AN ABSTRACT OF THE THESIS OF

Roger Barton Stickney for the degree of Master of Science

in Geology presented on June 9, 1976

Title: SEDIMENTOLOGY, STRATIGRAPHY, AND STRUCTURE OF THE LATE CRETACEOUS ROCKS OF MAYNE AND SAMUEL ISLANDS, BRITISH COLUMBIA

Abstract approved: Redacted for privacy

Keith F. Oles

An ancient delta complex is partly recorded by the upper seven formations of the Cretaceous Nanaimo Group exposed on Mayne and Samuel Islands of southwestern British Columbia. Features especially suggestive of deltaic sedimentation here are: upward-coarsening marine to fluvial sequences, cyclic repetition of facies, subaqueous slumping, fluvial-marine interfingering, facies changes, lobate geometry, and variations in thickness along strike. Clastics were derived from a varied terrane of the Paleozoic and Mesozoic basement both on Vancouver Island and farther southeast in the San Juan Islands of Washington. These pre-Cretaceous rocks largely include chert, limestone, pyroclastics, granitics, and low-grade metamorphics. Swift, short-headed streams from nearby mountains to the east and south carried detritus to a subsiding marine embayment adjacent to the southeast coast of Vancouver Island.

Locally on Mayne Island, the composite section is at least 8,000 feet thick. The oldest unit, only partially exposed, is the Extension-Protection Formation, made up of interbedded conglomerates and arkosic sandstones. Interfingering with it is the largely superjacent Cedar District Formation comprising a recurrent, marine turbidite facies. It contains a molluscan fauna as is also known in the similar younger strata. Overlying it, the DeCourcy Formation, a second fluvial unit of sandstone to conglomerate, shows a lobate development ascribed to distributary switching. This is the top member of an upward-coarsening, marine to fluvial deltaic cycle. Immediately above, a nearly identical cycle begins with the Northumberland Formation, composed of repetitiously graded turbidites. Overlying them is the Geoffrey Formation, the final part of the second exposed deltaic cycle. Within it, sandstones enclose especially coarse conglomerates, suggesting a change from an easterly to a proximal southerly source. Marine encroachment followed which allowed deposition of the Spray Formation, the third exposed monotonous turbidite sequence. The next higher unit is the fluvial Gabriola Formation which terminated Nanaimo Group deposition and completed the final deltaic cycle. Its upper contact is not exposed.

The study area lies on the north flank of the northwesterly trending Trincomali Anticline, which was folded during early Tertiary. Faults have offset this structure locally and at least two separate events are suggested.

# Sedimentology, Stratigraphy, and Structure of the Late Cretaceous Rocks of Mayne and Samuel Islands, British Columbia

by

Roger Barton Stickney

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed June 1976

Commencement June 1977

APPROVED:

Redacted for privacy

Professor of Geology
in charge of major

Redacted for privacy

Chairman of Department of Geology

Redacted for privacy

Dean of Graduate School

Date thesis is presented June 9, 1976

Typed by Mary Jo Stratton for Roger Barton Stickney

## ACKNOWLEDGEMENTS

Foremost, immeasurable yet insufficient thanks go to my loving wife Michele for her continued encouragement, support, and assistance in bringing this thesis to completion.

To Dr. Keith F. Oles, heartfelt gratitude is due for suggesting such an instructive and pleasant study area and for several field season visits. His critiques, while helpful, have allowed complete latitude in this endeavor. The efforts of Drs. H. E. Enlows, J. G. Johnson, A. R. Niem, and E. R. W. Berglund, who critically read the manuscript and provided advice along the way are also appreciated.

The warm Canadian reception and fine treatment caused we visiting "foreigners" to depart with regret and with the feeling of true countrymen. The writer is particularly indebted to the George Morrisons and to the Ned Eastons for the use of their boats and to Mrs. Kay Carpenter who made very comfortable living quarters available for the summer. To the many other residents and property owners who provided information and extended courtesies too numerous to recount, thank you.

The generous financial support from Union Oil Company of California is gratefully acknowledged here. A high point of the field season was the visit by Messrs. D. B. Braislin and H. Fothergill of Union.

## TABLE OF CONTENTS

Page

LIST OF FIGURES

# LIST OF PLATES

# SEDIMENTOLOGY, STRATIGRAPHY, AND STRUCTURE OF THE LATE CRETACEOUS ROCKS OF MAYNE AND SAMUEL ISLANDS, BRITISH COLUMBIA

## INTRODUCTION

### Location and Accessibility

Mayne Island is located halfway between Victoria and Vancouver, B. C. It is one of several Canadian "Gulf Islands," as they are called, which are a northwesterly continuation of the San Juan archipelago in Washington. This island group separates the southeast coast of Vancouver Island from the Strait of Georgia seaway.

Other major Gulf Islands which surround Mayne on three sides are Saturna to the southeast, the Penders on the south, and Galiano to the northwest. Between Mayne and Saturna lies Samuel Island. It is the largest of several adjacent smaller (privately owned) islands, reefs, and islets that are also included in this study (Fig. 1 and for regional setting see Fig. 2). The total area involved is slightly more than 10 square miles, all of which is underlain by Late Cretaceous rocks of the Nanaimo Group--a sedimentary sequence.

Although advance reservations may be necessary, daily ferry schedules afford ready access to Mayne Island. Service originates at Swartz Bay, due north of Victoria on Vancouver Island and also from Tsawwassen on the mainland, 20 miles south of Vancouver, B. C.

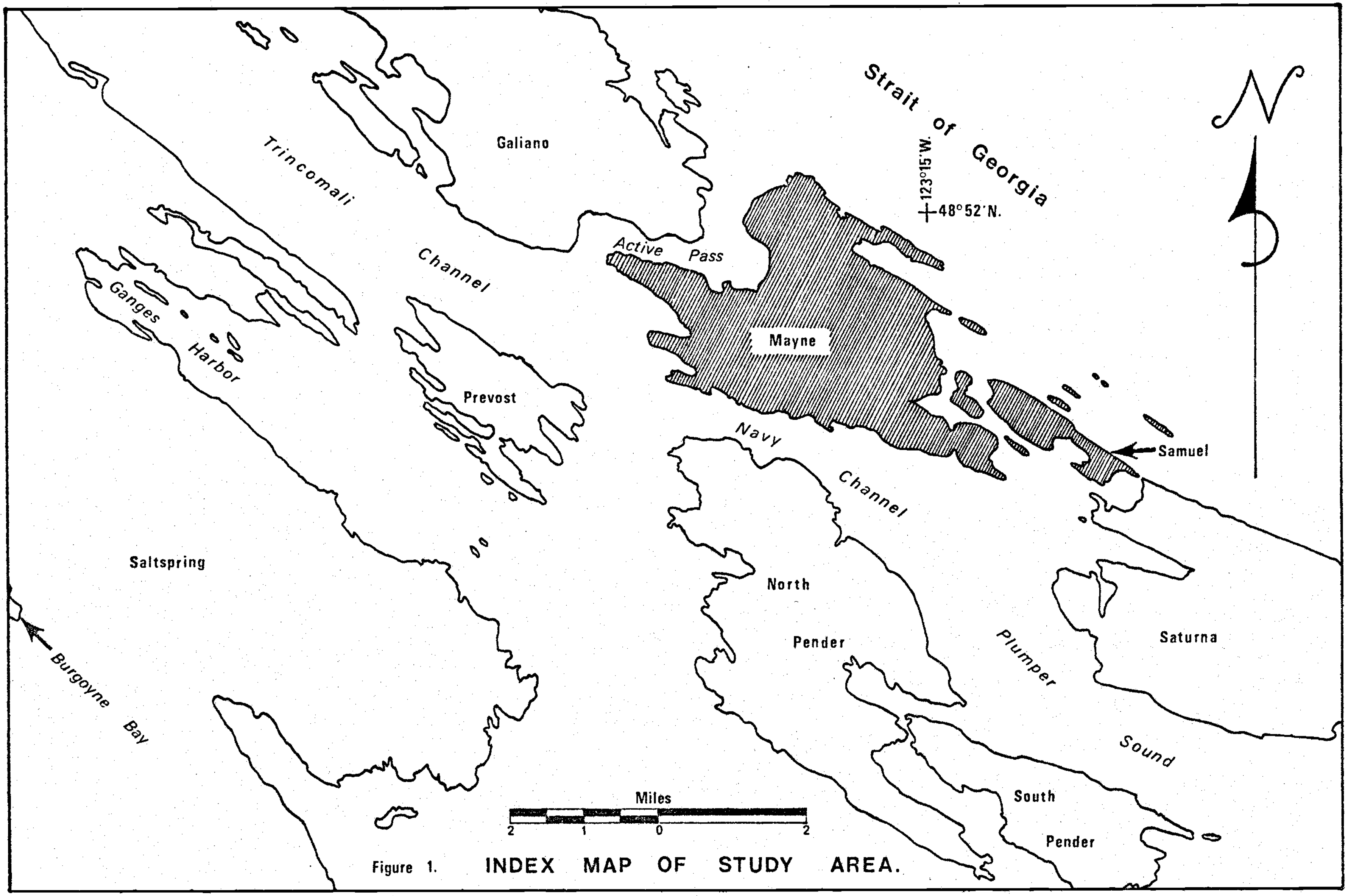



Figure 1. INDEX MAP OF STUDY AREA.

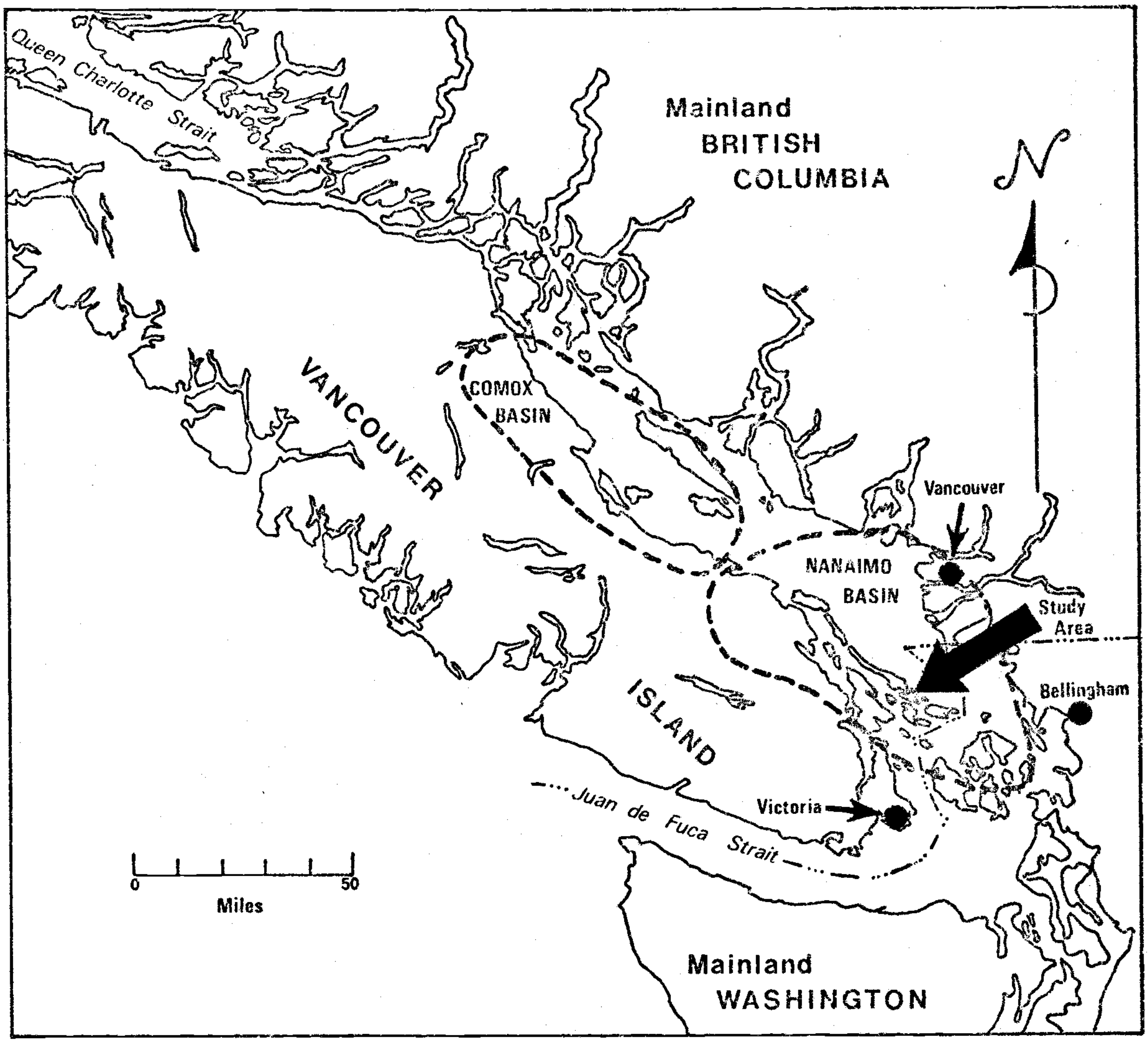



Figure 2. Approximate Relative Positions of Nanaimo and Comox Basins (modified after Richardson, 1872, 1878; Mc Lellan, 1927; Usher, 1952; Geologic Map of Canada, 1962)

Mayne Island is the ferry transfer point for passage to Saturna. The smaller islands in the study area can be reached only by private boats or by charter aircraft--mostly seaplanes.

Because of the easy access, residential development is expanding on Mayne. The major roads are paved or have well-maintained gravel surfaces. Others are generally private roads--some the result of earlier logging operations. Samuel Island is covered by older logging roads that are maintained for fire control.

Except where cleared for farming or grazing, the island interiors are covered by thick vegetation. Rock exposure is limited to road cuts, gravel pits, fault scarps, and the steep faces of antidip slopes. The shoreline perimeters yield continuous outcrop. Sheer cliffs render some sections impassable, but most can be easily reached by foot.

Mayne Island is named for Cpt. Richard C. Mayne (Royal Navy) who sailed on H.M.S. Plumper, a British survey ship which visited the Pacific Coast in 1859 (Foster, 1966). Surgeon Samuel Campbell, of the same ship, is the one for whom Samuel Island is named (Freeman, 1966).

## Purposes

The six objectives on which this study focuses are to:

1) describe the lithologies and relative thicknesses of the Late

Cretaceous rocks; 2) map bedrock distribution and structure on a 1:15,840 (1" = 1/4 mile) scale (Plate 1); 3) prepare structure cross sections (Plate 1); 4) describe lateral changes along and across strike; 5) determine sediment source areas, dispersal patterns, depositional environments, and paleogeography; 6) consider those aspects of the geology which might be significant for petroleum exploration.

## Investigative Methods

### Field

Preparations for the field were guided by a short reconnaissance visit to the area in March, 1975. Typical lithologies were briefly examined and permission was secured for access to private islands.

Aerial photo coverage on three scales (1" = 1/4 mi., 1" = 1/2 mi., and 1" = 1 mi.) and excellent topographic base maps (1" = 1/4 mi. scale) supplied by the British Columbia Department of Lands, Forests, and Water Resources in Victoria, were used to great advantage. Structural trends and tentative formation contacts were plotted on the photos, then field-checked for accuracy. To expedite work in the field, individual stations were located on air photos and transferred daily to the base map(s).

Attitudes of bedding and structural features were measured with a Brunton compass. Lithologic descriptions were facilitated with a 10X hand lens and dilute (0.1N HCl to verify the presence of carbonate minerals). Accepted color terms were determined from a Geological Society of America Rock-Color Chart. A sand gauge provided comparison standards for grain size (after Wentworth, 1922) and particle roundness (after Powers, 1953). Compton's (1962) terms for particle sorting are used and for stratification, those of McKee and Weir (1953) are followed. True formation thickness was measured in the field with a Jacob's staff and mounted Abney level. Contact relationships are generally either gradational (across several tens of feet) or indistinct. Because copious attitudes were recorded, trigonometric methods produced thickness approximations that showed remarkable consistency with field measurements in every case. In Village Bay, the upper and lower contacts of the Northumberland Formation are more clearly defined. Its thickness was measured and a representative interval was selected for detailed description (Appendix A).

Because certain sedimentary structures record paleocurrent flow directions, data from numerous examples of these features were collected. Their analysis is discussed under Paleogeography.

Various ammonites, pelecypods, gastropods, and ichnofossils were discovered in the study area; however, they were restricted to the fine-grained units (Cedar District, Northumberland, and Spray Formations). Only a few of these withstood the rigors of weathering and post-depositional compaction to emerge as reasonably well-preserved specimens. These were planispiral ammonites and high-spired gastropods.

## Laboratory

Samples of more than 200 clasts were extricated randomly from each of three conglomerate units--the Extension-Protection, DeCourcy, and Geoffrey Formations. These were identified using a binocular microscope and reflected light. Lithologies are described, by formation, and are summarized in tabular form in Appendix C.

Forty-seven thin sections were studied petrographically and modal analyses were derived by point-counting from 1 to 4 representative slides of each formation. At least 400 points were tallied per slide (Appendix B). The type of plagioclase found was identified using the Michel-Levy method. Relative abundances of quartz, plagioclase, and alkali feldspar were determined by point-counting representative billets which were selectively stained (Bailey and Stevens, 1960). These figures were integrated into the modal analyses to negate inaccuracies caused by failure to correctly differentiate quartz and feldspars in thin section. Sandstones were classified according to Gilbert (*in* Williams *et al.*, 1954) and Folk's (1962) limestone classification is used.

Heavy mineral studies involved identification in thin section. Because the samples were not easily disaggregated, and because heavy minerals are not sufficiently abundant for meaningful study, grain mounts were not made. See Appendix B for findings.

X-ray diffraction of selected samples was used to identify various minerals present. Results and procedures are shown in Appendices C and D respectively.

The Spray Formation was sampled for microfossils. Mudstones exposed only at very low summer tides escape much of the vigorous subaerial oxidation. It was hoped that these rocks would contain Foraminifera. None were found after laboratory treatment, although Foraminifera have been reported from the thesis area (McGugan, 1964). It is likely that more sophisticated sampling techniques would be necessary. Cuttings from rotary drilled water wells that penetrated Cedar District mudstones were also treated and examined, but no microfossils were recovered.

## PREVIOUS WORK

Economic interest was gradually attracted toward the northeast coast of Vancouver Island when coal was reported in 1835 by W. F. Tolmie of Hudson's Bay Company (Muller and Atchison, 1971). His announcement was based on samples Indians had brought to him from the local Suquash-Port McNeill area (Clapp, 1914a). Because the major deposit could not be located, both geologists and paleontologists joined the search.

Some of the ensuing historical developments, initially related directly to coal exploration, are summarized chronologically below. Most of these are reviewed by Clapp (1914a), Usher (1952), and Muller and Jeletzky (1970).

<u>1849</u>: Hudson's Bay Co. stepped up lagging exploration in the Suquash area (Clapp, 1914a), and J. W. McKay, of same company, found coal at Nanaimo (Usher, 1952).

<u>1850</u>: McKay's continued exploration revealed the rich Douglas seam at Nanaimo and drew major interest away from the Suquash area (Usher, 1952).

<u>1852</u>: Commercial mining operations were started at Nanaimo (Usher, 1952).

<u>1853</u>: Prolonged investigation failed to locate economic reserves near Suquash and forced abandonment. Full attention

concentrated at Nanaimo. Initial coal shipments by Hudson's Bay Co. (operating as Nanaimo Coal Co.) exceeded 2,000 long tons (Clapp, 1914a).

1857: Fossils collected from Nanaimo coal beds were dated as Cretaceous by geologist J. S. Newberry (Usher, 1952).

1860: H. Bauerman verified a Cretaceous age using collections from the same area (Usher, 1952).

1861: On an exploratory expedition from the Great Lakes to the Pacific Coast, Capt. J. Palliser was accompanied by J. Hector, geologist and physician, who sampled rocks of the Nanaimo and Comox areas. These also confirmed a Cretaceous age (Usher, 1952).

1861-1864: General acceptance of a Cretaceous age was further supported by additional efforts of F. B. Meek on Vancouver and Sucia Islands and also by Newberry and W. M. Gabb in the Nanaimo area. Their work with invertebrate and plant fossils yielded similar conclusions (Usher, 1952).

1871-1878: J. Richardson's far-reaching, pioneer studies of Vancouver Island Cretaceous rocks, for the Geological Survey of Canada, established a foundation for further refinement. He recognized more than one Cretaceous depocenter and defined boundaries for the Cowichan, Comox, and Nanaimo Basins (the latter two shown in

Fig. 2). As illustrated on the geologic map with cross sections in his summary work (Richardson, 1878), he established Cretaceous stratigraphy and structure (still essentially unmodified in this thesis area for those units he recognized). He also pointed out similarities of mainland rocks at the mouth of Burrard Inlet (near Vancouver), with typical Cretaceous on Vancouver Island and vicinity (Richardson, 1872, 1878; Usher, 1952).

1879: Mesozoic Fossils, Part II, was published by J. F. Whiteaves--a thorough compilation of invertebrate fossils of this area (Clapp, 1914a; Usher, 1952; Muller and Jeletzky, 1970).

1890: J. W. Dawson formally named the Nanaimo Group, although sufficient fossil control was lacking in the uppermost sandstones to clearly establish a Cretaceous age. Equivalence of the Nanaimo Group and the Chico Group of California was inferred (Dawson, 1890).

1908-1917: C. H. Clapp's monumental undertaking, during this interval, was aimed toward a detailed geological understanding of all rocks on eastern Vancouver Island. Enlarging on Richardson's work, he subdivided the strata beneath the easily recognized Protection Formation into 6 of the 11 lithostratigraphic units he formally named and described (Clapp, 1912; Muller and Jeletzky, 1970, Table 1). He expanded usage of "Nanaimo Group" to include the whole "conformable" sequence overlying basement (Clapp, 1914a). His consulting work included evaluation of coal potential in three southern Gulf Islands (Clapp, 1914b). Beneath the Cretaceous rocks he recognized an irregular erosional surface. He noted the Nanaimo Group was deposited in alternating marine to nonmarine environments ending finally with unfossiliferous, possibly terrestrial sands. The entire section, he pointed out, is characterized by abrupt variation laterally and vertically hindering accurate correlation (Clapp, 1914a; Usher, 1952). Total thickness of the Nanaimo Group in the southern Gulf Islands is twice that observed in the Nanaimo area (Clapp, 1914b).

<u>1921-1923</u>: Mapping of J. D. MacKenzie expanded efforts initiated by Clapp. He re-evaluated the coal reserve potential of southern Vancouver Island (Buckham, 1947).

<u>1927</u>: On small Barnes and Clark Islands, Nanaimo Group rocks are mapped within five miles of Chuckanut exposures (with a more subaerial aspect) on Lummi Island near Bellingham. Similar structural trends and plant fossils

from each formation suggested both are at least partly coeval (McLellan, 1927; Miller and Misch, 1963).

1939-1948: A. F. Buckham reviewed Vancouver Island coal fields focusing on coal deposition and reinterpretation of the structure as a series of northwest-trending post-Cretaceous thrust faults. Problems in development were related to these combined factors (Buckham, 1947).

1952: Biostratigraphic zonation of mulluscan faunas (principally ammonites) by J. L. Usher enabled a correlation of the Nanaimo and Comox Basins. His formation descriptions refined those of Clapp (1914a), and his fossil localities include five on Mayne Island (Usher, 1952).

1957: Examination of plant fossils by W. A. Bell suggested climatic conditions during Nanaimo Group deposition may have ranged from warm temperate to tropical. Interbasinal correlation of floras was inconclusive with available evidence (Bell, 1957).

1963: J. E. Muller, of the Geological Survey of Canada, initiated mapping of the Vancouver Island area (Muller and Jeletzky, 1970). Revision of palynology and plant megafossil data, supported with field work, strongly pointed to correlation between the Nanaimo Group and mainland rocks near Vancouver and Bellingham. Representation of possible

Cenozoic floras in the youngest of these mainland rocks suggested deposition in a large Cretaceous to Paleocene basin (Crickmay and Pocock, 1963).

1964: A. McGugan undertook the first foraminiferal zonation leading to a correlation between the Nanaimo and Comox Basins. His results are consistent with subsequent mulluscan-based faunal correlations (Muller and Jeletzky, 1970). Five of his fossil localities occur on Mayne Island (McGugan, 1964).

1964-1970: Continued studies begun by Muller in 1963 were complemented by paleontological assistance from J. A. Jeletzky which started during 1965. A progress report (Muller and Jeletzky, 1970) presented a splendid 1:250,000 reconnaissance-scale map which reflects their standardization of stratigraphic nomenclature for both Nanaimo and Comox Basins (correlated on molluscan faunas). Stratigraphically, they recognized a sequence of four (transgressive) fining upward depocycles with only a partial record of a fifth (see Fig. 3). Structure is controlled by fault blocks tilted slightly to the northeast (Muller and Jeletzky, 1970). In 1966, more than a century of coal production was essentially terminated by closure of the

| Clapp (1912-1917) | Buckham, 1947 Usher, 1952 | | | Muller & Jeletzky, 1970 | | | As interpreted (this paper) |
|---|---|---|---|---|---|---|---|
| Nanaimo Basin | | Nanaimo Basin | Comox Basin | | Nanaimo and Comox Basins | Trans-gres-sive Cycles | Deltaic Cycles |
| Gabriola | Maestrichtian | Gabriola | Hornby | Maestr. | Gabriola | Non-marine | Youngest Deltaic Cycle |
| | | North-umberland | Spray | | Spray | Fourth Cycle | |
| | | | Geoffrey | Campanian | Geoffrey | | Second Youngest Deltaic Cycle |
| North-umberland | | | Lambert | | Northumberland | Third Cycle | |
| DeCourcy | Campanian | DeCourcy | Denman | | DeCourcy | | Third Youngest Deltaic Cycle |
| Cedar District | | Cedar District | Trent River | | Cedar District | | |
| Protection | | Protection | Comox | | Extension-Protection | | Older Cycle (?) Base Not Exposed |
| Newcastle | | Newcastle | Qualicum | | | | |
| Cranberry | | Cranberry | | | | | |
| Extension | | Extension | | | | | |
| East-Wellington | | East-Wellington | | | | | |

(Older Units Not Shown)

(Older Units Not Exposed in Thesis Area)

Figure 3. Evolution of stratigraphic nomenclature and Nanaimo-Comox interbasinal correlations 1912 to present (modified from Muller and Jeletzky, 1970).

Tsable River Mine, 12 miles south of Comox (Muller and Atchison, 1971).

1971-1976: Mapping and related efforts by Geological Survey of Canada workers continues. Graduate students from Oregon State University, guided by Dr. Keith F. Oles, have undertaken detailed mapping and paleoenvironmental studies of Nanaimo Group rocks on Vancouver Island (Rinne, 1973) and several Gulf Islands (Packard, 1972; Simmons, 1973; Hudson, 1975; Sturdavant, 1975; Hanson, 1976; Carter, in preparation).

## REGIONAL BASEMENT STRATIGRAPHY

For an admirable detailed summary of the regional stratigraphy, see Muller and Carson (1969) and the generalized cross section by Muller (1974, Fig. 1).

The oldest rocks of the basement assemblage exposed on Vancouver Island and vicinity are at least of Pennsylvanian to Permian age. Originally termed the "Mount Sicker Series" by Clapp in 1909, they were not elevated to group status until 1955 by Fyles (Muller and Carson, 1969). Recent efforts (Muller, 1975, 1976), backed by radiometric dating, indicate that some Sicker Group rocks are pre-Devonian.

Aggregate thickness of the Sicker Group is at least 13,000 feet, presently subdivided into three parts. The lowest is most widely distributed and has a minimum thickness of 10,000 feet. This sequence, dominated by complexly deformed metavolcanics, includes greenstones, tuffs, and graywackes or their lower grade metamorphic equivalents. The middle part, of Pennsylvanian age, contains up to 2,000 feet of locally fossiliferous clastic rocks, mostly occurring in resedimented graded packets. It too is metamorphosed and is similar in composition to the subjacent unit. Uppermost is the Permian Buttle Lake Formation, the only named unit of the Sicker Group. It is characterized by as much as 1,000 feet of locally cherty limestones.

Although sparsely represented, various shelly faunas have been reported. In mainly the upper reaches of the Sicker Group, igneous sills of basic composition are exposed. These are not known in later rocks (Muller and Carson, 1969).

At the base of the sequence described above, there appears to be at least one more Sicker Group formation previously unrecognized (Muller, 1976). Within it, intrusives of granitic composition called Tyee Intrusions (Muller, 1975) have been dated as Early Devonian (Muller, 1976) which suggests the enclosing rocks are older than Devonian. Pending further work, the stratigraphic extent of Sicker Group rocks affected by the Tyee Intrusions is not yet clear (Muller, 1976).

The Vancouver Group, approximately 22,000 feet thick, is the next younger unit which accumulated during a Triassic to Early Jurassic interval. A ternary subdivision is recognized (Muller and Carson, 1969):

The lowermost Karmutsen Formation, no younger than Late Triassic, is the thickest and most extensive. It contains 7,000 to 19,000 feet of pillow basalts, yielding upward to breccia and finally capped by lava flows. Very low grade metamorphism accompanied only moderate deformation. Minor fossiliferous limestone occurs near the top (Muller and Carson, 1969).

The middle subdivision, the Quatsino Formation, represents 500 to 2,000 feet of Upper Triassic limestone. Individual beds may be up to several feet thick with a few ammonites present (Muller and Carson, 1969).

The third or uppermost subdivision, the Bonanza Subgroup, is itself broken into an older "sedimentary division" of unknown thickness and a younger "volcanic division" approximately 1,000 feet thick or less. Both were laid down before the Early Jurassic ended. The sedimentary division is characterized by limestone to calcareous graywackes or shales, minor tuffs, and some fossil material. By contrast, moderately acidic lavas and pyroclastics make up the volcanic division. Tabular intrusions are not always differentiable from the extrusive bodies (Muller and Carson, 1969).

Succeeding the Vancouver Group was an episode of plutonism resulting in the Island Intrusions. These are several granitic bodies of batholithic proportions that are dated as Middle to Late Jurassic using the potassium-argon method (Muller and Carson, 1969).

# NANAIMO GROUP STRATIGRAPHY

## Areal Stratigraphy

Nonconformably overlying the basement complex is the Upper Cretaceous Nanaimo Group whose composite thickness probably ranges between 9,000 and 13,500 feet (Hanson, 1976; Muller and Jeletzky, 1970). It is a sequence of clastic rocks alternating from a generally marine to nonmarine aspect. Excepting scattered outliers, its exposure is confined to a narrow belt varying from 2 to 27 miles in width and over 150 miles in length. One end of this strip lies in the Campbell River area on the east coast of Vancouver Island and the other is less than three miles west of Lummi Island near Bellingham, Washington (McLellan, 1927; Usher, 1952; Muller and Carson, 1969).

Up to 440 feet of relief had developed on the basement erosional surface before Late Cretaceous deposition began (Buckham, 1947). Although Richardson (1872, 1878) recognized several depocenters for these sediments, the most important ones are the Comox and the Nanaimo Basins (Fig. 2). The Nanoose Arch, a northerly trending Paleozoic uplift (Muller and Carson, 1969), separates the two.

As interpreted by Muller and Jeletzky (1970), the Nanaimo Group is a succession of transgressive sedimentary cycles; four are complete and the fifth is incomplete (Fig. 3). Two formations, that emphasize a fining upward trend, record each whole cycle. Conglomerates to coarse sandstones of nonmarine to shallow marine character are deposited first. Much finer material, generally observed in graded deposits, indicates deeper water sedimentation for the second. In delineating these cycles, biostratigraphic correlation by Muller and Jeletzky (1970) enabled them to adopt standardized formational names applicable to both the Comox and Nanaimo Basins. This nomenclature (followed herein), formational thicknesses, and facies are reproduced below in order of increasing age (after Muller and Jeletzky, 1970):

Fifth cycle: (incomplete)
  Gabriola Formation: 600 to 3,000 feet.
    Deltaic: sandstone, conglomerate and shale.

(Unconformity or Disconformity?)

Fourth cycle:
  Spray Formation: 950 to 1,770 feet.
    Marine: shale.
  Geoffrey Formation: 400 to 1,500 feet.
    Deltaic: sandstone, conglomerate.

(Unconformity or Disconformity?)

Third cycle:
  Northumberland Formation: 500 feet.
    Marine: shale, siltstone, fine-grained sandstone.
  DeCourcy Formation: 900 to 1,400 feet.
    Deltaic: conglomerate, sandstone.

(Unconformity or Disconformity?)

Second cycle:

<u>Cedar District Formation</u>: 1,000 feet.

Marine: shale, siltstone, fine-grained sandstone.

<u>Extension-Protection Formation</u>: 200 to 1,900 feet.

Deltaic to Lagoonal: conglomerate, sandstone, shale, coal.

(Unconformity or Disconformity?)

First cycle:

<u>Haslam Formation</u>: 200 to 500 feet.

Marine: shale, siltstone, fine-grained sandstone.

<u>Comox Formation</u>: 150 to 2,000 feet.

Lagoonal to Fluvial: coal, shale, sandstone, graywacke, conglomerate.

An alternate interpretation has been proposed following detailed stratigraphic and paleoenvironmental studies of several Gulf Islands. Simmons (1973), Hudson (1975), and Sturdavant (1975) suggest that episodes of deltaic progradation have produced the observed cyclic alternation of facies. However, within each cycle of the deltaic progradational model, there is a pattern of coarsening upward (not fining upward as with the transgressive model depicted above). Hudson (1975) believes the Extension-Protection Formation (the oldest unit occurring on Pender Island) is the coarse upper part of an incompletely exposed cycle--the oldest one he could map. Similarly, he would view the Spray-Gabriola couplet as a complete final cycle (his fourth) except the Gabriola is missing on Pender. Sturdavant (1975) concurs with this interpretation.

If only the repeated juxtaposition of marine, deltaic, and fluvial facies is considered, the choice between a transgressive or a progradational model is arbitrary. Either one can produce a similar vertical pattern and whether each cycle is considered to be upward-coarsening or upward-fining depends upon the datum chosen within the section. In this area, deltaic progradation and transgression are not mutually exclusive. They are components of each cycle irrespective of which occurred first. Both are caused by relative changes in sea level. Definite knowledge of how such relative sea level fluctuations were produced is lacking. Possibilities worthy of consideration are eustatic change, basin tectonics, and variation in the rate of sediment input. It seems more likely that a combined influence is responsible rather than any single factor.

To determine whether transgression or progradation controlled deposition, one must rely on detailed study of the rocks in terms of the environments they record. Because of the many variables involved, change in the dominant process can interrupt the cyclicity. Based on a study of Saltspring Island, Hanson (1976) feels that a combination of the transgressive and progradational models best explains the sedimentary sequence as he observed it.

The transitional relationship between fluvial and marine facies within the Nanaimo Group was noted by Muller and Jeletzky (1970) as representing deltaic accumulation. In proposing a transgressive model for these sediments, they appear to have drawn their conclusions mostly from field relationships observed on a regional scale. Their excellent comprehensive effort has served effectively as a guide in the paleoenvironmental analyses of subsequent workers from Oregon State University (listed individually under Previous Work). By comparing field observations of these Cretaceous rocks with features of modern and ancient deltaic sequences described in the literature, a strong correspondence is suggested. The evidence has been sufficiently compelling that several recent investigators have appealed to a progradational deltaic model for at least a major part of the Nanaimo Group (Simmons, 1973; Hudson, 1975; Sturdavant, 1975; Hanson, 1976; Carter, in prep.).

## Local Stratigraphy

The seven youngest units of the Nanaimo Group are exposed in the thesis area. As indicated in the preceding section and in Fig. 3, they are (from oldest to youngest): 1) the Extension-Protection, 2) the Cedar District, 3) the DeCourcy, 4) the Northumberland, 5) the Geoffrey, 6) the Spray, and 7) the Gabriola Formations representing a maximum cumulative thickness approximating 8,000 feet.

The Extension-Protection conglomerates and interbedded sandstones represent fluvial deposits transported by competent tractive currents occupying braided channels near the basin margin. Incursion of the Cedar District sea terminated fluvial activity and established the first of three complete, upward-coarsening cycles of deltaic sedimentation.

Each one of the even-numbered units above forms the base of a cycle. Internally, they are characterized by laminated to very thin-bedded rhythmic packets of a predominantly marine aspect. The upper member of each cycle is a coarser grained sandstone to conglomeratic unit deposited by unidirectional tractive current processes.

Some features considered characteristic of deltaic sedimentation are described in the published literature, were noted by other workers in the area, or were observed by the writer. These are: 1) upward-coarsening marine to fluvial sequences (Visher, 1965; Selley, 1970), 2) cyclic repetition (Coleman and Gagliano, 1964; Morgan, 1970; Selley, 1970), 3) mass movements or slumping of "prodelta" sediments deposited on unstable slopes (Dott, 1963; Morgan, 1970; Selley, 1970), 4) interfingering relationships (Coleman and Wright, 1975), 5) variable geometry (Coleman and Wright, 1975), 6) facies changes, and 7) variations in thickness along depositional strike. Certain associations of sedimentary structures (Visher, 1965) and fossil assemblages can provide evidence of a deltaic environment as well. Wherever possible, these features were noted in the field for comparison with modern and ancient analogs.

