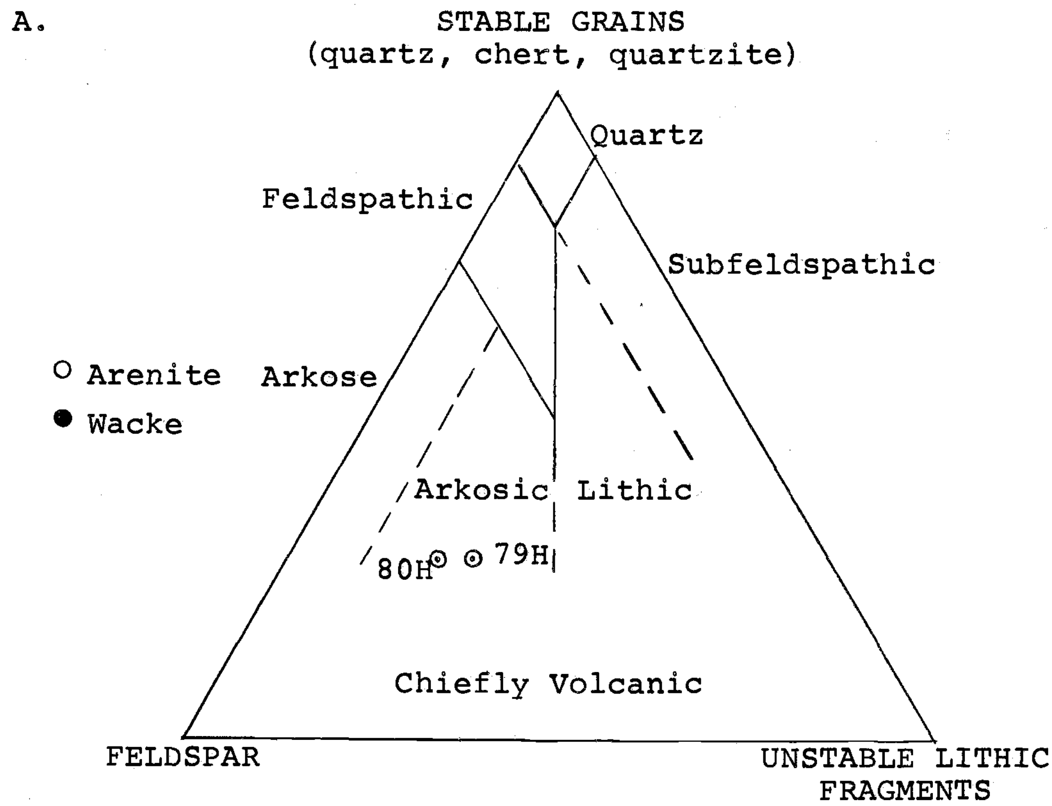
Classification

The Gilbert classification (in Williams and others, 1954) is used for sandstone classification. This classification utilizes ternary diagrams with stable grains (quartz, quartzite, and chert), feldspars and unstable lithic fragments as end members. Gilbert distinguishes wackes and arenites on the basis of 10 percent matrix, wackes having at least 10 percent matrix, arenites having less than 10 percent matrix. This classification is preferable to others because it is purely descriptive and is easy to use.

De Courcy Formation. Two samples of the De Courcy sandstones were analyzed by point count. Both of these plot as arkosic arenites (Figure 15A). Feldspars make up approximately 50 percent of the total rock. Quartz comprises 29 percent while lithic fragments make up the remainder of the major framework components. Detrital matrix constitutes only about 3.0 percent of the total rock.

Northumberland Formation. Northumberland rocks plot in the arkosic arenite and "arkose" fields (Figure 15B). The arkosic arenite (sample 73H) is a medium- to coarse-grained thick-bedded sandstone and contains abundant lithic fragments. Sample 85H is a fine- to medium-grained thin-bedded turbidite sandstone and consists of 66 percent feldspar and 30 percent quartz with only 4 percent lithic fragments. The difference between the two samples is a result of grain size, lithic fragments being more abundant in the coarser-grained sandstones.

Geoffrey Formation. All of the Geoffrey sandstones plot as arkosic wackes with one sample (27H) plotting in the "arkose" field (Figure 16A). These all are fine- to coarse-grained, moderately to poorly sorted, submature sandstones. Samples 5H and 27H have 52 and 55 percent quartz respectively while samples 20H and 45H have 21 and 19 percent quartz respectively. Samples 5H and 27H have an average of 29 percent feldspar and 17 percent matrix whereas



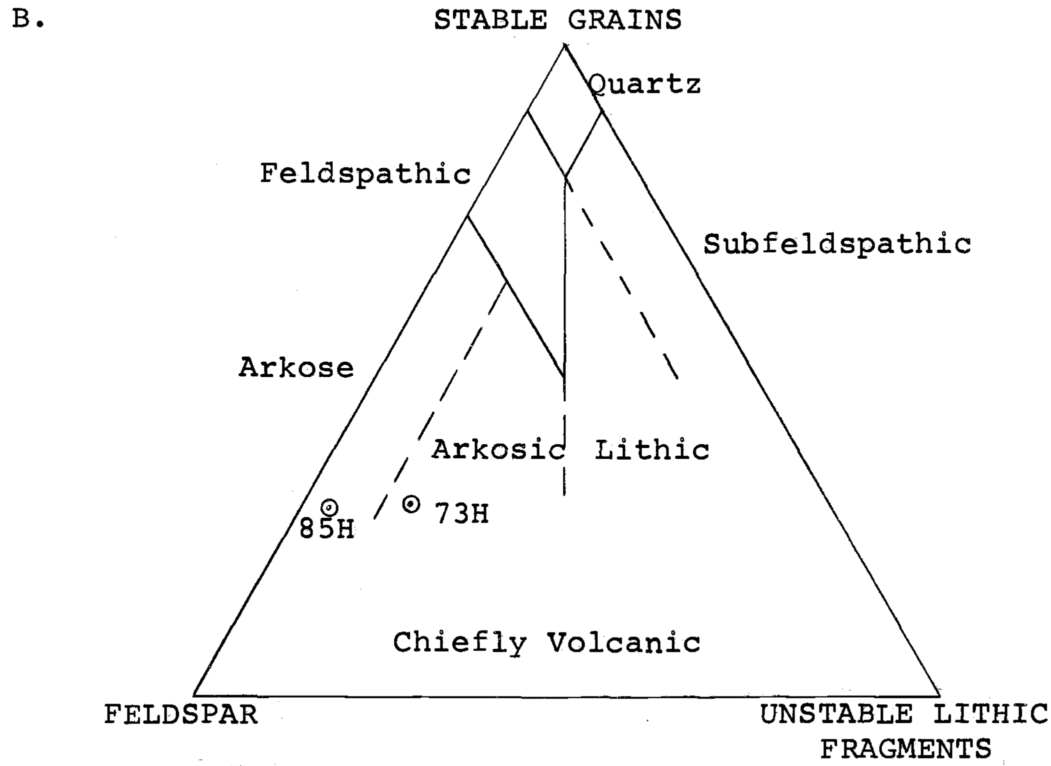


Figure 15. Classification of De Courcy Formation (A) and Northumberland Formation (B) sandstones (after Gilbert in Williams and others, 1954).

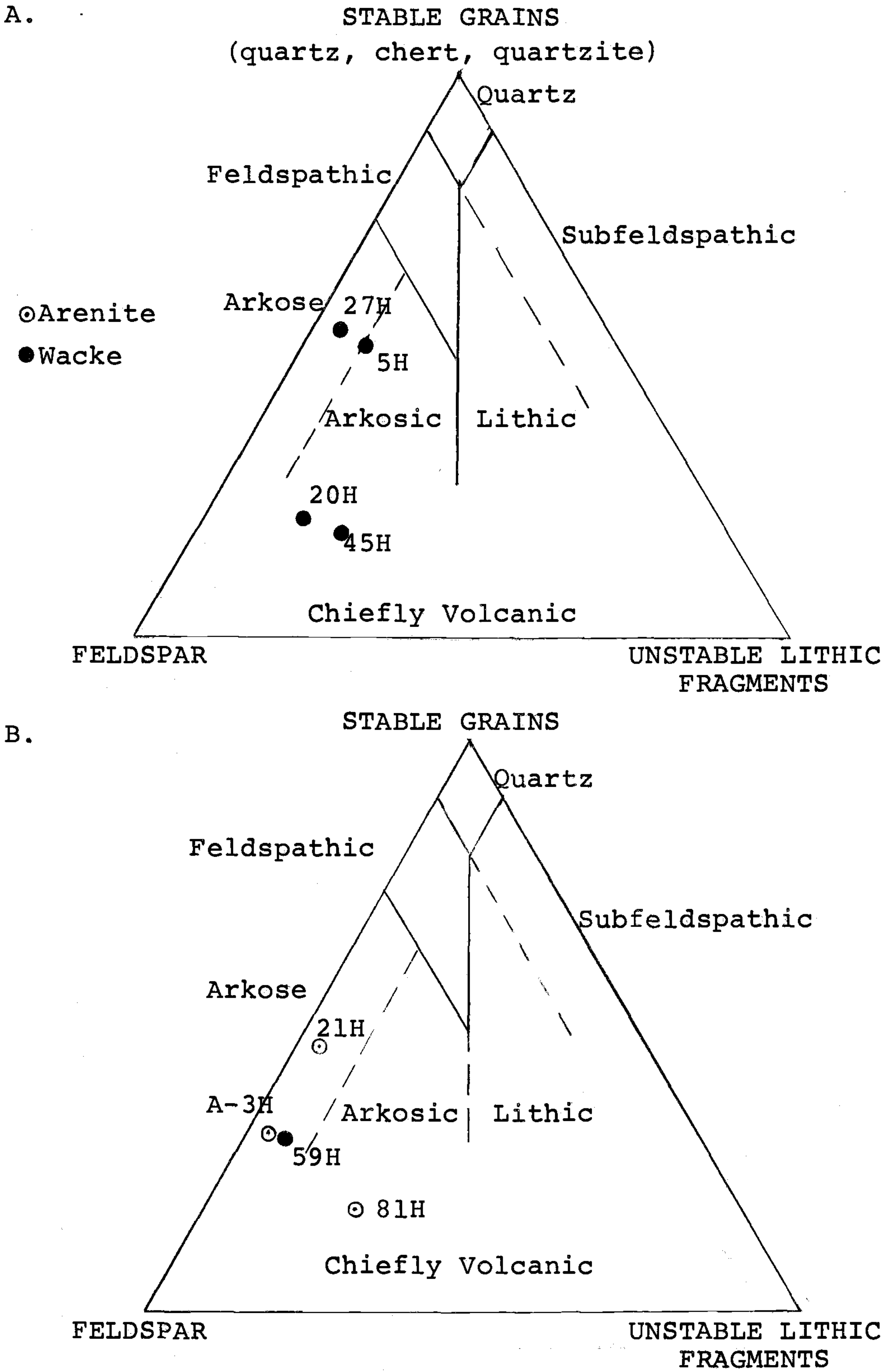


Figure 16. Classification of Geoffrey Formation (A) and Spray Formation (B) sandstones (after Gilbert in Williams and others, 1954).

samples 20H and 45H have an average of 41 percent feldspar and 21 percent matrix. Sample 27H was taken from a thick-bedded sandstone unit that is interpreted as a beach deposit. This is based on facies relationships, geometry, and internal structures. As such, the grains composing the sandstones would have been subject to greater amounts of mechanical abrasion which may explain the lesser abundance of the less resistant feldspar and lithic fragments and the apparent enrichment of the more resistant quartz. Since sample 5H displays similar lithologic characteristics, it is presumed that it too was deposited in a beach environment. Samples 20H and 45H contain a greater abundance of the less stable constituents indicating a history of much less abrasive energy.