## Extension-Protection Formation

Nomenclature. The lithostratigraphic interval to which the name Extension-Protection is now applied, was originally separated into eight units formally named and described by Clapp (1912). To five of these he assigned formation status. However, beyond the coal-producing area where Clapp observed them, the individual units are not found to be mappable. Therefore, it was recently proposed to regard them locally as members of a single, more widely recognizable formation. The names of the two most distinctive "members" (ranked as formations by Clapp in 1912) are combined to designate the entirety (Muller and Carson, 1969; Muller and Jeletzky, 1970), hence the Extension-Protection Formation.

The Extension "Member" is strikingly conglomeratic with non-persistent interbeds of sandstone, shale, and coal (Clapp, 1912, p. 97). Although not specifically mentioned in the original reference (Clapp, 1912), the name was probably taken from the small town of Extension, approximately four miles south of Nanaimo. The Protection "Member," a marker unit of light-colored kaolinitic sandstone, is conspicuously exposed on Protection Island (Clapp, 1912, p. 99) between Nanaimo and Gabriola Island.

General Character. The Extension-Protection Formation is characterized by a sequence of thick, ridge-forming conglomerates, interbedded with less competent, slope- and valley-forming sandstones. It is the oldest unit in the thesis area and is found only on the peninsula between Dinner Bay and Navy Channel (Fig. 4 and Plate 1). Proximity to the axis of the Trincomali Anticline (Plate 1) is indicated by the steep (54° to 69°), northeast-facing dip slopes. This makes access to parts of the continuously exposed shoreline difficult. Along antidip slopes, preferential weathering of less resistant sandstone interbeds has commonly provided a narrow, wave-cut platform easily transversible at low tide. Where the sea cliff is dominated by conglomerate, this feature is less frequently observed.

The base of the formation is not exposed in this area. Precise location of the upper contact is complicated by faulting, beach cover, or intertonguing. The thickness is estimated to be 913 feet. At the southeast corner of Dinner Bay, near the upper contact, interfingering relationships can be seen. Moderately graded packets of medium- to fine-grained, laminated sandstone are visible during low summer tides. A resemblance was noted between these rocks and the Cedar District Formation in its typical development (described in the following section). They are succeeded up-section by a discontinuous body of Extension-Protection conglomerate and interbedded coarse- to very coarse-grained sandstone. It thins to the west along strike and disappears underwater. Where the lower surface of this body is visible, primary current lineations are present as sole marks.

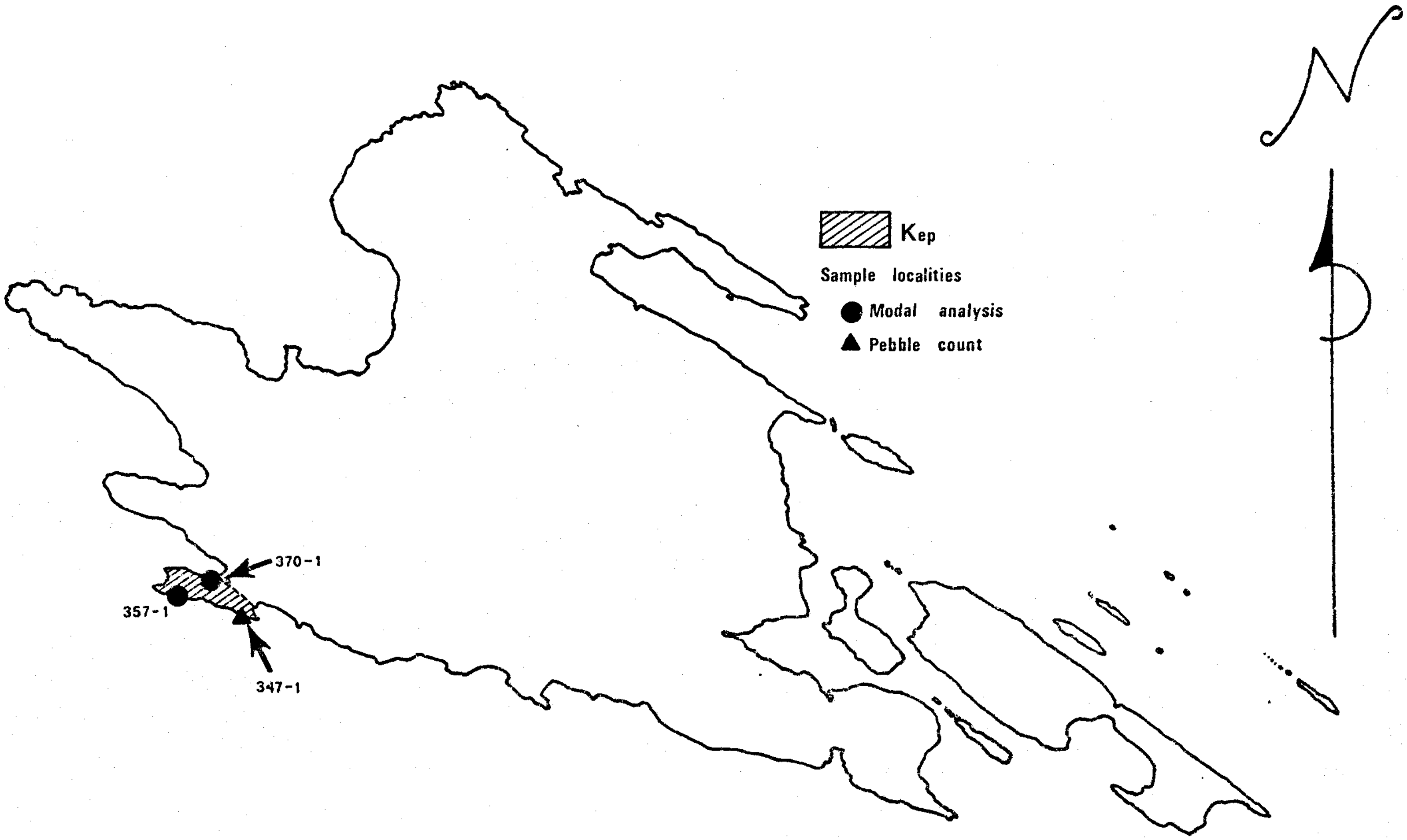



Figure 4. **Distribution of Extension - Protection Formation and Sample Localities**

Internally, the conglomerate shows scour-and-fill with the enclosing sandstone.

Northward across the bayhead, other prominent ribs of coarse-grained sandstone occur and also appear to pinch out beneath the water. Beach sands cover the intervals between these resistant projections, concealing all but a hint of the mostly younger Cedar District unit inferred to be present.

The Cedar District Formation is sandwiched between two very similar units: the Extension-Protection below and the DeCourcy (described in a following section) above. Therefore, it was necessary to entertain the possibility that the rib-like tongues belong to the lowermost DeCourcy instead of the older unit. Several features are more prevalent or show better development in the DeCourcy rocks than in the beach ribs or the upper Extension-Protection proper. They are: oscillation between parallel- and cross-laminated sandstone interbeds; generally wider variations in grain size of the sandstones; load structures; coarse-grained, calcareous sandstone concretions; and a strong, cliff-forming tendency. These indicators support assignment of the sandstone and conglomeratic lenses to the underlying Extension-Protection Formation.

Lithology. Included within this formation, as it is typically exposed here, are mudstones, sandstones, and conglomerates. A fairly well-developed stratification, which occurs in places, generally does not persist laterally more than a few tens of feet. It is often interrupted by pinching out along strike and also by numerous scour-and-fill structures. This lack of continuity precluded differentiation of separately homogeneous members within the unit. Following a description of each lithology represented, progressive up-section variation will be discussed under Environments of Deposition.

Mudstone seldom occurs as planar interbeds. It is more commonly a channel in-filling, ranging from 1 to 12 feet wide and with up to 6 feet of relief. In a vertical section, more than one may be observed, indicating a periodic event such as shifting of a braided channel. They are often separated by or intercalated with sandstone to conglomerate. Because they are subject to rapid erosion, fresh exposures are not available. Depending largely upon the degree of iron mineral oxidation, colors of the weathered surfaces vary. A typical example noted was moderate yellowish brown (10YR 5/4).

Where coarser sand is incorporated with the mudstone, laminations exhibiting normal grading locally appear. A crude internal stratification defined by finer grained and frequently imbricated mudstone rip-ups is commonplace. Some of these clasts are locally between 1 and 2 feet long and up to 10 inches thick. They are usually succeeded by smaller ones elongated subparallel to the bedding. Such a trend signifies decreasing current energy as the deposit came to rest. In one channel-filling (Fig. 5), a mudstone rip-up projects

Figure 5. Note the mudstone rip-up (near tip of hammer handle) from channel in-fill which penetrates the underlying conglomerate indicating nearly contemporaneous deposition of both. Also note upward transition from clast imbrication to elongation parallel with bedding. Current flowed right to left. Extension-Protection Formation, 0.4 mi. S. E. of Dinner Point, Mayne Island.

into the underlying conglomerate implying nearly contemporaneous deposition for both.

Sandstone, varying from thinly laminated to very thick-bedded (McKee and Weir, 1953), is the predominant lithology within this unit. To supplement field observations, representative samples were collected (see Fig. 4 for localities). Three thin sections were made so variations among the sandstones and microscopic features could be studied in detail. Two of these were point-counted to determine the mineralogy (Appendix B) and to facilitate classification.

Where fresh exposures were located, the prevailing color is light olive gray (5Y 6/1) that becomes grayish orange (10YR 7/4) to very pale orange (10YR 8/2) upon weathering. Because of the intimate association with conglomerate, a complete spectrum of particle sizes is represented ranging from coarse pebbly sandstone to silt and clay. Medium to coarse size fractions seem to predominate.

In thin section, grain shapes for all samples are angular (Powers, 1953). Obviously graded sandstones are very poorly sorted, closely packed, and are texturally immature (Folk, 1951). The lesser amount of clay-size material in coarser sandstones elevates them to the texturally submature stage. A preferred grain elongation, parallel to internal lamination, points to a tractive current transport mechanism. In the absence of abundant matrix, there is a notable degree of framework grain interpenetration and mica booklets paralleling the laminae are severely contorted. The excellent depositional porosity anticipated from particle shape is virtually destroyed. Post-depositional compactive forces must have been considerable to produce these effects.

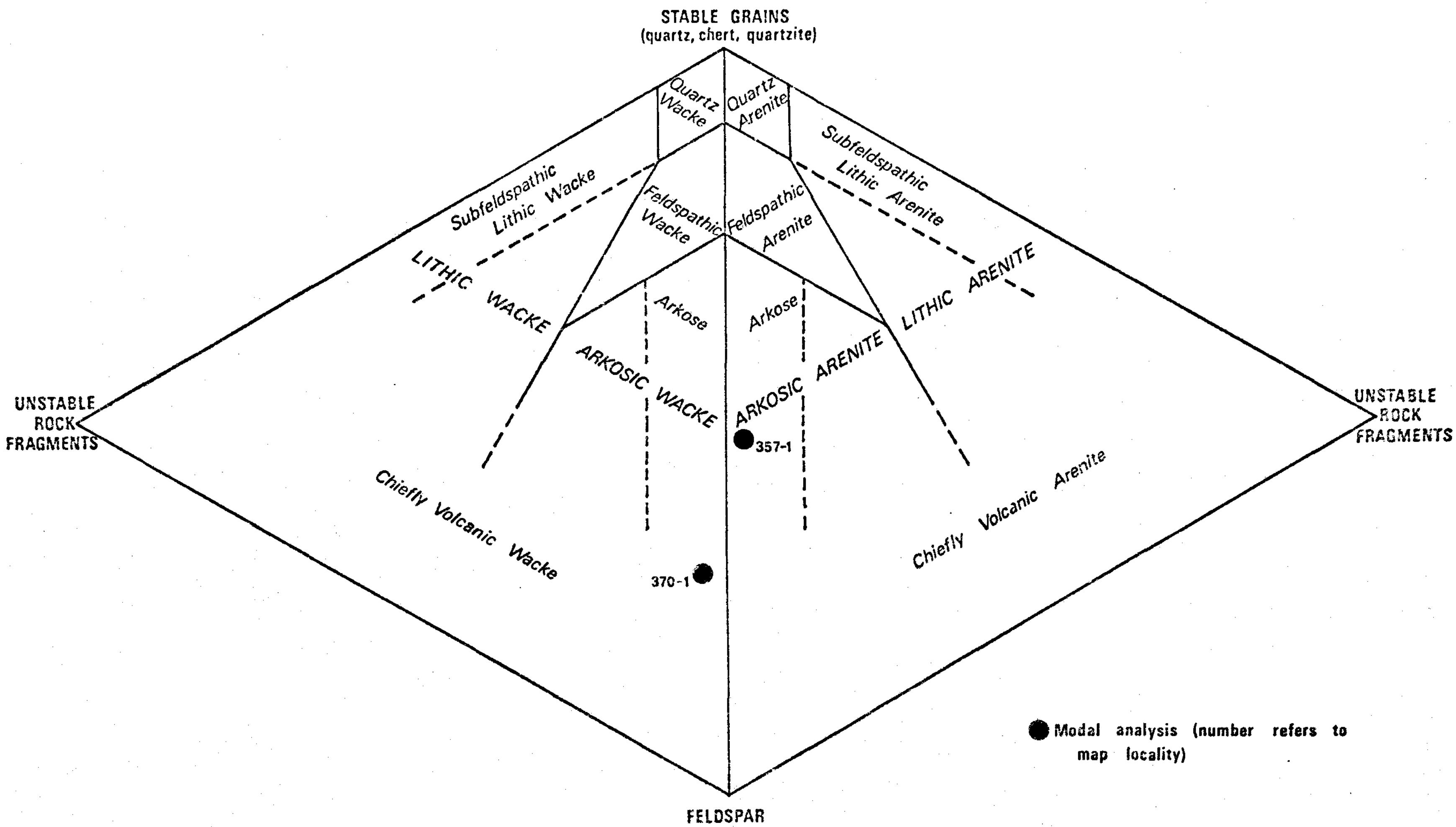
During microscopic study, the following trends were found broadly applicable to nearly all the rocks of the study area which were analyzed: 1) in the coarse-grained sandstones lacking appreciable calcareous cement, feldspar and stable grains (i.e., quartz and chert) account for well over half the total rock; 2) plagioclase exceeds alkali feldspar by approximately one-third; 3) of the quartz polytypes, strained quartz is much more common than polycrystalline quartz, chert, or the unstrained normal variety; 4) compared to those of metamorphic or plutonic origin, volcanic rock fragments are substantially more plentiful; 5) biotite is more than twice as abundant as either muscovite or chlorite; 6) biotite has progressively altered to magnetite, then hematite; and 7) the heavy mineral suite is most widely represented by epidote, magnetite, and hematite. These trends will be referred to, from time to time, and the few exceptions will be mentioned individually.

In the Extension-Protection Formation, the only departure from the generalizations above is an excess of metamorphic rock fragments relative to volcanics in one sample. This may be accounted for by more rapid diagenetic alteration of the less stable volcanic fragments contributing partly to the high matrix content. Because all the rock fragments have not yet disappeared, these samples are compositionally immature.

Andesine ($An_{31-36}$) was the only type of plagioclase found and myrmekitic intergrowths with quartz are not unusual. Orthoclase, the dominant potassium feldspar, similarly exhibits micrographic intergrowths with quartz. Products of chemical attack on the feldspars are kaolinite and sericite. Chloritic matrix appears to have been produced by diagenetic alteration of biotite and possible volcanic rock fragments. Gradational color loss suggests that some muscovite formed as biotite and was "bleached" by acidic fluids (Milner, 1962)--a phenomenon which also favors kaolinization. The most abundant heavy minerals, not yet mentioned, are clear garnet, ilmenite, leucoxene, and zircon, with traces of apatite and sphene.

Although zeolites or remobilized silica may contribute to induration of these rocks, no quartz overgrowths or zeolitic minerals were distinguished. Undifferentiated clay minerals and iron oxides seem to hold them together effectively as would truly precipitated cements. Of the two samples point-counted, one is an arkosic arenite and the other an arkosic wacke (Fig. 6).

Primary sedimentary structures common in the sandstone intervals are: scours in-filled by coarser sandstone to conglomerate; stratification, usually with gradational upper and lower contacts;




**Extension-Protection Formation**

Figure 6. Classification of Sandstones (after Gilbert in Williams et al., 1954)

normal grading; parallel laminations; festoon cross-laminations defined by particles elongated parallel to the layers; bedding lenticularity; and contorted laminae or other load features in beds overlain by thicker, more competent strata. Secondary structures include honeycomb weathering patterns and calcareous concretions up to one foot in diameter.

Conglomerates are the most resistant rocks of this unit. They occur in both channelized and possibly nonchannelized deposits. Although the clasts are usually smaller than coarse pebbles, all sizes from sand to cobbles or boulders can be found. The particle distribution is ordinarily bimodal and both clast- and matrix-supported intervals are seen throughout. Except in the smallest pebbles, a high degree of rounding is typical, but many have chipped surfaces indicating excessive transport energy. Color is variable from pale yellowish brown (10YR 6/2), on the freshest surface obtainable, to very dusky red (10R 2/2) where weathered. A pebble count (Appendix C) showed that roughly half the clasts examined were chert and a similar number were quartzite, granitics, and basalt in nearly equal proportions. The remainder were foliated metamorphics and a subordinate amount of andesite. The metamorphics, being very friable and easily weathered, were frequently uncollectible, and thus were slightly more abundant than the pebble count indicated.

Sedimentary structures observed in the conglomerates were the following: undulating depositional surfaces carved by channels; current lineations and groove marks on the soles of channel-fills; subparallel, horizontal stratification, nearly always defined by well-imbricated layers (Fig. 7); coarse-tail grading, where a waning current deposited progressively smaller clasts and all but a narrow range of in-filling particle sizes remained in transport; normal grading; lenticular bedding; and large-scale trough cross-lamination (1 to 3 feet wide with 3 to 6 inches of relief).

Environments of Deposition. A major key to the depositional history of the Extension-Protection Formation is the abundance of conglomerate. Looking to modern environments for analogy, conglomerate is generally restricted to both alluvial and deep-sea fans, glacially-influenced terranes, braided rivers, and shorelines (Walker, 1975).

A glacial association here can be immediately dismissed because a tropical to warm temperate Late Cretaceous paleoclimate is well-known (Bell, 1957). Physiographic conditions then were much as they are today (Usher, 1949). Coal, which was mined from this formation at Nanaimo, probably accumulated in coastal plain swamps and marshes near sea level. Continental to shallow marine features, reported from Saltspring (Hanson, 1976), include abundant plant fragments and current-oriented pelecypod valves. Usher (1949) referred

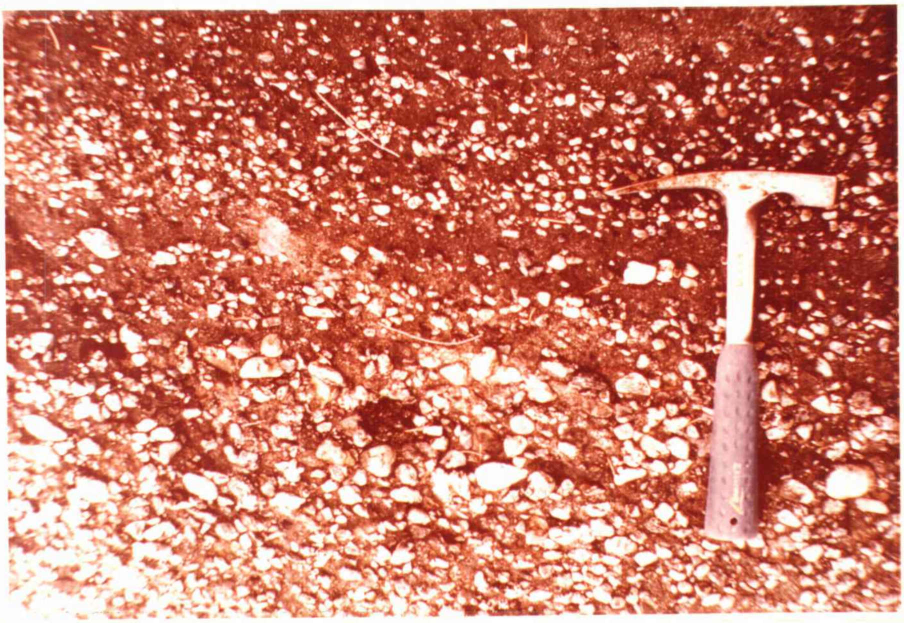


Figure 7. Note the crude stratification defined by pebbly layers, a hint of coarse-tail grading, and the imbricated fabric. Current flowed from right to left. Extension-Protection Formation, 750 ft S. E. of Dinner Point, Mayne Island.

to the basin as "shallow." Such evidence makes it difficult to consider the conglomerates as possible deep sea fan deposits.

Sedimentary structures give strong testimony that the Extension-Protection Formation is the product of an active, braided fluvial system. Megascopic and microscopic features support this argument. The thick-bedded, well-imbricated conglomerates were deposited by swift, unidirectional currents sufficiently competent to move large quantities of pebbles and cobbles in the bedload. Steep-gradient feeder streams drained source areas of high relief. Fluctuations in current energy are illustrated by repeated normally graded intervals of varying clast sizes within the conglomerate beds. Periods of extreme energy, generating impacts that chipped well-rounded clasts, contrast with quiescent times when thinly laminated silt and clay were deposited.

Thick sheet sands and multiple upward-fining sequences of variable grain sizes, both widely represented here, are characteristic of braided streams (Coleman and Wright, 1975). Innumerable scour-and-fill structures were produced by channel-switching and distributary migration. The mudstone rip-ups were probably derived from nearby areas of intermittent flow re-subjected to vigorous currents (Fig. 5).

Pebbly layers in the conglomerate are discontinuous laterally; vertical transitions to interbedded sandstone are gradational. These properties help resolve fluvial sediments from those of shallow marine origin where more persistent beds with sharper contacts are expected (Clifton, 1973). No fossils were discovered here, but marine pelecypods occur farther west on Saltspring (Hanson, 1976). Fluvial sedimentary features and the lack of marine fossils (recognizing that negative evidence may be misleading) suggest these deposits lay somewhat east of the shoreline. Scant paleocurrent data indicate westerly flow from an eastern source--not inconsistent with measurements on Pender (Hudson, 1975) and Saltspring (Hanson, 1976) Islands.

Selley (1970) points out that braided rivers commonly develop on piedmont fans if the discharge and rate of sediment supply are both high. On Mayne, the overwhelming abundance of well-rounded and well-sorted Extension-Protection conglomerate clasts might represent deposition farther basinward than the fan environment. Also, because of much lower mass, the observed angularity of smaller particles could have been sustained in transport over considerable distance.

Upward from the base of the exposed section on Mayne Island, two gradations from predominantly conglomerate to sandstone sedimentation are recorded. The conglomeratic intervals appear as salients on the west end of the peninsula; Dinner Point is one and the other is continuous with the south side of Dinner Bay. Both wedge out to the east. A transition to sandstone between the two is essentially duplicated within the tongues at the head of Dinner Bay. This sequence suggests two episodes of major distributary migration which preceded the final phase of Extension-Protection deposition.

Cedar District Formation

Nomenclature. Not far southeast of Nanaimo, a valley stretches between Ladysmith Harbor and the mouth of the Nanaimo River. It has resulted from differential erosion of a dark, iron-rich, non-resistant rock unit of sandy to shaly character. A political zone, through which most of the valley passes, is called Cedar District. The name was also applied to this valley-forming sequence of rocks (Clapp, 1912, p. 99) which rests upon the Extension-Protection Formation.

General Character. The fossiliferous Cedar District Formation is a highly erodable, monotonous succession of laminated to very thin-bedded rhythmic packets of a predominant marine aspect. The varied fauna is known to include ammonites--both straight and coiled types, gastropods, pelecypods, trace fossils, and Foraminifera. These are dealt with individually later in this section under Fossils. The term "shale" has been applied to the finer-grained parts of this and similar units (Clapp, 1914a; Usher, 1949; Muller and Jeletzky, 1970). Whereas some workers regard fissility as an essential property of shale (Blatt et al., 1972), either fissility or lamination is accepted by other definitions (Pettijohn, 1957). While these rocks are nearly always laminated, their angular, chippy talus shows they are essentially nonfissile. Such rocks, dominated by silt- to clay-size fractions, and lacking fissility, are henceforth called "mudstone" after Wilkinson and Oles (1968). To avoid confusion, use of the term "shale" is abandoned here.

Cedar District rocks in the study area are exposed only on Mayne Island. Most of these are limited to a discontinuous, narrow strip along Navy Channel, seldom wider than 500 feet. It stretches from the small cove near St. John Point to the head of Dinner Bay.

On the southeast end of Mayne Island, two graded sandstone-mudstone intervals emerge. They are inferred to be Cedar District tongues within the DeCourcy Formation (discussed in the following section). Of the two, the southernmost reappears along strike in the aforementioned cove west of St. John Point. The other shows up on the east side of the most southerly extremity of Horton Bay. There is an uncertainty factor in these correlations, which are based mostly on similarity of appearance and superposition, because of extensive cover between outcrops.

The stratigraphic complexity of the tongues has been tentatively ascribed to faulting (Muller and Jeletzky, 1970), but a strong supporting case could not be demonstrated by the present writer. Available joint and fault plane orientations were plotted for the general area.

Nearby trends sub-parallel to the proposed fault are virtually lacking, and disparities between 40° and 60° were very commonly noted. Slickensides, where found on outcrops, seem to have resulted from bed-on-bed slippage related to folding of the Trincomali anticline (discussed further under Structural Geology--Longitudinal Faults). Additional foundation for the revised interpretation presented here is the similar interfingering relationship mapped on the facing tip of Saturna, 1.6 miles southeast along strike (Sturdavant, 1975). The Cedar District-DeCourcy contacts, near St. John Point on Mayne Island, are remarkably comparable to their analogs on Saturna as described by Sturdavant.

As mentioned in the preceding section, Cedar District rocks are believed to lie interjacent to the Extension-Protection tongues at the head of Dinner Bay. Although truly distinctive Cedar District exposure is lacking, the following points substantiate its actual existence here: first, all the major bays in the area have formed where waves impinge upon rocks virtually identical to Cedar District lithologies; second, between the head of Dinner Bay and the east side of the peninsula, where somewhat typical Cedar District is exposed, there is a continuous topographic low; third, a thick soil cover, suitable for cultivation in this low area, has developed elsewhere on surfaces underlain by rocks of the Cedar District type; finally, a very fine-grained, Cedar District-like sandstone to siltstone occurs beneath one of the Extension-Protection tongues. It has mostly been selectively eroded away exposing sole marks, but the small remaining part contains soft-sediment deformation features and some graded packets. Considering this evidence in toto, the Cedar District contacts here are mapped as shown on Plate 1 and Figure 8.

Approximately 600 feet north-northeast of Dinner Point, a previously unmentioned tongue of apparent Cedar District affinity is actually present within the Extension-Protection Formation. It is from 15 to 20 feet thick and consists of medium- to fine-grained sandstone to mudstone deposited in graded beds. Its lateral extent along strike could not be traced because of cover, and it is not a wide enough interval to map at the scale used here. The parallelism with Cedar District rocks is emphasized by the presence of abundant, microcrystalline, calcareous concretions along bedding planes. Some have irregular, flattened shapes, but most are oblate ellipsoids up to 4 inches in length. Concretions of this type seem to be peculiar to the rocks of marine origin and are plentiful in other outcrops of this formation. The events recorded in these strata were a preview of a later, more widespread submergence.

The generally unsheltered Cedar District Formation is vulnerable to pounding storm waves which have shaped a broad platform. It normally stands slightly above low tide level and outcrops here are easily observed. The sea cliffs, however, are difficult to ascend because of the crumbly nature of the rocks where weathered.

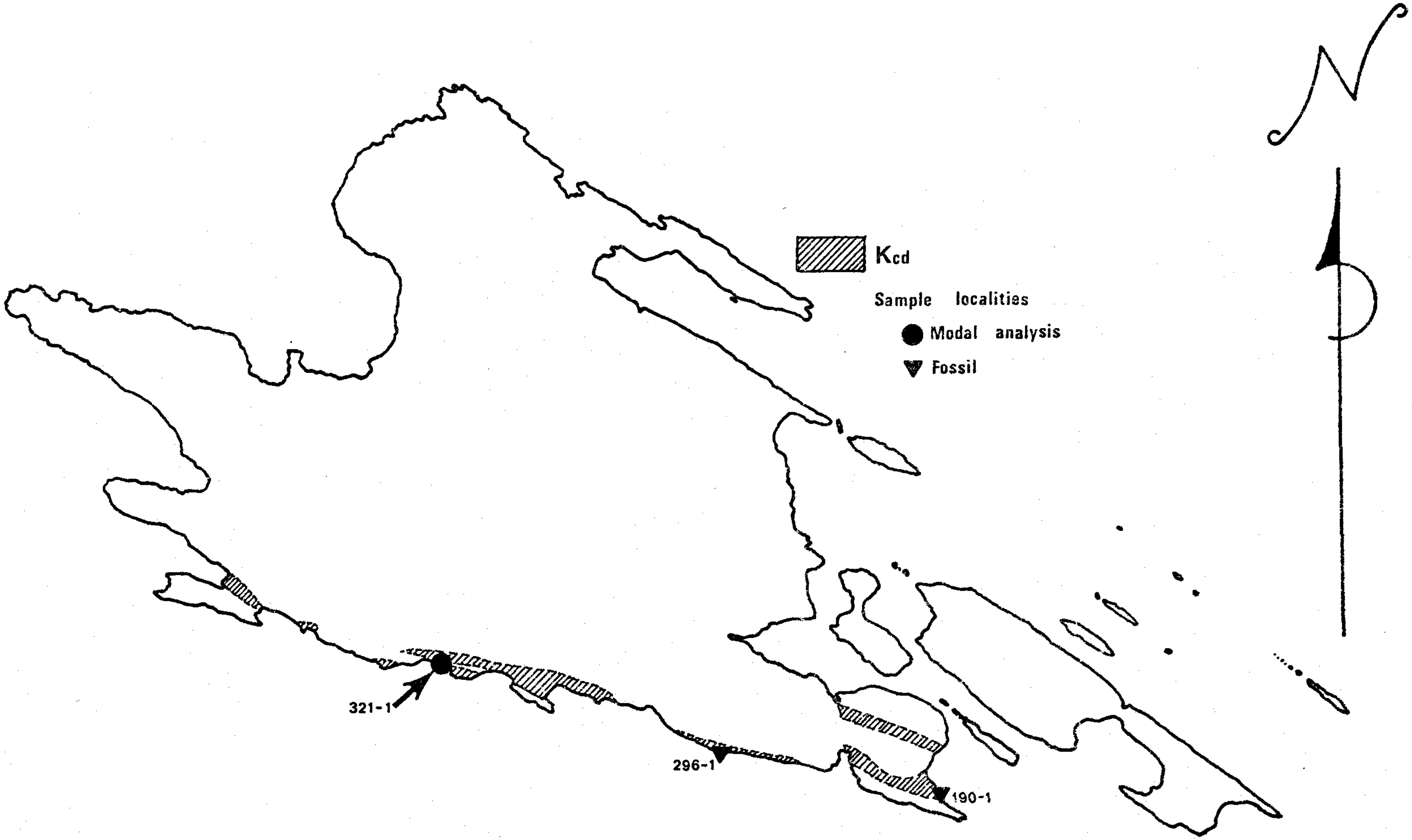



Figure 8. Distribution of Cedar District Formation with Sample and Fossil Localities

The lower Cedar District contact within the Extension-Protection Formation was discussed in the preceding section. Two other types of contact relationships with the DeCourcy Formation are well-represented: one involves complex interfingering and the other is relatively simple. A planar contact of the latter type is exposed in the sea cliff 1.3 miles west of St. John Point (Fig. 9). It also occurs 0.5 mile farther west with undulating scour-and-fill (Fig. 10). Approaching the contact from below, sandstones progressively increase in thickness at the expense of mudstone--a coarsening upward sequence.

Complex interfingering contacts are best displayed on the southeast end of Mayne Island. Major transitions from Cedar District to DeCourcy tongues, up- or down-section,are denoted by the disappearance of mudstone and a concomitant increase in beds of coarser sandstone. The interval over which this occurs is usually less than 50 feet, but without sharp breaks the contact therein is necessarily arbitrary. Several discrete beds of DeCourcy aspect commonly lie within such a zone and call attention to the fluctuating conditions until Cedar District deposition terminated.

Larger structures attributable to soft-sediment deformation can be found within the Cedar District Formation. In one beach exposure due north of Conconi Reef, normal to moderately deformed strata are truncated abruptly by a block of similar lithology. Adjacent bedding

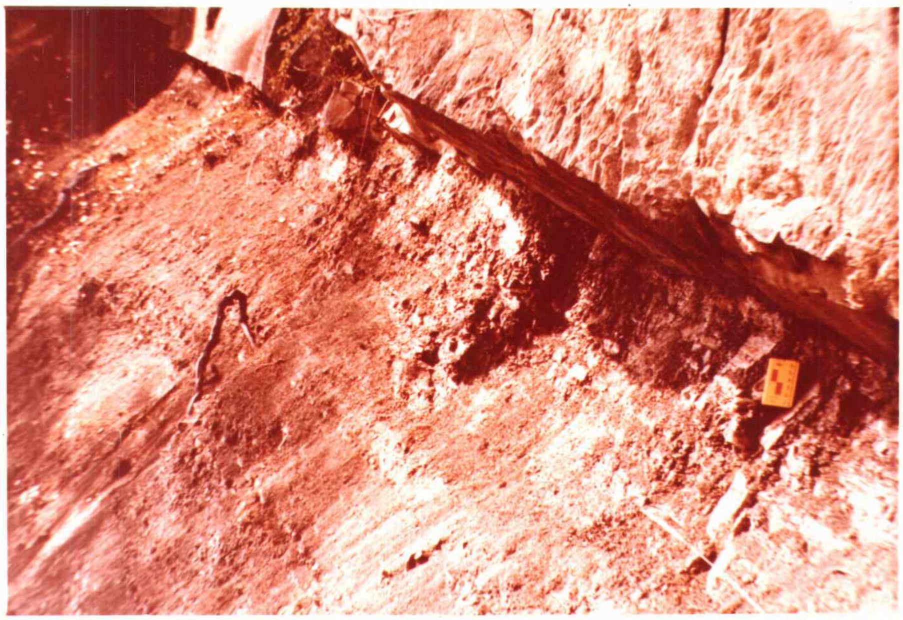


Figure 9. Note planar contact with DeCourcy sandstone underlain by weathered sandstone to mudstone of the nonresistant Cedar District Formation. Exposed in sea cliff facing Navy Channel, 1.3 mi. N. W. of St. John Point, Mayne Island.

Figure 10. Undulating scour-and-fill contact of DeCourcy conglomerates above normally graded sandstones and interbedded mudstones of the Cedar District Formation. Note sandstone rip-up blocks of underlying unit contained within the centermost part of the conglomerate. In sea cliff facing Navy Channel, 1.8 mi. N. W. of St. John Point, Mayne Island.

planes are almost at right angles to each other (Fig. 11). Nearly identical features, which are ostensibly coeval, reappear in a sea cliff cut less than 200 feet away. The blocks are interpreted as products of subaqueous slumping--a common occurrence, for example, on prodelta platforms where the water content of accumulating unstable muds is high (Coleman and Wright, 1975). Integrity of the blocks was probably maintained during movement by the cohesive, clay-rich interbeds. In weathered outcrops, it is not easy to differentiate these structures from their much more recent subaerial equivalents. On the southeast end of Mayne Island, the upper contact of the northern-most Cedar District tongue has apparently been deformed by one or both of these processes.

Thickness approximations derived trigonometrically were found most satisfactory. By collecting and plotting numerous attitudes, local anomalies became obvious and were discarded in calculations. Using these methods, thicknesses are: 353 feet at the head of Dinner Bay; 455 feet at Piggott Bay; and 345 feet on the southeast end of Mayne Island, including both tongues. At these localities, thicknesses do not appear to have been significantly reduced by erosion, because each exposure is protected by more resistant strata.