Even though all Geoffrey samples plot as wackes, they were probably deposited as arkosic arenites. This is suggested by the abundant (average 15%) diagenetic matrix derived from altered volcanic lithic fragments.

Spray Formation. Three of the Spray sandstones plot as arkosic arenites and one as an arkosic wacke (Figure 16B). Two of the arenites (A-3H, 21H) and the wacke (59H) plot in the "arkose" field. However, sample 59H contains abundant diagenetic matrix derived from altered volcanic fragments and probably was deposited as an arkosic arenite. Like the Northumberland sample (85H), the two fine- to medium-grained turbidite sandstones plot in the "arkose" field. These two samples (A-3H, 21H) display a paucity of matrix (average 5.0%) of probable detrital nature.

Gabriola Formation. Two of the Gabriola samples (65H, 76H) plot as arkosic wackes while sample 61H is an arkosic arenite plotting very close to the lithic arenite field (Figure 17). Sample 61H was taken from a calcareous concretion and displays a great abundance of unaltered lithic fragments and only five percent matrix that is detrital in origin. The calcite cement occurs as pore fillings. It seems probable that the two wackes were deposited as arkosic or lithic arenites but because they lacked calcite cement (which effectively "sealed" sample 61H against alteration) were altered to wackes by post-depositional diagenesis. This is substantial evidence for pre-alteration preferential cementation by calcite (see Cement Paragenesis).

Conglomerates

A total of five samples were inspected, three from the Geoffrey Formation and two from the Gabriola Formation. Collection methods have been previously described (Investigative Methods). Between 100 and 200 pebbles of one to four inch size were identified from each sample. Pebble lithologies were determined by inspecting freshly broken surfaces with a 7 to 30 power binocular microscope and reflected light. The various lithologic groupings and relative abundances are given in Appendix C.

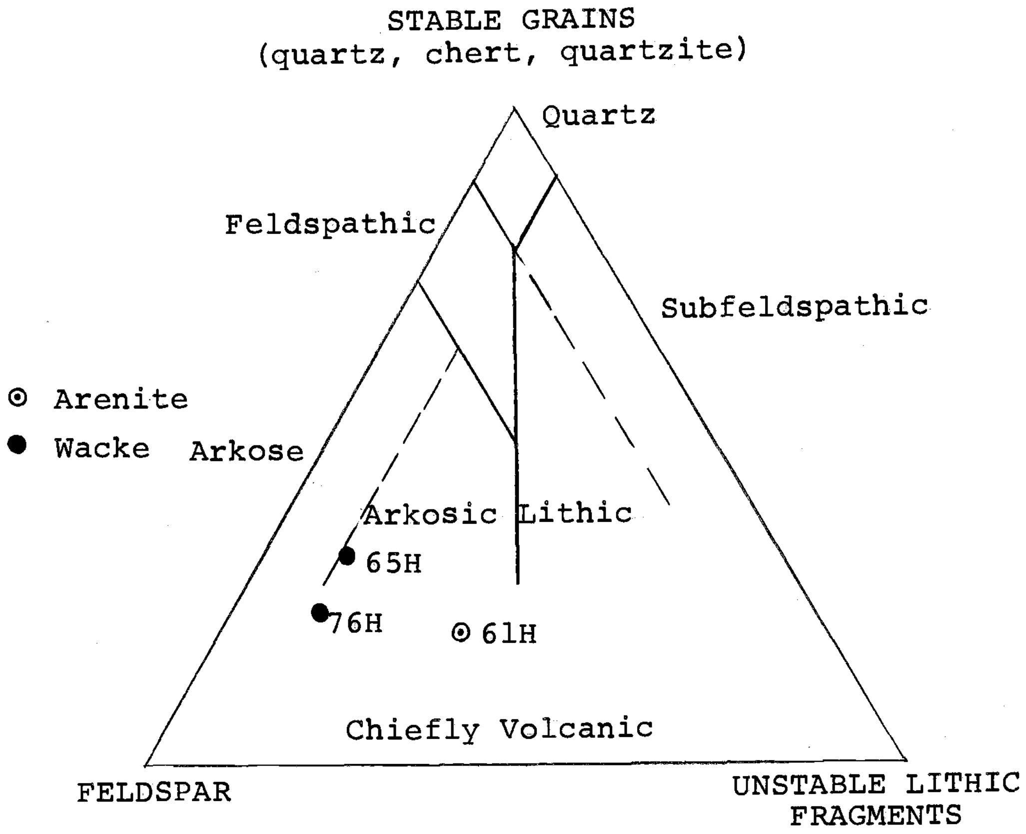


Figure 17. Classification of Gabriola Formation sandstones (after Gilbert in Williams and others, 1954).

The criteria for most lithologic groupings is based on mineral species content and texture and follows the definitions of Williams, Turner and Gilbert (1954). The distinction between basalt and andesite is poorly defined in macroscopic inspection so a color index criterion was adopted. The basalts are characterized by a very dark gray color and an aphanitic to very finely porphyritic and amygadaloidal texture. Andesites are considered to be those clasts of lighter gray to greenish-gray color and coarsely porphyritic texture.

The Geoffrey conglomerates consist predominantly of andesite (25%), basalt (17%), chert (18%), and metaquartzite (11.5%). The abundance of metaquartzite may be misleading because sample 3H contains an anomalously high 23 percent. Other samples contain an average of only 6 percent. An explanation for this discrepancy may be a change of source rocks. Sample 3H was taken low in the section whereas samples 2H and 39H were taken near the top. Clast size is not an influencing factor as all three samples are of approximately the same clast size.

Gabriola conglomerates consist predominantly of basalt (25%), andesite (15%), chert (15%), and metaquartzite (15%). The majority of the remainder consists of diorite (7%), granite (6%), and dacite (5%). The abundance of basalt and andesite is noticeably dissimilar to that of the Geoffrey conglomerates. The Geoffrey conglomerates contain 25 percent andesite and 17 percent basalt. This may reflect a change in source areas. However, the inverse relationship may be caused by statistical error since only five samples were taken. Also, the Geoffrey sample 3H indicates that there can be major lithologic variations even within the same formation.

Impure Limestone

Impure limestone pods occur within the thick mudstone units of the Northumberland Formation. These are located one-half mile southeast of Phipps Point. Field description of these limestone pods occurs in Appendix A, Northumberland Formation.

Two thin-sections were studied for the purpose of classifying and determining the origin of the limestone. Textures, detrital grain size and lithology, fossil content, and type of calcium carbonate present were especially noted. These limestones resemble fossiliferous micrite, containing greater than 66 percent lime mud matrix and 1.0 to 10.0 percent fossils (Folk, 1959). However, as noted by Hanson (1976), the calcium carbonate appears to be secondary and not a product of primary crystallization of carbonate ooze. Hanson classifies such secondary limestones as calcareous mudstones or argillaceous limestones.

Thin-section inspection reveals that these "pods" consist predominantly of calcareous mudstone with subordinate amounts of microspar and sparry calcite. The mudstone appears dirty and "felted" under plain polarized light. Silt-sized grains of detrital quartz and feldspar are present within the mudstone but constitute a small part (1%) of the total rock. Spherical and ellipsoidal "ghosts" are filled with coarser-grained microspar. These geometric forms are one to two millimeters across and probably represent replaced microfossils. Fecal pellets are common throughout the calcareous mudstone. Pyrite nodules from 0.1 to 1.0 millimeters in size are dissiminated throughout the "muddy" phases of the limestone. Pelecypod, ammonite, and scaphopod fossils are common to these rocks.

The origin of these argillaceous limestone pods is speculative at best but certain features suggest secondary crystallization. Internally, the calcareous mudstone displays discontinuous parallel laminations, much like that of the surrounding non-calcareous mudstone. Detrital silt-sized grains have etched grain boundaries suggestive of replacement. Finally, the mudstone that surrounds these argillaceous limestone pods contain an abundance of spherical to ellipsoid calcareous concretions of inferred preferential cementation origin. However, the apparent local abundance of fossils may indicate a localized microenvironment that was conducive to the in situ preservation of the biota and the formation of a calcareous deposit. Such an environment would probably have a reducing characteristic and be of very low energy. The abundance of fossils, particularly of pelecypods in growth position, indicate a lack of scavenging and current energy. The evidence to positively distinguish between a secondary or primary crystallization is lacking and further investigation is needed.

PALEOGEOGRAPHY

Paleocurrent Data

Reconstruction of the paleodispersal patterns for the rocks exposed on Hornby Island was accomplished by recording the attitudes of paleocurrent indicators -- unidirectional and bidirectional -- and plotting these on base maps (Figures 19 through 23). Local directional means for each formation were compiled and statistically treated to find the grand mean direction and the standard deviation (Royse, 1970). Bidirectional indicators are included in the statistical calculations to compensate for a paucity of unidirectional paleocurrent indicators and follow suggestions for this method by Potter and Pettijohn (1963).

In general, paleocurrent indicators are scarce in the exposed rocks of Hornby Island, especially in the sandstones. This is the result of several factors. First, the dip of the beds generally ranges from 5° to 8°. The low dip inhibits the exposure of the bottom surfaces where a majority of the unidirectional and bidirectional indicators -- flute casts and groove casts -- are found. Secondly, the majority of the sandstone beds have been eroded parallel to strike, thus cross-sectional views are seldom seen. Consequently, internal structures (e.g.: cross-bedding) can be used only rarely for the determination of paleocurrent flow. Lastly, many of the Hornby Island sandstones have a black manganese oxide surface staining and/or beehive and honeycomb erosional textures which obscure the internal structures.

Despite the dismal portrait described above, there are paleocurrent indicators to be found. The majority of these are bidirectional; that is, they indicate a trend in paleocurrent flow but do not specify from which direction it flowed. Bidirectional paleocurrent indicators that were recorded include groove casts, parting lineations, scour channel axes, pebble elongation, and aligned plant and fossil fragments.

Unidirectional paleocurrent indicators are less common in the sandstones of Hornby Island but are abundant in the Geoffrey and Gabriola conglomerates in the form of pebble imbrication. Unidirectional sole markings (flute casts) on the sandstone bed bottom surfaces are rare but can be found.

Paleocurrent Analysis

De Courcy Formation

The De Courcy Formation lacks well defined paleocurrent indicators. A total of six were measured in the De Courcy sandstones and include flame structures, channel axes, and slump structures. The grand mean is N. 42° E. with a standard deviation of 25°. Statistically, the

De Courcy grand mean is viewed with skepticism because of the low number of local measurements. Because of this, a valid statement about the paleodispersal system will not be attempted. However, the few scattered measurements do indicate a general southwest to northeast transport (Figure 18).

Northumberland Formation

A total of 13 paleodispersal indicators were recorded for the Northumberland Formation. These were all found in the thin-bedded intercalated sandstones and mudstones between Phipps Point and Collishaw Point. None were found in the southern exposures. A total of four unidirectional (flute casts) and nine bidirectional (groove casts, aligned fossil and organic debris) indicators were measured. The grand mean is N. 35° W. with a standard deviation of 17° (Figure 19). Again, the total number of measurements produces statistical instability but the low standard deviation suggests that this probability is a valid estimation of the paleodispersal.