On Saturna to the southeast, Sturdavant (1975) determined the Cedar District Formation to be 1, 127 feet thick. Hudson's (1975) estimate from the Penders is at least 2, 200 feet. On these

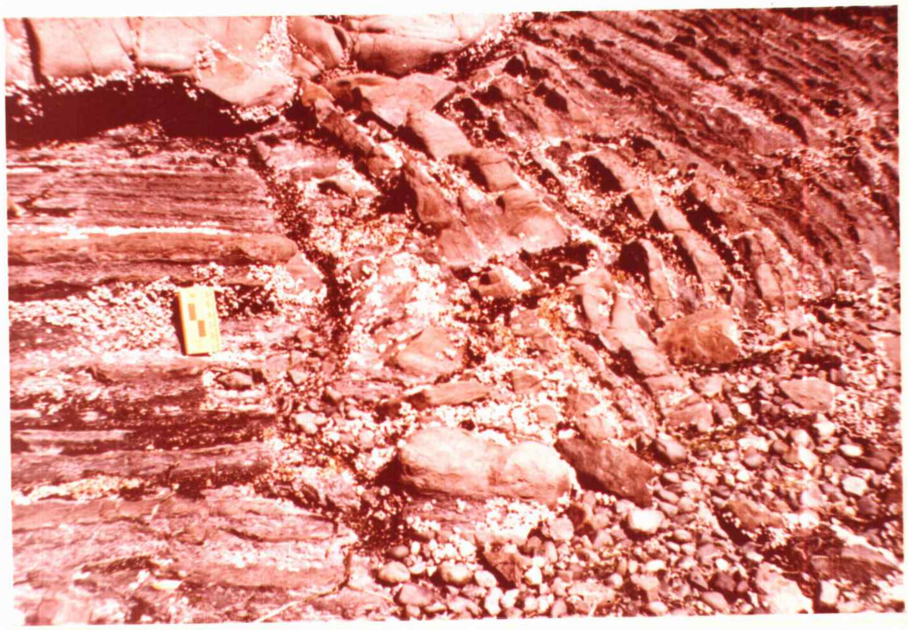


Figure 11. Note juxtaposition of sharply discordant strata, likely produced before lithification by subaqueous slump activity. Integrity of blocks was maintained by cohesive, interbedded muds. Mayne Island beach outcrop of Cedar District Formation N. 16° W. from the Conçoni Reef navigation light.

last-mentioned islands, and also on Saltspring, to the west, multiple Cedar District members or tongues were mapped (Hudson, 1975; Sturdavant, 1975; Hanson, 1976). As suggested by thickness comparisons, the sparse outcrop pattern, and field observations, most of this unit has been stripped from Mayne Island by erosion. Local paleocurrent data are insufficient to interpret lateral thickness variations with confidence.

Lithology. Finer grained sandstones to mudstones deposited in repeated graded packets typify Cedar District lithologies. Resistant calcareous interbeds are also frequently observed. Given sufficient exposure, the very persistent stratification within the sandstones is traceable over several tens of feet. Less commonly, some beds are interrupted by minor scour-and-fill structures and others simply pinch out. Lithology remains quite constant vertically except near contacts. These relations have been described earlier in this section under General Character.

The calcareous interbeds seldom exceed 6 inches in thickness and are usually devoid of internal structures. At many places they grade laterally into detached lenses and finally to individual concretions, some less than 3 inches in diameter, scattered along the bedding planes. Superficially they resemble the enclosing sandstones to siltstones, but close inspection reveals notable differences. Some of these are: more rapid smoothing of surface irregularities where the rocks are exposed only at lower tides; well-developed pseudo mudcracks are abundant (see explanation below); incipient solution pits and cuspate features typical of carbonate weathering in subaerial outcrops; intermittent occurrences of small burrow structures resembling Helminthoide (?); much greater hardness, related to internal homogeneity and absence of pore space; and vigorous reactivity with dilute hydrochloric acid. The color of these rocks is light bluish gray (5B 7/1) to light olive gray (5Y 6/1) when weathered and medium gray (N5) to dark gray (N3) on fresh surfaces. Folk (1962) restricts the term "micrite" to "clay-sized carbonate." In certain samples, only trace amounts of silt-sized terrigenous grains are observed microscopically and such rocks are considered here to be silty micrites (after Hanson, 1976). Some of them contain just enough pelletal material to be called silty pelmicrites (modified from Folk, 1962). Where terrigenous silt content exceeds trace quantities, they are termed calcareous siltstones.

Except for suggestions of parallel to contorted laminae, primary sedimentary structures either did not form in these beds or were obliterated, possibly by organic burrowing activity or penecontemporaneous disturbances. The formation of concretions, an early secondary modification, demonstrates the mobility of mineralized pore fluids. In many instances, the concretions preceded lithification, because the enclosing strata are differentially compacted around them. These limey mudstone beds are possible sources for much of the calcium carbonate cement observed in adjacent coarser grained layers. This would imply a diffusive process. In other places, calcareous molluscan fossils, within the concretions, appear to have acted as nuclei for precipitation of inwardly migrating solutions. Either one or both processes, or even others less obvious, may have contributed depending upon existing chemical conditions.

Pseudo mudcracks are prevalent where the surfaces of calcareous interbeds are generally submerged. They are polygonal to reticulate patterns of V-shaped (in cross section) lineations, possibly joints, that have been selectively dissolved and resemble classical mudcracks.

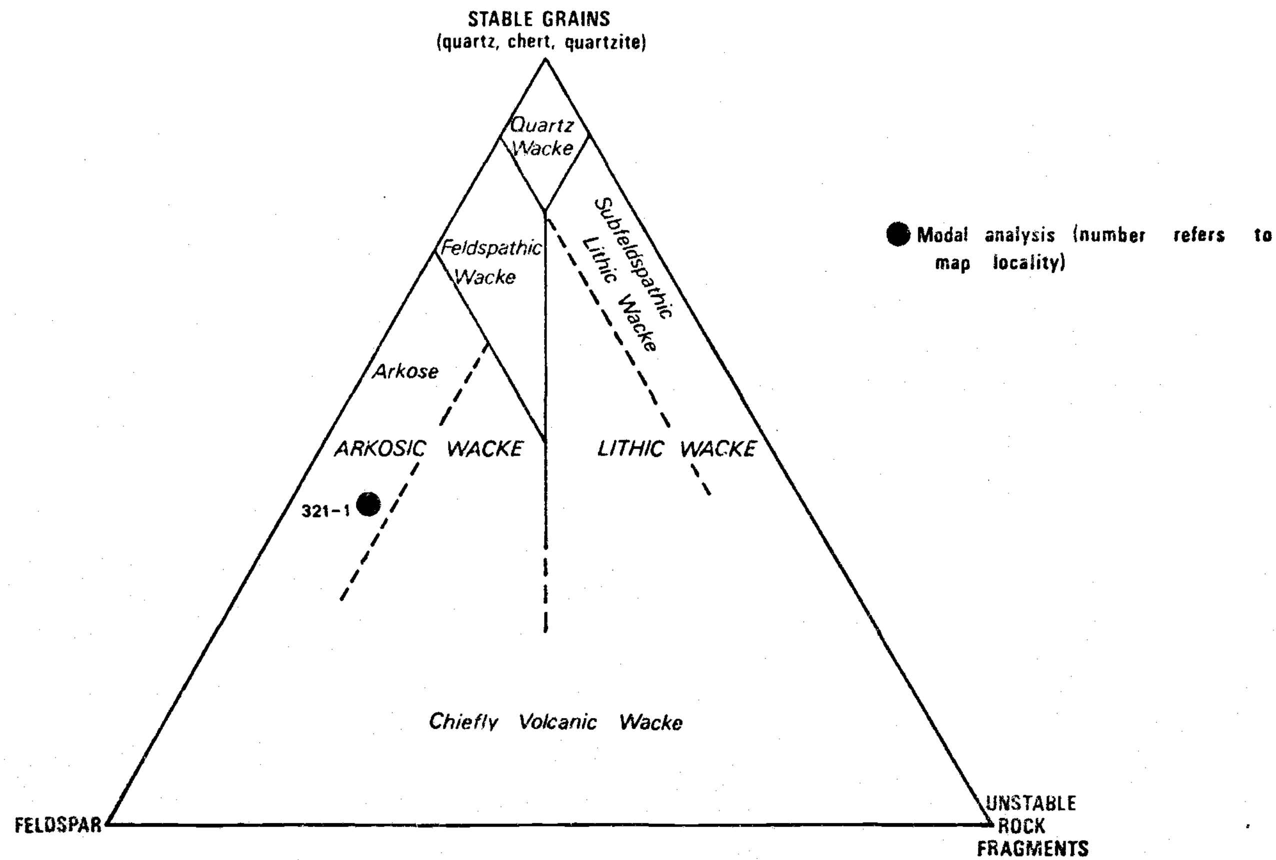
Mudstone is a major Cedar District lithology. The thinly laminated character is usually obscured by the chippy fracturing that results from weathering. Individual chips are very angular and seldom longer than 1/2 inch. Representative weathered colors are light gray (N7) to medium dark gray (N4) and they are medium gray (N5) to dark gray (N3) where fresh.

Sandstones are the other principal rock type of the formation. They are laminated to thin-bedded (McKee and Weir, 1953) and are separated by interjacent mudstone beds having thicknesses that vary within similar limits. The ratio of sandstone to mudstone increases approaching the DeCourcy contacts, but farther away stratigraphically, either lithology may dominate locally.

Four thin sections of Cedar District rocks were prepared and examined microscopically. From the strong mutual resemblance of the sandstones collected, the fine grain sizes, and the limited outcrop area, significant lateral variations were not expected. Thus, only one thin section was point-counted to illustrate the mineralogy (Appendix B) and the classification (Fig. 12) of a typical sample.

Typical colors of the sandstones are light olive gray (5Y 6/1) to dusky blue (5PB 3/2) when weathered and light gray (N7) to dark gray (N4) if fresh. In general, the normally graded beds show continuous transitions from medium or fine sand to mudstone, but the fine sand size is most widely represented. Over small intervals, the sandstones are moderately sorted, contain angular to subangular particles (Powers, 1953), are very closely packed, and fall within Folk's (1951) texturally immature to submature stages as matrix content decreases. There is a barely discernible preferred grain elongation parallel to laminae which are defined by concentrations of hematite, finely divided chloritic material, and mainly dark stringers of biotite. Cross-laminations, with festoons ranging from 3 to 5 inches wide and about 1/2 inch deep, indicate the fabric is current-produced.

Dissolution, replacement, cementation, and breakdown of unstable minerals and rock fragments are the diagenetic processes




Cedar District Formation

Figure 12. Classification of Sandstones (after Gilbert in Williams et al., 1954)

responsible for destruction of original porosity. The calcite cement, while not pervasive in some samples, has noticeably embayed the older quartz grains.

There is only one exception to the general trends determined petrographically in the preceding section (cf. microscopic observations under Extension-Protection Formation--Lithology and Appendix B). Polycrystalline quartz was found to be nearly twice as abundant as strained quartz instead of the reverse. However, sutured grain boundaries of the polycrystalline quartz particles are indistinct and there is no clear demarcation between the two polytypes. Unavoidable overlap is likely to have exaggerated the apparent difference.

Andesine ($An_{38}$) and labradorite ($An_{53}$) exemplify the plagioclase suite here, while orthoclase dominates the potassium feldspar types. Some of the matrix was derived from plagioclase decomposition recognizable along grain boundaries. Part of the calcareous cement may have come from the feldspar alteration products (Williams et al., 1954; Milner, 1962). From X-ray diffraction, only chlorite and kaolinite are present in the amounts necessary to yield interpretable peaks (Appendix C). The main heavy minerals identified are: epidote, ilmenite, leucoxene, and magnetite with only accessory apatite, hematite, and sphene. Compositional immaturity is indicated by the presence of volcanic rock fragments. According to Gilbert's classification (in Williams et al., 1954), the Cedar District sample (Appendix B) is an arkosic wacke (Fig. 12).

Among the myriad sedimentary structures present are: repeated normally graded bedding, parallel or contorted laminations, load casts, flame structures, festoon cross-laminae, incomplete Bouma sequences, scour-and-fill, clastic dikes, incipient prolapsed bedding (Fig. 13), particle elongation, and trace fossils. Secondary features noted include pseudo mudcracks, explained earlier in this section, and concretions, which are variously composed of calcium carbonate or iron sulfide.

Fossils. Locally, the sparse, but somewhat diverse Cedar District fauna is represented by the few molluscs collected and trace fossils observed in the field. Crushed Inocerami, often found in calcareous concretions, were recognized by their typical prismatic shell structure. Another unidentified pelecypod was noted with a shell composed of more equant crystals of sparry calcite--probably a replacement phenomenon. With only one exception, all the pelecypods were disarticulated and usually broken.

Ammonites occur in the mudstones, but only one small, coiled variety was discovered in untransported beach float (Fig. 14). Because preservation is poor, it could be identified only generally as Pachydiscus sp., known from rocks of both Campanian and Maestrichtian ages (Mallory, written communication, 1976). Much more

Figure 13. Incipient prolapsed bedding, manifest as a recumbently folded interbed, was produced by downslope shifting of overlying water-saturated cohesive muds and sand before lithification. Paleoslope declined from upper left to lower right. Cedar District Formation in sea cliff at north side of Gallagher Bay, Mayne Island.

Figure 14. Coiled, Pachydiscus sp., ammonite fragments preserved in untransported beach float. Note suture pattern at lower left. Cedar District Formation in bay facing Samuel Island, 800 ft N. W. of St. John Point, Mayne Island.

common are the straight types, resembling *Baculites*, or other slightly curved varieties. None of these were found in good enough condition to warrant collection. Considering the marginal preservation, some of these elongate, conical fossils may be scaphopods, an externally similar mollusc. While ammonites are a pelagic fauna, scaphopods are benthic feeders with a broad depth range. Neither can be used to accurately infer the paleobathymetry.

A sample from a micritic limestone interbed was also found as untransported beach float and several high-spired gastropods are scattered on the upper surface. Albeit not well-preserved, they are tentatively identified as ?*Nerinea* by Mallory (written communication, 1976). He also points out that their subparallel alignment is quite suggestive of current orientation in a relatively shallow marine environment.

Foraminifera were collected (McGugan, 1964) from what are believed to be Cedar District localities (McGugan, 1964; Muller and Jeletzky, 1970) on Mayne Island and immediately across Navy Channel on the north end of Pender Island. Generic and specific names made available to the present writer include only those from Pender (McGugan, written communication, 1976), and the rocks sampled there have been subsequently interpreted as upper Northumberland (Hudson, 1975). It is prudent here to avoid detailed conclusions based on these foram data until this apparent inconsistency has been resolved.

During the field season, four rotary-drilled water wells penetrated Cedar District rocks on Mayne Island. Fresh cuttings, collected and examined in the laboratory for a possible microfauna, were disappointingly barren.

Trace fossils can be seen on many bedding surfaces, but their identity is generally elusive. Many structures were recognized as _Thalassinoides_ from comparison with a sample (cf. Hanson, 1976, Fig. 17) identified by Chamberlain (1975). Well-developed branches, commonly intersecting at angles circa 120° are typical of shallower occurrences; they are less prominent at outer shelf to upper bathyal depths (Chamberlain, 1975). Isolated vertical burrows are frequently observed within the mudstones and have been in-filled later during deposition of coarser detritus above. Similar borings are also attributed to _Thalassinoides_ by Sturdavant (1975, Fig. 12, p. 25). In Recent fine-grained sediments with a high organic content, shallow anaerobic conditions severely limit the depth hospitable to burrowing organisms within the substrate (Howard, 1972). Numerous pyrite/marcasite concretions and the abundant burrow structures parallel to the stratification suggest a locally comparable Cedar District environment.

Within calcareous interbeds, irregular and discontinuous structures suggestive of Helminthoida (Hanson, personal communication) were collected. In thin section, clustered pelletal material was often found associated with these forms. This may be Tomaculum, a name for beaded fecal material (Hass et al., 1962) identified with Helminthoida from other rocks of this area (Chamberlain, 1975).

A coalified woody fragment, just over one foot long, was the only obvious plant material noted in this formation.

Environments of Deposition. Cedar District graded sediments were laid down as the sea encroached upon the previously described Extension-Protection fluvial system. This was not a single event, but was interrupted by minor regressive shifts that allowed fluvial conditions to dominate sporadically. The lenticular, Extension-Protection sandstone and conglomerate bodies at the head of Dinner Bay are probably in-filled channels carved into the underlying marine tongues. Locally, the noticeably sparse distribution of Cedar District rocks in some places, does not seem plausibly accounted for by either faulting or nondeposition. An undeterminable thickness was probably eroded preferentially along weaknesses created during flexure of the Trincomali Anticline.

More than one process can produce graded beds. However, recent studies have shown that they are a common sedimentary response to subaqueous, downslope movement of sediment-charged density currents induced by gravity (Bouma, 1962; Dott, 1963; Middleton and Hampton, 1973). Such deposits, called turbidites, are widely described from modern and ancient environments (Selley, 1970). The Cedar District Formation on Mayne Island appears to be the upper part of a marine turbidite sequence of locally unknown thickness. It is an assemblage of features, rather than a single characteristic, that supports this contention.

That these sediments are largely marine accumulations is uncontestably demonstrated by the various molluscs, Foraminifera and trace fossils they contain. The only depth implication of turbidites is that deposition occurs below wave base where prospects of reworking are minimal (Walker and Mutti, 1973). The most convincing argument for this process is the combination of "repeated" graded bedding with displaced or "resedimented" biogenic material (Dott and Howard, 1962). Recurrent graded packets are clearly evident here. The coalified woody material, mentioned earlier, probably represents transported organic debris because it was altered to coal beforehand. The disarticulated, broken pelecypods may have been transported also. However, the general paucity of fossils makes the latter difficult to prove.

If the above features are present, the Bouma (1962) sequence, although usually truncated, is regarded as further evidence for turbidite origin. Lower parts of the sequence are likely to be omitted in distal turbidites because only the finest material is carried farthest where it settles gradually. Progressively improved completeness of the sequence suggests that deposition was more proximal. Cedar District rocks commonly exhibit sedimentary structures inferred to be analogous with those described by Bouma. The successions most frequently encountered here are the B and C or the B through D intervals. Bouma (1962) observed that the lime content of the pelitic E interval often shows a marked increase. Perhaps this is reflected by the Cedar District occurrences of silty micrite or calcareous siltstone. Loadcasts and clastic dikes, also of turbidite association (Selley, 1970), are conspicuous.

Marine turbidite environments receiving much attention in the literature include submarine fans (Nelson and Kulm, 1973), deep flysch basins (Graham et al., 1975; Selley, 1970), reefs or carbonate banks, and deltas (Selley, 1970); undoubtedly there are others. Although generalized foram data suggest depths between 800 and 1,000 meters for part of the Cedar District sea (Sliter, 1973), there is evidence on Mayne Island for shallower deposition. Repeated interfingering with the fluvial domain, as suggested at Dinner Bay, suggests proximity to the basin margin. More completely developed Bouma sequences provide a similar clue (Selley, 1970). Observed alignment of gastropods may be attributed to longshore bottom circulation or deep-reaching storm wave influence. Occurrences of branching Thalassinoides suggest the water was shallower than upper bathyal (Chamberlain, 1975). Relatively short transport may be indicated by incomplete fragmentation of fossil material.

Provided shallower water deposition is correctly interpreted from the severely limited evidence above, a deltaic model begins to emerge as an attractive possibility. In this vein, Selley (1970) writes, "A thick sequence of turbidites may thus record a gradual advance of the sediment source into the depositional area." Some features observed within the Cedar District Formation have analogs in other deltaic environments reported in the literature. Turbidites are a common feature of the delta slope (McBride et al., 1975). At or near the rivermouth, interfingering, as mentioned above, is expected (Coleman and Wright, 1975). Marine sequences that coarsen upward into fluvial facies (Fig. 15) are also typical (Visher, 1965; Selley, 1970). Although they may also occur elsewhere, various expressions of soft-sediment deformation (Fig. 13) are especially common in deltas (Dott, 1963; Coleman and Wright, 1975). The reasons include: an increased depositional slope, high sedimentation rate, alternation of coarse and finer strata, and instability resulting from trapped water in the rapidly flocculated clays (Dott, 1963). Although a similarity with certain deltaic features is intimated above, a judgment would be premature that failed to consider additional evidence yet to be presented.

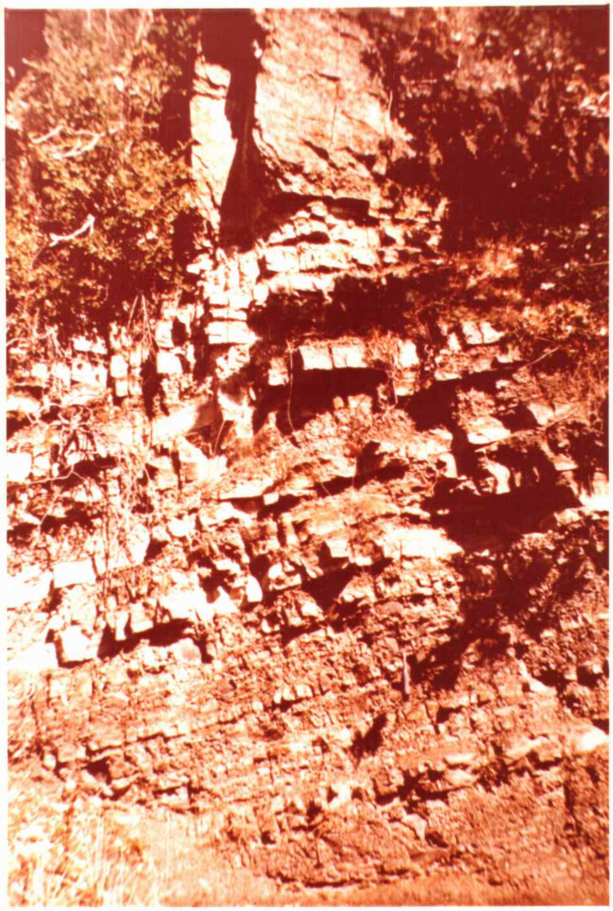


Figure 15. Cedar District Formation sandstone interbeds increase in thickness approaching overlying DeCourcy contact near top of picture. This denotes a "coarsening upward" sequence. Sea cliff facing Navy Channel, 1.8 mi. N. W. of St. John Point, Mayne Island.

Despite incursion of the Cedar District sea, it may be speculated that rapid sedimentation continued along with fairly steady uplift of the source terrane. Within many of the mudstone beds, preservation of the laminae suggests that bioturbation was yet incomplete when the succeeding layer was deposited. While the paucity of fossils may be a diagenetic effect, it is possible that each bed accumulated faster than the organisms could re-establish themselves. A steadily increasing sediment load is also suggested by subaqueous slump features, although an increase in slope, caused by rapid basin subsidence, could be wholly or partly responsible. The latter inference is given substance by Sullwold (1961) who states, "In areas of rapid subsidence and active upland erosion, turbidites may follow one another rather rapidly with intervening pelagic deposits thin or missing." Silty micrite interbeds can be interpreted as minor variations in the clastic influx which allowed the pelagic rain of organisms to accumulate. Alternatively, landward displacement of the shoreline would diminish the sediment supply to the deeper water. A "gradual deepening" of the basin during Cedar District time is documented by Sliter (1973) based on his analysis of Foraminifera.

Cedar District deposition was ended by the onset of considerably more vigorous fluvial conditions that locally overwhelmed the marine domain.

DeCourcy Formation

Nomenclature. The small DeCourcy Island group is situated west of Valdes and south of Gabriola Islands near Nanaimo. The formation named for this locality is generally a gray to yellowish brown, coarse-grained sandstone. Thin, fine-grained interbeds and very minor coally lenses are also characteristic (Clapp, 1912, p. 99) of these strata which overlie the Cedar District Formation.

General Character. The DeCourcy Formation is a prominent cuesta-forming assemblage of thick-bedded sandstones and conglomerates with usually thinner mudstone intervals. It is exposed along a prominent, once-continuous ridge extending from Lizard Island and St. John Point on the east to Crane Point on the west (Fig. 16 and Plate 1). This linear topographic feature, which narrows on both ends, is interrupted by transverse fault valleys (mentioned under Structural Geology--Transverse Faults) forming a series of hills approximately 250 to 600 feet high.

While it may appear that Lizard Island should be included within the Northumberland Formation (described in the next section), field relationships indicate that it was faulted into place. Attitudes here, which are consistent with those on Samuel Island, intimate that both were part of the same fault block. It is believed that a palinspastic restoration would demonstrate that Lizard Island belongs to

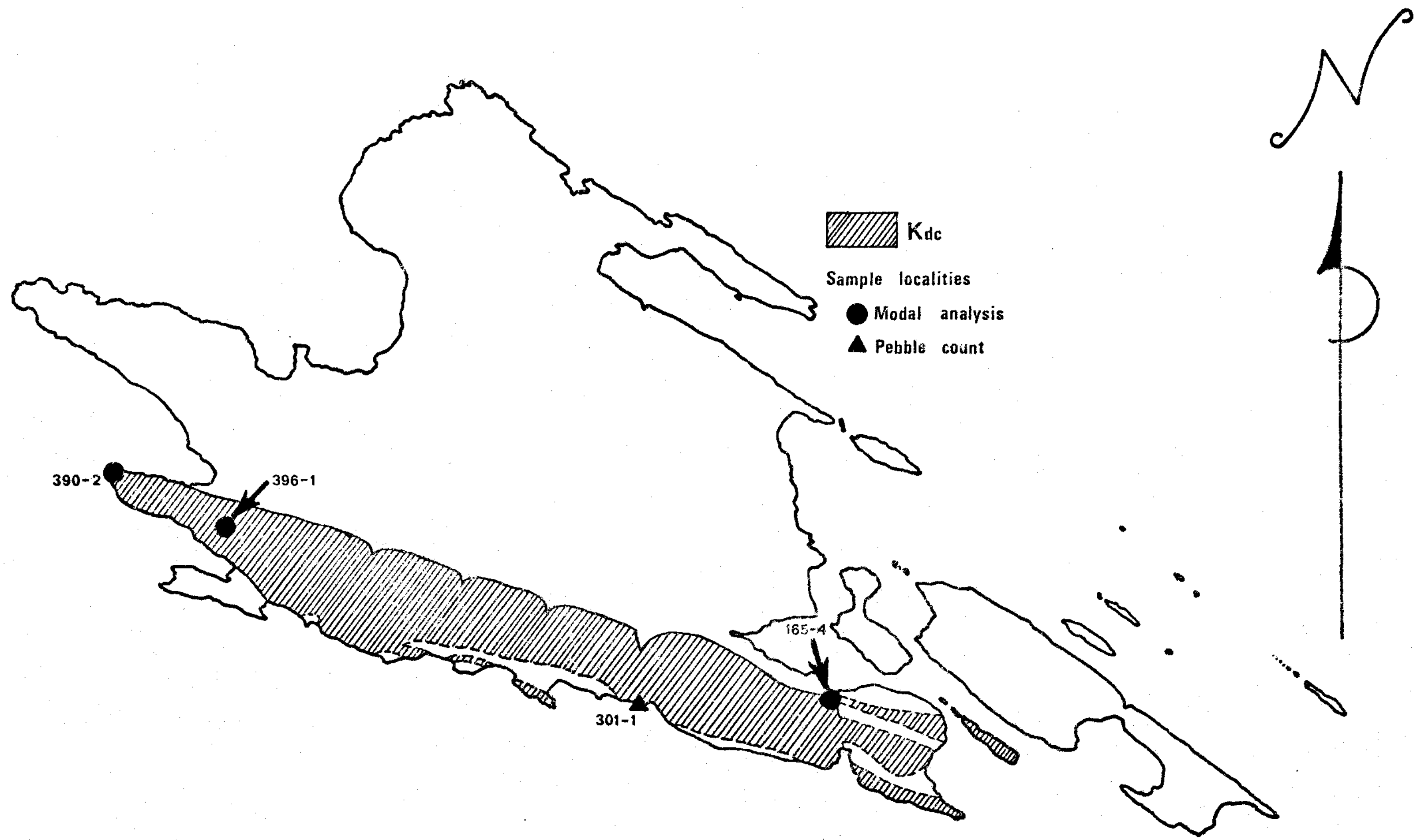



Figure 16. Distribution of De Courcy Formation and Sample Localities

the DeCourcy Formation. Within a mile of Lizard Island along strike, Sturdavent (1975) mapped DeCourcy rocks at Mikuni Point on Saturna.

Flanking Navy Channel, several minor occurrences of DeCourcy rocks are isolated from the bulk of the formation by what are interpreted as Cedar District tongues. While some of these are not wide enough to map, others form small salients that help protect the superadjacent mudstones from wave action. These are best shown on Plate 1; the largest example is located south of Piggott Bay. From here, the remainder lie 1/2 mile east to 1-1/2 miles west along strike.

Except where too steep to support vegetation, the southwest-facing antidip slopes are usually covered. Most of the fine DeCourcy exposure along the shoreline can be reached via the generally narrow, wave-cut bench. Access has also been improved by erosional removal of the underlying Cedar District mudstones. The best outcrops are found on the south side of Lizard Island and on Mayne, both along the north side of Dinner Bay and adjacent to Navy Channel. On the other hand, shelving dip slopes are less instructive because cross sectional views of the strata are seldom available.

The interfingering nature of the lower contact has been discussed in the previous section. Clastic dikes that intrude Cedar District strata, immediately beside Navy Channel, are likely to have originated within even lower DeCourcy tongues which today lie below water level. Thus, except for discrete, mappable tongues, the most realistic contact is chosen where Cedar District mudstones disappear up-section (Fig. 9).

Interfingering is also typical of the upper contact where DeCourcy sandstones give way to largely marine Northumberland (discussed in the next section) mudstones. The inferred contact lies within a zone of transition which is narrower at Village Bay than elsewhere. For this reason, its intersection with the shoreline was used as the initial point of a measured Northumberland section. A detailed location is given in Appendix A. The contacts that separate each tongue are commonly planar and range from sharp to gradational. At Village Bay, earliest Northumberland deposition is marked by an interval of sandy to silty graded beds between 10 and 15 feet thick. Mudstone interbeds within the DeCourcy proper seem to be much thinner on the west end of Mayne Island. Farther east the contact is more subjective because separate sandstone tongues are frequently observed to have more gradational contacts with the intervening mudstones.

Near the southern extremity of Horton Bay, the upper DeCourcy contact is placed at the apparent lower stratigraphic limit of Northumberland graded packets. If others occur farther down-section, they are covered by fill from recent road-widening activity or by vegetation.

On Mayne, opposite Lizard Island, the uppermost DeCourcy is somewhat easier to recognize than the lowermost Northumberland. Graded intervals with a superficial Northumberland aspect occur throughout this DeCourcy section. The lower limit of the graded packets, used to locate the contact elsewhere, is not readily defined here. Also, the graded intervals do not show a continuous increase in thickness upward. However, at one point in the section here, the graded interbeds were found internally similar to DeCourcy rocks examined on the south side of Horton Bay. The analogy is supportable in terms of grain size, texture, structure, and mineralogy as identified in the field. These reasons, and the lack of better evidence, justified mapping the contact immediately above this exposure. Actually, the transition probably occurs within a zone, but the width is not readily determinable. Outcrop accessibility is a hindrance to a more satisfactory resolution.

Locally contorted bedding in the sandstone was observed near the upper DeCourcy contact. A good example can be seen along the shoreline approximately 300 feet northwest from the head of the federal dock at Horton Bay. The exact origin is not clear; however, possibilities include subaqueous slumping or more probably soft-sediment dewatering phenomena.

Some error in formation thickness is certain to have resulted from the unavoidable imprecision with which the contacts are located.

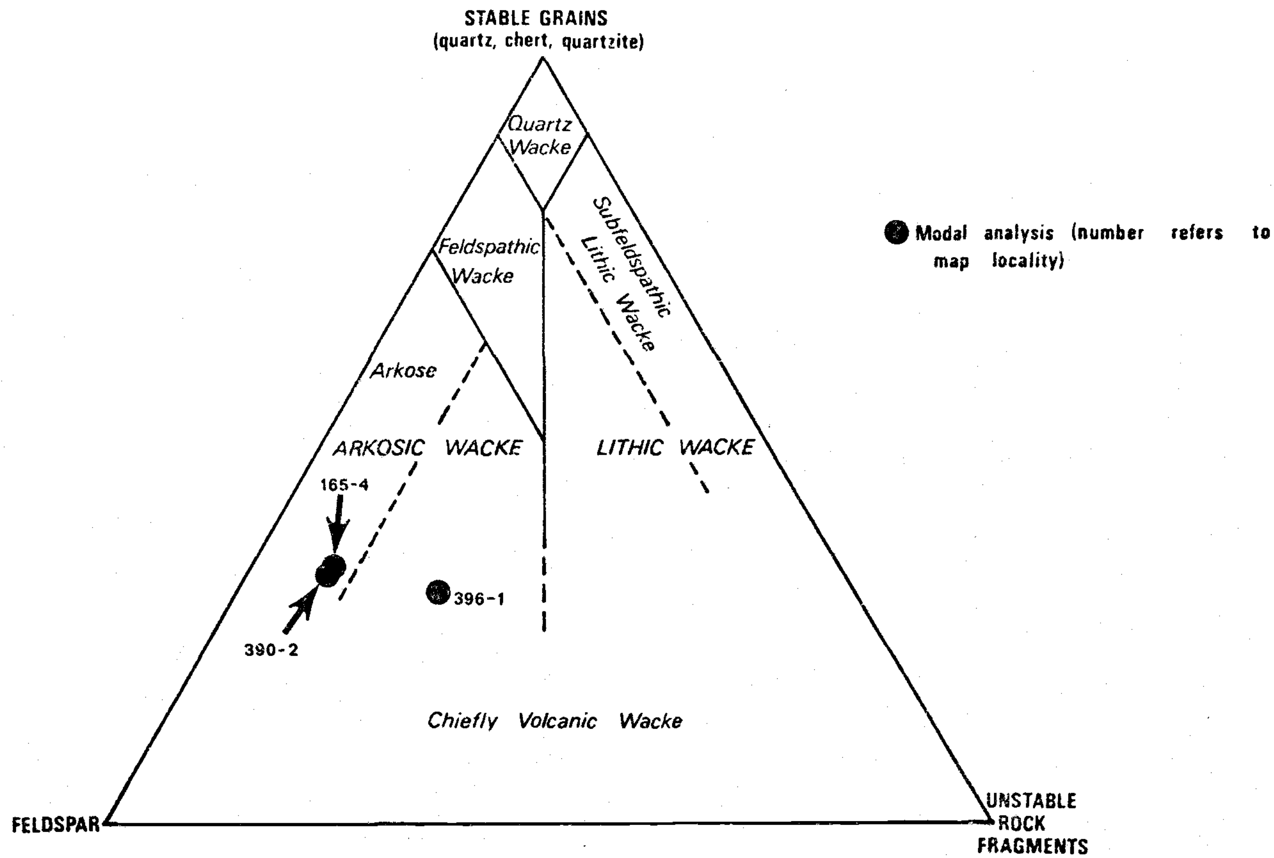
Thicknesses were determined by the method described in the preceding section. Because the contacts are best defined on the west end of Mayne Island, measurements here are the most reliable. Between Dinner Bay and Village Bay, the formation is 807 feet thick. Northwestward from St. John Point, the southeast tip of Mayne Island, cumulative thickness of all three DeCourcy tongues is 647 feet.

Lithology. Well-developed bedding, where present within the DeCourcy Formation, is commonly defined by laterally persistent planar mudstone intervals composed of graded packets. Although they are locally from 6 to 10 feet thick on the southeast end of Mayne Island, the normal range of thickness is from several inches to 2 feet. The intervening strata are generally sandstones and, while the rule is not inviolable, there is a tendency for mudstone and conglomerate to be mutually exclusive. Considering the variability, it is not possible to distinguish these mudstones from those of the Extension-Protection or Cedar District Formations on the basis of color.

The mudstones display a plethora of sedimentary structures and many are related to soft-sediment deformation. Common ones include: normal grading; parallel to contorted laminae; festoon cross-laminae, usually 3 to 6 inches wide with 1/4 inch of relief; flame structures; pull-aparts; scour-and-fill; scattered burrows, the vertical ones commonly in-filled; and overthrust features reflecting greater internal strength of an interbed that results in brittle fracture rather than plastic deformation during bed-on-bed sliding.

Thinly laminated to very thick-bedded (McKee and Weir, 1953) sandstone is the main DeCourcy lithology. Between mudstone interbeds, the internal structure is often concealed by overall textural and compositional homogeneity. Similarly, the abundant trough cross-laminae tend to obscure the major bed stratification. Eight thin sections were prepared and examined petrographically. Three were point-counted; two from fresh samples collected in recently blasted road cuts and a third from a shoreline exposure for comparison (for sample locality and classification see Figures 16 and 17 respectively).

Where fresh, typical color ranges from yellowish gray (5Y 7/2) to medium light gray (N6); however, weathering produces colors between grayish orange (10YR 7/4) and moderate yellowish brown (10YR 5/4). Because there is closely associated conglomerate, the gamut of particle sizes represented here is extended. Thus, coarse pebbly sandstones coexist with the clay fractions. This observation was also mentioned for the strikingly similar Extension-Protection Formation. Other prevailing textural features were noted. Grain shapes are angular to subangular (Powers, 1953) at best. Strata which are normally graded usually occur between thicker and coarser beds. Because of very poor sorting, that results from the much wider range of particle sizes represented, these beds are texturally




**De Courcy Formation**

Figure 17. Classification of Sandstones (after Gilbert in Williams et al., 1954)

immature (Folk, 1951). Grading calls attention to the generally well-developed parallel laminae. Quite commonly, they are further emphasized by: subparallel particle elongation; layers of plant debris, sometimes aligned by the current; and discolored laminae caused by preferential oxidation where permeability is greatest. As grading becomes less distinct, sorting also improves. Because many of the coarse sandstones are moderately sorted, they are texturally submature (Folk, 1951). Most of the depositional porosity has been destroyed by the formation of diagenetic matrix. However, distorted platy micas and interpenetrating grains, some with distinct sutured boundaries, show that compaction as a result of deep burial has also contributed to this effect.