Geoffrey Formation

Thirty paleocurrent measurements were taken from the Geoffrey conglomerates and sandstones at a total of 20 different geographic localities (Figure 20). The control of the Geoffrey Formation is very good because the topographic

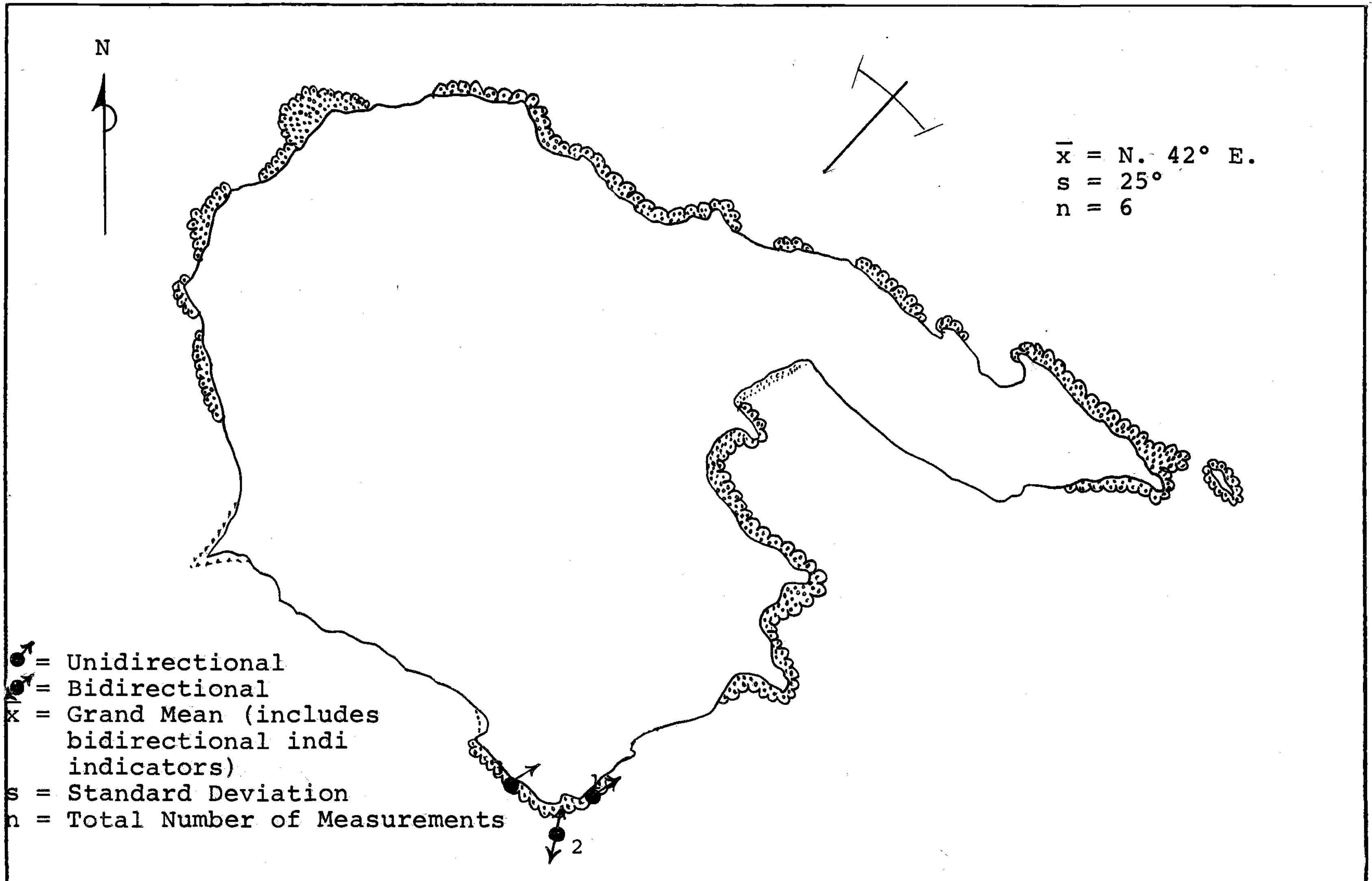


Figure 18. Local and grand mean paleodispersal directions for the De Courcy Formation.

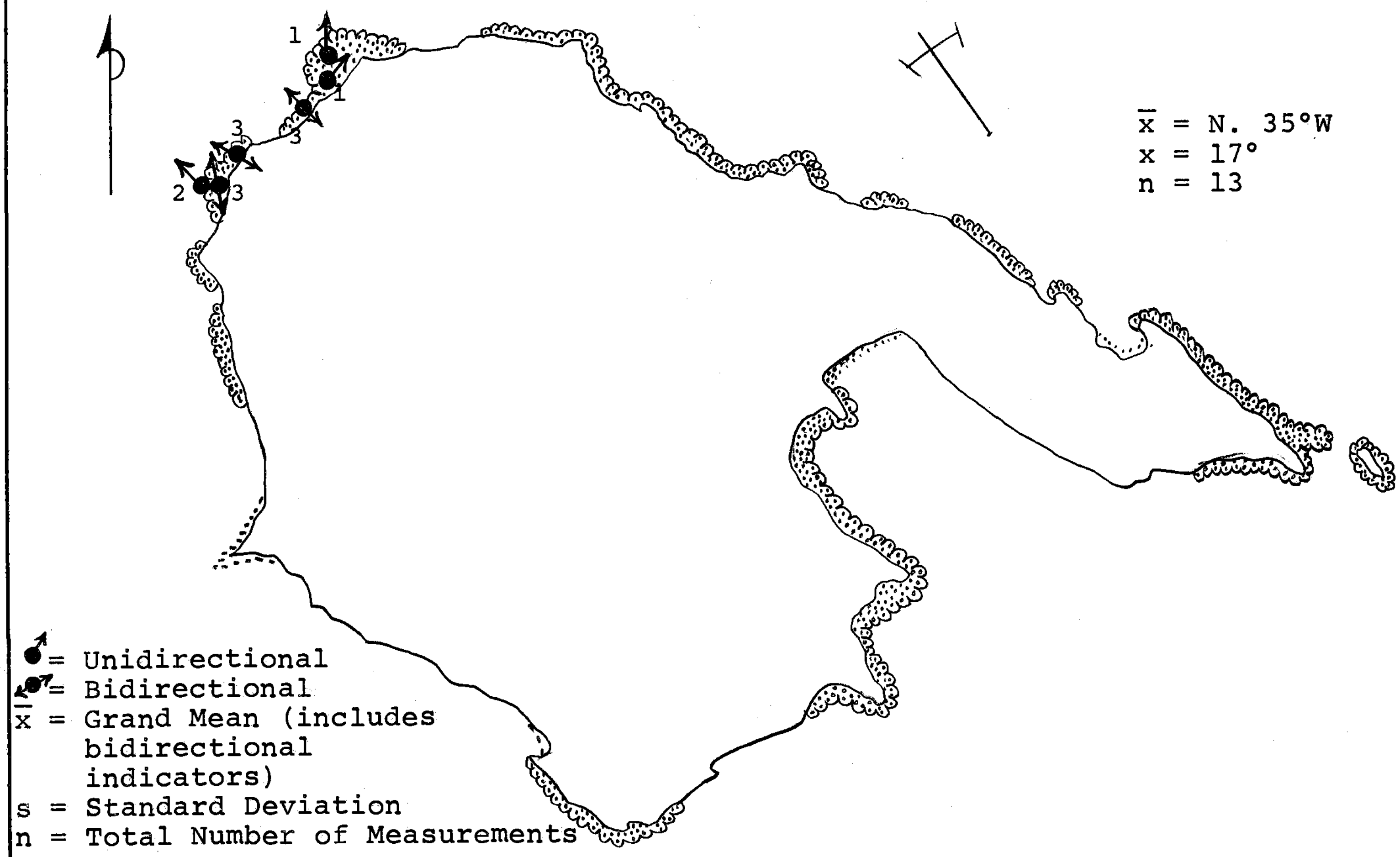


Figure 19. Local and grand mean paleodispersal directions for the Northumberland Formation.

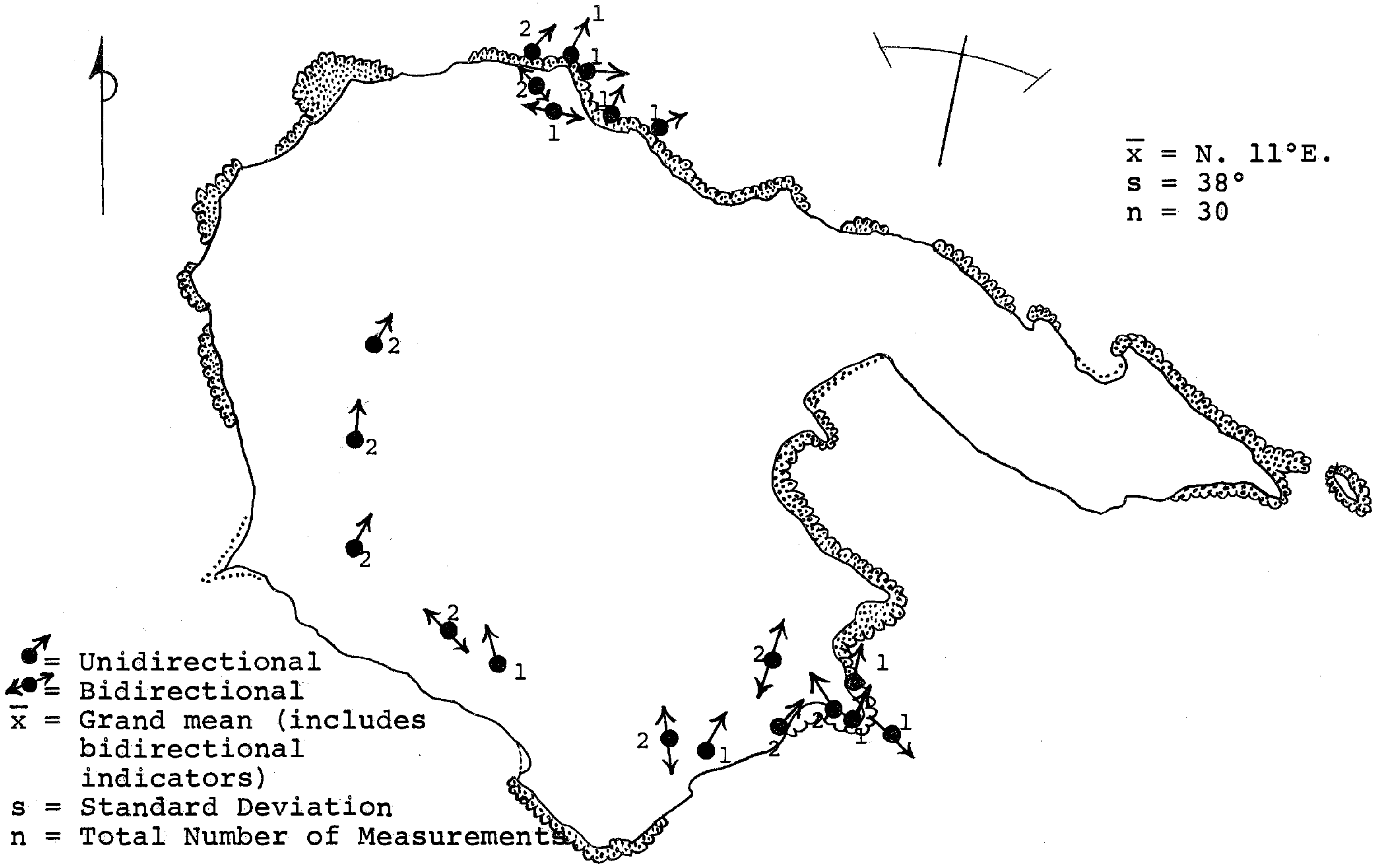


Figure 20. Local and grand mean paleodispersal directions for the Geoffrey Formation.

expression (resistant cliffs and wave-cut benches) provides nearly continuous outcrops the entire length of the island. Paleodispersal indicators include predominantly unidirectional pebble imbrication but also include bidirectional pebble elongation and channel axes. The grand mean is N. 11° E. with a standard deviation of 38°. As such, the Geoffrey is interpreted as the first major change in the paleodispersal pattern and differs from the N. 35° W. direction obtained for the Northumberland Formation.

Spray Formation

A total of 10 measurements were taken from the Spray Formation, all between Downes Point and Spray Point (Figure 21). Unidirectional indicators include rare flute casts and small scale,cross-bedding that indicate a N. 25° W. transport. Bidirectional indicators include groove casts and channel axes that suggest a N. 40° E. - S. 40° W. transport. The combined grand mean is N. 03° W. with a standard deviation of 39°. The low number of measurements produces a statistically invalid situation and only assumptions concerning paleodispersal can be made.

It is thought that the bidirectional channel axes represent the true trend of the paleodispersal and that the unidirectional indicators represent overbank deposition as is found in modern studies of deep sea fan turbidities (Walker and Mutti, 1973). The lateral facies relationships

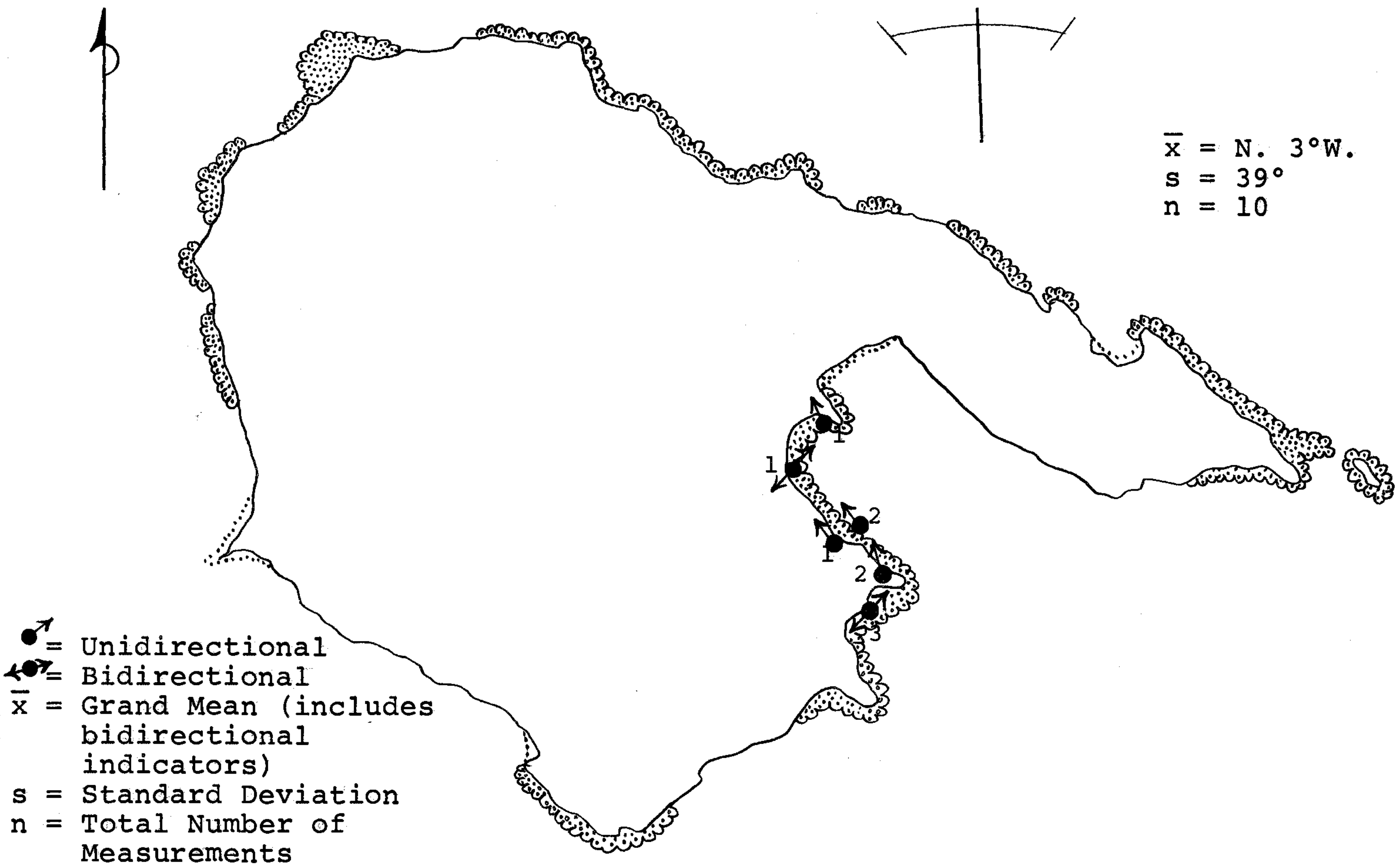


Figure 21. Local and grand mean paleodispersal directions for the Spray Formation.

(see Local Stratigraphy, Spray Formation) suggest that the Spray source lay to the southwest, thus indicating a northeast transport.

Gabriola Formation

Like the Geoffrey, paleocurrent indicators were measured at 20 geographic locations (Figure 22). Twenty-four attitudes were taken from pebble imbrication, pebble elongation, and channel axes. Control for the Gabriola is considered very good.

The grand mean is N. 13° W. and standard deviation is 48°. Like the Geoffrey, pebble elongation is oblique to or perpendicular to the unidirectional pebble imbrication. This explains the relatively large standard deviation.

Provenance Lithologies

The analysis of sandstone and conglomerate petrography can provide meaningful insight about the rocks of the source areas, the topography and weathering mechanisms in the source areas, and the conditions of deposition. The conglomerate clast lithologies are probably a good indication of source rock type although it is acknowledged that the less resistant rock types (foliated metamorphics and sedimentary) can be selectively decreased in relative abundance because of transport abrasion and differential weathering in outcrop. Thus, the relative abundance of the

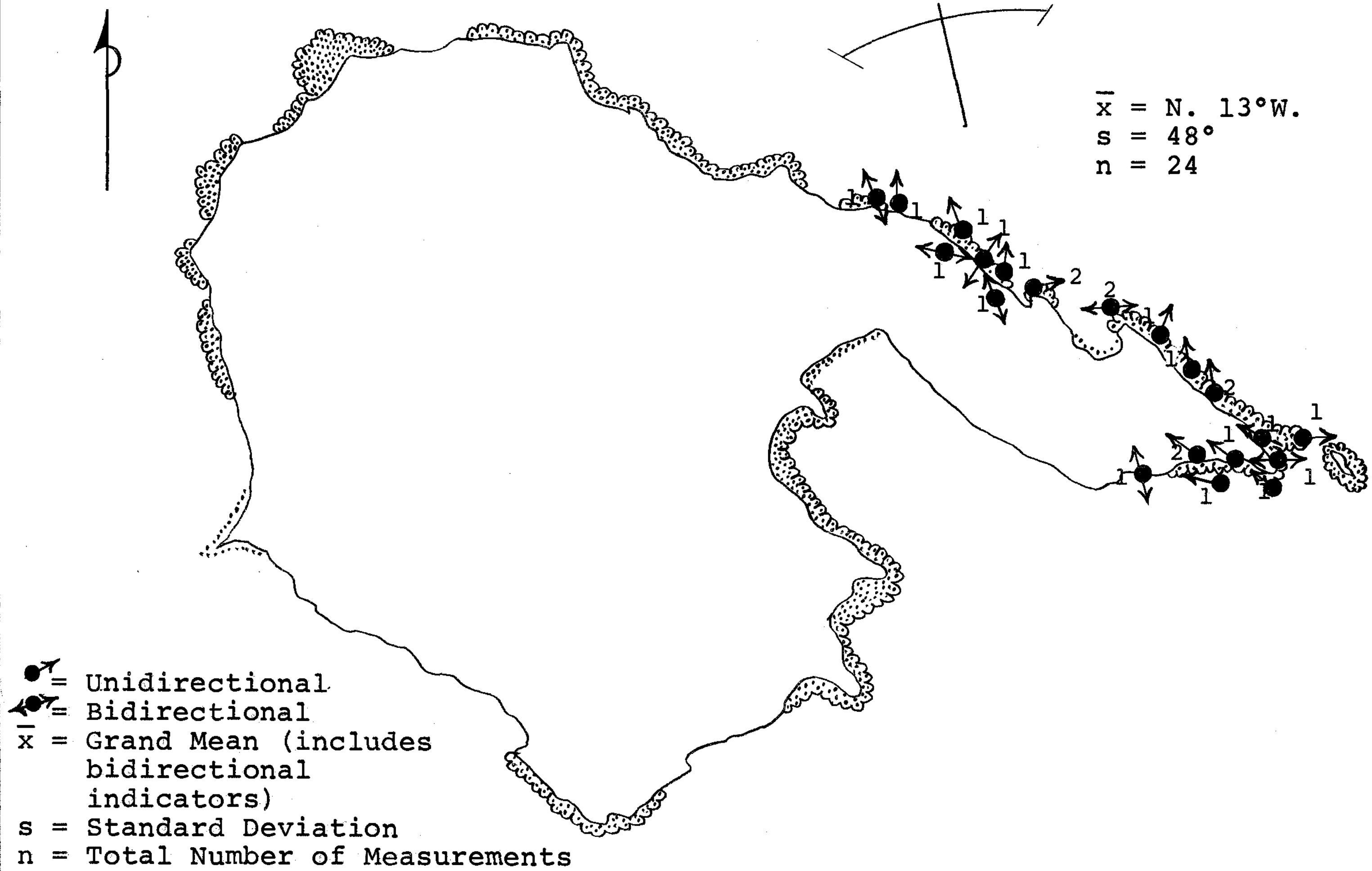


Figure 22. Local and grand mean paleodispersal directions for the Gabriola Formation.

more resistant lithologies (basalt, andesite, igneous intrusives) will increase.

The lithologically heterogeneous source area consisted of volcanic, igneous intrusive, metamorphic and sedimentary rocks (Appendix C). Several lines of evidence indicate that Vancouver Island was the source area for the clastic rocks of the Nanaimo Group of Hornby Island. First, the eastern and southern areas adjacent to Vancouver Island lack the basaltic and metamorphic rocks that were seen in the conglomerate clasts. Even though paleocurrent data suggests a southwest and southeast source, the paucity of compatible source rocks would preclude these areas as sources. Secondly, the fact that some of the conglomerate clasts consist of phyllite, mudstone, and sandstone suggests a short transport period with little reworking. Lastly, the conglomerate clasts have lithologic analogues that can be found on Vancouver Island. These are the Sicker Group, Karmutsen Basalts, Bonanza Volcanics, and the Island Intrusions.

The volcanic clasts in the conglomerates represent a majority (45%) of the total rock. Realizing that this is probably a biased figure, the assumption can still be made that the source area was composed of predominantly volcanic rocks, more specifically, andesite, basalt, and rhyodacite (see Appendix C). These clasts were probably derived from the Karmutsen Formation and Bonanza Volcanics that crop out to the west of Hornby Island on Vancouver Island.

Clasts of igneous intrusive quartz diorite to granite composition compose 18 percent of the total conglomerate clasts. These are similar to the Jurassic Island Intrusions described by Carson (1973) and rarely contain finely disseminated chalcopyrite that has been associated with porphyry copper deposits of Jurassic age (Muller and others, 1974).