There are few exceptions to the general petrographic trends iterated earlier (cf. microscopic observations under Extension-Protection Formation--Lithology and Appendix B). In all samples analyzed, the plagioclase content, relative to alkali feldspar, is greater by half rather than the typical one-third. In one sample, polycrystalline and strained quartz are present in subequal amounts, whereas the latter usually dominates. Noticeable amounts of garnet and sphene appear in the heavy mineral assemblage and the decrease in hematite is probably a consequence of analyzing relatively unaltered samples. Where present, the hematite is only a very finely comminuted particle coating. One rock also contains zircon as an accessory.

Greenschist fragments are the dominant foliated metamorphic noted.

Andesine ($An_{37}$) and oligoclase ($An_{20}$) represent the plagioclase series while the potassium feldspars include orthoclase and lesser amounts of microcline and sanidine. Myrmekite and micrographic quartz-feldspar intergrowths were observed. Both kaolinite and sericite on the feldspars confirm widespread chemical breakdown. Microperthite, also present, seems to stand out by virtue of selectively kaolinized alkali feldspar. The significant abundance of volcanic rock fragments was possibly underestimated because diagenetically altered particle boundaries are commonly indiscernible. That they are basaltic and/or andesitic is inferred from: 1) the felted texture of both pilotaxitic and randomly oriented microlites of plagioclase; and 2) what appears to be considerable interstitital chlorite or celadonite that may have formed by decomposition of associated ferromagnesian minerals. This material was simply recorded as "matrix" because it is too finely divided to be readily identified. Therefore, the percentage of chlorite in the DeCourcy modal analyses (Appendix B) may be deceptively low. The well-indurated character of these sandstones, plus the absence of precipitated cements, indicate that the matrix binds the rock effectively. For two DeCourcy samples, the modal analyses are virtually identical (cf. Fig. 17). Both are from nearly equivalent stratigraphic positions which are over 4 miles apart laterally (cf. Fig. 16 and Plate 1). The fact that only one of these was a fresh sample suggests that chemical weathering effects are negligible here. Textural features of these rocks are not inconsistent with paleocurrent data, regarding an eastern source direction, but the very minor differences are not statistically significant. Both are classified as arkosic wackes; the third sample, because of its high content of volcanic rock fragments, is called a volcanic, arkosic wacke (Fig. 17). Considering the cumulative abundance of unstable rock fragments (Appendix B), all the rocks analyzed are justifiably regarded as compositionally immature.

Within the study area, better access enabled observation of more sedimentary structures in the DeCourcy Formation than any other unit. Many are exposed as sole marks that yield valuable paleocurrent data. These include current lineations, groove casts (Fig. 18); prod casts; flute casts (Fig. 19); and flame structures, where the axis of the associated antiform is visible--provided they are interpreted with caution (Fig. 20). Others are of little to no value for their directional properties, but they serve as useful environmental indicators. Among these are: climbing ripples (Fig. 21) and festoon cross-laminations seen in cross section only; parallel or contorted laminae; layers of mudstone rip-ups; sand particle elongation; normal grading; scour-and-fill; lenticular bedding; slump structures; soft-sediment injection diapirs; and load structures.

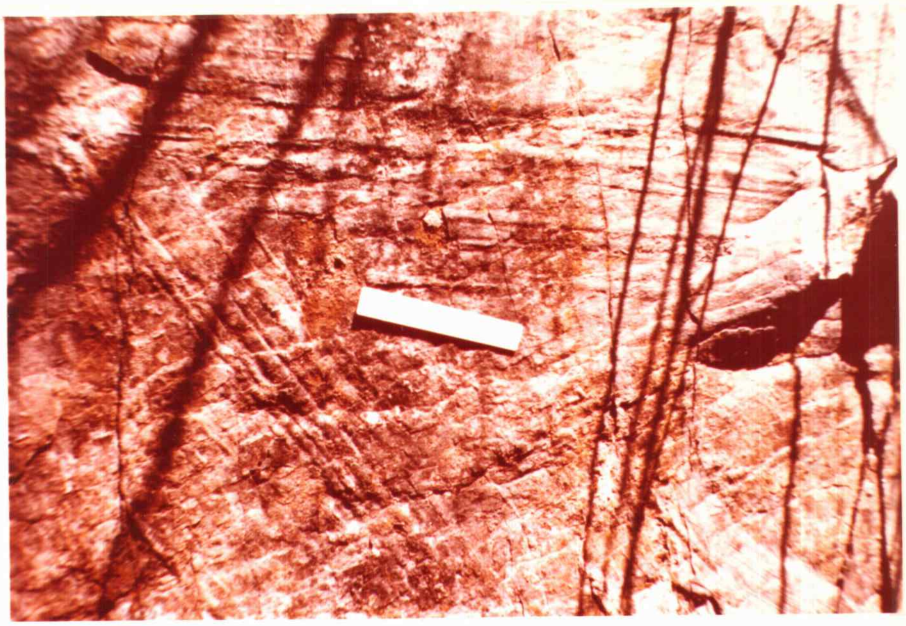


Figure 18. Three generations of groove casts on undersurface of a DeCourcy Formation sandstone bed. Each set is a bidirectional paleocurrent indicator. In sea cliff approximately 2,000 ft east from head of Piggott Bay, Mayne Island. White scale is 6 in. long.

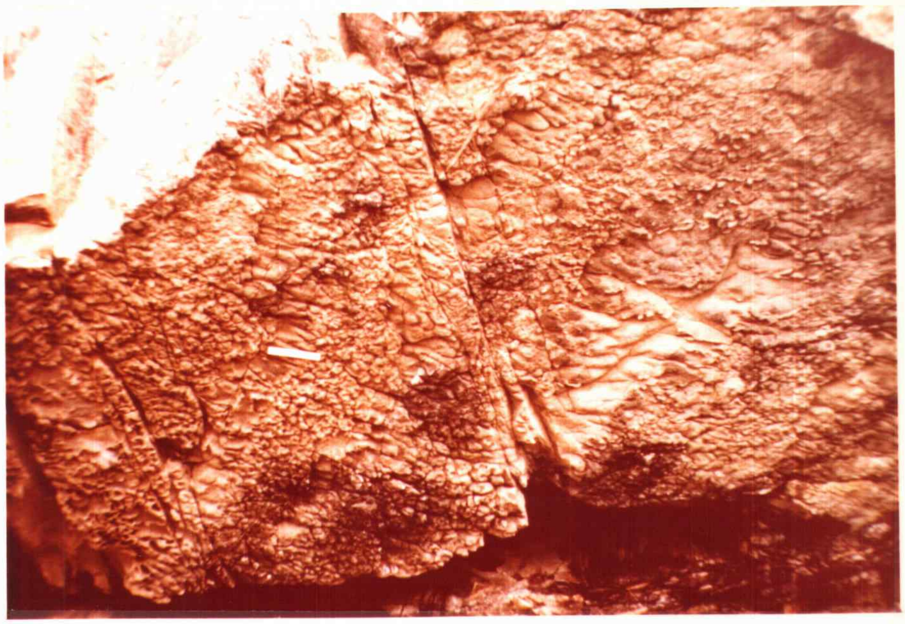


Figure 19. Weathered flute casts on base of thick sandstone bed are unidirectional paleocurrent indicators. They record transport from right to left. White scale is 6 in. long. DeCourcy Formation 400 ft S. E. of Crane Point, Mayne Island.

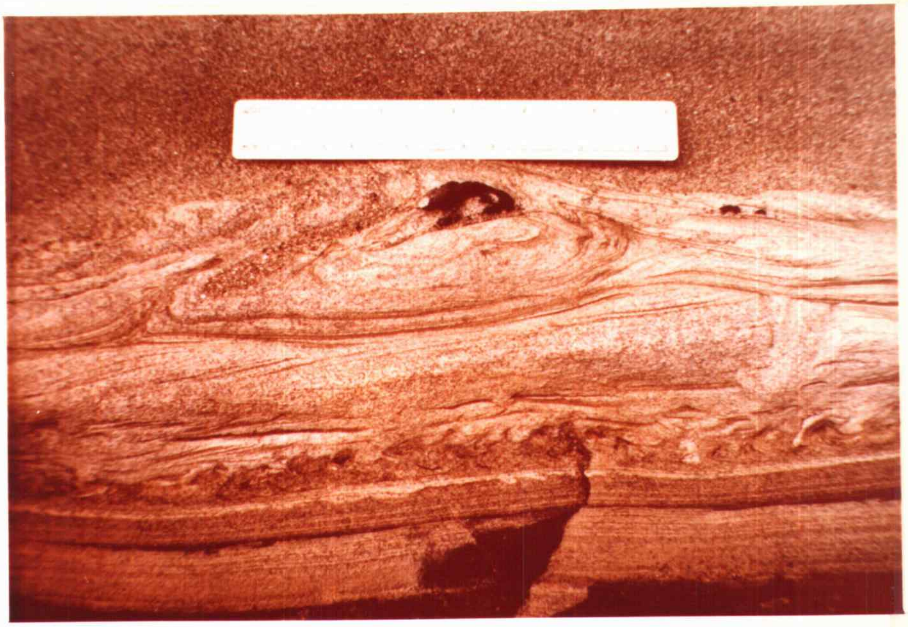


Figure 20. Opposing flame structures immediately below white scale emphasize that the upper tips do not always point toward the declining paleoslope. Such conclusions are valid only when the orientations of many flame tips show general agreement. DeCourcy Formation at Crane Point, Mayne Island.

Figure 21. Climbing ripples. In the fluvial environment they develop where the sand supply exceeds that needed to form a rippled surface--as might occur during flooding (McKee, 1965). DeCourcy Formation on south side of Lizard Island, 1,000 ft from S. E. end.

Clearly secondary structures also abound as indicated by honeycomb weathering and galleries (Fig. 22), that result from wave and spray action, and also calcareous concretions which commonly transect undistrubed bedding planes.

DeCourcy conglomerates are very much like those of the Extension-Protection Formation. Individual beds up to 10 feet thick are not unusual. They are generally very resistant and severely inhibit development of a wave-cut platform. While they are probably channelized deposits, the outcrops are limited and the actual confines, for other than the smallest ones, are rarely exposed completely. In both directions along strike from the center of the island, there is a conspicuous decrease in clast size and in the ratio of conglomerate to sandstone. Conglomerate becomes quantitatively insignificant nearer than approximately 1/2 mile of St. John Point or Dinner Point. Just over a mile west of St. John Point, a sandstone clast found within some conglomerate beach float (approximately 15 inches in diameter) was the largest observed. From a Decourcy pebble count (Appendix C), chert accounts for half the clasts. Subequal amounts of quartzite and granitics, plus very minor basalt, andesite, metamorphics, and sandstone, make up the other half.

Pebble imbrication was a frequently recorded paleocurrent indicator. Other sedimentary structures noted are coarse-tail

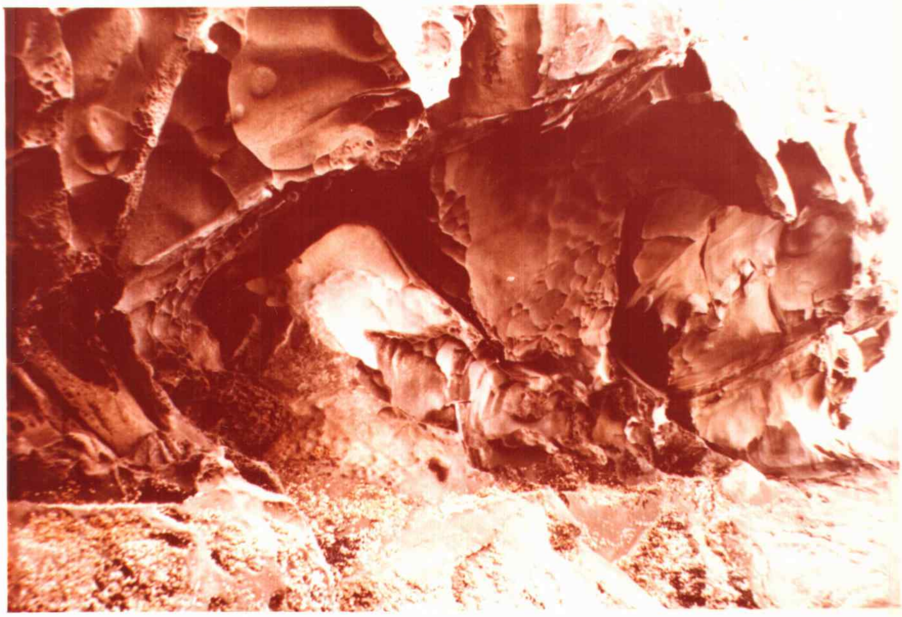


Figure 22. Gallery structure with incipient honeycomb weathering, both the result of wave and spray action. At upper left, resistant calcareous concretions stand out in relief. DeCourcy Formation at Crane Point, Mayne Island.

grading, horizontal stratification, lenticular bedding, and scour-and-fill (Fig. 10).

Environments of Deposition. On Mayne Island, there is convincing evidence that the DeCourcy and Extension-Protection Formations were deposited by very similar fluvial processes. Well-imbricated DeCourcy conglomerates fill numerous channels scoured in the underlying sandstones and create lenticular stratification of fluvial association (Clifton, 1973). Energy conditions of the tractive current(s) fluctuated broadly, which is possibly attributable to perennial flow. Indicators of higher energy transportation include chipped, well-rounded conglomerate clasts and layers of intraformational mudstone rip-ups in the sandstones, some up to 3 feet long. By comparison, reduced energy was responsible for the intervals of coarse-tail grading also observed in the Extension-Protection Formation (Fig. 7). Also, the sandstones contain vertical successions of structures that mimic the A through C and sometimes D intervals of the Bouma sequence. Harms and Fahnestock (1965) interpret the Bouma sequence as a product of waning flow regime in turbidites. Therefore, it seems reasonable that the analogous pattern mentioned probably indicates a diminishing flow regime in the fluvial environment.

Discontinuous sandstone beds commonly display sets of large-scale festoon cross-laminations from 1 to 3 feet wide with 2 to 6 inches of relief. They are likely formed by subaqueous dune migration (Harms and Fahnestock, 1965). Paleocurrent directions were determined from laterally equivalent, imbricated conglomerate clasts of the adjacent bedload and only moderate divergence was noted from one locality to the next. Based on the collection of features presented here and the overall likeness to the Extension-Protection Formation, these rocks were deposited from highly competent braided streams.

Even while Cedar District marine conditions dominated here, the coarse interbeds of DeCourcy aspect portended a major change in the character of deposition. It may have been caused by renewed or continued uplift of the source terrane, temporary cessation of basin subsidence, eustatic change, or a combination of these. Whatever the cause, delivery of an apparently large volume of clastics to the basin margin finally forced the sea to retreat completely. In the absence of littoral processes capable of redistributing this terrigenous material, a prograding delta formed. Dott (1966) fittingly asserts that "Apparently deltaic sedimentation will occur inevitably where sufficient sediment is delivered. Cyclic patterns may result therein simply due to the fluctuating rates of sedimentation even without vertical relative changes of sea level."

Granting many differences, particularly in scale, the modern Mississippi delta has some properties analogous to those inferred for the DeCourcy deposystem. The most significant ones, briefly explained below, include: 1) upward-coarsening (Visher, 1965; Selley, 1970; Coleman and Wright, 1975), 2) a high rate of sediment supply (Coleman and Wright, 1975), 3) a lobate growth pattern (Coleman and Wright, 1975), 4) fluvial-dominated sedimentation (Galloway, 1975), and 5) a cyclic pattern of accumulation (Coleman and Gagliano, 1964).

A major upward-coarsening sequence typical of deltas (Visher, 1965; Selley, 1970; Coleman and Wright, 1975) formed through DeCourcy time as shoreline out-building superposed fluvial sediments over the marine Cedar District assemblage. A high rate of clastic influex is suggested by the textural immaturity of the rocks and the coarseness of the bedload.

Available paleocurrent data on Mayne Island indicate essentially east to west fluvial transport and no clear evidence of marine deposition in DeCourcy time was located here. Yet, approximately 3-1/2 miles southeast on Saturna, Inocerami were reported from the DeCourcy by Sturdavant (1975). These molluscs may have lived in a marine embayment adjacent to one or more prograding fluvial lobes on the delta platform. Diverging mean paleocurrent indications, on several islands partly surrounding the study area, are consistent with the concept of splaying deltaic lobes. Clockwise from the southeast, these directions are reported as being approximately: east southeast on Saturna (Sturdavant, 1975); southwest to southeast on

Pender, where calculations also included the Cedar District data (Hudson, 1975); northwesterly on Saltspring (Hanson, 1976); and northerly on Thetis, with Cedar District data being included in these calculations (Simmons, 1973). Following this interpretation, temporary abandonment of a particular lobe would explain the Cedar District marine sequences within the DeCourcy Formation on the east end of Mayne Island. This results in several upward-coarsening successions as noted above. DeCourcy paleocurrent trends agree with speculation that one deltaic lobe may have prograded from the study area as far as Saltspring. Marine fossils mentioned by Hanson (1976) perhaps occur very close to the seaward pinchout of the fluvial facies.

Fluvial-dominated sedimentation is indicated by a lobate geometry (Galloway, 1975) and by the many structures associated with high-energy tractive currents. This also presupposes that sufficient detritus is transported basinward to overwhelm the marine environment.

Only one complete, major cycle of deposition has been discussed so far--the Cedar District-DeCourcy couplet. It consists of an overall upward-coarsening sequence of fine-grained marine rocks overlain by coarse terrigenous clastics here interpreted as resulting in deltaic progradation.

Based on the Mississippi analogy, the main sand body type associated with this fluvial-dominated, lobate delta, is the distributary mouth bar (Gould, 1970; Coleman and Wright, 1975). Such is typified by a convex seaward, U-shaped outline (Gould, 1970) not recognizable in the study area. The possibility was considered that several of these bars might have coalesced forming sheet sands in response to longshore drift. Yet, sedimentary features definitely attributable to marine processes were not observed. The only fossils located were some burrows of unknown affinities and also rare, small woody fragments concentrated in thin laminae. At the westernmost DeCourcy exposure on Mayne Island, which is also the most basinward, linear sole marks are present that were scoured by tractive currents.

The overall interpretation suggested here is that these deposits are part of a westerly trending lobe which rapidly prograded across the delta plain/delta platform environments. The actual seaward extremity of the fluvial distributaries lies even farther west. As mentioned earlier, there is a suggestion of at least one marine embayment separating this lobe from another to the south. However, the marine interfingering that would be expected between these lobes is not exposed in the thesis area. Such evidence could have been removed during erosional breaching of the Trincomali Anticline.

DeCourcy conglomerates are best developed approximately midway between each end of the island and laterally change to sandstone both east and west along strike. Lateral oscillations of the main channel thalweg(s) are apparently marked by the limit of these conglomerate bodies. While natural levee deposits seem to be conspicuously absent, they may not have developed fully or were possibly redistributed by channel shifting. The latter would be expected of braided streams. Planar mudstone interbeds separating the thick, coarse-grained DeCourcy sandstones are believed to represent interdistributary deposits. Periodic exposure to current activity, possibly during flood stages, can account for incorporated layers of mud rip-ups. The graded bedding results from a waning flow regime and the unoriented woody fragments settle out last during quiet water conditions. Deposition of this major, upward-coarsening deltaic cycle was terminated by the initially wavering encroachment of the Northumberland sea.

## Northumberland Formation

Nomenclature. The southwest shore of Gabriola Island flanks Northumberland Channel. Typically exposed here are fine-grained shaly rocks stratigraphically succeeding the DeCourcy Formation. Clapp (1912, p. 100) termed these the Northumberland Formation. However, in his original description, he included the overlying coarse conglomerates and sandstones. Usher (1952, p. 18) recognized a three-fold subdivision and considered the conglomerates as a middle member. Muller and Carson correlated this middle member with a distinctive conglomerate formation, the Geoffrey, named by Usher (1952) on Hornby Island in the Comox Basin (for details see following section). Concurrently they redefined the Northumberland as the fine-grained rocks beneath the conglomerates, but above the DeCourcy Formation (Muller and Carson, 1969, p. 18).

General Character. Locally the Northumberland Formation is characterized by a repetitious sequence of normally graded sandstone to mudstone packets much like the Cedar District Formation already described. A marine origin is verified by the abundance of ammonites, pelecypods, scaphopods (?), and trace fossils in these strata. Prominent sandstone beds with fluvial affinities, suggested by current-oriented woody material, are intercalated with the marine rocks. The sandstones are thickest in the southwest-facing sea cliffs of Samuel Island west of Irish Bay and also on Curlew Island. Although these sandstones do create some discontinuous relief, the formation is mostly a valley-forming sequence.

Within the study area, Northumberland rocks are confined to a strip extending from Village Bay on Mayne Island to the East end of Samuel Island facing Winter Cove (Plate 1 and Fig. 23). Breaks in the continuity occur at three places: 1) immediately east of the

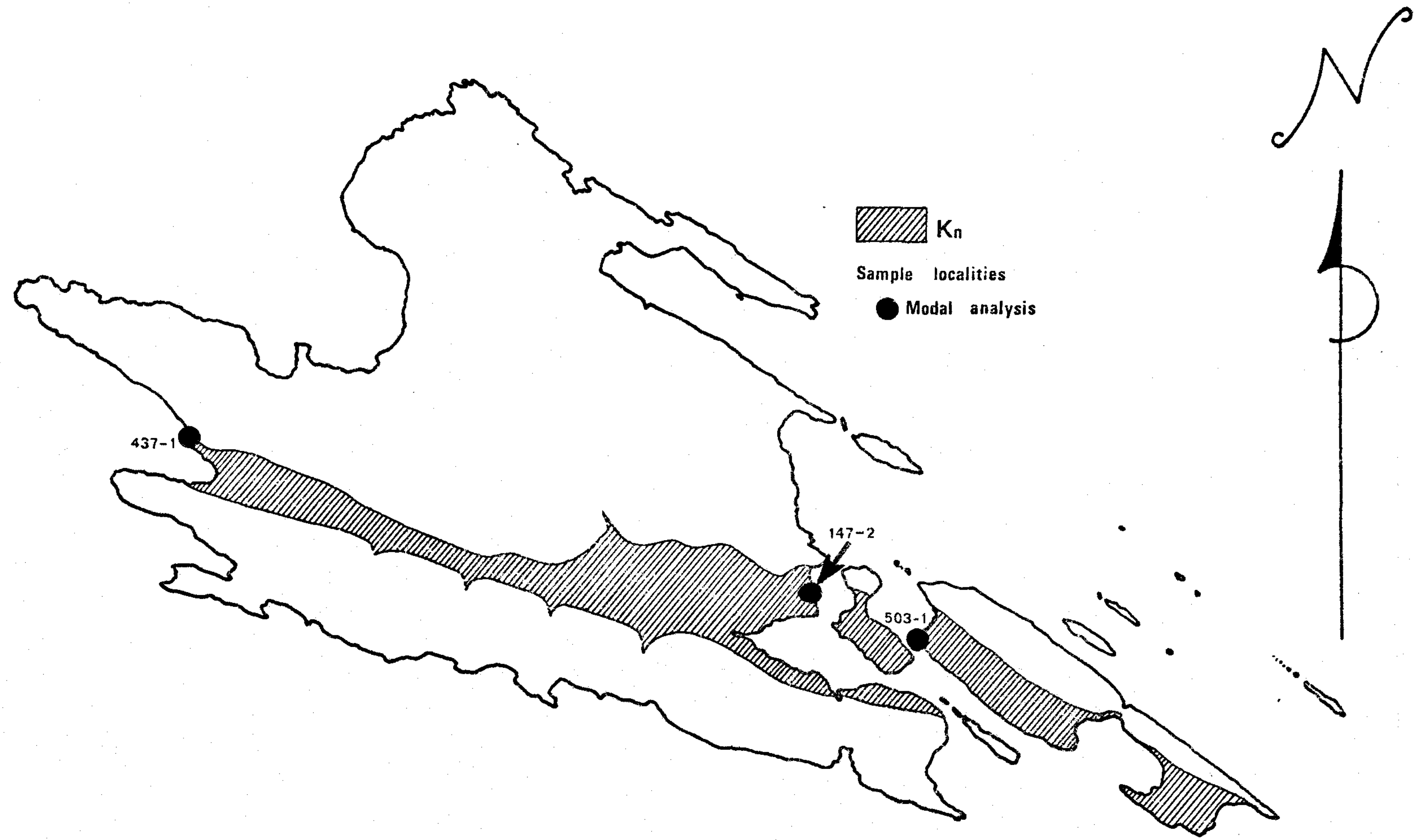



Figure 23. Distribution of Northumberland Formation and Sample Localities

northernmost part of Irish Bay on Samuel Island; 2) at Georgeson Passage adjacent to the southwesternmost tip of Samuel Island; and 3) in the unnamed channel separating Mayne and Curlew Island. All these interruptions are mostly, if not completely, attributable to erosion within fault zones.

Where Northumberland rocks are exposed along the shoreline, access is generally quite good because of the broad, wave-cut bench. The only exception is where precipitous antidip slopes of cliff-forming sandstone interbeds descend sharply into the water. These are exemplified along the southwest side of Samuel Island facing Georgeson Passage. Scattered road cuts provide the few remaining exposures of the Northumberland Formation where the generally thick vegetation has been removed. Although such outcrops do provide additional attitude control, they are usually deeply weathered and unsuitable for detailed study.

The nature of the lower Northumberland contact was discussed in the preceding section. There are few places where the upper contact with the superjacent Geoffrey Formation (described in the next section) can be clearly observed. One locality is on the east side of Mayne Island opposite the north end of Curlew. Here, Northumberland mudstones sharply give way to thin-bedded sandstones of the overlying unit (Fig. 24). Even though there is interstratified mudstone farther up-section, the contact is chosen at the base of the lowest

Figure 24. A weathered contact between Northumberland Formation mudstones and the overlying sandstones of the Geoffrey Formation. Exposed in the south-facing sea cliff on Mayne Island opposite the north end of Curlew Island.

Figure 25. A sharp, planar contact between Northumberland Formation mudstones and superjacent Geoffrey Formation sandstones. Exposed in a roadcut on Samuel Island, 0.4 mi. N. W. along strike from the northernmost extremity of Irish Bay.

visible, prominent sandstone bed. A blocky weathering pattern is displayed by the Geoffrey sandstones at the lower contact here. Sapping of the mudstones below, may have allowed slight differential downslope movement of these sandstone blocks. This possibly created minor undulations on a surface that was originally planar. Therefore, this exposure may not be truly representative. A better example occurs in a road cut on Samuel Island northwest of Irish Bay. The very thickly bedded Geoffrey sandstones are much fresher here and the sharp, planar contact with the underlying mudstones is very distinct (Fig. 25).

At Village Bay, the upper Northumberland contact (Terminal point Y of measured section X-Y, Appendix A) is obscured by beach cover, but it appears to lie within an interval less than 20 feet wide. Its approximate position is indicated by a change to boulder talus upsection adjacent to a noticeable break in slope. Some contorted Geoffrey sandstone blocks are suspended in the Northumberland graded packets below the inferred contact. This is probably a manifestation of subaqueous slumping induced by the weight of overburden and accompanying dewatering processes.

The measured thickness of the Northumberland at Village Bay (section X-Y, Appendix A) is 646 feet. Apparently because of faulting, this is nearly doubled on the east end of Mayne Island where the estimated thickness is 1, 169 feet. For comparison, thicknesses reported for this formation on adjacent islands are: 1,669 feet on Saturna to the southeast (Sturdavant, 1975); at least 2,500 feet to the south on the Penders (Hudson, 1975); 1,090 feet on Saltspring to the west (Hanson, 1976); and on Galiano, to the northwest, it is only 482 feet (Carter, in preparation).

Lithology. The recurrent Northumberland graded packets are virtually identical to those described in the Cedar District Formation. Stratification is well-defined and laterally extensive where there is sufficient exposure to follow more resistant key beds. Very minor undulations produced by scour-and-fill are generally localized; lenticular calcareous interbeds create similar irregularities.

The calcareous layers just mentioned are seemingly confined to marine strata. They occur unpredictably throughout the formation and are recognized by the same features iterated under Cedar District Formation--Lithology. Their presence invited speculation as to an origin for the carbonate. Crushed pelecypod tests lie within some concretions along these interbeds and furnish an explanation for part of it. However, there is doubt that these visible fossils alone can account for all the carbonate observed here. This association suggests the remainder is also biogenic, but no evidence was located to demonstrate this with certainty. While the concretionary layers are themselves micritic and generally devoid of internal structure, they have apparently supplied some of the abundant carbonate cement found in adjacent strata.

Measured Northumberland section X-Y (Appendix A) in Village Bay contains a "representative interval" from 257.5 to 262.5 feet (above the lower contact). There, the graded packets of sandstone to mudstone typical of this formation are described in detail. The mudstones and siltstones, which are not differentiable from those of the Cedar District, are not redescribed here.

Sandstones appear to be the major Northumberland lithology. Within the rhythmic sequences, they mostly range from laminated or cross-laminated to thin-bedded (McKee and Weir, 1953). Near the middle of section X-Y (Appendix A), five more prominent medium- to very fine-grained sandstone beds occur which are between 1 and 2 feet thick. Stratigraphically, these beds are from 10 to 50 feet apart. Because of cover they cannot be traced far along strike and the topography suggests they pinch out eastward. Thus, where similar beds appear on the east side of Mayne Island at Aitken Point, and are there more closely spaced, a one-to-one correspondence is unlikely. A progressive increase in grain size and thickness to the southeast along strike appears to culminate on Samuel Island adjacent to Georgeson Passage (Plate 1). Here lie cliff-forming sandstone beds in excess of 25 feet thick. They contain very fine pebbles locally and are very coarse-grained at the base, but grade upward into much finer sand sizes.

Six thin sections of Northumberland sandstones were studied petrographically and three of these were point-counted for classification. The color of fresh surfaces is typically dark gray (N3) to light olive gray (5Y 6/1). Weathering results in colors ranging from dusky blue (5PB 3/2) to yellowish gray (5Y 8/1) and grayish orange (10YR 7/4) where iron oxides are present. The sandstone part of the graded intervals is most commonly medium- to very fine-grained, poorly sorted, with angular to subangular particles (Powers, 1953). These rocks are placed within Folk's (1951) texturally immature stage because the matrix content is at least 10% in each case. In thin section, the major cliff-forming sandstone examined differs only by its content of coarser particles. A preferred grain elongation parallel to festoon cross-laminations indicates that tractive currents deposited these rocks.

Diagenetic processes that were effective in reducing original porosity here seem to have occurred in the following order: 1) the alteration of volcanic rock fragments to celadonite (?) or chlorite was accompanied by in-filling with detrital clay material; 2) oxidized iron minerals formed a coating on individual mineral grains; and 3) pervasive calcite cementation occurred, partly at the expense of quartz grains.

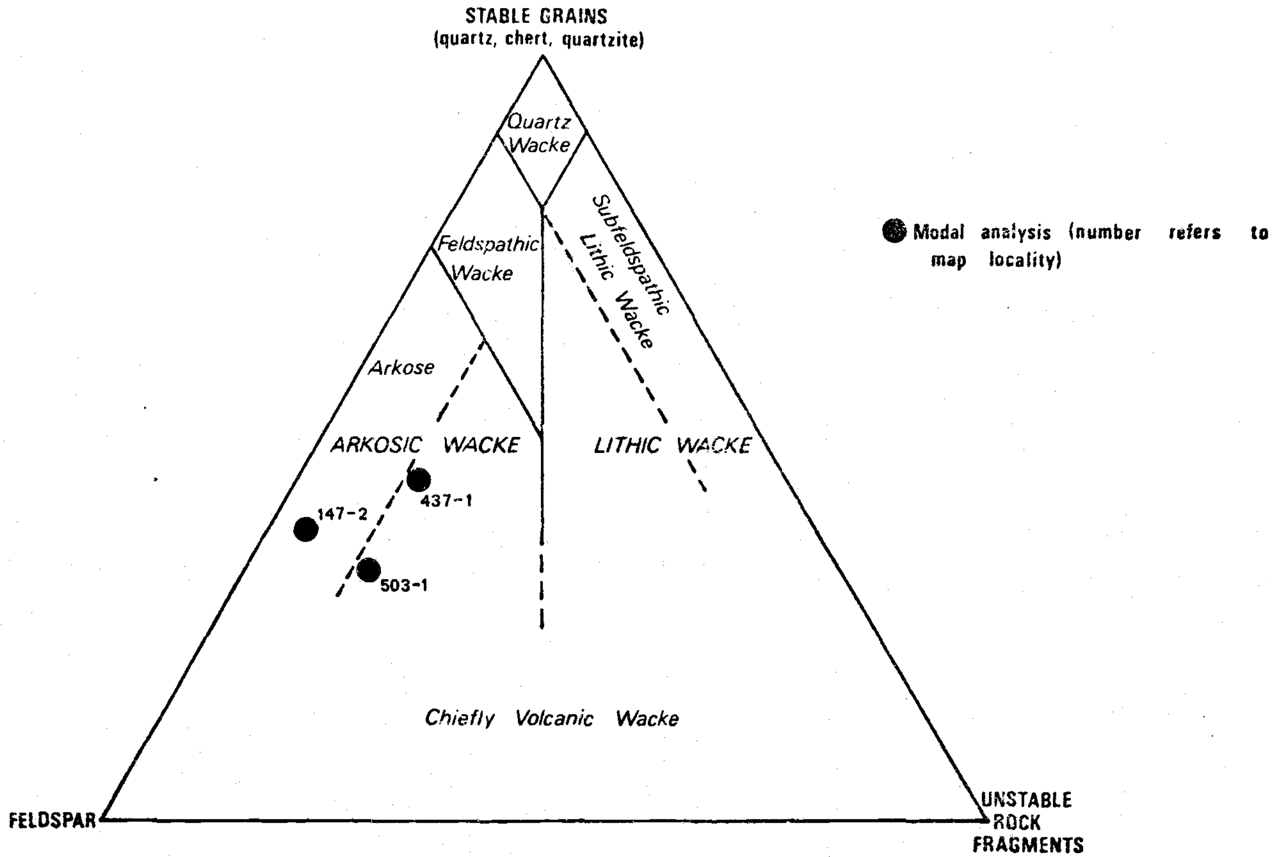
In the Northumberland Formation, there are only two exceptions to the petrographic trends enumerated in an earlier section (cf. microscopic observations under Extension-Protection Formation--Lithology and Appendix B): 1) in one sample, chlorite exceeds biotite by a factor of two, rather than vice versa; and 2) sphene and zircon are present in the heavy mineral suite of this same sample in addition to the usual epidote, hematite, and magnetite. The sample containing an excess of chlorite also shows a slight decrease in the abundance of volcanic rock fragments. This possibly suggests that more of them have diagenetically altered to chlorite. Sphene and zircon occur sporadically throughout the section and neither is quantitatively significant enough to warrant explanation except as an indicator of provenance.

Orthoclase is the main potassium feldspar noted and oligoclase ($An_{26}$) to andesine ($An_{49}$) represent the plagioclase minerals. Only minor alteration of the feldspars to kaolinite and sericite has taken place. From one Northumberland sandstone sample which was analyzed by X-ray diffraction to identify the clay minerals present, only chlorite, kaolinite, and muscovite produced diagnostic patterns.

Judging by the relative abundances of unstable rock fragments in two of the three samples investigated (Appendix B), they should be regarded as compositionally immature. The third, which contains less, is considered to have reached submaturity. After plotting the modal analyses for each of these rocks on Gilbert's diagram (Fig. 26), all are found to be arkosic wackes and one is a true arkose.

Three types of sedimentary structures were observed in the Northumberland strata: 1) current-produced features; 2) others caused by gravity-induced soft-sediment deformation; and 3) those of secondary origin. The first category includes festoon cross-laminations, current lineations, groove casts (Fig. 27), apparent BCD intervals of the Bouma sequence, and flute casts. Penecontemporaneous deformation was responsible for contorted bedding, load casts, flame structures, and clastic dikes. Both pyrite/marcasite and calcareous concretions are the secondary structures seen most frequently.

Fossils. Several types of fossils were observed in the Northumberland Formation. Lebensspuren, the most common, are widely distributed on the originally horizontal, upper surfaces of sandstone beach ribs. There they occur as hyporeliefs and in many places show meniscate backfilling. One of these, which is recognizable for the reasons discussed under Cedar District Formation--Fossils, is Thalassinoides. Similar, but more vertically oriented, sand-filled burrow structures that transect the bedding are ascribed by Sturdavant (1975, p. 25, Fig. 12) to this same organism. Many burrows that are apparently equivalent were found in the study area (Fig. 28) and perhaps are also attributable to Thalassinoides. Other




**Northumberland Formation**

Figure 26. Classification of Sandstones (after Gilbert in Williams et al., 1954)

Figure 27. Large groove casts are visible parallel to the long edge of the photo. Preserved on the soles of two Northumberland Formation sandstone beds. Paleocurrent flow inferred from right to left or vice versa. Fieldbook at bottom center for scale. In sea cliff on Samuel Island, N. 13° W. from S. E. tip of Lizard Island.