Chert is the third most prevalent lithologic type (17%) and probably originated from interbedded chert layers of the Bonanza Volcanics and Sicker Group. Metaquartzite (12% of the total conglomerate clasts) probably had its origins in the pre-Sicker Group metamorphic complex.

The amount of chert and metaquartzite is anomalous to the relative abundance of parent rocks in the presumed source area. This may be explained by differential weathering and abrasion, the more resistant clasts withstanding greater amounts of abrasion than less resistant clasts and hence, becoming concentrated in the clastic detritus. Another possibility is that the chert and metaquartzite are recycled from older conglomeratic units such as those of the Sicker Group and Parson Bay Formation. Evidence to differentiate between the two modes of origin is lacking.

Minor amounts of foliated metamorphics, gneiss, aplite, vein quartz, and sandstone occur in the conglomerates of Hornby Island. Amounts range from one to four percent. However, the metamorphics and sandstones that comprise the "softer" lithologic types are easily broken down by abrasion. Therefore, the relative abundances (Appendix C) are thought to be misleading. The most that can be derived from the data is that there was some input from metamorphic, secondary igneous intrusive, and sedimentary source rocks.

Provenance Topography and Tectonic Implications

The study of grain textures in thin-section makes it possible to deduce certain aspects concerning the topographic relief of the source area, type of weathering prevalent in the source area, and the transportational and depositional history of the detrital grains. In general, fresh grains indicate a predominance of mechanical weathering, rapid transport, and quick burial at the depositional site. Such conditions could be attributed to a tectonically active area where source rocks were being uplifted (promotes rapid mechanical weathering, rapid transport) and depositional areas were subsiding (promotes rapid burial, little reworking). A tectonically inactive area would be characterized by a low-relief, mature topography (promotes chemical weathering, slow erosion and transport) and stable depositional conditions (promotes extensive reworking of sediments). This type of situation would produce clean sands consisting predominantly of stable grains.

There is a third possibility and that is a combination of active tectonic elements and associated intense chemical weathering. This type of situation would promote rapid erosion, rapid transport, and rapid burial. The resulting deposits would be characterized by an abundance of compositionally immature grains and textural immaturity fo submaturity (Folk, 1951). The detrital grains would be an admixture of fresh and altered caused by chemical and mecanical weathering (Krynine, 1950). This last hypothetical case best explains the compositional and textural characteristics of the Hornby Island sandstones.

In summary, the grains composing the Hornby Island sandstones are interpreted as having been eroded from a high-relief source area that consisted predominantly of andesite, basalt, quartz diorite to granite intrusions, chert and metaquartzite. The climate was conducive to chemical weathering as inferred from grain textures. Bell (1957) suggests a warm temperate to tropical climate on the basis of plant fossils.

Immature grain compositions (feldspars, lithic fragments), grain textures (partial alteration, angular terminations) and the generally poor to moderate sorting of the sandstones suggests rapid transportation and deposition with little reworking. This is most likely to occur in an actively subsiding depositional basin where sediment supply exceeds the rate of subsidence and results in marine regression.

GEOLOGIC HISTORY

It has been stated previously (General Straigraphy section) that the rocks underlying Hornby Island were deposited in Late Cretaceous time (Late Campanian through Maastrichtian and possibly early Tertiary) in what has been interpreted as a progradational delta sequence. As such, the Late Cretaceous-Early Tertiary (?) sequence of Hornby Island consists of offshore, nearshore marine, delta plain, and fluvial facies in repeated upward coarsening cycles. These have previously been described in detail in the Paleoenvironmental interpretation discussion.

Deposition of the Nanaimo Group clastic sequence occurred in the Georgia Seaway (Sutherland-Brown, 1966), a subsiding trough that lay off the northeast coast of Vancouver Island. Deposition of the Nanaimo Group was well advanced by the time the De Courcy rocks of Hornby Island were laid down in Late Campanian time. On Hornby Island, these rocks are of fluvial channel, interchannel, nearshore marine, and offshore facies that represent delta lobe progradation. Paleodispersal data is inconclusive but a general southwest to northeast transport is inferred. As such, the delta lobe transgressed eastward over the underlying Cedar District rocks of marine origin. The De Courcy sandstones of Hornby Island represent the last pulse of progradation in De Courcy time. The upper De Courcy rocks (turbidites northeast of

Norman Point) reflect an abandonment of fluvial sedimentation that is related to delta lobe switching and the onset of Northumberland offshore sedimentation.

The Northumberland Formation (latest Campanian-early Maastrichtian) represents the basal member of an upward coarsening cycle. It was characterized by long periods of slow marine sedimentation resulting in thick mudstone units and intervening periods of turbidite deposition that may have been deposited from the southeast. Again, a definite statement cannot be made because of the high degree of statistical error. The water depth has been variously interpreted from 30 feet to 1,800 feet (Sliter, 1973). The thick-bedded sandstones at Phipps Point are of fluvial origin and as such would tend to indicate a minor episode of deltaic progradation associated with a change in delta lobe deposition. The association of these sandstones with the thick offshore marine mudstones indicates that perhaps the deposition of the Northumberland took place in shallower water than that proposed by Sliter (1973).

The Geoffrey Formation (early Maastrichtian) represents the first well documented change in the paleodispersal pattern. Deposition began with fluvial and nearshore sandstones prograding over the Northumberland Formation. Within this basal sandstone unit are small intercalations (20 feet thick) of thin-bedded sandstones and mudstones that probably represent marine embayments, possibly estuarine in nature. The sandstones grade upward into a thick sequence of channelized conglomerates that issued forth from the southwest in highly competent streams. This was probably associated with continuing uplift to maintain the gradient and sediment input. The conglomerates intertongue with thick-bedded sandstones to the northeast that locally contain echinoid spines and indicate that the sea lay in this direction.

The Geoffrey conglomerates are overlain by sandstones of fluvial and nearshore marine character. These sandstones contain a thin tongue (50 feet thick) of marine turbidite deposits near the top of the section which attests to minor fluctuations in the sedimentation of upper Geoffrey sandstones. These fluctuations may have been caused by temporary distributary switching or a temporary reduction of sediment input.

The Spray Formation (early to late Maastrichtian) marks a return to marine turbidite sedimentation. The high sand/shale ratio prevalent in the bottom of the section attests to the proximity of the strand line. As time and deposition progressed, the sand/shale ratio decreased to one which suggests that either the strand line was gradually shifting to the southwest (as indicated by paleocurrent data) caused by basin subsidence and marine transgression or that sediment influx was waning as a result of distributory switching or waning source area uplift.

The thick-bedded sandstones of Spray Point mark an interruption in marine sedimentation and the onset of a short episode of fluvial sedimentation. This could have been brought about by distributary switching. The rapidity with which the transition from marine to fluvial sedimentation was made suggests that perhaps the depth of sedimentation was shallow and the slopes of the delta front were not steep. The remainder of Spray time was completely dominated by offshore marine sedimentation. Paleodispersal data is subject to high statistical error because of a low number of measurements. Hence, a definite statement cannot be made concerning the paleodispersal of the Spray Formation.

In latest Maastrichtian or early Tertiary time, the fluvial and nearshore marine rocks of the Gabriola Formation prograded over the Spray Formation. Widespread and abundant unidirectional pebble imbrication indicates that these rocks were deposited from the south-southeast.

The basal sandstones of the Gabriola consist of fluvial channel and interdistributary deposits and represent a progradational delta plain facies. The Gabriola conglomerates prograded over the delta plain facies and is interpreted to represent fluvial deposition similar to the Geoffrey conglomerates. The upper conglomerate member contains a marine tongue (Whaling Station Bay) that encroached for a brief transgressive period in Gabriola deposition.

This could be interpreted as the product of distributary switching or as a marine embayment of similar origin to that described in the Geoffrey.

Following deposition, the rocks of the Nanaimo Group in the Comox Basin were mildly folded to a southeast-plunging syncline. Faulting occurred either simultaneously or subsequent to folding and is represented by northeast and northwest-trending faults and fracture sets that are perpendicular to each other (see Structural Geology section). Following uplift, the glacial scouring and glacial outwash erosion modified the topography of Hornby Island leaving behind accumulations of glacio-fluvial deposits and boulder erratics which are strewn over the entire island.

STRUCTURAL GEOLOGY

Regional

The regional structure of the Vancouver Island area is dominated by faults -- thrust, transverse, and normal -- that are thought to be surface manifestations of a deeper inherent fault system created during the subsidence of a tectonic Jurassic highland that formed the Georgia Seaway (Sutherland-Brown, 1966). Muller and Jeletzky (1970) concur with this hypothesis and suggest that the basement consists of northeast-tilted fault blocks that are bounded by northwest-trending faults. As a result of Late Cretaceous and Tertiary movement along these zones of weakness, northwest- and northeast-trending fault systems have developed in the overlying Cretaceous rocks.

Folding has also been reported from the Vancouver Island vicinity and like the faulting, is attributed to subsurface movements along the pre-Cretaceous fault systems (Buckham, 1947). Both anticlinal and synclinal fold axes trend northwest (Sutherland-Brown, 1966).

Vancouver Island is tectonically active with seismic activity common, especially in the southern half. This has been attributed to the subduction of the San Juan Plate at the interplate boundary between the Pacific and North American plates (Crosson, 1972). Various studies have indicated that the fault scarp bounding Vancouver Island to the southwest is caused by an active right-lateral strike-slip fault (Queen Charlotte-San Andreas Fault System) and has caused regional north-south or northeast-southwest compressional stresses (Atwater, 1970; Monger and others, 1972; Crosson, 1972; Mayers and Bennett, 1973). Such a stress system would lend itself to the formation of northwest-trending normal faults.

Local

Structural deformation is not as intense in the Comox Basin as it is in the Nanaimo Basin. Indeed, nearly all the beds exposed on Hornby Island have homoclinal dips ranging from 4° to 15° whereas strata in the Nanaimo Basin are often tilted to vertical.

Richardson (1878) suggests that Hornby Island lies on the southwest limb of a southeast-plunging syncline. Bedding attitudes are inconclusive but do suggest broad synclinal folding (Plate 1). The arcuate outcrop pattern also suggests broad folding. Minor folds other than those attributed to a soft-sediment deformation were not found.

Faulting was found to be widespread and is especially well exposed in the wave-cut benches. The predominant faulting styles consist of near vertical normal and strike-slip faults with maximum vertical displacement of 100 feet. Hoen (1958) interpreted a hinge fault trending northwest between Shingle Spit and Ford Cove with the southwest side and northwest end down. Maximum displacement is approximately 400 feet. However, in my opinion this is a slump block. Extrapolation of Hoen's hinge fault dictates that if faulting occurred, the fault trace should be in the sea cliff north of Shingle Spit. It does not exist. Therefore, I interpret the downthrown block as a gravity slump block probably caused by the undercutting of the underlying less resistant Northumberland Formation.

A major fault trends northwest with the southwest side down between Phipps Point and Collishaw Point. Displacement is estimated between 50 and 100 feet and is best exposed in the northwest-facing cliff of Mt. Geoffrey.

Figure 23 represents 45 bearings taken on the fault planes, fault traces, and joint traces. It very definitely shows two sets of structural trends: one to the northwest, the other to the northeast. Field observations indicate that the northeast-trending faults are offset by the northwest-trending faults, hence revealing a relative time of formation. However, this relationship was found to be nonrepresentative in all cases with the northeast trending faults offsetting northwest trending faults.

The structure of Hornby Island does indicate that it was caused by north-south or northeast-southwest compressional stresses. However, the magnitude of deformation is definitely lower than in the Nanaimo Basin. One

44 bearings

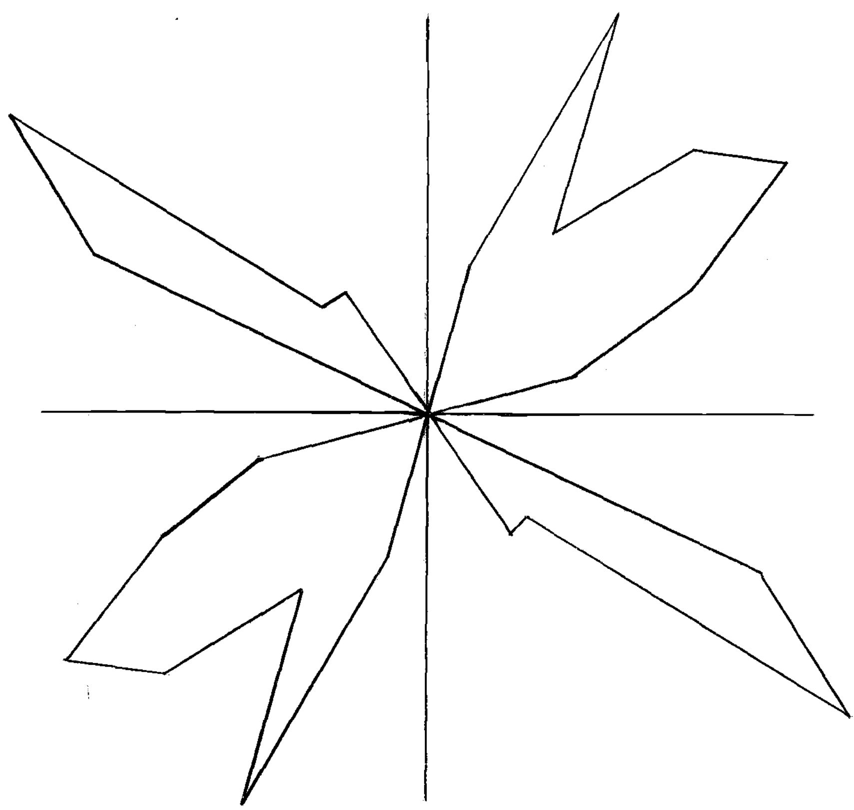


Figure 23. Structural rosette diagram for Hornby Island. Fault traces, fault planes and joints display northwest and northeast trends.

explanation for this relationship is that the Nanaimo Basin underwent greater stresses and that these stresses dissipated to the north. Hanson (1976) and Stickney (1976) have described transverse faults from the Nanaimo Basin. Perhaps movement along these faults can explain the greater magnitude of deformation.

PETROLEUM POTENTIAL

The petroleum potential was evaluated for the rocks of Hornby Island. This involved the analysis of Northumberland source rocks (mudstones) by using a Turner #110 Fluorometer and the analysis of reservoir rocks (sandstones) by determination of void space in thin-section.

All but one of the samples analyzed for source rock quality contained between 30 and 56 PFU (Pyrolysis-Fluorescence Units) hydrocarbon. In terms of weight percent, these samples contain between 0.5 and 1.3 percent live hydrocarbons. These values are equivalent to marginal source rocks. Several samples contained less than 0.5 weight percent live hydrocarbons and are classified as non-source rocks. However, these samples were slightly weathered and contained iron oxide stain that could have invalidated the results. Therefore, the mudstones of the Northumberland Formation do have the potential to yield petroleum.

Reservoir rocks on Hornby Island are rare. Most of the sandstones are tightly cemented or bound by calcium carbonate and diagenetic matrix. Void space determination by point counting thin-sections ranged from zero to two percent but was found in three of the fifteen samples counted (Appendix B). Therefore, despite the presence of hydrocarbons and the likelihood of stratigraphic traps, the lack of porosity would tend to discourage the collection of petroleum.

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APPENDICES

APPENDIX A

Representative Measured Section D-D', De Courcy Formation

Representative intervals of each formation on Hornby Island were measured to provide detailed descriptions. This was accomplished by using a five-foot Jacob's staff and a mounted Abney level, Brunton compass, sand gauge, and a rock-color chart (Goddard and others, 1970). Field descriptions were facilitated by the use of a 10x hand lens and (0.1N) hydrochloric acid.

The measured section D-D' of the De Courcy Formation is located between Norman Point and Ford Cove. This location was chosen because of the good exposure and stratigraphic control.

The terminal point (D', plate 1) is located in the sea cliff in the S.W. corner of the S.W.¼ of the S.W.¼ of section 2 below the Bait and Tackle Shop at Ford Cove. The ferry landing on the east coast of Denman Island lies on a bearing of N. 72° W. from D' and the light on Chrome Islet lies on a bearing of S. 15° W. from D'.

Interval feet	Description

Unit Description: Sandstone, cliff and bench former, light olive gray (5Y 6/1) and yellowish gray (5Y 7/2) weathered, medium gray (N5) fresh. Medium- to very coarse-grained, poorly sorted, angular to subangular, feldspar, quartz, lithic fragments, and micas tightly cemented with calcite. Mudstone rip-ups and pebbles to 0.5 inches in diameter common. Internal structures: festoon cross-bedding, horizontal bedding, and normal grading. Beds are thick to very thick, ranging from 2 to 7 feet. Upon weathering, these sandstones form beehive and honeycomb structures and gallery structures.

Sandstone, light olive gray (5Y 6/1) to light gray (N8) weathered, medium light gray (N6) fresh. Fine-grained, angular to subangular, moderate to well sorted, predominantly consists of feldspar, quartz, and micas. Thin parallel laminations, flame structures and contorted bedding common. Normally grades into overlying siltstone. Coal stringers and carbonized plant debris very common and aligned parallel to bedding. These rocks occur rhythmically bedded and pinch out to the southeast.

90	- 100	Thick- to very thick-bedded sandstone as in unit description. Gallery structure well developed.
87	- 90	Thin-bedded sandstone and siltstone as in unit description.
78	- 87	Thick- to very thick-bedded sandstone as in unit description.
		Offset 30 feet along bearing N. 05° W. to pick up beds in sea cliff. Attitude: N. 80° W., 5° N.E. Proceed along bearing N. 10° E.
76	- 78	Thin-bedded sandstone and siltstone as in unit description.
70	- 76	Thick- to very thick-bedded sandstone as in unit description. Honeycomb weathering texture less pronounced, clacareous cement is less abundant. Sandstones form flat benches.
68.5	- 70	Thin-bedded sandstones and siltstones as in unit description. Intense horizontal and vertical bioturbation.
50.5	- 68.5	Thick- to very thick-bedded sandstones as in unit description. Beds range from two to seven feet in thickness.
49	- 50.5	Thin-bedded sandstones and siltstones as in unit description.
		Offset 60 feet along bearing N. 05° W. to pick up beds in sea cliff. Attitude: N. 75° W., 4° N.E. Proceed along bearing N. 15° E.
30	- 49	Thick- to very thick-bedded sandstones as in unit description. Honeycomb weathering texture very pronounced. Scour-and-fill channels are prevalent and filled with mudstone breccias. Thin interbeds of siltstone are intensely bioturbated.
29	- 30	Thin-bedded sandstones and siltstones as in unit description.

15 - 29		Thick- to very thick-bedded sandstones as in unit description.
		Offset 40 feet along strike to pick up stratigraphically higher beds. Attitude: N. 67° W., 5° N.E. Proceed along bearing N. 23° E.
0 - 15		Thick- to very thick-bedded sandstones as in unit description. Beehive and honeycomb erosional textures very well developed in wave-cut bench. Scour-and-fill channels common and filled with mudstone breccias.

Initial point (D, plate 1) is located in the center of the S.E.¼ of the N.E.¼ of section s18. This point was arbitrarily chosen for the degree of exposure and stratigraphic continuity it offered. The ferry landing on the east coast of Denman Island lies on a bearing of N. 69° W. from D and the light on Chrome Islet lies on a bearing of S. 28° W. from D. Starting attitude is N. 65° W., 5° N.E. The section is measured stratigraphically up heading N. 25° E.

APPENDIX A-a

Representative Measured Section N-N', Northumberland Formation

The measured section N-N' of the Northumberland Formation is located between Shingle Spit and Phipps Point. This is thought to represent the lower Northumberland Formation on Hornby Island and does not include the turbidite sequences northeast of Phipps Point.

The terminal point (N', plate 1) is located at a large sandstone dike that forms a resistant "wall" in the surrounding mudstones of the wave-cut bench. This occurs in the N.E.¼ of the N.E.¼ of the S.W.¼ of section 13. The ferry landing on the east coast of Denman Island lies on a bearing of S. 30° W. from N' and Mt. Geoffrey lies S. 35° E. from N.

Interval Feet	Description

Unit Description: Mudstone, greenish black (5G 2/1) and dark reddish brown (10R 3/4) weathered, greenish black

(5G 2/1) fresh. Non calcareous, contains very fine-grained sand sized and silt sized grains of quartz and feldspar, angular to subangular. Very fine-grained nodules of pyrite (marcasite ?) disseminated throughout in small (1 to 2 mm) local clusters. Locally fossiliferous with ammonites, pelecypods, scaphopods, and fish vertebrate (?) common to abundant in places. Fossils usually crushed and unidentifiable except when found in calcareous concretions.

Internally the mudstone is unevenly parallel laminated. Bioturbation and plastic deformation structures prevalent. Calcareous concretions (2 to 15 inches in diameter) of spherical, ellipsoidal, and rod-shaped geometries are abundant throughout. Entire unit weathers to a hackly appearance with chips and small blocks.

Sandstone, moderate yellowish brown (10YR 5/4) weathered, medium bluish gray (5B 5/1) fresh. Fine- to medium-grained, moderately sorted, tightly cemented with calcium carbonate. Consists of angular to subangular grains of feldspar, quartz, and chert. Sharp undulatory bottom contact. Sandstone grades upwards into overlying mudstone. Internal structures: parallel laminations, cross-ripple laminations. The sandstone and siltstone occur as thin interbeds and the top surfaces are often covered with sand filled horizontal burrows.

Sandstone dikes occur throughout the unit, dusky yellowish green (10 GY 3/2) weathered, grayish green (5G 5/2) fresh. Consist of fine- to coarse-grained, poorly sorted, angular to subangular feldspar, quartz, micas, and mudstone rip-ups. The rip-ups range in size from 0.5 to 3 inches in length. The sandstone dikes range in thickness from 4 inches to 3 feet and form resistant ribs in the less resistant mudstones of the wave-cut bench.

103 - 106	Sandstone dike as described in the unit description.
76 - 103	Mudstones and thin interbedded sandstones and siltstones typical of unit description.
	Offset 75 feet along N. 20° W. to pick up stratigraphically higher beds. Same attitude.
75 - 76	Sandstone dike forming resistant rib structure typical of unit description.
70 - 75	Mudstones typical of unit description
49 - 70	Covered by water

	Offset 167 feet to pick up stratigraphically higher beds. Attitude: N. 20° W., 11° N.E. Proceed up section N. 70° E.
43.5 - 49	Argillaceous limestone pod, light bluish gray (5B 7/1) and greenish yellow (10Y 7/4) weathered, dusky blue green (5BG 3/2) fresh. Consists of micrite, sparry calcite, vug and vein fillings of sparry calcite, and finely disseminated pyrite nodules (0.5 mm). Contains abundant fossil remains of ammonites, pelecypods, and scaphopods. The limestone forms resistant mound-shaped structures with a "scoriaceous" weathering texture. Internal structures are obscure. Contact with the surrounding mudstones is sharp.
35.5 - 43.5	Mudstones and interbedded siltstones typical of unit description.
31 - 35.5	Mudstones and interbedded siltstones typical of unit description.
20 - 31	Mudstones and sandstone dike (1.0 feet wide) typical of unit description.
15 - 20	Mudstones and interbedded sandstones and siltstones typical of unit description.
	Offset 30 feet along strike to pick up stratigraphically higher beds. Attitude: N. 38° W., 11° N.E. Proceed N. 52° E. up section.
0 - 15	Mudstones and siltstones typical of unit description.