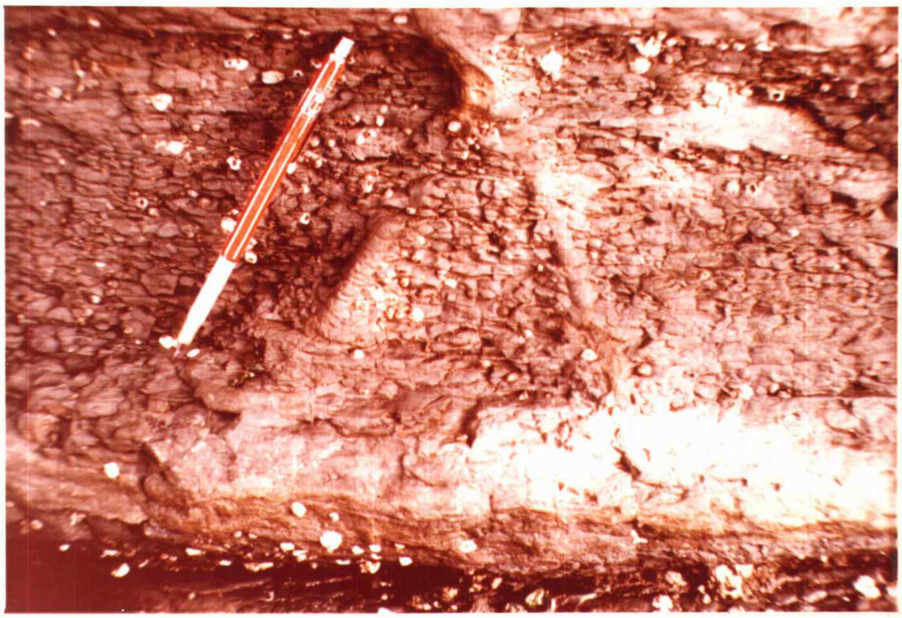


Figure 28. Inverted, V-shaped, filled burrow structure in the Northumberland Formation mudstone. Pencil for scale. Near upper contact with Geoffrey Formation on north side of Village Bay, Mayne Island.

trace fossils noted are associated with micritic interbeds. Based on comparison with identical boring patterns observed in the Cedar District Formation, these are tentatively assigned to ?Helminthoida.

Among the molluscan fossils were crushed Inocerami, quite commonly within calcareous concretions along lime-rich interbeds. One such test was found to be at least a foot long. Straight ammonites are prevalent throughout this formation, but they are poorly preserved and none were located with exposed sutures. As in the Cedar District strata, it is possible that fossils resembling uncoiled ammonites may actually be scaphopods. The latter are reported from Northumberland rocks on Saltspring by Hanson (1976). Modern varieties burrow slightly into the substrate and feed in a nearly upright position. Therefore, they could likely be preserved normal to the bedding. Without better morphological detail, the difference between these two molluscs is commonly indistinct.

In the coarser fluvial sandstones lacking marine character, the only fossil material found was a dark carbonaceous interbed, which lacked obvious structure, and some current-oriented woody debris (Fig. 29).

Environments of Deposition. After several early Northumberland oscillations of the strand line, a marine facies completely inundated the DeCourcy river mouth(s). From the abundant ammonites, scaphopods (?), pelecypods, and trace fossils, there can be

Figure 29. Current-oriented plant debris on the undersurface of a Northumberland Formation sandstone bed. The inferred paleocurrent flow direction is either from upper left to lower right or vice versa. Exposed on the S. W. shore of Samuel Island 0. 1 mi. S. E. of the entrance to Irish Bay.

little doubt that the resulting sequence of repetitiously graded beds was, in fact, a marine accumulation. By the Cedar District analogy, these sediments appear to have been deposited by turbidity currents. While obviously transported organic material was not located, the sedimentary structures present are consistent with such a hypothesis. Some of these include: small-scale festoon cross-laminae, current lineations, groove casts, parting lineations, and BC to BCD Bouma sequences, all of which are associated with tractive current activity. Also the generally poor sorting and particle angularity indicate that these sediments were never subjected to vigorous reworking by littoral currents. Despite an argument for turbidites, deep water is not implied.

There is foraminiferal evidence from the general Vancouver Island area suggestive of depths between 300 and 400 meters for the Northumberland sea (Sliter, 1973). While no microfossils were found in these rocks locally, field work yielded clues that the study area actually lay nearer the basin edge where water was not as deep. As discussed earlier, it appears that a deltaic lobe prograded westerly from the basin margin in DeCourcy time. Temporary abandonment of the lobe set the stage for onlap of the Northumberland sea which was tantamount to a shoreward-advancing outer delta platform/upper delta front facies. The fine sand, silt, and clay that were deposited in these graded beds is typical of an outer deltaic environment (Visher, 1965;

Coleman and Gagliano, 1964; McBride _et al._, 1975). Deformation structures, such as subaqueous slumps, common to prodelta environments are almost completely absent here--an intimation that the depositional slope was less steep. This might be taken as additional evidence that the Northumberland marine rocks accumulated on a delta platform. Abundant branching forms of _Thalassinoides_ suggest that water depths were somewhat shallower than upper bathyal (Chamberlain, 1975).

Marine deposition was interrupted by fluvial conditions that laid down the thick, cliff-forming sandstones exposed on Samuel Island adjacent to Georgeson Passage. Paleocurrent trends here are almost the same as those of the underlying DeCourcy Formation. This, together with upward-coarsening, supports a conjecture that the westerly prograding delta lobe, temporarily abandoned at the end of DeCourcy time, once again became active. However, because of Northumberland onlap, the strand line had shifted east of its earlier position near Saltspring Island. Lateral facies changes along strike hint that it lay, at least during part of the Northumberland interval, either close to or possibly across Mayne Island.

Along the southwest shore of Samuel Island east of Irish Bay, current-oriented plant fragments occur on the base of a thick sandstone interbed (Fig. 29). Pebbly sandstones that contain festoon cross-laminations also crop out farther west on the island. These features point to a fluvial origin. Following the cliff-forming sandstones toward Mayne Island, they show a general decrease in both thickness and particle size. At Village Bay, the major Northumberland sandstones within measured section X-Y (Appendix A) are thought to be laterally equivalent to those on the east end of the Island. The apparent lack of continuity in between may be a result of interfingering. Largely from their position in the section, these sandstones are interpreted as distal extremities of the fluvial domain. Hanson (1976) reports that thick sandstones do not occur within the Northumberland Formation on Saltspring. Hence, in keeping with the trend noted above, they appear to pinch out not far west of the study area.

As the deltaic lobe was reabandoned for the remainder of Northumberland time, deposition of graded packets resumed. These conditions prevailed awaiting the next major episode of progradation that influenced the area during the Geoffrey part of this deltaic cycle (described in the following section).

## Geoffrey Formation

Nomenclature. Mt. Geoffrey, on Hornby Island in the Comox Basin, is supported by a very resistant, cliff-forming conglomerate with interbedded sandstone. Usher (1952, p. 28) named this unit the Geoffrey Formation. However, its equivalence to what he considered as the middle member of the Northumberland had not yet been indicated. This resulted from later work (Muller and Carson, 1969; Muller and Jeletzky, 1970). Currently, the name denotes a very prominent, readily mappable unit, between the Northumberland and the superjacent Spray Formations, in both the Nanaimo and Comox Basins (Muller and Carson, 1969).

General Character. The Geoffrey Formation is a striking cuesta-forming unit which is responsible for the greatest relief in the thesis area--857 feet on Mt. Parke. It contains very resistant, thick, channel conglomerates, both interbedded and laterally equivalent sandstones, and subordinate mudstone intervals. There are over 7 miles of nearly continuous Geoffrey exposure from Helen Point to the east tip of Samuel Island (Plate 1 and Fig. 30). A small unnamed island immediately north from the center of Samuel Island is included with the Geoffrey Formation. It is located on trend with a small peninsula on Saturna, near the west end of Tumbo Channel, which is also mapped as a Geoffrey tongue (Sturdavant, 1975). Topographic offset or changes in strike show where transverse faulting has influenced the once linear outcrop pattern that thins on both ends. Despite the continuity of outcrop, much of it is confined to inaccessibly steep cliffs. Especially southeast of Helen Point, but elsewhere as well, the formation is so resistant that a wave-cut bench has not developed and access is limited.

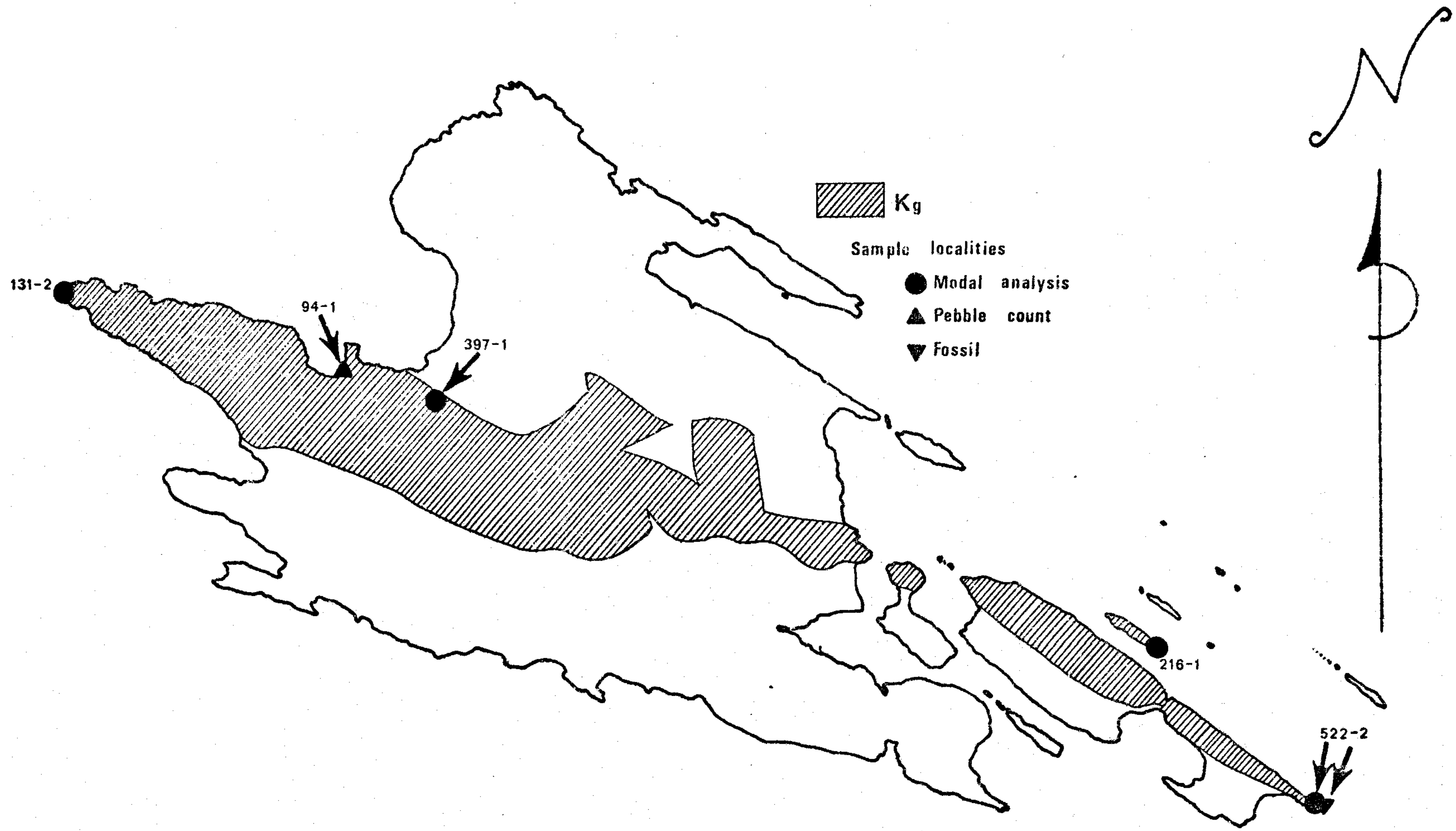



Figure 30. **Distribution of Geoffrey Formation with Sample and Fossil Localities**

The interfingering nature of the lower Geoffrey contact on the east end of Mayne Island was alluded to briefly in the preceding section. On the mutually facing sides of Curlew and Samuel Islands, such relationships are also manifest. Sandstone beds of Geoffrey affinity up to 10 feet thick are suspended within the graded Northumberland sequence as much as 40 feet below the contact.

The upper contact of the Geoffrey Formation is also characterized by interfingering. Along the south side of Miners Bay, its position is arbitrarily selected where coarse-grained sandstone becomes subordinate to the graded packets of the overlying unit upsection. To the south of Bennett Bay the contact is a shelving Geoffrey dip slope (Fig. 31) that extends farther southeast along strike than the nonresistant, overlying graded beds of the Spray Formation (discussed in the next section). While this feature is used as the contact here, it is actually transitional over a covered stratigraphic interval of probably 20 feet or less. Very near this locality on the east end of Mayne Island, a puzzling soft-sediment, injection-like deformation structure was observed. It may have been produced by dewatering diapirism as a Geoffrey sandstone tongue, between 10 and 15 feet thick, loaded into an underlying mudstone interbed.

Thickness of the Geoffrey Formation was found (for method cf. Cedar District Formation--General Character) to be 1, 107 feet between Village Bay and Miners Bay. Lateral thinning has left

Figure 31. Nonresistant graded beds of Spray Formation in foreground. Shelving dip slope of underlying Geoffrey Formation, extending S. E. along strike (center to upper left), marks the contact. Located on east side of Mayne Island, at prominent shoreline indentation 0.2 mi. N. W. of Paddon Point.

420 feet at the east end of Mayne Island. This trend continues easterly and only 140 feet are exposed at the east tip of Samuel Island where the upper contact lies beneath the water. Contacts are necessarily picked subjectively and thicknesses are not exact; however, the error is believed to be quite small.

Lithology. Mudstones of the Geoffrey Formation generally occur in planar beds that separate sandstone units. Thicknesses show considerable variation from a few inches to approximately 10 feet. These mudstones do not have unique colors that differentiate them from similar rocks in associated formations. This is controlled locally by the vigor of weathering.

Usual sedimentary structures in the mudstones produced by tractive currents include: normal grading; parallel lamination; small-scale festoon cross-laminae, on the order of 3 inches wide; and apparent CD intervals of the Bouma sequence. By contrast, penecontemporaneous deformation is responsible for contorted bedding, flame structures, and sedimentary overthrusts. Both horizontal and vertical worm burrows were observed--the latter in-filled with coarser material from next younger beds.

Sandstones are the most widely distributed Geoffrey lithology in the study area. From Helen Point to the approximate center of Mayne Island along strike, the sandstone contains progressively thicker intercalations of conglomerate. Farther east, the conglomerate disappears altogether. These sandstones are very much like the ones already described in the Extension-Protection and DeCourcy Formations. They are thinly laminated to very thick-bedded (McKee and Weir, 1953) and usually have a coarse appearance. Festoon cross-stratification with cut-and-fill structures is most typical and planar beds occur only locally.

In order to investigate possible lateral variations within the Geoffrey Formation along strike, seven thin sections were made and examined microscopically. Four of these, from the locations shown on Fig. 30, were point-counted so they could be classified. The analysis of one sample, collected in a freshly blasted road cut, was not significantly different from the others that were more weathered.

The spectrum of color noted is from pinkish gray (5YR 8/1) or yellowish gray (5Y 7/2) to moderate reddish orange (10YR 6/6) on fresh surfaces and between very pale orange (10YR 8/2) and very dusky red (10YR 2/2) after weathering. While medium to coarse grains predominate, the generally subangular (Powers, 1953) particles occur in all sizes throughout the sand range and grade continuously into conglomerate in places. The quality of sorting is usually poor enough to place these rocks within Folk's (1951) texturally immature stage, but near the border approaching submaturity.

Several features which help delineate stratification in the sandstones are: layers of calcareous concretions, zones of preferential oxidation, layers of mudstone rip-ups, normal grading, pebbly zones, and darker laminae containing organic material. As with the other resistant formations described earlier, lenticular bodies of sandstone are frequently observed as channel in-fillings. One such example occurs on the southeast end of Mt. Parke above the Gallagher Bay road (Fig. 32). Here, the convex downward protrusion from the cliff face is a channel cast from which the original mold has been eroded away. The undersurface shows well-displayed current lineations and groove marks.

There are some minor deviations from the general petrographic trends (cf. microscopic observations under Extension-Protection Formation--Lithology and Appendix B) mentioned earlier. While strained quartz is consistently more abundant than the polycrystalline variety, the difference is less pronounced in all the Geoffrey samples compared to adjacent formations. This could suggest less complete disaggregation because of a more proximal source. Volcanics do not seem to be substantially more plentiful than other rock fragments in two thin sections. It was also noted, however, that these fragments where present grade imperceptibly into matrix and easily could have been underestimated. In fact, this matrix material obscures most of the original porosity that was not reduced by compaction. In one instance, the biotite content is not quite twice that of the other micas. Perhaps this is an indication of more advanced oxidation to hematite.

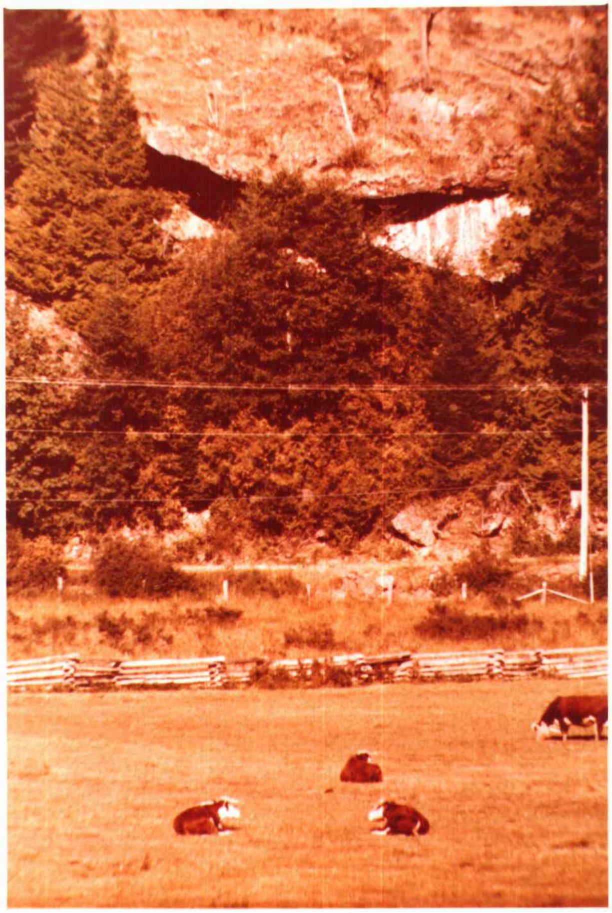


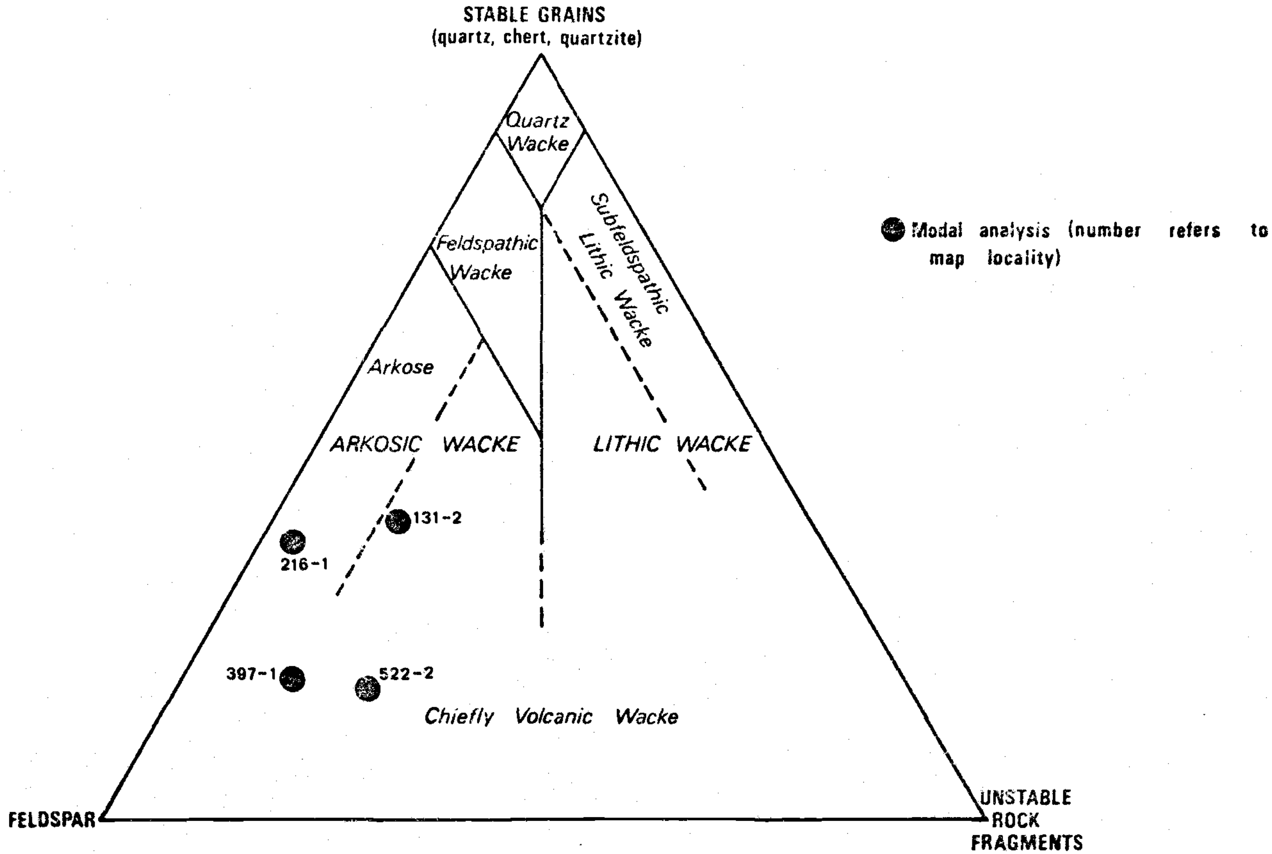
Figure 32. Large channel cast protruding from cliff. Approximately 15 ft of relief at channel center. Located on S. E. end of Mt. Parke beside Gallagher Bay Road, 0. 2 mi. south from junction with Horton Bay Road.

It is possibly misleading that only trace amounts of hematite are recorded for rocks with such a reddish color. Much hematite was observed, but it is so finely divided that it cannot be point-counted accurately. Only rarely is a hematite grain coating not present. In addition to the usual heavy minerals, grossularite garnet and hornblende first appear in the Geoffrey Formation. The latter is generally quite extensively altered to biotite. Apatite, clear garnet, sphene, and zircon are also represented in very small amounts.

Andesine ($An_{49}$) to oligoclase ($An_{25}$) are the plagioclase feldspars that were identified. Orthoclase is the major alkali feldspar but microcline, with its characteristic quadrille twinning structure is also well-represented. Microperthitic and myrmekitic integrowths with quartz are ubiquitous. The degree to which kaolinization and sericitization have attacked the feldspars varies from moderate to high. In addition, partial zeolitization locally disrupts plagioclase twinning. One sample, which was X-rayed to identify the clay minerals, revealed kaolinite, chlorite, and mica. The chlorite may have been derived from altered volcanics or from the greenschist which is one of the main types of metamorphic rock fragments noted. As with the DeCourcy Formation, most of the chlorite was included as matrix which explains the misleadingly low percentages recorded. The hardness of the sandstone may be partly attributable to cementation with silica freed during chemical breakdown of volcanics. All the samples are sufficiently rich in volcanic rock fragments to require that they be considered compositionally immature. According to Gilbert's classification, the term "arkosic wacke" applies to all four rocks. Two of these are true arkoses and the modifier "volcanic" arkosic wacke is fitting for another (Fig. 33).

Sedimentary structures in the Geoffrey sandstones include: normal grading, parallel laminae, festoon cross-laminations to contorted bedding with flames, all of which commonly occur in apparent Bouma sequences; cut-and-fill, flute and groove casts; mudstone rip-ups; load casts; sedimentary overthrusts; and worm burrows. In places, large-scale festoon cross laminations are from 2 to 5 feet wide with up to 9 inches of relief. Both calcareous and iron sulfide concretions are among the secondary structures. Spheroidal weathering, exfoliation, and honeycomb weathering leading to gallery development are also typical.

Conglomerate in the Geoffrey Formation is exposed from approximately 1/2 mile west of Paddon Point on Mayne Island to Helen Point. It is almost exclusively tightly packed and well-imbricated. In the few localities where this shingling effect was not found, the outcrops may have been oriented parallel to the paleocurrent direction. In one instance, pebble elongation subparallel to the stratification was discovered and recorded. The lenticular bedding style resulting from scour-and-fill dominates the




**Geoffrey Formation**

**Figure 33. Classification of Sandstones (after Gilbert in Williams et al., 1954)**

conglomerate. Such a feature is prominently displayed immediately south of the Helen Point navigation light (Fig. 34) where conglomerate fills a large channel cut into coarse-grained Geoffrey sandstone. Colors exhibited by the conglomerates are grayish orange (10 YR 7/4) to dark yellowish brown (10 YR 4/2) for weathered samples and light olive gray (5 Y 6/1) to moderate reddish orange (10 R 6/6) on the freshest surfaces available.

Notwithstanding wide fluctuations in clast size at any given locality, there is a general decrease in diameter eastward. Near Helen Point (1,400 feet east of the navigation light), a tabular greenschist clast approximately 5 feet in diameter by 3 feet thick is floating in the conglomerate. A mudstone block of slightly larger size which contains ammonites or scaphopods (?) was also found here. A similar distance southeast of Helen Point toward Village Bay, another mudstone clast is suspended in the conglomerate. It is 10 feet wide by 3 feet thick and the internal graded packets are still preserved. These examples are the largest ones that were noted. At the summit of Mt. Parke, there is another greenschist clast 1 foot in diameter. Farther east, the conglomerate gradually pinches out, but the exact point of transition to sandstone is not exposed.

Carter (personal communication) subdivided the Geoffrey Formation into three members in which conglomerate is sandwiched between two sandstone units. A similar relationship may exist on the

Figure 34. Conglomerate fills a large channel carved into subjacent sandstone within Geoffrey Formation. Stratification is visible at bottom. Hammer at upper right for scale. South side of Helen Point, Mayne Island.

west end of Mayne Island, but outcrop inaccessibility precludes adequate study. However, sandstone occurs at the upper and lower contacts in Miners and Village Bays respectively, with conglomerate intervening locally. Because each member or tongue cannot be followed along strike to the southeast, they are considered together here.

A pebble count of the conglomerate clasts (Appendix C) showed that granitics, quartzite and chert in subequal amounts represent nearly 85% of the total. Basalt, and a very minor amount of andesite, make up the remainder. It is worthy of mention here that the weathered foliated metamorphics were not collectible, even though they were often the largest clasts observed.

Environments of Deposition. Earlier discussions of the Extension-Protection and DeCourcy Formations presented evidence for considering those units as products of braided fluvial systems. Based on very similar lithologies and sedimentary structures, this same argument can be extended to the Geoffrey Formation. One difference is the much higher energy that influenced Geoffrey deposition on Mayne Island. The large mudstone inclusions and greenschist blocks in the conglomerate near Helen Point required powerful currents to dislodge them from their respective sources and bring them to their present positions. Streams competent enough to carry material of this size could rapidly incise the underlying strata. In so doing, stream bank undercutting could have provided large mudstone blocks such as those just mentioned. Because they are slightly rounded and readily broken down in trans- port, a nearby source is indicated. Muller and Jeletzky (1970) suggest that these sediments were deposited as "deltaic fans issuing from separate streams onto a coastal plain" and were derived from the south to southwest. The internal character of the rocks exposed on Mayne Island is compatible with such a hypothesis. The moun- tainous axis of Vancouver Island (Usher, 1949), where Sicker Group greenschist is exposed, may well have been the source for such blocks in the Mayne Island conglomerates. Topographic relief there could easily have been sufficient to sustain swiftly moving streams capable of transporting a coarse bedload. Sicker Group rocks also occur on Saltspring Island (Hanson, 1976). In addition, Clapp (1912) regards an axis of basement granitic rocks on Saltspring, probably the Tyee Intrusion (mentioned under Regional Basement Stratigraphy), as a source of conglomerate. In terms of field relationships here, this is also very likely.

Paleodispersal trends reflect a shift in the source area, as suggested above, following Northumberland time. The newer pattern, using the thesis area as a reference point, shows trends (clockwise from the southeast) that are: southerly on Saturna (Sturdavant, 1975); southeasterly on Pender, where data are combined for the Northumberland and Geoffrey Formations (Hudson, 1975); slightly northeasterly on Saltspring, also including both formations (Hanson, 1976); slightly northwesterly on Thetis and Kuper Islands, again combining both units (Simmons, 1973) and northwesterly on Galiano (Carter, personal communication). The general direction for the study area is southeast. Sediment emanating from the sides of a northerly prograding deltaic lobe could account for the fan-shaped dispersal pattern described here.

Aside from intertonguing relationships at the contacts, the writer did not locate clear evidence for marine deposition of Geoffrey rocks with one possible exception. A mudstone interbed on the northeast side of Curlew Island displays branching, horizontal burrows, possibly representing Thalassinoides. However, at the easternmost tip of Samuel Island, well-preserved leaf fossils were found within coarse-grained Geoffrey sandstone (Fig. 35) that are suggestive of continental deposition. Farther south on Pender and to the southeast on Saturna, Hudson (1975) and Sturdavant (1975) respectively acknowledged marine affinities for the Geoffrey Formation. This is consistent with the conglomerate thinning trend and paleocurrent data on Mayne and Samuel Islands. Perhaps the leaf fossils mentioned were deposited at the outermost part of the coastal plain or in the active part of an estuary where coarser sand could be deposited with intermixed plant debris.


Figure 35. Note the well-preserved leaf fossil in coarse-grained sandstone of the Geoffrey Formation. From east end of Samuel Island at Boat Passage.

In summary, the Northumberland-Geoffrey couplet is interpreted as an upward-coarsening cycle of deltaic progradation. It is very similar in character to that described for the Cedar District-DeCourcy cycle but with an intervening shift from an easterly to a southerly source area. When stream discharge was sufficient to sustain current activity in the upper flow regime, a high volume of sediment was poured into the basin and rapidly buried without later reworking by currents. In between times are recorded by the deposition of graded siltstone to mudstone intervals when flow was less vigorous. While the overall geometry of Geoffrey sandstone bodies is not always apparent, tractive current features suggest they belong to the fluvial domain. The large-scale trough cross-laminations mentioned earlier are thought to be associated with subaqueous dune migration in streams (Harms and Fahnestock, 1965).

Attendant to a waning clastic influex, upper Geoffrey sandstones that succeeded conglomerate deposition were possibly the harbinger of returning marine conditions that followed during Spray time.

## Spray Formation

Nomenclature. A seaward projection into Tribune Bay on Hornby Island, southeast of Comox, is called Spray Point. Although this name was only recently formalized in 1968 (explaining its omission from older maps), it was used by Usher during earlier field work (Muller and Carson, 1969; Muller and Jeletzky, 1970). Thinly bedded mudstones to sandstones occur here. Also, along part of the northern shore of Hornby, a thickly bedded, light gray to brown, arenaceous unit is exposed. Both of these were designated the Spray Formation by Usher (1952, p. 29) and it is differentiable from the next lower Geoffrey ridge-former. Within the immediately overlying Gabriola Formation are the uppermost Cretaceous rocks in either the Nanaimo or the Comox Basins.

General Character. The Spray Formation, largely a valley-former, is the uppermost of the repetitiously graded marine sequences in the thesis area. It includes a ridge- to cuesta-forming fluvial sandstone member near the upper contact. Compared to similar formations described earlier, the marine rocks are quite fossiliferous. Both straight and coiled ammonites, pelecypods, trace fossils, and some Foraminifera occur here.

Spray Formation outcrops are generally confined to a belt that reaches from Miners Bay to Campbell and Bennett Bays (Fig. 36 and Plate 1). The resistant sandstone member extends farther east where it underlies Georgeson Island and a small islet in the Belle Chain along the same trend. Thickness of this upper sandstone member between Bennett and Campbell Bays is shown to be approximately 225 feet (Muller and Jeletzky, 1970, Fig. 6). It splays westward into

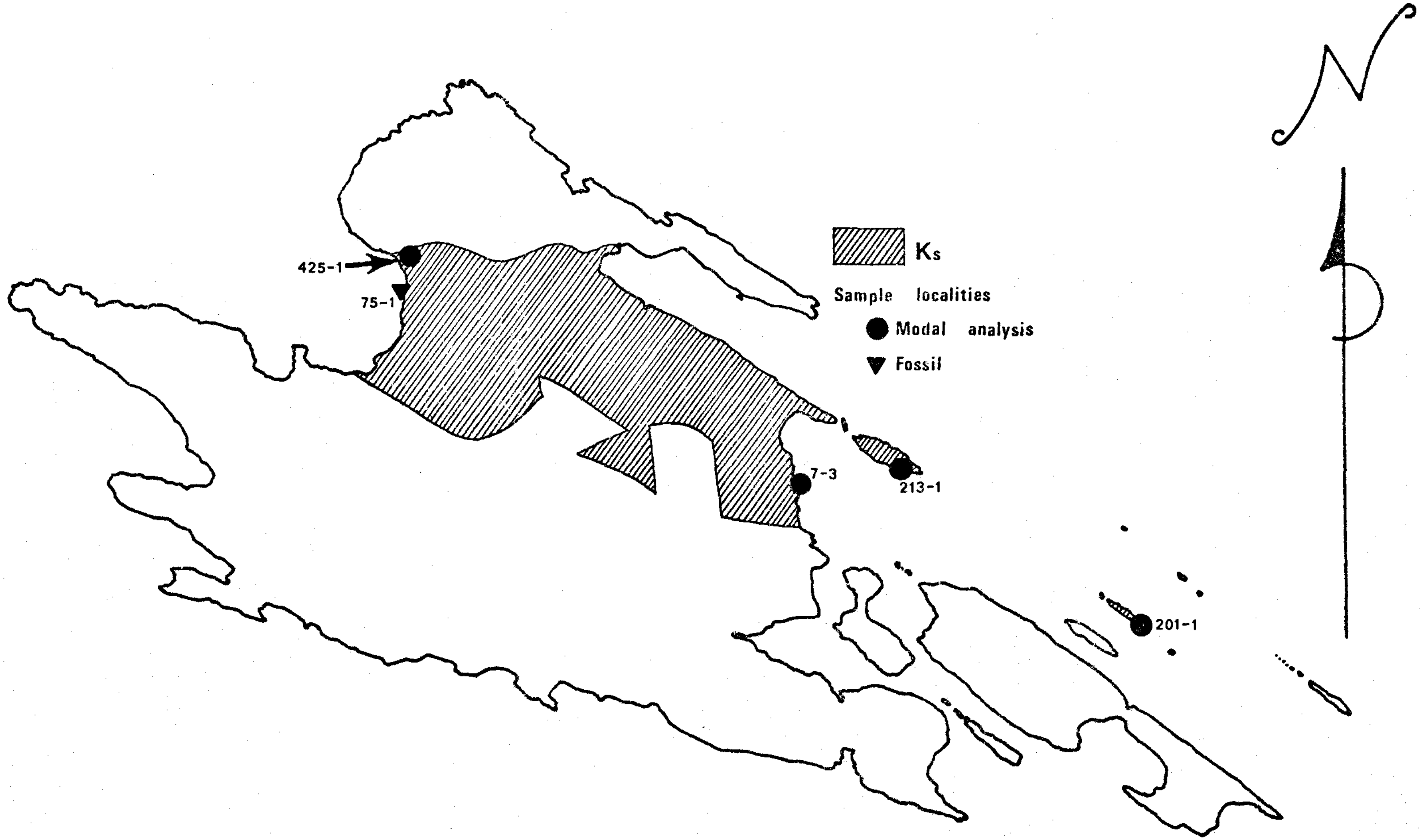



Figure 36. **Distribution of Spray Formation with Sample and Fossil Localities**

several tongues at Miners Bay. Some of these, which must lie beneath the water there, ostensibly acted as sources for exposed clastic dikes. Consequently, aggregate thickness of the member at this locality is indeterminate.

Elevated blocks of the underlying Geoffrey Formation have created an irregular lower (south) Spray Formation contact near the center of Mayne Island (Fig. 36). In the preceding section, the seaward extremities of this contact were described as interfingering. Close to the upper contact at Miners Bay, sandstones up to 8 feet thick are interbedded with graded intervals. It is not clear whether the former are tongues of the upper Spray sandstone member, or actually belong to the lithologically similar Gabriola Formation. For convenience, the contact is picked above the topmost observable graded packets. There possibly may be more upsection, but if so, they are covered by debris which has sloughed off the sea cliff.