Initial point (N, plate 1) located in the N.W. corner of the S.W. of the S.E. of the S.W. of section 13. The ferry landing on the east coast of Denman Island lies on a bearing of S. 48° W. from point N and Phipps Point is N. 18° W. from point N. Starting attitude is N. 45° W., 7° N.E. Proceed N. 45° E. up section.

APPENDIX A-b

Representative Measured Section G-G', Geoffrey Formation

The measured section G-G' of the Geoffrey Formation is located between 1/4 mile west of Gallean Beach and Gallean Beach Park. The section includes the lower thick- to very thick-bedded sandstones and the lower part of the overlying conglomerates.

The terminal point (G', plate 1) is located on the northernmost point of Gallean Beach. This is located on the map at the N.E. corner of the N.E.¼ of the N.W.¼ of section 16. Triangulation location could not be used because of a lack of suitable landforms.

Interval Feet	Description

Unit Description: Sandstone, cliff and bench former, light olive brown (5Y 5/6) weathered, grayish green (10GY 5/2) fresh. Medium- to very coarse-grained, poorly to moderately sorted, tightly cemented with calcium carbonate. Consists of feldspar, quartz, lithic fragments and micas. Sharp planar to undulatory bottom contacts. Sandstones grade upward into siltstone. Bed thickness ranges from two to four feet. Internal structures consist of festoon (?) cross-bedding, cross-ripple laminations, mudstone rip-ups, and contorted mudstone interbeds. These rocks weather to resistant beehive and honeycomb structures. Locally, these rocks contain abundant marcasite or pyrite nodules (1/2 to 3 inches diameter) that weather to reddish brown iron oxide.

Conglomerate, cliff and bench former, grayish brown (SYR 3/2) weathered, grayish olive (10Y 3/2) fresh. Poorly sorted, ranging from granules to boulders (2 to 256 mm), tightly bound by a calcium carbonate cemented sandstone matrix. The clasts consist predominantly of andesite, basalt, silicic igneous intrusives, metamorphics, and chert. Internally the conglomerates are normally graded displaying pebble imbrication and elongation. In cross-section, scour-and-fill channels are common.

Interbedded within the conglomerates are channel sandstones of lenticular geometry. These are moderate olive brown (5Y 4/4) weathered and grayish green (5G 5/2) fresh. Moderate to poorly sorted, medium- to very coarse-grained and tightly cemented with calcium carbonate.

Grains are angular to subangular and consist of feldspar, lithic fragments, quartz and micas. Internal structure consists of normal grading and cross-ripple lamination. Pebble trains and mudstone rip-ups are common.

90 - 100	Typical of unit description, conglomerate and interbedded lenticular sandstones. Offset set - 70 feet along bearing N. 30° E. to pick up stratigraphically higher beds. Attitude: N. 28° E. 5° S.E., Proceed S. 62° E.
75 - 90 a	Typical of unit descriptions, conglomerate and lenticular sandstones. Offset 30' along bearing N. 30" E. to pick up stratigraphically higher beds. Attitude N. 22° E., 4° S.E. Proceed S. 68° E.
50 - 75	Covered by driftwood pile Offset 35 feet along bearing N. 30° E. to pick up stratigraphically higher beds. Attitude N. 22° E., 4° S.E. Proceed N. 22° E.
25.5 - 32	Typical of section, conglomerates and lenticular sandstone. Contact: sharp, erosional, conglomerates in vertical scour contact with thick-bedded sandstones.
0 - 25.5	Typical of section, thick to very thick-bedded sandstones. Marcastie or Pyrite (?) nodules especially abundant in a 2 foot zone below the scour contact.

The initial point (G, plate 1) is located 0.25 miles east of the salient that comprises Gallean Beach. Point G occurs on the map at the N.W. corner of the N.E.¼ of the N.W.¼ of the N.W.¼ of section 16. Triangulation location methods could not be used because of a lack of suitable landforms.

APPENDIX A-c

Representative Measured Section S-S', Spray Formation

The measured section S-S' of the Spray Formation is located between Downes Point and Dunlop Point. The section includes the lower 200 feet of the Spray Formation and consists of thin-bedded intercalate sandstones and mudstones.

The terminal point (S', plate 1) is located on the wave-cut bench below a red house surrounded by a grove of alder trees. Map location is in the center of the N.E.¼ of the S.W.¼ of the N.E.¼ of the N.E.¼ of section 1. Dunlop Point lies on a bearing of N. 55° E. from S' and Downes Point lies at S. 10° E. from S'.

Interval Feet	Description

Unit Description: Intercalated thin-bedded sandstone and mudstone in repeated graded packets. The more resistant sandstone beds from rib structures in wavecut bench. Color is moderate olive brown (5Y 4/4) and light olive gray (5Y 5/2) weathered, medium bluish gray (5B 5/1) and yellowish gray (5Y 7/2) fresh. Fine- to medium-grained, moderately to well sorted, some beds tightly cemented with calcium carbonate. Grains are angular to subangular and consist predominantly of feldspar and quartz. Bottom contact is sharp and planar. Beds are laterally continuous for 200 yards and display a subtle thinning to the southeast.

Internally the sandstones display the BCE and DE Bouma units. They grade upward into a sandy siltstone and mudstone. This is olive gray (5Y 4/1) weathered, dark gray (N3) fresh and contains very fine grained sandsize and siltsize particles of quartz and feldspar.

150 - 200	Typical of described unit, except sand/shale ratio is approximately one.
	Offset 50 feet to miss covered interval along strike bearing S. 65° E. Attitude: N. 65° W., 10° N.E. Proceed along bearing N. 25° E.
110 - 150	Typical of described unit except sand/shale ratio is approximately one.

Offset 40 feet to pick up stratigraphically higher beds along strike S. 60° E. Attitude: N. 60° W., 1° N.E. Proceed along bearing N. 30° E.

60 - 110 Typical of unit description

Offset 60 feet to pick up stratigraphically higher beds along strike S. 60° E. Attitude: N. 60° W., 10° N.E. Proceed up section along bearing N. 30° E.

50 - 60 Sandstone, moderate olive brown (5Y 4/4) weathered, medium bluish gray (5B 5/1) fresh. Medium- to very coarse-grained, poorly sorted, tightly cemented with calcium carbonate. Grains are angular to subangular consisting predominantly of feldspar and quartz. Bottom contact is sharp with groove casts oriented N. 40° E. - S. 40° W. Bottom 1.5 feet contain abundant mudstone rip-ups and pebbles to 1/2 inch diameter. Internal structures are obscure.

The geometry of this unit is elongate and trends N. 40° E. The thin-bedded intercalated sandstones and mudstones grade laterally into this unit and thin away from it.

Offset 30 feet to pick up very thick-bedded elongate sandstone unit along strike N. 60° W. Attitude: N. 60° W., 10° N.E. Proceed along bearing N. 30° E.

10 - 50 Typical of described section.

0 - 10 Typical of unit description. A representative 10 foot sequence is detained below.

s. Fine to medium-grained sandstone, 1.1 feet, normally grades into very fine-grained sandy siltstone, sharp, planar contact. Internal structure: CDE Bouma units.

r. Mudstone, 0.3 feet, unevenly parallel laminated, horizontal burrows present. Contact with underlying sandstone gradational.

q. Fine-grained sandstone, 0.9 feet, normally grades into very fine-grained sandy siltstone, internal structure: CE Bouma units, contact sharp, planar.

p. Mudstone, 0.4 feet, sand filled burrows (horizontal), contact with underlying sandstone gradational.

o. Similar to q, 0.5 feet.

n. Similar to p, 0.2 feet, no burrows present.

m. Similar to q, 0.5 feet.

l. Similar to p, 0.3 feet.

k. Similar to q, 0.6 feet, numerous sandstone dikes 0.5 to 1.0 inches wide.

j. Similar to p, 0.5 feet, no burrows present, numerous sandstone dikes 0.2 to 1.3 inches wide.

i. Similar to q, 0.5 feet, fine- to medium-grained sandstone.

h. Similar to p, 0.2 feet.

g. Similar to q, 0.8 feet.

f. Similar to p, 0.3 feet, no burrows.

e. Similar to q, 0.7 feet, fine- to medium-grained sandstone.

d. Similar to p, 0.3 feet, no burrows present.

c. Similar to q, 1.1 feet, medium- to coarse-grained sandstone.

b. Similar to p, 0.2 feet.

a. Similar to q, 0.6 feet, medium- to coarse-grained sandstone.

Initial point (S, plate 1) is located below Downes Point Park and consists of the first sandstone bed above the Geoffrey-Spray contact. Map location is in the center of the S.E.¼ of the N.E.¼ of the S.W.¼ of the N.E.¼ of section 1. Dunlop Point lies on a bearing of N. 53° E. from point S and the light on Flora Islet lies at N. 75° E. from point S.

APPENDIX A-d

Representative Measured Section Ga-Ga', Gabriola Formation

The measured section Ga-Ga' of the Gabriola Formation is located on the southwest facing cuesta scarp of St. John Point. The interval measured was chosen to include the thick- to very thick-bedded sandstones, the thin-bedded sandstones and siltstones, and the overlying conglomerates.

The terminal point (Ga', plate 1) is located on the southwestern side of Mushroom Beach. Map location is in the center of the N.W.¼ of the S.W.¼ of the S.W.¼ of the N.W.¼ of section 7. Dunlop Point lies S. 68° W. from point Ga' and Spray Point lies N. 77° W. from point Ca'.

Interval Feet	Description

<u>Unit Description</u>: Sandstone, cliff and bench former, light olive brown (5Y 5/6) weathered, dusky yellow (5Y 6/4) fresh. Medium- to very coarse-grained, poorly sorted. Angular to subangular grains of feldspar, quartz, lithic fragments, chert, and micas. Large calcareous concretions to 4 feet in diameter. Thick- to very thick-bedded. Large scale cross-bedding (festoon ?), horizontal bedding, and contorted bedding are the predominant internal structures. Normally grades into siltstone interbeds, 0.5 to 1.5 feet thick. Scour-and-fill channels up to 8 feet across are common and are infilled with pebbly sandstone. Mudstone rip-ups are common throughout. This unit weathers to gallery and beehive and honeycomb structures.

Intercalated sandstone and siltstone, intertongues with thick- to very thick-bedded sandstone described above. Sandstone color is dark yellowish green (10GY 7/2) weathered and pale yellowish green (10GY 7/2) fresh. Fine- to medium-grained, well to moderately sorted. Angular to subangular grains of feldspar, quartz, and micas. Abundant clays, silts, and organic debris. Non-calcareous, thin to very thin-bedded. Internal structures include the BCE, CE, and DE Bouma units. Bottom contacts are sharp and undulatory. Sandstone normally grades into overlying siltstone, color is medium gray (N5) weathered, dark gray (N3) fresh. Very fine-grained sand and silt sized grains of quartz present. Parallel laminated, extreme bioturbation and sand filled burrows.

Conglomerate, cliff and bench former, dark reddish brown (10R 3/4) weathered, moderate brown (5YR 4/4) fresh. Consists of well rounded to rounded granules (0.25 inches) to boulders (12 inches) of predominantly andesite, basalt, chert, and metaquartzite. Thick- to very thick-bedded, conglomerates contain scour-and-fill, pebble imbrication and elongation, and normal grading. Channel sandstones abundant, lenticular in geometry. Pebbles held in a matrix of tightly calcium carbonate cemented medium- to coarse-grained sandstone.

85.5 - 100	Conglomerate as in unit description.
	Contact: conglomerate and underlying thick- to very thick-bedded sandstone. Sharp, scour-and-fill, vertical relief approximately 50 feet.
60 - 85.5	Sandstone, thick- to very thick-bedded as in unit description. Beds from 2 to 8 feet thick and pinch out to the southwest.
	Offset along strike to pick up stratigraphically higher beds. Attitude: N. 30° W., 5° N.E.
43.5 - 60	Sandstone, thick- to very thick-bedded as in unit description.
23.5 - 43.5	Intercalated sandstone and siltstone as in unit description.
15.5 - 43.5	Sandstone, thick- to very thick-bedded as in unit description.
0 - 15.5	Sandstone, thick- to very thick-bedded as in unit description.

Initial point (Ga, plate 1) is located on the map in the N.W. corner of the S.W. of the S.W. of the N.E. of section 8. Dunlop Point lies N. 55° W. from Ga and Spray Point lies N. 77° W. from Ga. Starting attitude is N. 30° W., 4° N.E.

APPENDIX B

MODAL ANALYSIS OF SANDSTONE SAMPLES

	Formation and Sample			
	Kdc		Kn	
Mineralogy	79H	80H	73H	85H
Stable Grains				
Monoxlln Quartz	12.7	10.6	15.1	14.5
Polyxlln Quartz	2.3	1.8	2.5	1.6
Chert	3.0	4.8	1.7	1.1
Feldspar				
Plagioclase	22.1	23.8	27.1	31.6
K-spar	7.7	8.0	9.4	7.9
Lithic Fragments				
Volcanic	7.3	6.6	8.4	1.1
Foliated Met$^{\underline{M}}$	2.0	3.3	T	.7
Igneous Intrusive	2.8	T	T	T
Sedimentary	2.3	1.2	T	-
Mica				
Biotite	2.2	2.0	1.9	3.0
Muscovite	.7	2.0	T	1.3
Chlorite	.6	T	.7	.7
Heavy Minerals				
Epidote	T	.6	T	1.0
Garnet	-	-	-	T
Hematite	1.3	1.2	-	T
Hornblende	1.5	1.0	-	-
Ilmenite	-	.4	T	.5
Leucoxene	-	-	-	.5
Magnetite	1.5	1.2	2.4	2.0
Pyrite	-	-	T	-
Pyroxene	-	1.6	-	-
Sphene	-	-	-	T
Tourmaline	-	-	-	T
Zircon	T	.6	T	1.0
Carbonaceous Matter	-	.4	T	-
Matrix	3.7	-	3.8	5.7
Cement				
$CaCO_3$	26.0	29.0	25.9	24.6
Iron Oxide	-	-	-	-
Voids	-	-	-	-

Appendix B (continued)

Mineralogy	Formation and Sample Kg 5H	20H	27H	45H
Stable Grains				
Monoxlln Quartz	31.5	8.3	33.0	11.5
Polyxxln Quartz	4.2	2.8	3.0	3.0
Chert	1.4	3.3	.8	.6
Feldspar				
Plagioclase	20.3	34.2	24.1	28.2
K-spar	6.8	10.1	6.3	9.2
Lithic Fragments				
Volcanic	2.4	5.9	T	12.1
Foliated Meta$\underline{M}$	2.1	1.4	1.6	1.9
Igneous Intrusive	1.7	1.9	T	1.3
Sedimentary	T	2.1	.8	-
Mica				
Biotite	6.0	2.4	6.0	5.2
Muscovite	1.4	.9	2.0	.8
Chlorite	T	T	1.4	-
Heavy Minerals				
Epidote	T	T	T	T
Garnet	T	-	-	T
Hematite	1.7	-	-	1.3
Hornblende	T	-	-	-
Ilmenite	T	-	-	-
Leucoxene	T	-	-	-
Magnetite	1.4	.9	.8	.9
Pyrite	T	-	-	T
Pyroxene	-	-	-	-
Sphene	-	-	-	-
Tourmaline	-	-	-	-
Zircon	T	T	T	T
Carbonaceous Matter	-	-	.8	T
Matrix	17.2	21.5	17.3	21.0
Cement				
$CaCO_3$	-	5.0	-	-
Iron Oxide	-	T	T	-
Voids	-	-	2.0	1.6

Appendix B (continued)

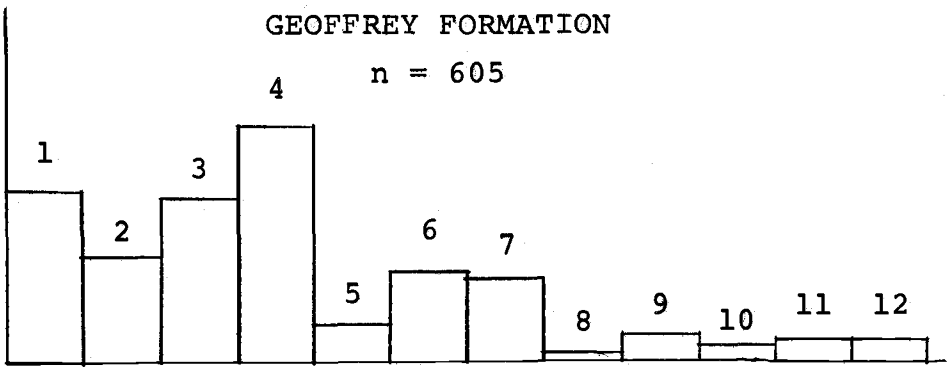
Mineralogy	Formation and Sample Ks A-3	21H	59H	81H
Stable Grains				
Monoxlln Quartz	15.0	17.2	18.2	10.4
Polyxlyn Quartz	1.6	1.6	2.7	2.0
Chert	T	1.0	1.0	1.5
Fedlspar				
Plagioclase	29.0	23.7	29.8	36.3
K-spar	7.3	5.5	16.1	11.4
Lithic Fragments				
Volcanic	.9	1.3	1.7	15.3
Foliated Meta-M	.5	T	2.1	1.0
Igneous Intrusive	-	-	T	2.2
Sedimentary	-	-	-	-
Mica				
Biotite	4.9	5.6	4.6	4.8
Muscovite	.9	1.5	1.7	.9
Chlorite	.5	.7	T	1.0
Heavy Minerals				
Epidote	.9	1.3	1.2	.5
Garnet	-	T	T	-
Hematite	1.8	1.1	1.2	-
Hornblende	-	-	T	-
Ilmenite	T	-	-	-
Leucoxene	.5	-	T	-
Magnetite	2.2	1.1	1.7	1.0
Pyrite	-	T	-	-
Pyroxene	-	-	T	-
Sphene	T	.7	-	-
Tourmaline	T	-	-	-
Zircon	1.5	T	T	-
Carbonaceous Matter	-	-	T	T
Matrix	5.1	4.9	13.4	8.5
Cement				
$CaCO_3$	27.7	33.3	3.0	3.1
Iron Oxide	-	-	-	T
Voids	-	-	1.2	-

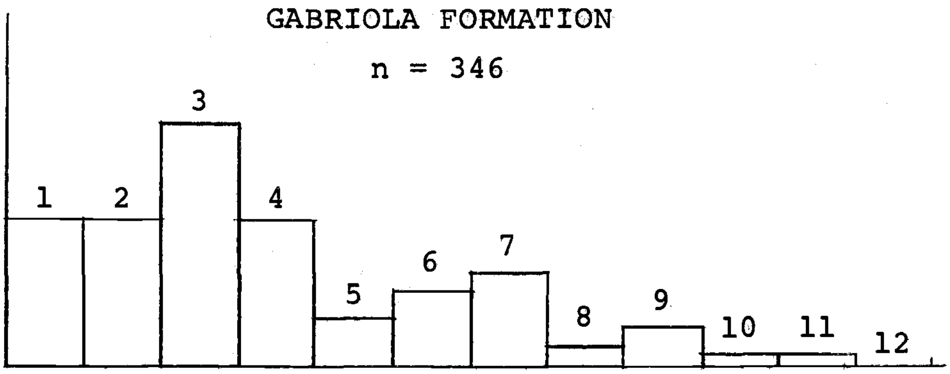
Appendix B (continued)

Mineralogy	Formation and Sample Kga 61H	65H	76H
Stable Grains			
Monoxlln Quartz	7.8	19.4	12.6
Polyxlln Quartz	2.3	4.1	4.1
Chert	4.3	.9	3.0
Feldspar			
Plagioclase	30.4	35.5	44.8
K-spar	5.6	10.0	10.2
Lithic Fragments			
Volcanic	19.3	2.7	4.3
Foliated Meta-M	2.5	1.2	2.3
Igneous Intrusive	-	1.2	.7
Sedimentary	T	1.4	-
Mica			
Biotite	1.3	5.1	4.3
Muscovite	.5	3.0	1.6
Chlorite	2.0	.7	1.1
Heavy Minerals			
Epidote	.8	1.4	T
Garnet	-	.5	T
Hematite	.7	T	-
Hornblende	T	-	-
Ilmenite	T	-	-
Leucoxene	-	-	-
Magnetite	1.0	1.0	T
Pyrite	1.1	-	-
Pyroxene	-	-	-
Sphene	-	T	T
Tourmaline	-	T	-
Zircon	T	.9	-
Carbonaceous Matter	T	-	T
Matrix	5.1	10.2	10.1
Cement			
$CaCO_3$	14.7	-	-
Iron Oxide	T	-	T
Voids	-	-	-

APPENDIX C

Relative Abundance of Pebble Lithologies





1-Chert and Silicified Mudstones
2-Metaquartzite
3-Basalt
4-Andesite and Greenstone
5-Dacite
6-Granitics
7-Diorite
8-Foliated Metamorphics
9-Gneiss
10-Aplite
11-Vein Quartz
12-Sandstone

APPENDIX D

SANDSTONE TEXTURES AND MATURITY

Sample number	Formation	Grain Size Wentworth (1922)	Sorting Folk (1968)	Roundness Powers (1953)	Maturity Folk (1951)
79H	De Courcy	medium to very coarse	moderate	A-a	Submature
80H	De Courcy	medium to very coarse	moderate	A-a	Submature
73H	Northumberland	medium to coarse	moderate	A-a	Submature
85H	Northumberland	fine to medium	very well	A-a	Mature
5H	Geoffrey	medium to very coarse	poor to moderate	A-a	Submature
20H	Geoffrey	Medium to coarse	moderate	A-a	Submature
27H	Geoffrey	fine to coarse	poor to moderate	A-a	Submature
45H	Geoffrey	very fine to very coarse	poor	A-a	Submature
A-3H	Spray	fine to medium	well	A-a	Mature
21H	Spray	fine to medium	well	A-a	Mature
59H	Spray	medium to very coarse	poor to moderate	A-a	Submature

Appendix C (continued)

Sample number	Formation	Grain size Wentworth (1922)	Sorting Folk (1968)	Roundness Powers (1953)	Maturity Folk (1961)
81H	Spray	medium to very coarse	poor to moderate	A-a	Submature
61H	Gabriola	medium to very coarse	poor to moderate	A-a	Submature
65H	Gabriola	fine to very coarse	poor	A-a	Submature