Slightly different complexity exists to the east. Penecontemporaneously deformed graded beds of the Spray Formation separate seaward projections of Gabriola sandstone at the northwest part of Campbell Bay. Abundant clastic dikes suggest that the mudstone strata were contorted by dewatering in response to loading before complete consolidation. Without laterally traceable bedding planes, a precise contact is not developed here. Again, it is considered to lie where the exposed, fine-grained interbeds seem to disappear upsection.

At Miners Bay, the Spray Formation is 833 feet thick (for determinative method cf. Cedar District Formation--General Character). The measured thickness on the east end of Mayne Island is 1,770 feet (Muller and Jeletzky, 1970). For Galiano (Carter, personal communication), Saturna (Sturdavant, 1975) and Pender (Hudson, 1975) Islands, thicknesses are close to 800 feet; however, in the latter two places, the section is incomplete. Comparing these values with Packard's (1972) measurement of 333 feet for the Spray Formation on Gabriola Island, a general thickening from there to the southeast may be suggested. This question fails to be resolved by the locally meager paleocurrent information here.

Lithology. The many gradations from finer sandstone to mudstone forms a well-stratified succession throughout most of the Spray Formation. Sporadically interbedded calcareous strata resemble the mudstones, but are far more resistant and commonly grade laterally into concretionary zones. Because the mudstones and the lime-rich beds do not differ significantly from their analogs in the Cedar District and Northumberland Formations, further description is unnecessary.

Near the base of the Spray Formation, the prominence of sandstone cannot escape attention. Individual graded intervals there are between 6 inches and 1-1/2 feet thick of which the lower 4 to 8 inches is fine- to very fine-grained sandstone. Here and there within the column, beds of sandstone which are much thicker (from 1 to 4 feet) seem to show a cyclic recurrence that becomes less conspicuous in the upper half of the section. Such a sedimentary record might be expected, for example, if active distributary switching periodically supplied more detritus to a basin with a slower initial rate of subsidence. Farther up-section, as at Bennett Bay, the bedding is much thinner (Fig. 37) and mudstone prevails.

Ten Spray Formation thin sections were studied petrographically and four were point-counted. Two of these (Samples 7-3 and 213-1, Fig. 36) were collected from sandstone beds within the graded sequence. The remainder are from the upper sandstone member at the east and west ends of the study area so that possible lateral variations could be analyzed.

Weathered sandstones in the graded packets are most typically light olive gray (5Y 5/2) and the fresh ones are from light olive gray (5Y 6/1) to olive gray (5Y 3/2). The basal part of each rhythmite is usually sharp or may show scour-and-fill. The festoon cross-laminae which at places dominate internally are 3 to 5 inches wide with 1/2 inch of relief. They are made visible by elongate flakes of biotite and by layers of increased magnetite concentration. In others, parallel laminations are the main structure and they can be defined by normal grading. Particles are usually the fine to very fine sand sizes. Their angularity (Powers, 1953) probably resulted in high

Figure 37. Note the thinness of the graded bedding within the Spray Formation at the south side of Bennett Bay, Mayne Island. Hammer at center for scale. Boulders at right are glacial erratics.

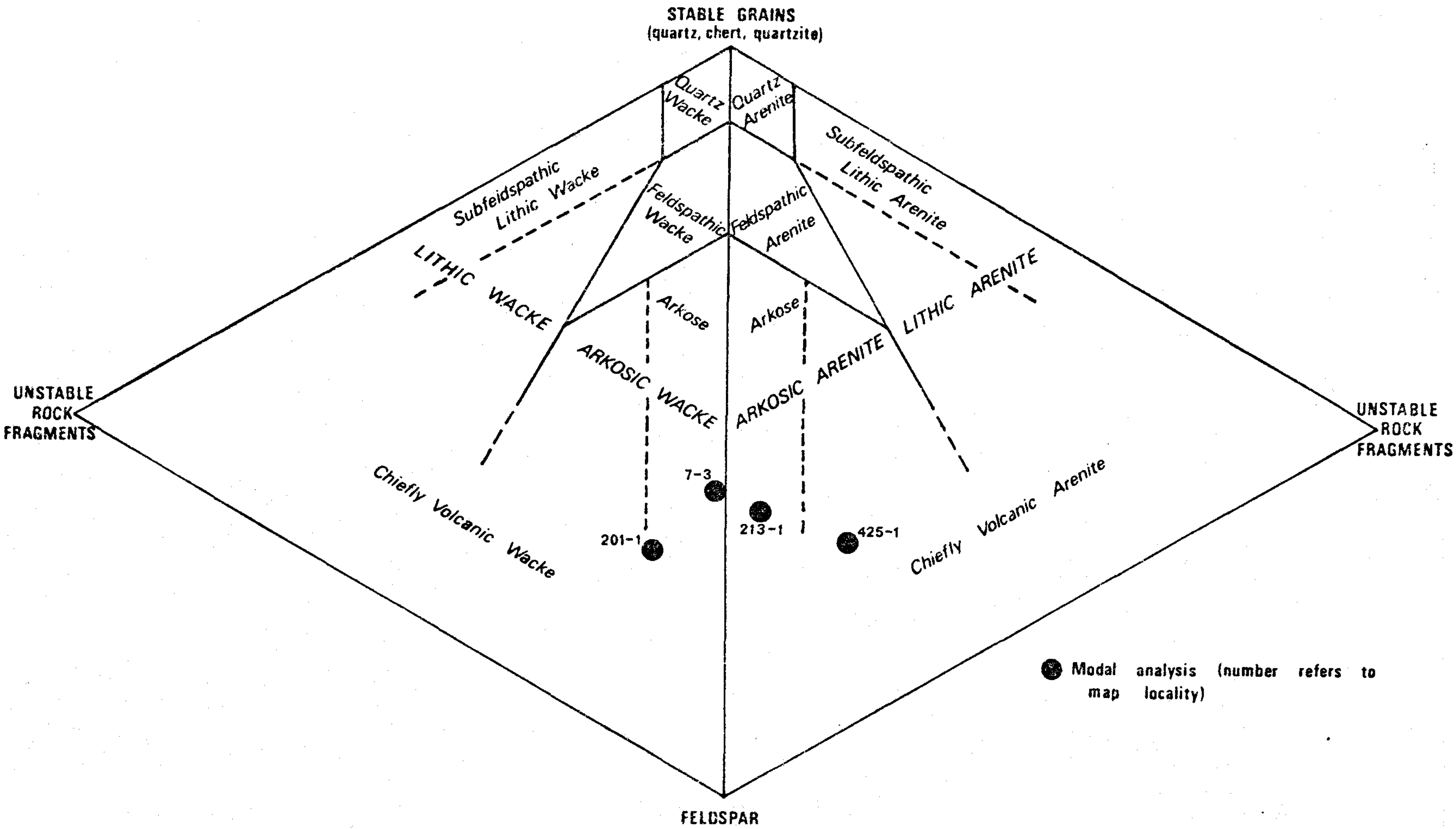
initial porosity. Based on Folk's (1951) criteria, these rocks are considered either texturally submature or immature if slightly more matrix is present. Most of the various rock fragments have been disaggregated by the time they are reduced to this size. The decomposition products are thought to be a significant part of the matrix. Pervasive calcite cement frequently makes it difficult to recognize all the matrix and some underestimation is likely. Quartz grains are in places strongly embayed by this cement and a secondary nature of the latter is so indicated. The cementation augments the effects of compaction in reducing depositional porosity.

The upper Spray sandstone member is sufficiently distinct from the main body of the formation to warrant brief, but separate description. Its fluvial character is indicated by: incorporated woody debris, some current-oriented, some not; a sharp scour-and-fill contact with the underlying graded packets where exposed on Georgeson Island; large-scale cross-laminations; and abundant mudstone rip-ups. The color of this sandstone member is from olive gray (5Y 4/1) to grayish orange (10YR 8/2) weathered and light olive gray (5Y 5/2 to 5Y 6/1) when fresh. Particles range from medium to coarse sand sizes and are also angular to subangular (Powers, 1953). Rock fragments and polycrystalline quartz are more abundant while calcite cement is negligible. Where volcanic rock fragments have not altered significantly, these sandstones are very clean.

Considering the formation as a whole, all the general petrographic trends outlined earlier (cf. microscopic observations under Extension-Protection Formation--Lithology and Appendix B) apply here. A minor addition is the inclusion of accessory clear garnet, sphene, and zircon in the heavy mineral assemblage.

The plagioclase feldspars observed are oligoclase ($An_{28}$) to labradorite ($An_{57}$). Orthoclase, microcline, and some sanidine are the potassium feldspars represented. Both myrmekite and microperthite can be found in most samples. Although some carbonate cement may have come from decomposition of the feldspars, the close association of calcareous concretions suggests that most was derived externally. Small amounts of prehnite and laumontite were also identified. X-ray diffraction analysis verified the presence of chlorite, kaolinite, and mica in these rocks. Diagenetic breakdown of the basic volcanic rock fragments probably accounts for most of the chlorite. Feldspar alteration is quite advanced in some of these rocks which explains the kaolinite and sericite. Some of the mica is also detrital muscovite. Phyllitic and schistose metamorphic rock fragments are widely distributed in the Spray Formation.

Following Gilbert's classification (Fig. 38), the rocks analyzed here include two arkosic arenites, one of which is a true




**Spray Formation**

Figure 38. Classification of Sandstones (after Gilbert in Williams et al., 1954)

arkose. The other two plot as arkosic wackes and both of these can be considered as true arkoses.

The Spray Formation is rife with sedimentary structures of environmental import; however, few of these yielded paleocurrent data. Current-produced features observed are: incomplete Bouma-like sequences, usually the BC, BCD, or ABCD intervals; mudstone rip-ups; current lineations; parting lineations; trough cross-laminae; normal grading; pebble imbrication in small channels; cut-and-fill; and oriented woody material. Soft-sediment deformation features that were noted include: sedimentary overthrusts; contorted stratification; flame structures; load casts; roll-over structures (Fig. 39); and clastic dikes which are the most outstanding examples found in the study area. Calcareous concretions are also ubiquitous. Pyrite/marcasite nodules indicate that a reducing environment obtained at least temporarily.

Fossils. Various molluscs and trace fossils were observed in rocks of the Spray Formation. Efforts by this writer to sample the microfauna of this unit were unsuccessful; however, Foraminifera have been reported by another worker (McGugan, 1964). Part of a coiled ammonite, nearly two feet in diameter, was recovered from the locality of Miners Bay shown in Fig. 36. It was identified as *Pseudophyllites indra* (Forbes) by Mallory (written communication, 1976). Muller and Jeletzky (1970) show this species as common to

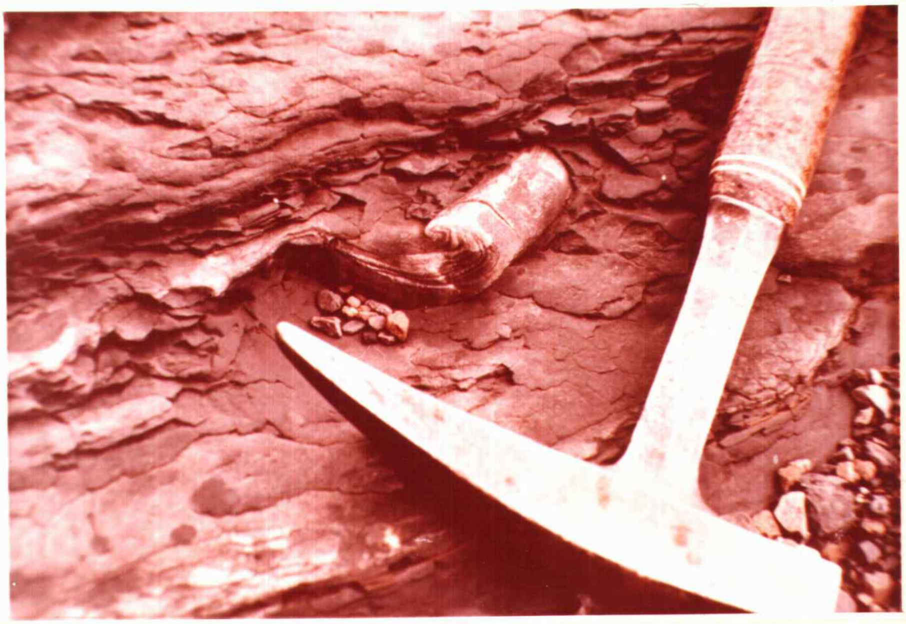


Figure 39. Soft-sediment roll-over structure produced in fine sandstone layer as overlying cohesive mud translated down paleoslope in direction indicated by pointed hammer tip. Exposed on wave-cut platform of Spray Formation, 0.3 mi. south from beach access road at Bennett Bay, Mayne Island.

abundant in the Suciaense biostratigraphic zone which straddles the Upper Campanian-Lower Maestrichtian stage boundary. Mr. Johnny DeRousie, a resident of Mayne Island, has personally collected several well-preserved ammonite specimens and permitted the writer to photograph them. Two of these appear in Fig. 40. Straight ammonites and possibly some scaphopods (?) are abundant in the Spray Formation. Many were located with original shell material, but none showed discernible sutures.

Numerous Inocerami, generally crushed or fragmented, were seen in the field. A particularly well-preserved, but uncollectible example at Miners Bay is not less than a foot in diameter. Another unidentified costate pelecypod (Fig. 41) occurs both at Bennett and Miners Bays.

A profusion of trace fossils is manifest throughout all but the upper sandstone member of the Spray Formation. Many were recognized as straight and branching forms of Thalassinoides while others remain problematical. Several structures resembling Zoophycos (Fig. 42), as described by Seilacher (1964) were found. These are also tentatively reported from the Geoffrey Formation of Pender Island by Hudson (1975). Vertical burrows of uncertain affinities are abundant.

The Foraminifera from Mayne Island include Eponides beisseli and Marssonella oxycona as well as agglutinated fauna that are

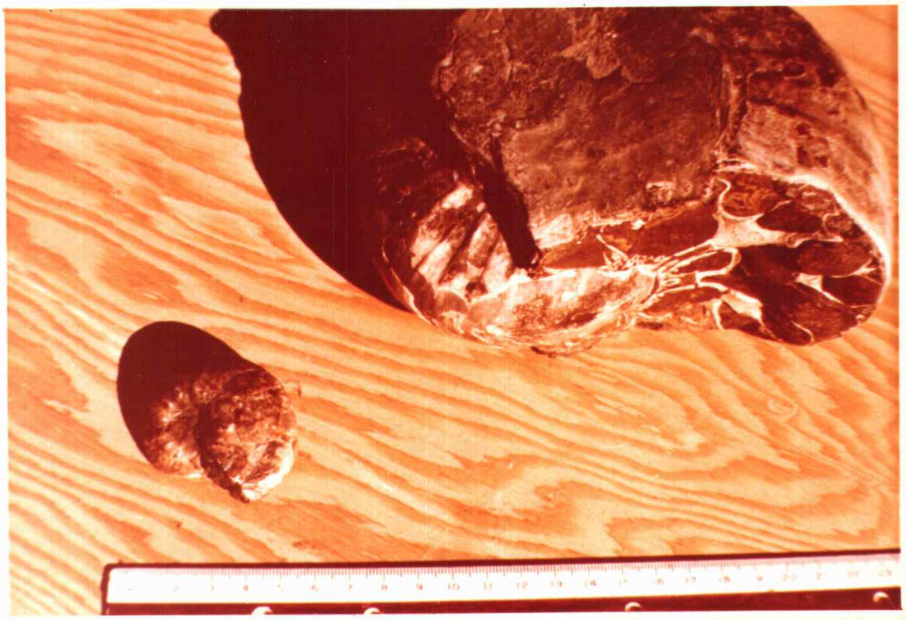


Figure 40. Unidentified coiled ammonites collected from the Spray Formation at Miners Bay, Mayne Island. Made available by Mr. Johnny DeRousie--long-time resident. Metric scale at bottom.

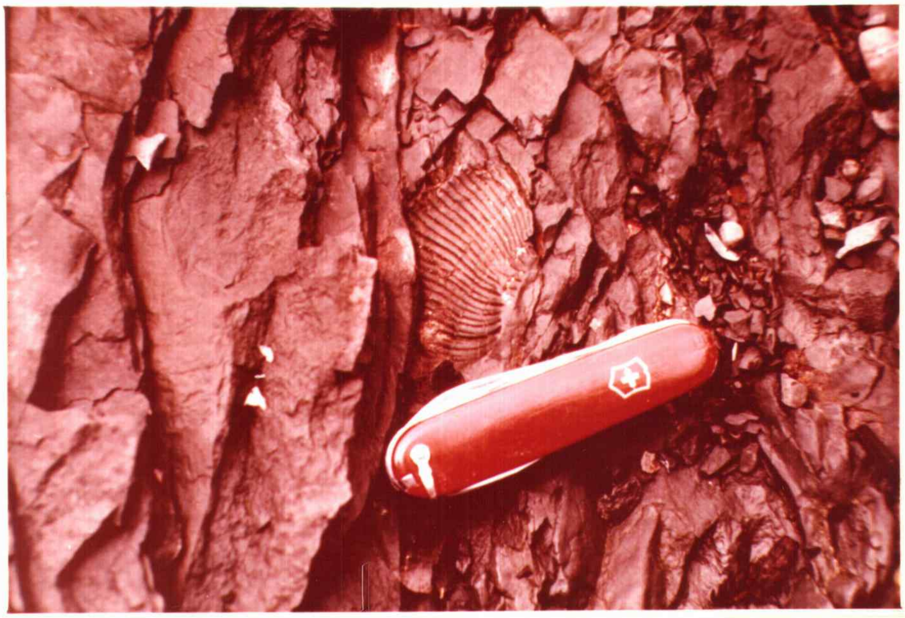


Figure 41. External mold of unidentified costate pelecypod test, apparently disarticulated and compacted. Exposed in siltstone on wave-cut bench at Bennett Bay, Mayne Island.

Figure 42. Irregular horizontal burrows preserved as hyporeliefs on upper surface of fine-grained sandstone bed. Note faint, meniscate back-filling at lower left. Similarly appearing structures are ascribed to Zoophycos (Seilacher, 1964). Spray Formation on south side of Bennett Bay, Mayne Island.

collectively ascribed to shallow water (McGugan, 1964 and written communication). McGugan (1964) considers the beds at Bennett Bay, from which these fossils were collected, as Upper Northumberland. They are mapped as Spray Formation in this thesis (Plate 1) following Muller and Jeletzky (1970). It is interesting to note that Spiroplectammina navarroana is "restricted to the Spray Formation of Hornby Island" and that ". . .a similar, but smaller form" occurs at this same Bennett Bay locality on Mayne Island (McGugan, 1964). Such appears to add some support to the correlation of these rocks with the Spray Formation of Hornby Island (Muller and Jeletzky, 1970).

Environments of Deposition. A relative rise in sea level shifted the strand line away from the study area and marine strata of the Spray Formation were concomitantly deposited. This is likely to have resulted from abandonment and gradual subsidence of a Geoffrey distributary system. Although evidence of a resedimented fauna was not found in it, the Spray Formation is a most impressive recurrent facies. From its striking similarity to the Cedar District and Northumberland Formations, there can be little doubt that all were deposited by comparable processes. The analogy holds up in terms of the faunas as well as mesoscopic internal structures and microscopic features. Therefore, the Spray Formation, exclusive of the upper sandstone member, is regarded here as a thick succession of turbidites. The well-established cyclic pattern of deltaic deposition represented by the Cedar District-DeCourcy and the Northumberland-Geoffrey couplets was reinitiated by the encroaching Spray sea.

The higher sandstone to mudstone ratio near the base of the Spray Formation might indicate: a reduced initial rate of basin subsidence, a slow eustatic rise, an equilibrated sediment supply, or some combination of factors. Sediment appears to have been delivered slowly enough that myriad bottom-feeding organisms could scavenge for food along or within the silty to muddy substrate. At least temporary anaerobic conditions existed as indicated by the abundance of authigenic pyrite/marcasite nodules in many beds.

Water depth of the Spray sea for the Vancouver Island area is inferred to have been 500 to 600 meters, based on broad Foraminiferal data (Sliter, 1973). However, McGugan's suggestion that it was shallow here (written communication), at least during part of the Spray interval, seems more plausible because it is grounded on local evidence. Further support comes from the abundant branching forms of Thalassinoides which are commonest in depths shallower than upper bathyal (Chamberlain, 1975). The paucity of subaqueous slumps in this formation argues that water was shallower where depositional slopes are not as great. It did, however, remain deep enough to prevent significant winnowing and grain rounding of the sediments.

Following deposition of the initial thick sequence of Spray turbidites, an episode of fluvial progradation or upward-coarsening is denoted by the appearance of the upper sandstone member. It is inferred to lie astride the Campanian-Maestrichtian stage boundary (Muller and Jeletzky, 1970). The direction of out-building is not determinable without better paleocurrent control. This episode was probably slightly more significant than the similar one associated with the middle sandstone beds of the Northumberland Formation. It gave way to a period of renewed marine turbidite sedimentation that preceded the Gabriola Formation yet to be described.

## Gabriola Formation

Nomenclature. The Gabriola Formation takes its name from Gabriola Island, east of Nanaimo, where characteristic outcrops appear (Clapp, 1912, p. 100). Clapp recognized it as a generally massive, medium- to coarse-grained sandstone--the youngest unit in the Nanaimo Group. He did not consider what are now the Geoffrey and Spray units as separate formations. To him, both were part of the Northumberland Formation, in turn directly overlain by the Gabriola Formation. These newer lithostratigraphic subdivisions (Usher, 1952) were established in the Comox Basin well before being refined and correlated with the Nanaimo Basin (Muller and Carson, 1969; Muller and Jeletzky, 1970; Fig. 3). Each is discussed individually in the respective preceding sections.

General Character. The Gabriola Formation here occurs as an eastward-thinning cuesta- to ridge-forming sequence which comprises conglomerate, generally coarse sandstone, and interbeds of mudstone. In the immediate vicinity of Mayne Island, the geographic limits of the formation are: Laura Point on the west, Georgina Shoals to the north, and Edith Point on the east (Fig. 43 and Plate 1). In addition, Anniversary Island, the largest of the Belle Chain Islets, marks the easternmost part of the study area. This island and the other reefs, that extend from here along strike toward Edith Point, are all part of the Gabriola Formation. Maximum local relief is slightly in excess of 600 feet on Hall Hill, Mayne Island. The steep, antidip slope cliff here is not accessible. Along the north side of Campbell Bay and in several places adjacent to Active Pass, it is difficult or impossible to reach outcrops on foot. The lower contact between the Gabriola and Spray Formations was described in the preceding section. Exposures of the upper contact, and hence the total thickness, remain unknown. Calculations of thickness between Miners Bay and the northernmost tip of the island give 1941 feet as a minimum. It thins to approximately 251 feet at Edith Point. East of Anniversary Island, the formation appears only on Tumbo Island where the thickness was not mentioned by Sturdavant (1975).

Lithology. Within the Gabriola Formation, planar interbeds of mudstone intercede between usually much coarser sandstones. Such

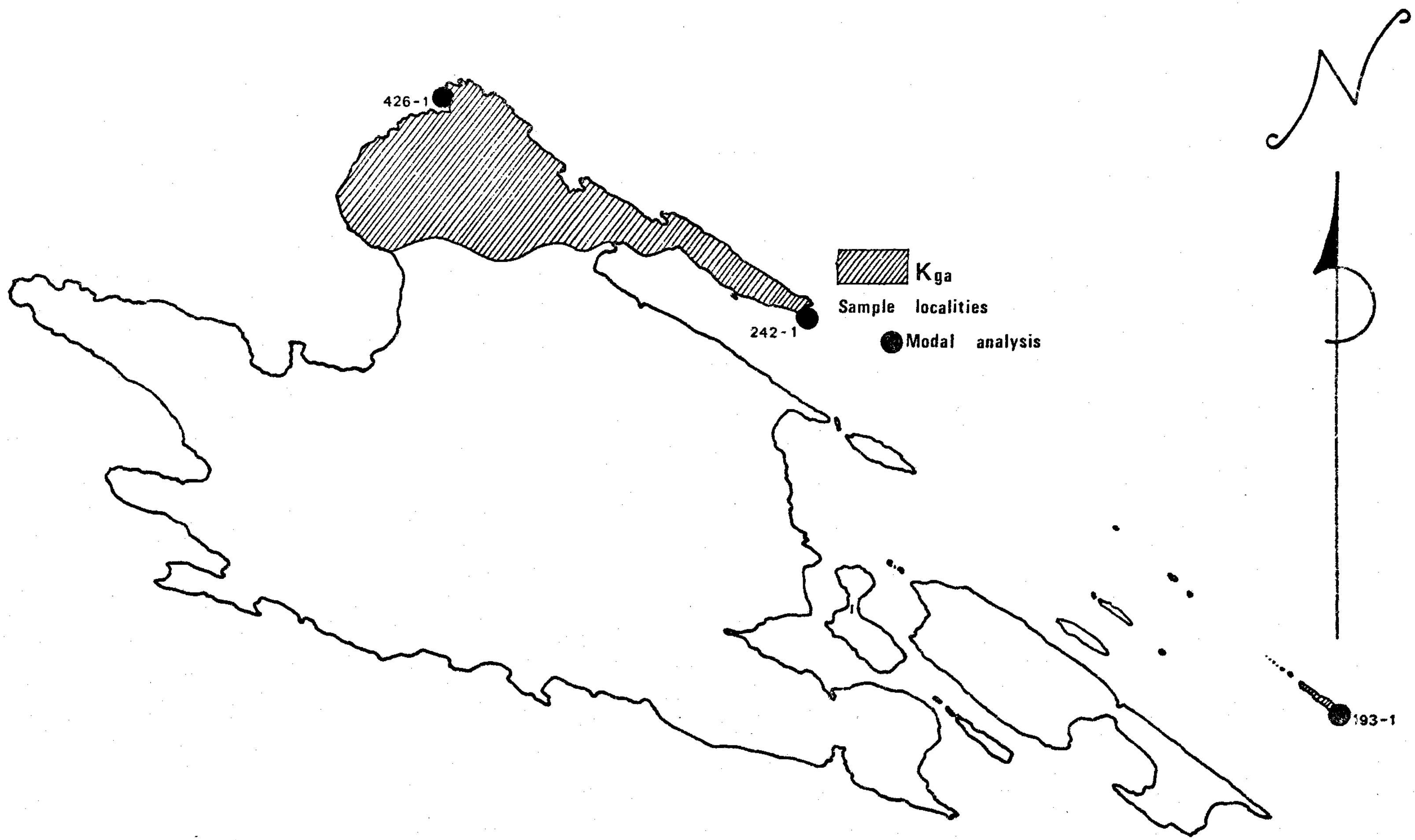



Figure 43. **Distribution of Gabriola Formation and Sample Localities**

interlayers typically include the finest sand sizes and many are normally graded with a small-scale cyclic pattern (Fig. 44). Contorted stratification produced by the weight of overburden before lithification is a common feature. Marine affinities are lacking in these interbeds with a possible exception noted at Maude Bay facing Active Pass. Here, graded packets with a Spray Formation aspect are exposed. They contain numerous unidentified burrow structures and oblate micritic concretions along bedding planes. Elsewhere, these seem to occur within marine rocks. Lacking more definite indicators to demonstrate association of this interval with the Spray Formation, it is not so mapped. However, intertonguing between the Spray and Gabriola Formations on the facing shore of Galiano Island (Carter, personal communication) suggests this as a possibility.

The bulk of the Gabriola Formation is coarse sandstone which ranges from thin- to very thick-bedded (McKee and Weir, 1953). Separate beds are usually difficult to follow any distance where festoon cross-laminae dominate internally. Scour-and-fill is prevalent throughout the formation and is usually developed on a small scale with individual channels only 1 or 2 feet wide (Fig. 45). Many of them contain fine to very fine pebbles and larger clasts are rare. Although no outcrop was found suitable for a pebble count, quartzite, chert, basalt, and foliated metamorphics are widely distributed in the Gabriola Formation. Coarser conglomerate occurs on Hall Hill, but

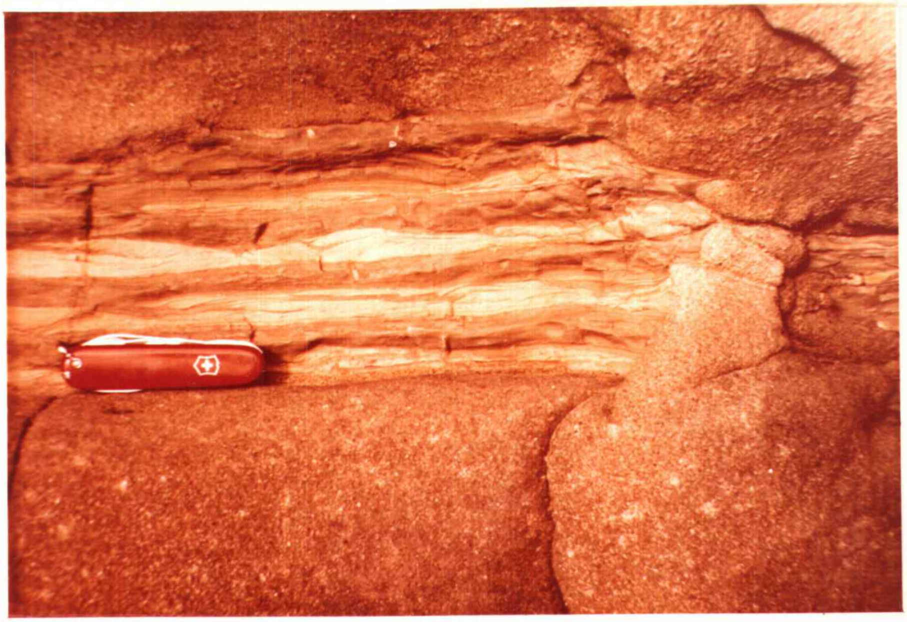


Figure 44. An interval of finer grained sandstone to mudstone rhythmites separates much thicker beds of coarse sandstone. Small-scale clastic dike at right transects the interbed. Gabriola Formation at the northernmost sea cliff exposure on Mayne Island.

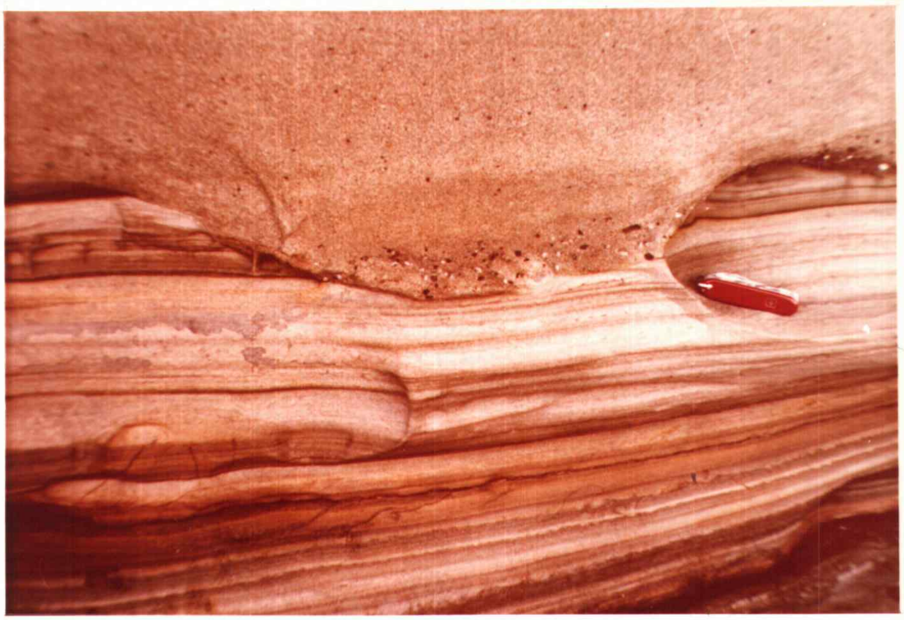


Figure 45. Parallel laminations are truncated where overlying coarse-grained and locally pebbly sandstone exhibits frequently observed cut-and-fill structure. Gabriola Formation, facing Active Pass, 0.5 mi. north from Laura Point, Mayne Island.

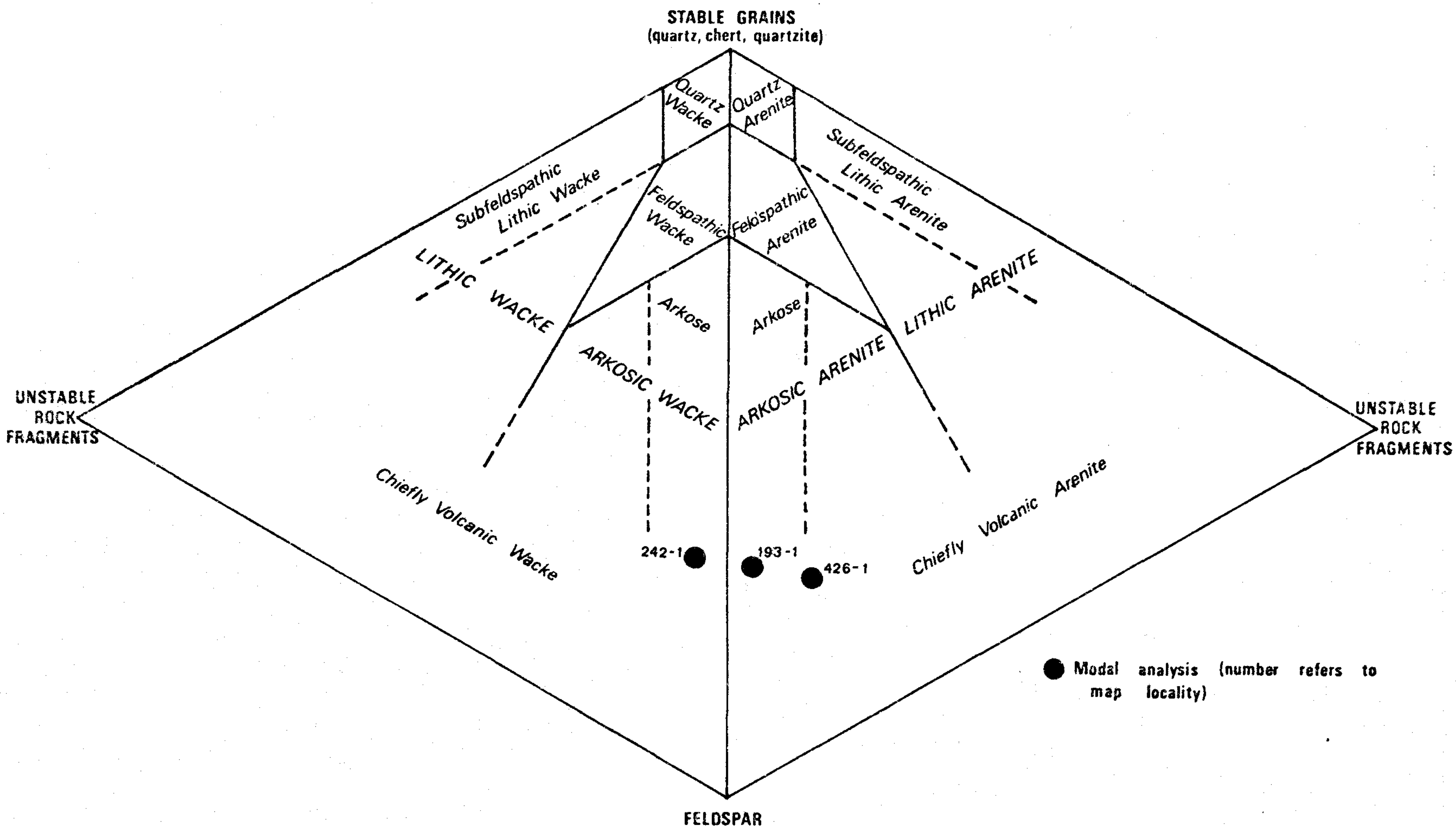
dense undergrowth prevented thorough study there. Judging from other units described earlier, it is probable that conglomerate makes the Gabriola Formation here sufficiently resistant to stand out as a prominent cuesta.

For detailed study, six thin sections were made of Gabriola Formation sandstones. The three that were point-counted are from localities shown in Figure 43. Colors observed generally range from light olive gray (5Y 6/1) to yellowish gray (5Y 8/1) or pinkish gray (5YR 8/1) on fresh and weathered surfaces. Because these rocks are matrix rich and poorly to very poorly sorted with particles that are angular to subangular (Powers, 1953) they are texturally immature (Folk, 1951). In addition to the usual heavy minerals (epidote, hematite, and magnetite), traces of clear garnet, hornblende, sphene, and zircon were recorded. The only exception to the general petrographic trends (cf. microscopic observations under Extension-Protection Formation--Lithology and Appendix B) is a paucity of notable hematite in one sample.

Oligoclase ($An_{24}$) to labradorite ($An_{53}$) constitute the chief plagioclase feldspars. They are moderately to intensely altered to kaolinite and sericite as identified microscopically and by X-ray diffraction analysis. Chlorite is likely to have been derived from breakdown of volcanic rock fragments. Laumontite is a zeolite which can form diagenetically from calcic plagioclase (Williams et al., 1954). It may be an effective cementing agent in these rocks, but because it is not easily recognized, its abundance is difficult to estimate. Microperthite, a rare occurrence of zoned plagioclase, and myrmekite were also detected. Orthoclase is the only alkali feldspar that was discovered. In terms of Gilbert's classification (Fig. 46) the one wacke is a true arkose as is one of the arenites. The other arenite, while close to the borderline, is best called a volcanic-rich arkosic wacke.

Sedimentary structures in the Gabriola Formation that were produced by tractive currents are: scour-and-fill; pebble elongation and imbrication within conglomerates; planar foresets (?); layers of mudstone rip-ups; current lineations; and the normal grading, parallel lamination, and festoon cross-lamination of incomplete Bouma sequences. Although exposures are less than ideal, some structures were found that possibly represent both symmetrical and interference-type ripple marks. Contorted stratification, flame structures and clastic dikes, as well as some major slump features, attest to the soft-sediment deformation that affected these rocks. Galleries and honeycomb weathering develop near the active surf and calcareous concretions are brought into relief by differential erosion.

Environments of Deposition. The Gabriola Formation appears to have been deposited in the fluvial environment. Large-scale festoon cross-laminations from 1 to 3 feet wide with up to 6 inches




Gabriola Formation

Figure 46. Classification of Sandstones (after Gilbert in Williams et al., 1954)

of relief together with widespread cut-and-fill support this suggestion. Layers of slightly abraded mudstone rip-ups required tractive current energy to dislodge them. Planar foresets, which are questionably exposed here, are elsewhere reportedly associated with downstream migration of fluvial bars (Harms and Fahnestock, 1965). Fossils useful as environmental keys were not located in these rocks anywhere in the thesis area. Conglomerate is far less prominent in the Gabriola Formation here than in the other coarser grained units. Yet, the strong similarity between all the respective sandstones seems a plea for a comparable interpretation. The textural features noted point to rapid burial with very minimal to no reworking. Evidence is conspicuously absent that could relate these strata to the shallow marine environment appealed to by Sturdavant (1975) for parts of the Gabriola Formation on Saturna. Therefore, these sediments are thought to be a delta-plain facies. The coarse internal character and the nearly uninterrupted sequence both hint that material was steadily delivered to the basin. Progradation across the underlying marine beds of the Spray Formation represented the final part of the third complete, upward-coarsening deltaic cycle exposed in the study area.

# PALEOGEOGRAPHY

## Paleocurrent Data

### General

Directional measurements were gathered from a variety of sedimentary structures, where available, as indicators of the paleoslope or the sense of paleocurrent flow. Most common are the elongate bidirectional features. They suggest current flow parallel to the long axis, but from either of two directions. Examples are groove (Fig. 18) or prod casts, pebble elongation, primary current and parting lineations, channel molds or casts (Fig. 32), and current-aligned woody fragments (Fig. 29). For the less common unidirectional structures, a single flow direction is discernible. Examples of these include flute casts (Fig. 19), flame structures (if the trend of the associated antiform can be measured), pebble imbrication in conglomerates (Fig. 7) and planar foresets (using the last two presupposes the beds are not overturned or that stratigraphic up is known).

Some of the above readings were corrected for tectonic tilt in the field using the method of Briggs and Cline (1967). For the rest, stereographic rotation was found most convenient. Vector mean sediment transport directions were then calculated following procedures described by Royse (1970) and Curray (1956). The mean of the paleocurrent indications at each locality is shown by formation (Figures 47 through 53). In addition, two grand means were determined. The first is a grand mean based only on unidirectional indicators. Next, a modified grand mean was determined that utilized the bidirectional indicators, but considered them to show a single transport direction closest to the unidirectional grand mean. The difference between the two grand means is consistently 12° or less. Data were not combined for both formations of each deltaic cycle (Fig. 3) because paleodispersal within the fluvial and marine facies was not everywhere consistent.

## Extension-Protection Formation

The Extension-Protection Formation here may represent the upper fluvial facies of an incompletely exposed cycle. Paleocurrent data are taken from pebble imbrication and current lineations and control is limited. The unidirectional and modified grand means are S. 89° W. and N. 79° W. respectively and dispersion is less than 70° (Fig. 47). As mentioned in the earlier discussion of this formation, these directions are consistent with a source to the east as suggested by other workers (Hudson, 1975; Hanson, 1976).

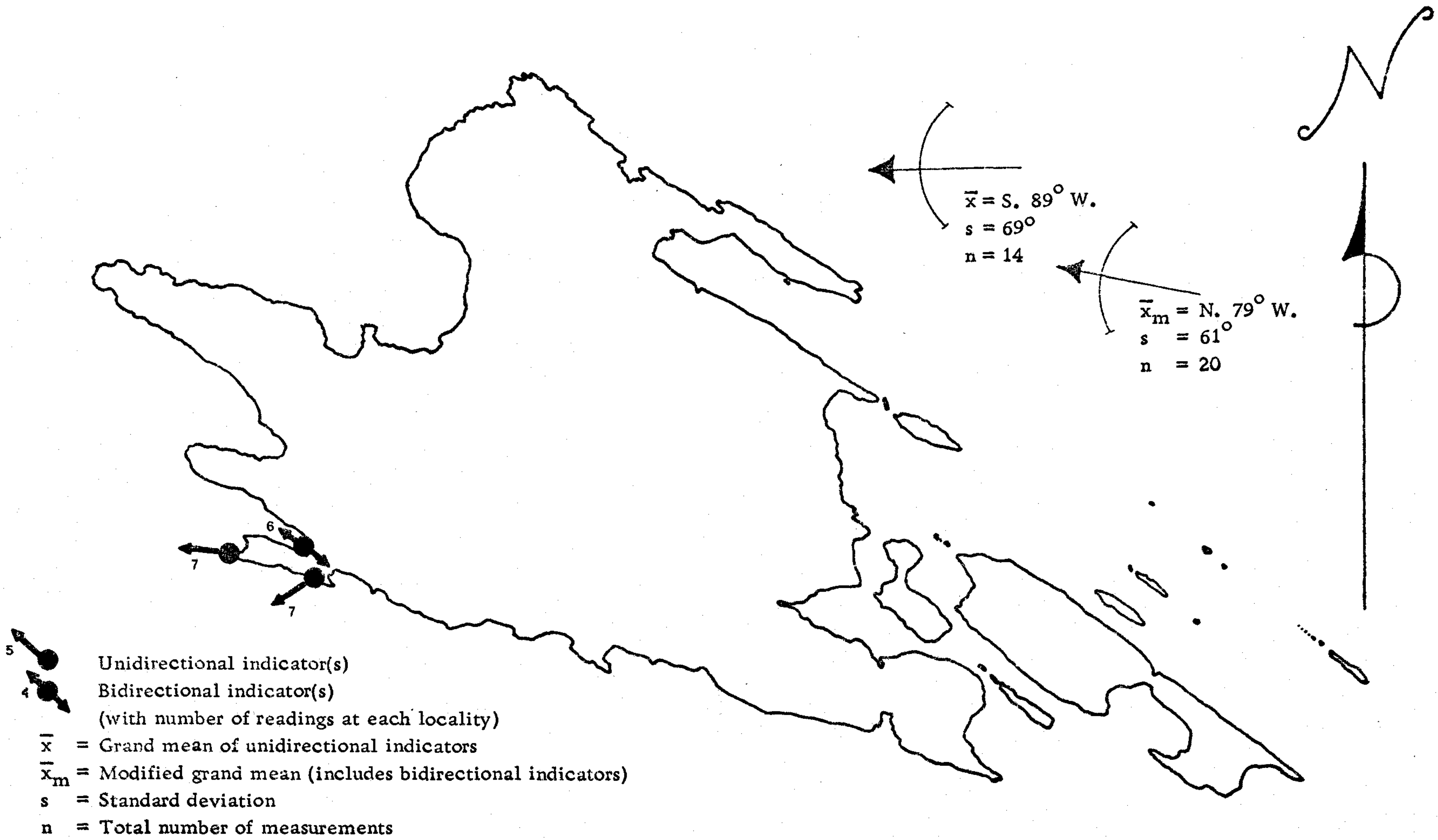



Figure 47. Local and grand mean paleodispersal directions for Extension-Protection Formation.

## Cedar District Formation

Paleocurrent indicators within the Cedar District Formation are especially scant (Fig. 48). Only six readings were available from axes of flame structures and recumbently folded interbeds as well as a possible current lineation. Both grand means are S. 75° W. Cedar District exposures on Mayne Island are less than ideal because of soft-sediment deformation features that disrupt original bedding orientations.

## DeCourcy Formation

The DeCourcy Formation provided the best control of any unit in the study area (Fig. 49). A total of 91 measurements was obtained, 35 of which are unidirectional and there is broad distribution along strike. The unidirectional and modified grand means are N. 61° W. and N. 55° W. respectively, with a maximal standard deviation of 54°. In the preceding discussion of the formation, these directions were explained in terms of lobate deltaic progradation that is consistent with all the surrounding islands where DeCourcy rocks are exposed.

## Northumberland Formation

Rocks of the Northumberland Formation show a dispersal

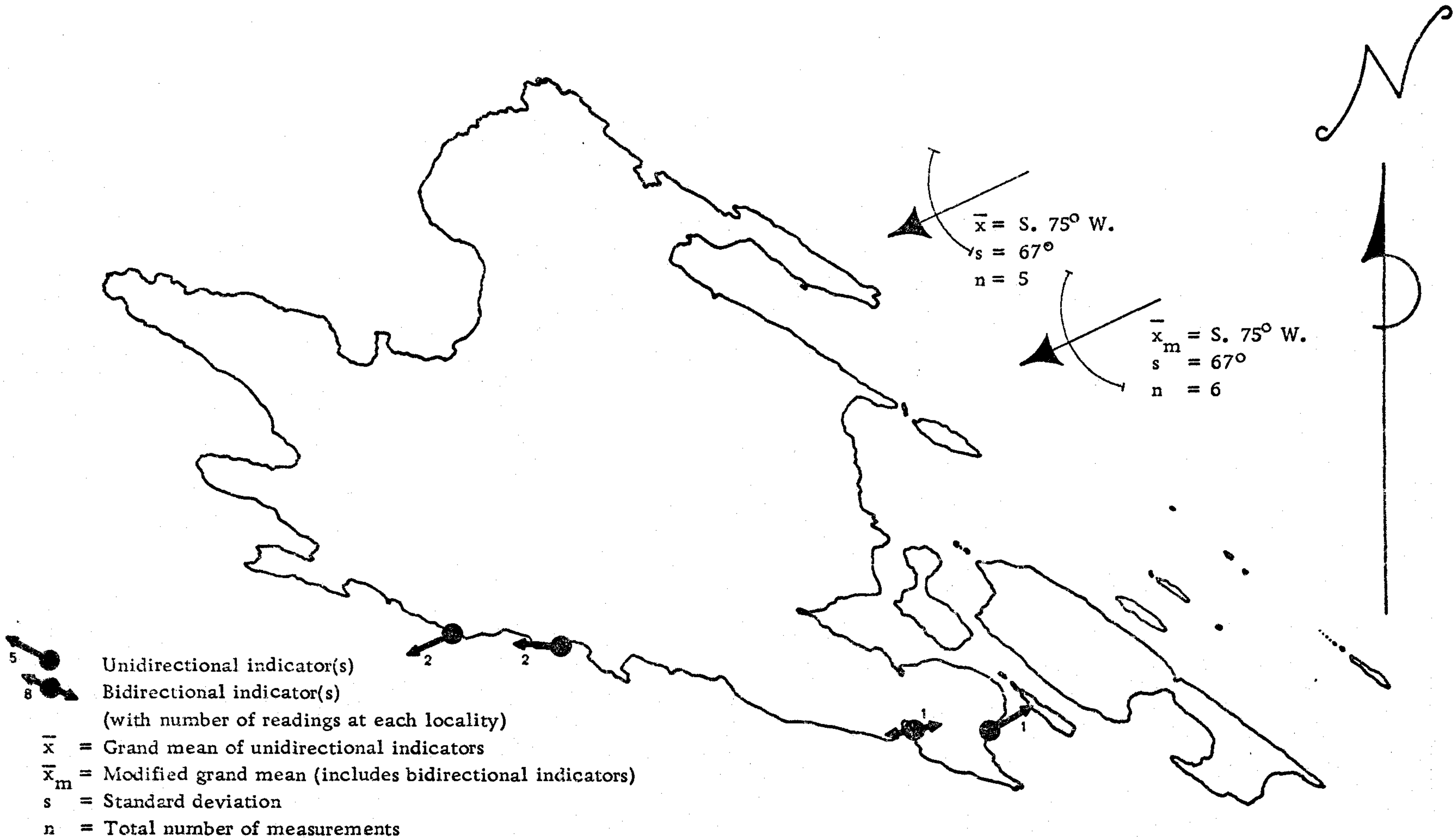



Figure 48. Local and grand mean paleodispersal directions for Cedar District Formation.

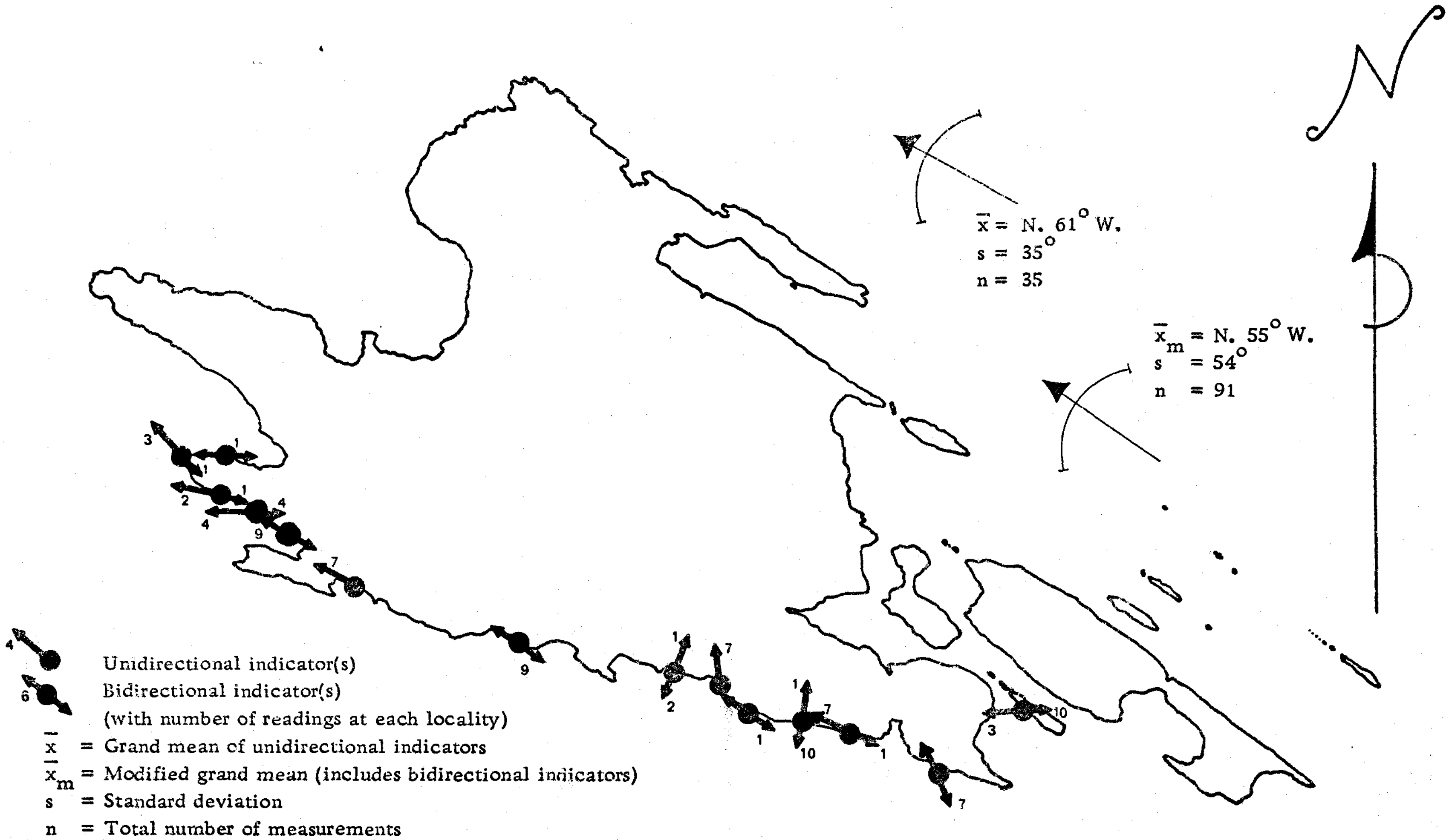



Figure 49. Local and grand mean paleodispersal directions for DeCourcy Formation.

direction that is essentially parallel with that of the underlying unit. Exposures are much more sparsely distributed, but they show nearly constant orientations on both ends of the thesis area (Fig. 50). The unidirectional grand mean is N. 84° W. and the modified counterpart is N. 74° W. with the greatest standard deviation being 70°. These directions and the apparent westerly interfingering of the coarser sandstone beds are indicative of a possible westerly transport.

Geoffrey Formation

The Geoffrey Formation is anomalous with respect to older units. Among the total of 56 measurements, 35 are unidirectional from well-imbricated conglomerates. The grand means are: S. 19° E. with S. 30° E. for the modified plot (Fig. 51). Very low dispersion is shown by a maximum standard deviation of 26°. This is the first indication of a major shift in the source area. By considering similar data from neighboring islands, this might be explained by lateral dispersal from a northerly prograding deltaic lobe with an origin nearer to Vancouver Island.

Spray Formation

Within the Spray Formation, data are again insufficient for any reliable conclusion. Only 11 total features were found suitable for measurement (Fig. 52). Both grand means are S. 15° W. Although

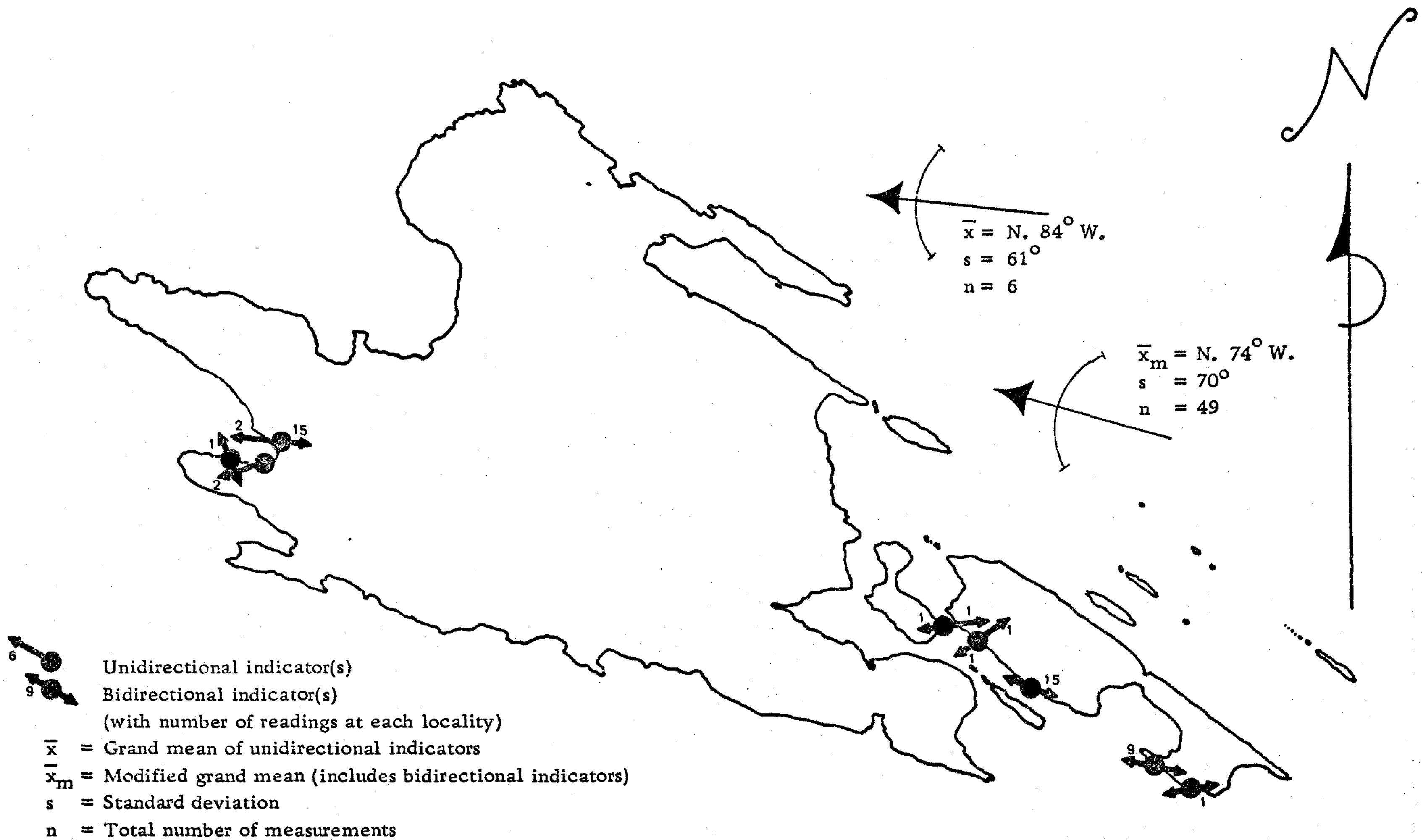



Figure 50. Local and grand mean paleodispersal directions for Northumberland Formation.

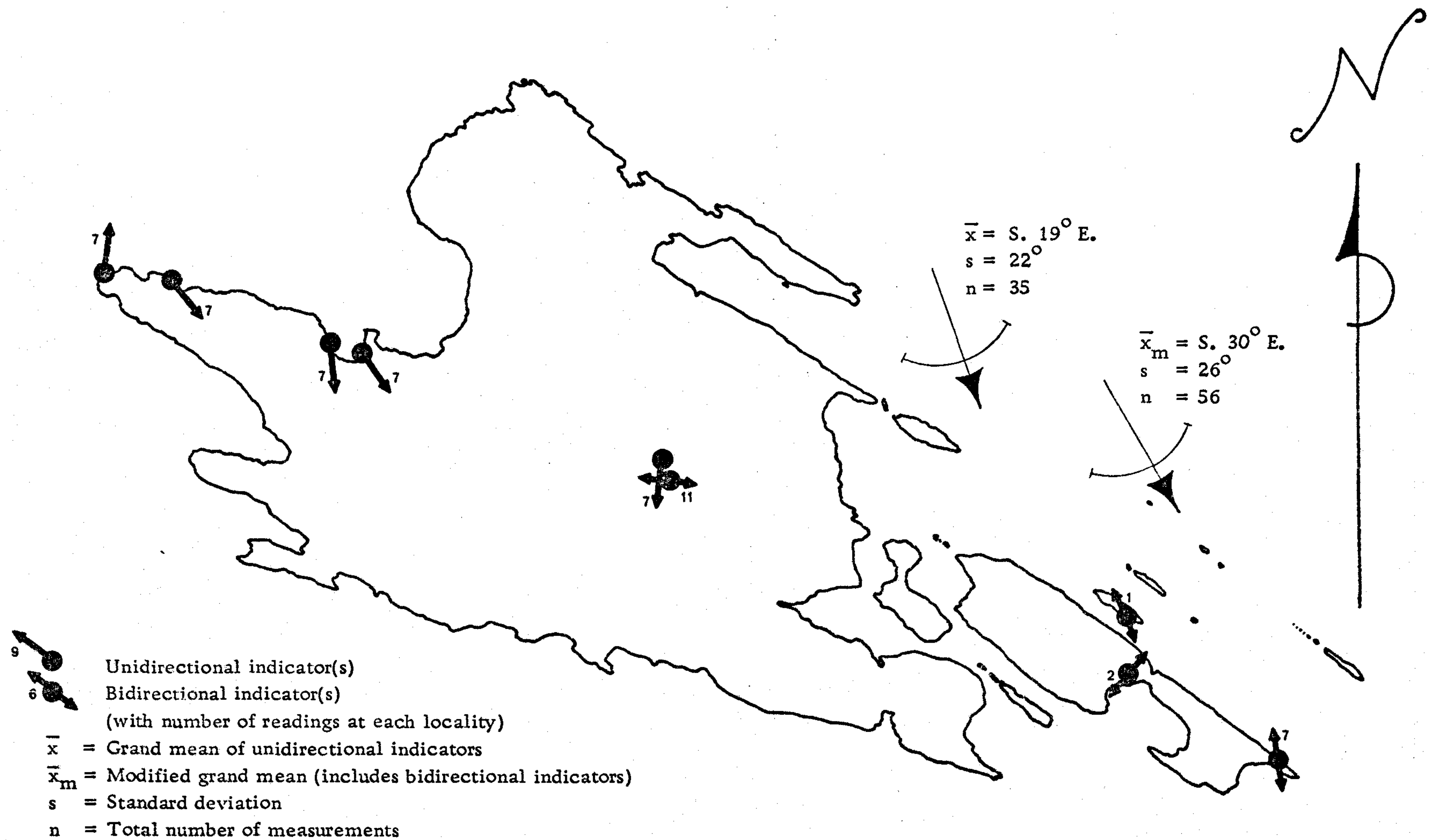



Figure 51. Local and grand mean paleodispersal directions for Geoffrey Formation.

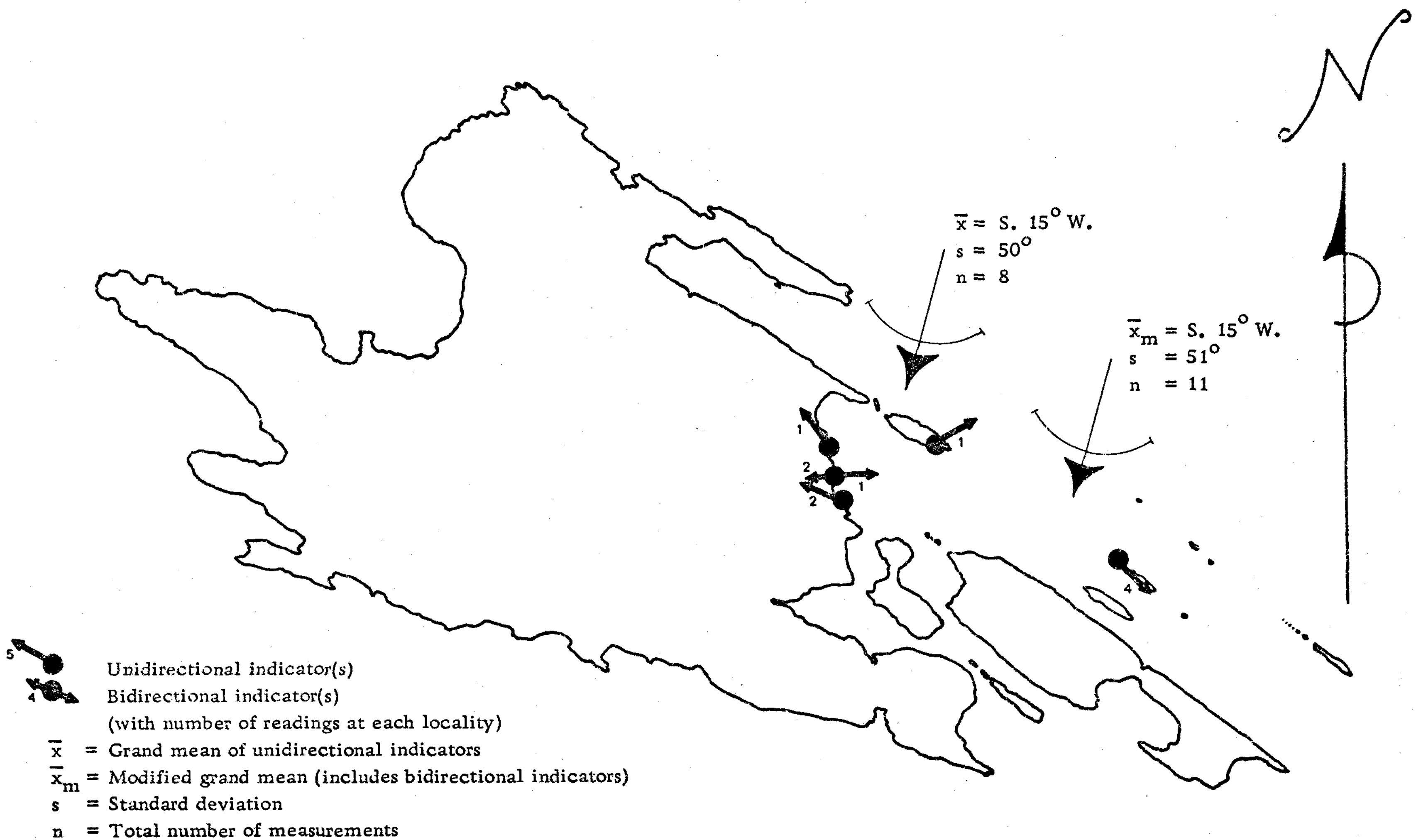



Figure 52. Local and grand mean paleodispersal directions for Spray Formation.

the map symbols do not appear to show this, the inconsistency resulted from averaging of localities too closely spaced to plot individually. The paleocurrent direction is not unlike that of the Geoffrey Formation, although this may be fortuitous.

Gabriola Formation

Paleodispersal within the fluvial system of the Gabriola Formation is westerly (Fig. 53). The modified grand mean is N. 81° W. which differs by only 1° from the unidirectional grand mean. This pattern seems to show a source to the east, but coarser conglomerates on Galiano Island farther west (Carter, personal communication) indicate a possible anomaly. Additional data are needed to resolve this apparent conflict. Conglomerate occurs within the Gabriola Formation on Tumbo Island to the southeast, but no paleocurrent data were collected that bear on the local dispersal directions there (Sturdavant, 1975).

## Postulated Source Areas

During the Late Cretaceous, a youthful Coast Range presumably lay to the northeast of the study area (Muller et al., 1974). Because the position of the marine embayment, the Georgia Seaway, is not precisely known, the degree to which a northeastern source may have influenced sedimentation here is very speculative. The proximity of

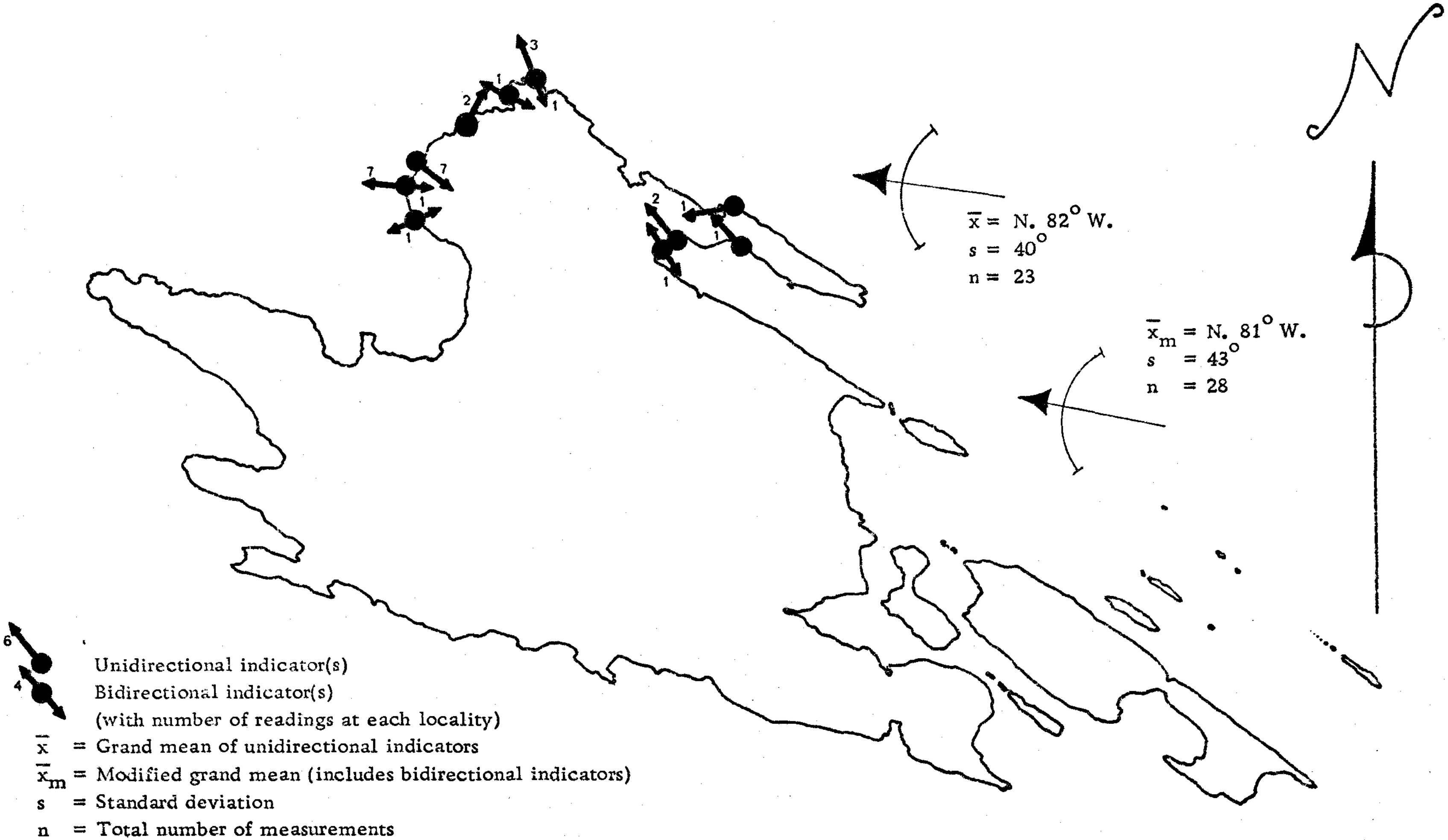



Figure 53. Local and grand mean paleodispersal directions for Gabriola Formation.

Vancouver Island immediately suggests it as a possible source of the clastics shed into the Nanaimo-Comox Basin area during the Late Cretaceous. Along the mountainous axis which existed there at the time (Usher, 1949; Muller et al., 1974), Sicker Group rocks of Pennsylvanian to Permian age were exposed. This is a mixed assemblage which includes: greenschist produced from deformed volcanics; greenstones; graywacke-argillite; chert; and limestone (Muller and Carson, 1969; Muller et al., 1974; Muller, 1976). The overlying Vancouver Group also contains limestone and graywacke as well as pillow basalts and basaltic lavas, andesitic pyroclastics, and conglomerate--all of which are Early Jurassic or older (Muller et al., 1974). Tyee Intrusions within the Sicker Group, on southern Vancouver and Saltspring Islands, are quartz porphyry to somewhat metamorphosed granitoids (Muller, 1976). Finally, the Middle Jurassic Island Intrusions, which comprise quartz diorite, granodiorite, and quartz-feldspar porphyry also occur on southern Vancouver Island (Muller et al., 1974). There are also basement exposures to the southeast in the San Juan Islands of Washington (Muller and Jeletzky, 1970). The rocks indicated above show sufficient variety to account for all the lithologies observed in Nanaimo Group strata of the thesis area.

Petrographic analysis, pebble counts, and X-ray study serve to characterize these sediments in a general way. However, comparing these data with the findings of workers on adjacent islands (Hudson, 1975; Sturdavant, 1975; Hanson, 1976; Carter, personal communication), major differences do not emerge that are likely to be statistically meaningful. Most variations noted appear to be irregularities attributable to a relatively small sample and seldom apply on a broad scale. In this study, most credence is given the textural features, many observable on outcrop, that relate to paleocurrent data where control is believed adequate.

## Geologic History

Foundation for the paleogeographic interpretation below is discussed in greater depth, by formation, under Environments of Deposition.

Adjacent to a narrow coastal plain, bordering the northeast side of Vancouver Island, lay a subsiding trough or graben (?) that was the depocenter for the Nanaimo Group. Sedimentation was well-established by the time rocks of the Extension-Protection Formation, the oldest unit in the study area, were laid down. During this interval, conglomerates were transported westerly in braided streams. Coarseness of the rocks suggests the source was probably undergoing steady uplift that could maintain the rapid supply and steep relief. In the vicinity of what is now Mayne Island, deposition occurred within choked, anastomosing distributaries before reworking could modify the sediment. Channel abandonment or floods periodically redirected swift, scouring currents across bedded interdistributary muds on the delta plain and such fragments were carried short distances farther downstream. On Saltspring Island to the west, marine fossils require placement of a strand line in that vicinity during part of this interval.

A Cedar District sea, containing numerous mulluscs, advanced eastward to interfinger with the established fluvial system. Probably in response to a continuing rapid sediment supply from the east, coupled with some basin subsidence, marine slopes steepened. Westerly flowing turbidity currents were generated and subaqueous slumping occurred. Periodic fluctuations in the sediment supply or pulses of basin subsidence may have allowed lime-rich interbeds to accumulate from a pelagic rain.

The advent of DeCourcy time was marked by renewal of fluvial deposition nearly identical to that of the Extension-Protection Formation. This is ascribed to distributary switching. As these coarse sediments were again spread into the area from the still active, or more active source terrane, accumulation resulted in progradation. Deltaic lobes appear to have been formed with at least one intervening marine embayment. These rocks emphasize an upward-coarsening sequence by their superposition over Cedar District strata. At least two more episodes of distributary abandonment temporarily directed fluvial sediments to another part of the delta allowing more marine turbidites to accumulate. The lack of fluvial affinities, in the DeCourcy Formation proper, indicates that they are most likely a delta plain facies. Accelerated basin subsidence or cessation of uplift in the source area gradually drowned the fluvial domain. This ended the first complete, upward-coarsening deltaic cycle exposed here.

Northumberland marine conditions were very similar to those of Cedar District time. However, trace fossils, the absence of subaqueous slumps, and somewhat coarser sandstones all argue that slopes were less steep than before. Turbidity currents issued toward the west (?) throughout most of the interval except when fluvial sediment was again channeled into the area. This resulted in a middle Northumberland Formation sandstone that emphasized a minor upward-coarsening cycle within the major Northumberland-Geoffrey couplet.

The Geoffrey Formation records the coarse upper part of the second deltaic cycle in the study area. It appears to have begun with dissemination of coarse basal sandstone that grades upward into conglomerate. Imbricate clasts within the latter, together with current lineations and channel axes collectively attest to a major change in the dispersal pattern (Fig. 51). Southerly to southeasterly flow is a distinct contrast to the heretofore established pattern suggestive of an eastern source. While these data alone would require a source to the northwest, such is unlikely. On Galiano Island, Geoffrey paleocurrents flowed toward, not from, the northwest. Northerly flow from Saltspring Island on the south, as pointed out by Hanson (1976), is consistent with a radial distribution to the north with a point-source in the vicinity of south Vancouver Island. If so, the local observations fit that pattern by considering them as having been shed from the east flank of a northerly prograding delta lobe.

Particularly striking is the size of material within the Geoffrey Formation conglomerates. Huge blocks of apparent Sicker Group greenschist up to 10 feet long were transported into the area by powerful tractive currents pouring forth from steep terrain. Further testimony to their unparalleled vigor are even larger mudstone blocks, probably derived from sapping of stream banks carved in the underlying formation. Because these mudstones were observed to contain ammonites or scaphopods(?), they probably originated in the Northumberland Formation. The locus of conglomerate on Mayne Island that pinches out into sandstone eastward suggests the strand line lay in that direction. Well-preserved leaf fossils at the eastern-most tip of Samuel Island show that deposition there was probably fluvial rather than marine. Hence, the shoreline was farther east(?) of this lobe. The return to sandstone deposition, following the conglomerate, heralded the end of the second deltaic cycle recognized in the thesis area.

Another sequence of turbidites, the Spray Formation, represents a long marine interval which was interrupted by fluvial conditions relatively briefly near the end of Spray time. The sea encroached, slowly at first, as suggested by the abundant sandstone relative to mudstone near the base of the formation. This may have been caused by a continued clastic influx that was not balanced by a sufficient rate of basin subsidence. Paleodispersal information for the Spray Formation is not considered reliable because of the small sample. Data are shown here (Fig. 53) only for reference. Therefore, conclusions as to the source direction are avoided. The Spray turbidites apparently accumulated in a fairly shallow marine environment as indicated by sparse, but local forams. The upper Spray Formation sandstone member, which records a fluvial interval, is much the same as the middle Northumberland sandstone. It contains both current-oriented and unoriented plant debris that likely was deposited in shallow water. No marine features are associated with this member. A much thinner sequence of turbidites was laid down before a last major fluvial episode.

The Gabriola Formation is a sandstone-conglomerate unit that represents the upper part of the final coarsening upward deltaic cycle in the Nanaimo Group. Again, a statement regarding the source direction is not yet possible. Carter (personal communication) mentions that on the west, dispersal on Galiano Island is northeasterly. However, on Mayne Island (Fig. 53) a westerly grand mean is shown. Because no information is available from Tumbo Island (Sturdavant, 1975) where Gabriola Formation conglomerate occurs, there is no clear means to resolve the conflicting data (?) above. Depositional conditions are distinctly fluvial because of the abundant festoon cross-laminae, conglomerate, channel scour-and-fill, and possible planar foresets. No association with the marine environment is indicated except for a possible marine tongue at Maude Bay which is not laterally persistent.

Following the last of Nanaimo Group deposition, subsequent folding resulted in flexure of the Trincomali Anticline during the early Tertiary. Several faults occurred even later as evidenced by structural offset of cuesta-forming sandstone units. Truncation of a longitudinal fault west from Horton Bay by a transverse fault (Fig. 59 and Plate 1) suggests that at least some of the latter were younger. Pleistocene glaciation, mentioned in some detail under Geomorphology--Glaciation, scribed its effects on the study area. In addition, locally thick accumulations of glacio-fluvial outwash lie in the valleys and boulder erratics are abundantly strewn along the wave-cut platforms.

# GEOMORPHOLOGY

Topographically, Mayne, Curlew, and Samuel Islands each appear as a sequence of linear ridges separated by elongate valleys with a northwest-southeast structural trend. Projection of the outcrop pattern southeastward from Mayne Island suggests the channels between the Belle Chain Islets probably occupy inundated valleys. Faulting has produced irregularities to this general pattern. Resistant sandstones and conglomerates make up the ridge-forming units, whereas much less resistant mudstone-siltstone sequences underlie the intervening valleys. Structure and lithology have acted together to influence erosional agents in shaping the topography. The ridges are actually cuestas because the strata dip gently to the northeast throughout the entire thesis area. Mt. Parke, the highest of these, is held up by well-indurated conglomerates of the Geoffrey Formation. From its 857-foot summit, precipitous cliffs of the antidip slope extend over 500 feet to the slightly-elevated valley below.

Several erosional processes have modified the topography. These include wave activity, mass-wasting, glaciation, and erosion by intermittent streams.

## Wave Activity

Where the much softer units intersect the shoreline along strike, these strata have been deeply incised by storm waves. Bay head beaches and wave-cut benches are so produced. In Bennett Bay, the extensive intertidal bench has nearly a half mile of frontage. The more competent rocks on either side of less resistant units stand out as prominent headlands. Steep sea cliffs up to 100 feet high usually form the southwest-facing antidip slopes. During the winter sea cliffs commonly yield large blocks to accelerated undercutting, also called sapping, by waves of increased violence.

In the restricted passages between islands, local ebb and flood tidal currents attain velocities as high as seven knots. Large detrital cobbles and boulders are made available by sapping. Bed load transport of such material must certainly enable effective channel scouring. Though this mechanism is not directly observable, Active Pass may owe much of its depth to such a process.

Within the sandstones of the more resistant formations, nearly spherical calcareous concretions are abundant. They range from a few inches to a few feet in diameter. Where waves or spray impinge upon these rocks, particularly on the antidip slopes, concretions are weathered out rapidly. The remaining depressions become focal points for hydraulic action to create irregularly shaped wave-cut notches. Larger ones have been called galleries (Clapp, 1912; Muller and Jeletzky, 1970) and some are 15 to 25 feet high. These structures are well formed along the north shore of Campbell Bay in the Gabriola

Formation and in the DeCourcy Formation immediately southeast of Crane Point. Within each of the major cliff-forming sandstones, isolated wave-cut notches were found which were estimated to lie between 30 and 75 feet above the present sea level. To carve such features, it is assumed that the sea must have stood higher temporarily. It was not clear from field observation whether a eustatic change or local subsidence might have been responsible.

Secondary mineralization along small networks of joints or fissures makes them more resistant than the enclosing sandstone. The intricate patterns are brought into relief by prolonged exposure to waves and spray. This leaching effect results in honeycomb weathering (Fig. 22). Once these small recesses develop, they too may eventually become galleries. By progressive lateral enlargement, the galleries gradually coalesce near sea level. When the roof sections finally collapse through sapping, narrow wave-cut platforms are left.

Because the shelving dip slopes are seldom steeper than 30$^{\circ}$, wave energy is dissipated on them much more slowly. Closely spaced concretions of various sizes, which are beginning to weather out, create an undulating surface (Fig. 54). Where they have been removed, shallow basins remain which are usually less than two feet across. Those that are above mean high tide receive a new supply of salt water only periodically. With this restricted circulation and high

Figure 54. Differential erosion has shaped this undulating surface with calcareous concretions standing out as resistant knobs. Spray Formation on south side of Campbell Bay, 1/2 mi. N. W. of Campbell Point, Mayne Island.

evaporation during drier periods, aggregates of halite crystals form there. Honeycomb weathering also thrives on the dip slopes, but because wave energy is less effective, it does not reach the gallery stage.

Along the beaches in some of the small coves and inlets, concentrations of disarticulated or fragmented pelecypods and molluscs bespeak the constant abuse by waves.

Above the zone of surf influence, the weathering processes described are generally absent and subaerial weathering prevails.

## Mass-Wasting

Creep, slumping, debris sliding, and rockfalls are the most striking vehicles of mass-wasting seen here. Four strongly interrelated factors seem to control exactly which expression will dominate at any given locality. These are lithology, structure, climate, and vegetation. Lithology is important because each rock type has a different susceptibility to mass-wasting. Also, less competent interbeds commonly act as "roller bearings" or glide planes between units which are more rigid internally. This is particularly true under conditions of adverse dip explained below. Structural considerations include the nature of faults, fissures and joints as well as tilting of the strata. The dip is said to be adverse if down-dip movement can occur that will increase the hazard to persons or property. The angle above which sliding will take place may be substantially less if water is present to decrease friction. Climate has a far-reaching influence. Besides governing the moisture available annually, it also dictates the amount and type of vegetation, and the thickness of the soil cover. Vegetation can have a pronounced effect on slope stability. A fine, matted root network can reinforce the soil. Thicker root systems, on the other hand, can reach into joints or fissures and wedge apart large blocks. Once loosened, they move downhill in response to gravity. Organic decay also fosters development of humic acids which contribute to chemical weathering.

The downslope inclination of trees shows the effect of creep. It is especially noticeable where dip slopes reach the surf zone. As the regolith is stripped from the toe of slopes by high waves, gravity, runoff, and to a minor extent wind, material farther uphill is no longer supported. It begins to creep and the process perpetuates.

Creep activity is most common within the thickly bedded sandstones of resistant formations. This is partly because they project farther seaward and expose more dip-slope shoreline to waves. Also, these units all have thinner interbeds of less competent, clay-rich rocks--mainly mudstones and siltstones. Abundant intersecting joint patterns form large, distinct blocks which can move independently where the slope is sufficient. During the wet season, joints channel moisture into the highly fractured, less competent interbeds. Once saturated, they act to lubricate the large blocks and allow downhill movement much more readily. Although this process could not be observed, large blocks were seen to have translated several feet, one upon the other. If undercutting were the dominant mechanism, it is more likely that these blocks would have collapsed in place with minimal sliding. The best examples are found along the south shore of Campbell Bay.

Within the less resistant formations creep does occur. However, these units are so readily eroded that more rapid forms of mass-wasting predominate. The two major ones are slumps and debris slides. Once mudstone-siltstone sequences are exposed to the atmosphere, closely-spaced, irregular fractures develop. Resulting small chips gradually accumulate as talus, especially at the base of antidip slopes. Particularly in the absence of vegetation, these fractures, which may penetrate several feet, together with minor joints and faults, enhance slope mobility. During the winter when the ground becomes saturated, moisture localizes within the numerous fissures. Besides reducing cohesion, it adds appreciably to the weight of the strata. As hydration causes clay minerals in the rock to expand, competence is diminished. When the increased load can no longer be sustained, failure will occur by slumping or debris sliding. At least temporarily, conditions return to equilibrium. Along the sea cliffs at two Mayne Island localities, these features are well-displayed. One is between the ferry terminal and the head of Village Bay. The other is at the major shoreline indentation opposite the north end of Curlew Island. Both are outcrops of the Northumberland Formation dominated by mudstones and siltstones.

Rockfalls are generally confined to the resistant cliff-formers such as the Gabriola, Geoffrey, and DeCourcy Formations. Large blocks produced by this form of mass-wasting are usually found at the base of antidip slope cliffs. Typical exposures occur along Horton Bay Road north of the Gallagher Bay junction. Similar examples line the north side of Campbell Bay. The exact causes are speculative. Several instances of root wedging by trees and shrubs were actually observed in scattered outcrops. Frost wedging is plausible because intermittent freezing temperatures are common in the area between December and March (Fig. 57). Another possibility includes weakening by joints or faults.

Exfoliation is not considered as a form of mass-wasting in the strict sense. However, this type of chemical weathering is significant enough in the thesis area that it should not be ignored. Its imprint can be found on each of the major sandstone formations here. These effects have also been reported in a nearby study (Sturdavant, 1975).

Less stable minerals within the rock, but near exposed surfaces, become hydrated and expand. Because integrity of the rock is lost within this thin, chemically weathered shell, spalling occurs. At this point, frost action or roots may help further pry these layers away. Where fissures are widened mechanically, water and air have better access to the rock enabling increased chemical activity. Thus, two very different modes of weathering can complement each other.

## Glaciation

Effects of late Pleistocene glaciation are well-documented in this region. Detailed studies of pollen assemblages, stratigraphy, and radiocarbon dating have delineated separate events (Hanson and Easterbrook, 1974; Easterbrook, 1969). Deposits of the Vashon glacial maximum, which occurred between 23,000 and 13,000 years B. P. (before present) are the most widespread. Because similar deposits of earlier events occur to the southeast of the study area, it is suspected that they were also laid down in the Gulf Islands. Post-glacial erosion and masking effects of subsequent glaciation could easily account for their relative absence now. A final ice advance circa 11,000 to 10,000 years B. P., the Sumas Stade, barely reached south beyond the Canadian border. Thus, it did not significantly affect the Gulf Islands.

During the height of Vashon glaciation, ice flowed south from highlands to the north and northeast forming the broad Cordilleran ice cap. It was bounded on the east by the Cascade Range and the

Olympic Mountains stood as a barrier to the south. One lobe extended a few miles south of Olympia, Washington (Easterbrook, 1969, Fig. 1).

Reports of Vashon ice in excess of 5,000 feet thick are common (Easterbrook, 1969; Muller and Carson, 1969; Clapp and Cooke, 1917). Although such reports could result from local phenomena, the summit of Mt. Constitution on Orcas Island (2409 ft.) is known to have been overridden by the ice (Easterbrook, 1969). It is probable that the topographically lower Gulf Islands were also covered. Evidence for this inference was found on Mayne Island. A glacially transported granitic boulder was discovered above the 600 foot contour on Mt. Parke, just 2,000 feet southeast of the summit. Similar glacial erratics are common along the highest parts of Samuel Island.

While movement was generally to the south in the relatively unobstructed upper part of the ice sheet, pre-existing elongate topographic features influenced the flow pattern at lower levels (McLellan, 1927; Clapp and Cooke, 1917). It has been pointed out that directional glacial features along the Strait of Georgia have a southeasterly trend, essentially parallel to its axis (Fyles, 1963). Directional features are rare in the study area; however, at one locality north of Samuel Island in the Belle Chain Islets, an abnormally planar bedding surface was noted. Internally, the subjacent bed contains only festoon cross-laminae. Because the top of such a bed is usually much more irregular, it may have been smoothed by moving ice. Equally spaced concentric arcs or V's, concave to the southeast along strike, may be interpreted as chattermarks. Narrow grooves were seen to extend for several feet, also along strike. Chattermarks are not reliable unidirectional indicators (Flint, 1947), yet movement to the northwest would oppose the regional pattern. Therefore, these marks appear to confirm transport to the southeast.

Evidence suggests that during the late Pleistocene, sea level reached between 500 and 700 feet higher. Apparently this effect was neutralized by a subsequent emergence of similar magnitude. The length of time required for such large fluctuations to take place was probably no longer than the 1,500 year interval immediately after Vashon glaciation. These are inferences suggested by stratigraphic and radiocarbon studies (Easterbrook, 1963). The combination of isostatic adjustment in response to glacial loading and readjustment following melting seems inadequate, by itself, to account for variations of this scale. Tectonic activity is thought to have played an active role as well, but the relative influences of both factors remain speculative (Easterbrook, 1963).

Although not studied in detail, topographic modifications by glaciers have occurred in the thesis area and various records of their presence can be seen. One is a general "softening" of the topography where erosional agents have infilled the low areas with glacial debris.

The most obvious indicators of glacial activity are the numerous pebble to boulder erratics found mainly on the beaches. These were probably left not far from their present positions when the ice retreated or were rafted in by floating ice. A few major lithologies are represented. Most are coarsely crystalline plutonic rocks of granitic or gneissoid aspect. Many are fine-grained schists and mafic igneous rocks. Volcanics are far less common.

At the head of Bennett Bay, a thin veneer of stratified, but unconsolidated glacial outwash is exposed in the sea cliff (Fig. 55). Here it lies with angular unconformity on the northeast-dipping strata of the Spray Formation. A comparable relationship can also be observed on both Samuel and Curlew Islands where glacio-fluvial material covers the low areas underlain by nonresistant Northumberland mudstones. In Bennett Bay and on the northwest end of Samuel Island, the tops of these glacial deposits contain shelly debris of recent marine pelecypods. The possibility was considered that these represent kitchen middens of early Indian inhabitants. In some cases this may be true. However, a similar occurrence in a gravel pit nearer the center of Mayne Island argues against this as the most likely interpretation in every case. Sea level is known to have been higher in the not too distant past (Easterbrook, 1969; Hanson and Easterbrook, 1974). Because many of these shells have a freshly broken appearance, it indicates that considerable energy was

Figure 55. Veneer of stratified, glacio-fluvial debris overlies the northeast dipping Spray Formation (below light colored bed) with angular unconformity. At westernmost exposure in Bennett Bay, Mayne Island.

expended on them. This would be expected if the sediment-laden waters of melting ice debouched quickly into a shallow marine environment. The edges of the shell fragments would remain sharp if burial preceded significant reworking.

On Mayne Island, there are pits where glacial gravels are excavated for road surfacing. These yield cross sectional views of fan-type deposits. Sedimentary structures commonly observed here include scour-and-fill, crude coarse-tail and normal grading, interlaminated coarse and fine sand, stratification, and festoon cross-laminae. With the exceptions of gravel pits and scattered road cuts, such accumulations are obscured by vegetation on the interior of the islands.

## Intermittent Streams

Except when unusually wet weather persists through the summer months, there are no perennial streams in the thesis area. This results largely from normally low rainfall and a small surface area available for catchment. Topographic relief and surface impermeability cause runoff to exceed infiltration of available moisture. This effect has become even more noticeable during the last 25 years where logging activity has removed ground cover (Hunt-Sowrey, personal communication, 1975). The infiltration that does occur is confined mainly to joints and faults. Many of these are interconnected and some emerge along the shoreline. Following heavy rainfall, a significant volume of water is lost to the sea through these fissures.

Between Deacon and Heck Hills on Mayne Island, faulting has created a zone which has been eroded across strike. Similar features were observed elsewhere in the area. Otherwise, surface runoff is channeled into the elongate valleys by linear ridges that divide the catchment area.

In zones undisturbed by jointing, moisture is contained within the soil cover and small swamps are formed. An example is found on the northwest end of Samuel Island. Although standing water evaporates during the summer, the tall reed-like swamp grass indicates the local water table is quite near the surface.

Through the wet season, the ground becomes saturated and water is carried seaward by many small streams. The deep valleys and the widened fault zones stand as evidence that intermittant streams are important erosional agents here.

The soil cover is a response to the vigor of weathering and erosional processes and the ability of the rocks to withstand them. It follows that it is thickest on the nonresistant valley floors and almost totally lacking on ridge tops where runoff precludes accumulation.

## Vegetation

The climate here supports a lush flora which renders some inland areas virtually impassable to foot travel. Common deciduous trees are red alder (Alnus rubra Bong.), Oregon white oak (Quercus garryana Dougl.), vine maple (Acer circinatum Pursh), bigleaf maple (Acer macrophyllum Pursh), black willow (Salix scouleriana Barr.), and Pacific madrone (Arbutus menziesii Pursh). Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco), western hemlock (Tsuga heterophylla [Raf.] Sarg.), lodgepole pine (Pinus contorta Doug. ex Loud.), and western red cedar (Thuja plicata Donn) are the main evergreens found locally.

Salal (Gaultheria shallon Pursh) forms the densest ground cover, but other shrubs are well represented. Oregon grape (Berberis nervosa Pursh), salmonberry (Rubus spectabilis Pursh), thimbleberry (Rubus parviflorus Nutt.), blackberry (Rubus sp.), wild rose (Rosa sp.), and nettles (Stachys sp.) occur abundantly. On southwest-facing steep slopes of Samuel Island which receive maximum sunlight, even small pricklypear cactus (Opuntia sp.) plants are successful.

Grasses of many types cover drier areas which are not heavily forested. These include patches where timber and underbrush have been removed by man. Where the soil remains damp, various ferns, mosses, horsetail (Equisetum sp.), and even marsh grasses or reeds flourish.

Of course, this list is by no means exhaustive. It is only meant to indicate some of the vegetation frequently encountered.

## Climate

Relief in the study area is insufficient to modify weather patterns to any great extent. Because of its location nearly halfway between Vancouver and Victoria, the climate is an admixture of that which affects both cities.

Greater Vancouver lies adjacent to the Strait of Georgia near the mouths of the Fraser River distributaries. Burrard Inlet reaches eastward and divides the north side of the city. Immediately north and northeast, the Canadian Coast Range stands high above the Vancouver lowlands.

Two main factors combine to suppress climatic variation in Vancouver. One is the Strait of Georgia. Such a large water mass does not experience rapid temperature change. This moderating effect is felt by adjoining areas. The second factor is the Coast Range which shields Vancouver from cold polar air masses that influence the interior of British Columbia.

During the winter months, prevailing winds blow from the east to southeast. In summer, they are mainly out of the west and northwest. More humid air is carried across the city toward the mountains. Here, orographic lifting causes a large moisture loss. Precipitation in Vancouver is about 60 inches annually. This increases steadily to well over 100 inches in the Coast Range only a short distance away (Atmospheric Environment Service, 1974a).

Victoria, on the southeast end of Vancouver Island, enjoys an even milder climate than does Vancouver. Winter sees prevailing winds blowing from the east to southeast, while in summer they are mainly out of the west and northwest.

The Olympic Mountains remove moisture from clouds coming from the south. Victoria is also afforded similar protection by the mountains to the west on Vancouver Island itself. Consequently, annual precipitation in Victoria averages just over 26 inches (Atmospheric Environment Service, 1974b).

Between Vancouver and Victoria, average monthly precipitation should range between that of these two cities. Comparison of available records on Mayne with long term averages for Vancouver and Victoria (Hunt-Sowrey, 1975; Atmospheric Environment Service, 1974a, b) shows this to be generally true (Fig. 56). The annual average on Mayne is just over 31 inches.

Official records of wind velocity are not kept for Mayne and surrounding islands. However, trees blown down show, in places, a preferred orientation attesting to the destructive capability of occasional gales from the southwest. High winds from the southeast are also not uncommon. All of these naturally exaggerate the effects of wave action.

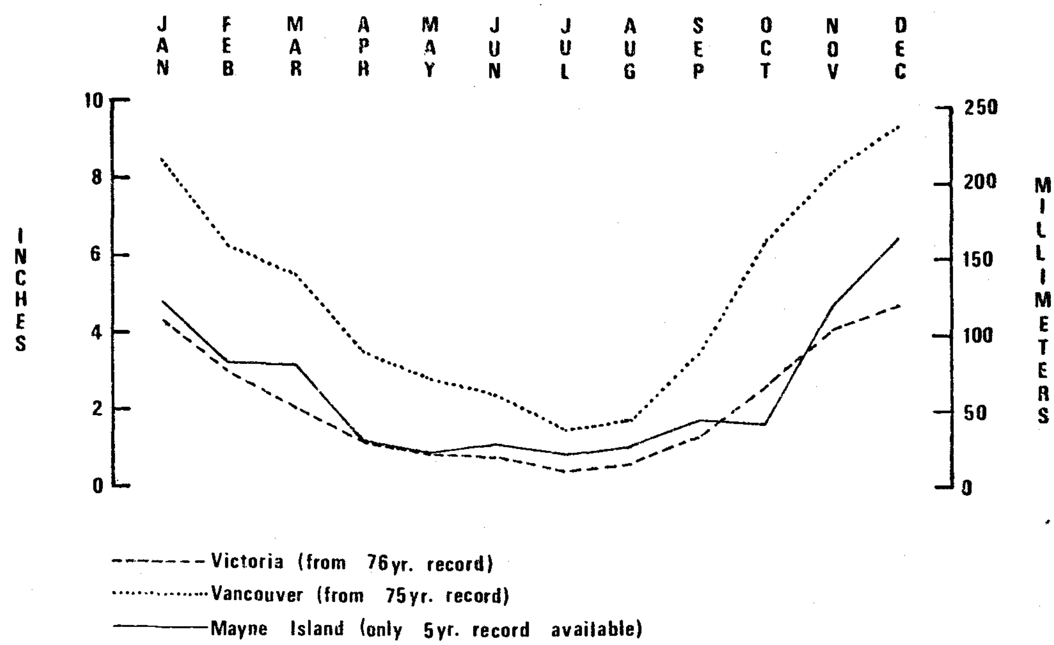



Figure 56. Average Monthly Precipitation in Study Area Compared to Victoria and Vancouver, B. C.

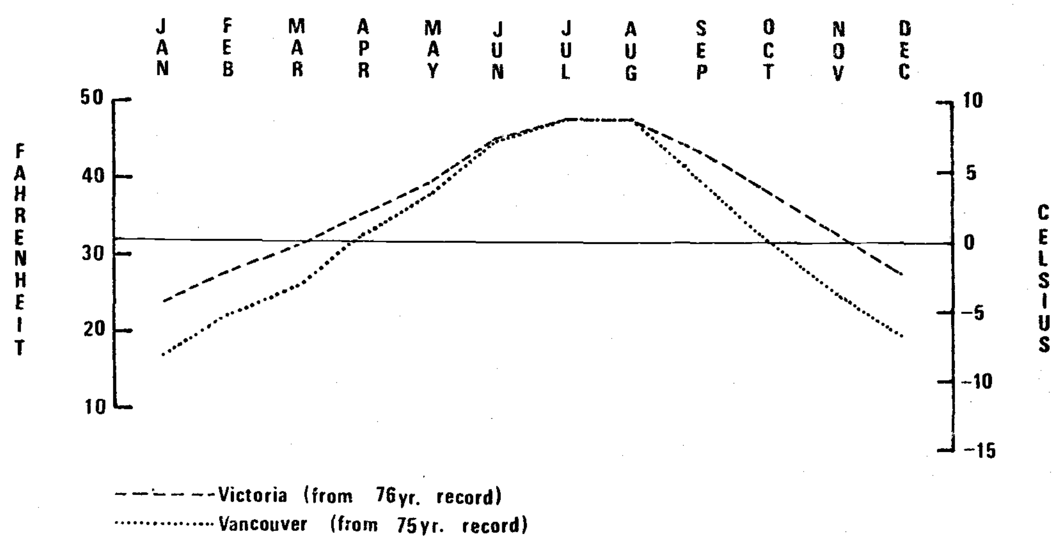



Figure 57. Average Monthly Minimum Temperatures for Victoria and Vancouver, B. C.

Although temperature is not officially recorded on Mayne, monthly averages would probably fall between those of Victoria and Vancouver. Average minimum temperatures (Atmospheric Environment Service, 1974a, b) show that freezing is common in both cities between December and March (Fig. 57). This substantiates the inclusion of frost wedging with other weathering agents in this region.

Overall, the climate in the thesis area is quite pleasant. Nevertheless, it effectively supports a variety of degradational geologic processes. The most important ones were discussed individually in the immediately preceding sections.

# STRUCTURAL GEOLOGY

## Regional Structure

The Georgia Seaway formed through gradual, differential subsidence of a Jurassic tectonic highland. By middle Late Cretaceous (Santonian), it was the locus of Nanaimo Group sedimentation and since has not been emergent (Jeletzky, 1965).

The Nanaimo Group bears a tectonic overprint of folding and faulting. Both were recognized in early studies, but folding received greater attention (Richardson, 1872, 1878), perhaps largely a result of its more obvious topographic expression here. Several northwest-trending folds, noted by Richardson (1872, 1878), were named and described in some detail by later workers (Clapp, 1914a; Clapp and Cooke, 1917). From Vancouver Island on the southwest to the outer Gulf Islands on the northeast, the most important folds are: the Extension Anticline, the Kulleet Syncline, the Trincomali Anticline, and the Gabriola Syncline (Clapp, 1914a). Two smaller folds, the Thetis Anticline and the Channel Syncline, were inferred to separate the Trincomali Anticline and the Kulleet Syncline (Clapp and Cooke, 1917). However, Simmons (1973) suggests the Trincomali and Thetis Anticlines are likely the same structure.

Recognition of faulting as an important structural element came slowly. Away from shorelines, glacial debris and vegetation often combine effectively to mask surface indications. Faults were alluded to only briefly by Richardson (1872, 1878). As coal mining progressed, subsurface data were also utilized in mapping several faults (Clapp, 1914a). Clapp (1914a) noted the overall pattern was dominated by northwesterly trending, strike-oriented, thrust or reverse displacements of up to 6,000 feet (Clapp and Cooke, 1917), but usually less than 500 feet. Presence of numerous transverse faults was also acknowledged; however, some clearly resulted from shear during soft-sediment deformation (Clapp, 1914a).

More recently, faulting has received increasing attention. Buckham (1947) made use of additional subsurface control and newly developed aerial photography for a review of Nanaimo Coal Field structure. According to his reinterpretation, the tectonic style is dominated by a northwest-trending system of thrust faults. These are responses to vertical adjustments of basement fault blocks along previously established fractures caused by northeast to southwest regional compression. The folds and faults are believed to have a common origin, and some of the smaller folds resulted from upward attenuation of faults (Buckham, 1947).

The Nanaimo Group, as shown by more recent studies, lies within the Insular Belt--a regional tectonic province

(Sutherland-Brown, 1966; Monger et al., 1972), in which folding is dominated by faulting (Sutherland-Brown, 1966). Folds, superimposed on the Upper Cretaceous rocks of southern Vancouver Island and vicinity, represent surface manifestations of basement activity along northwest-oriented faults (Sutherland-Brown, 1966). Muller and Jeletzky, who support this view, believe the basement structure to consist of large, imbricate, fault-bounded blocks tilted slightly northeast. Their general northwesterly elongation, defined by primary strike faults, is interrupted by a system of north- to northeast-trending faults (Muller and Jeletzky, 1970).

Timing of the major tectonism that affected rocks of the Late Cretaceous is variously reported. Clapp and Cooke (1917) refer to local uplift as the Mesozoic ended which was not accompanied by significant tilting. The Nanaimo Group folds, they suggest, are related to early Oligocene deformation. According to Miller and Misch (1963), the folding was pre-middle Eocene. If interpretations of basement structure mentioned above are correct, then some strike faulting should have been concurrent with folding. However, later faulting is also clearly indicated by structural offsets resulting from one or more events of uncertain age.

A plate tectonic synthesis of the northeast Pacific continental margin is beyond the scope of this study. In broadest terms, present plate geometry here has resulted from convergence of the Pacific (oceanic) and North American plates. The remnant of a third, interjacent oceanic slab, now only partially subducted beneath the continent, shows evidence of recent activity (Crosson, 1972). It is called the San Juan plate. Along the Queen Charlotte-San Andreas fault system, active right-lateral strike-slip displacement is reported between the North American plate and the Pacific-San Juan plate couplet (Atwater, 1970; Monger et al., 1972; Crosson, 1972; Mayers and Bennett, 1973). This has resulted in regional compressive stress acting north-south (Crosson, 1972) or northeast-southwest (Mayers and Bennett, 1973). A similar stress orientation appears to have prevailed during Tertiary folding that involved the Nanaimo Group (Clapp and Cooke, 1917), but its origin is still moot.

Field evidence for nearby ancestral plate consumption has recently emerged from Muller's continuing regional studies. The San Juan and Leech River Faults (Fig. 58) separate two types of lithosphere on southern Vancouver Island. Rocks north of the San Juan Fault represent Cretaceous and older continental crust. Those south of the Leech River Fault are younger, Tertiary oceanic basalts. The rocks between these two zones are interpreted as a Late Jurassic to Early Cretaceous trench-slope assemblage more recently metamorphosed. Correlation is suggested with a melange unit of Franciscan aspect, approximately 40 miles northwest, that was possibly

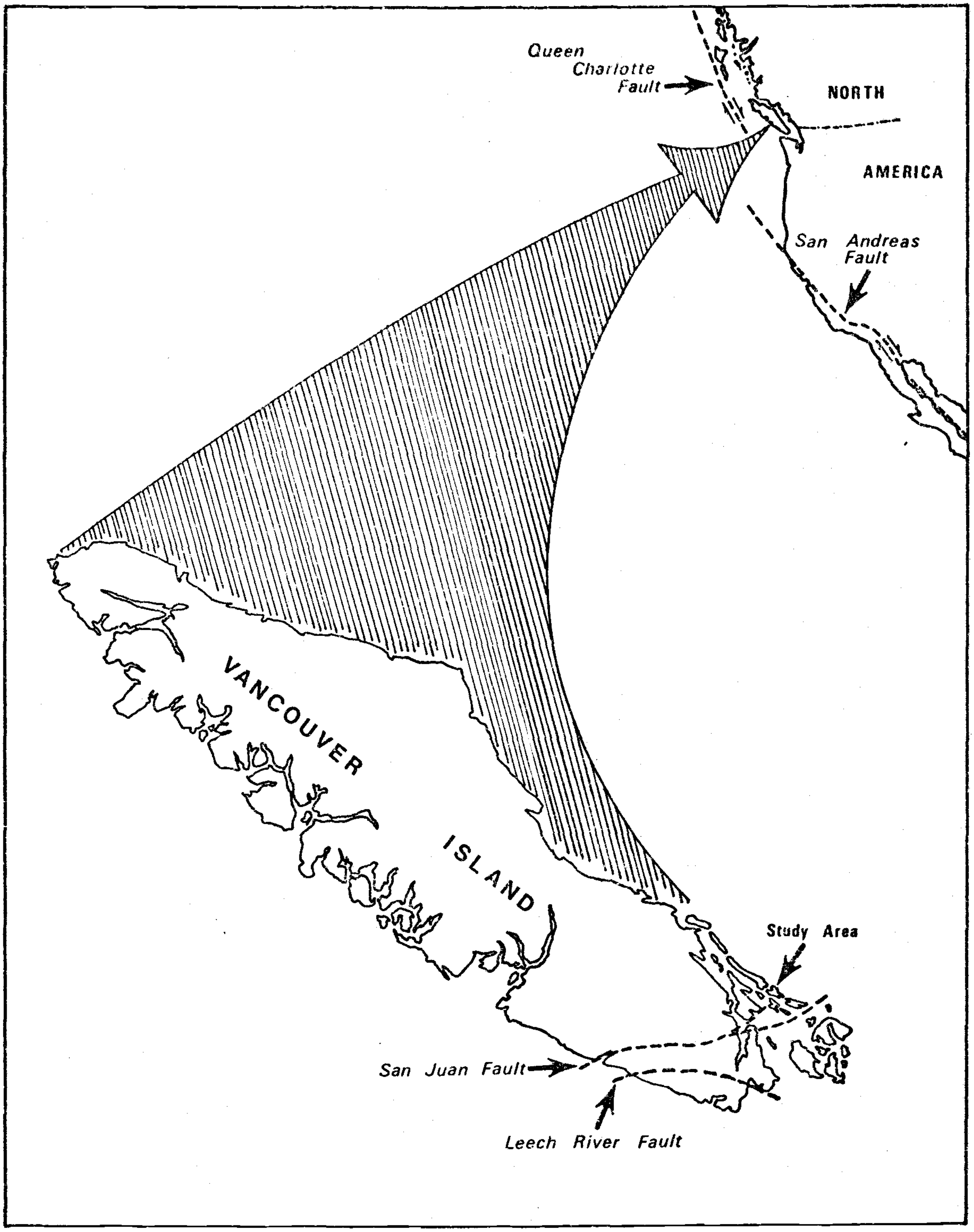



Figure 58. Approximate Present Position of San Juan and Leech River Faults on Vancouver Island, also the Regional Queen Charlotte - San Andreas Fault System (modified from Wilson, 1965; Sutherland-Brown, 1966; Muller, 1975, 1976)

deformed during Late Cretaceous to Eocene subduction (Muller, 1975, 1976).

## Local Structure

### Folds

Within Trincomali and Navy Channels (Fig. 1) lies the axial trace of the breached Trincomali Anticline (cf. Fig. 59 or Plate 1). The entire thesis area is located on its northeast flank as shown by the homoclinally dipping strata. This fold is locally asymmetrical (Simmons, 1973), but on Mayne and Pender Islands, the northeast and southwest limbs, respectively, show nearly equal declivity (Fig. 60). Across the study area, dip progressively decreases toward the Georgia Strait.

Clapp (1914b) referred to a synclinal structure near St. John Point on the southeast tip of Mayne Island. This is possibly the same one mentioned by Muller and Jeletzky (1970). Here, local attitude variations from the overall pattern, noted above, are attributed to soft-sediment deformation and slump activity. However, obvious inflections or a dip reversal that would indicate the presence of a syncline could not be located by this writer.

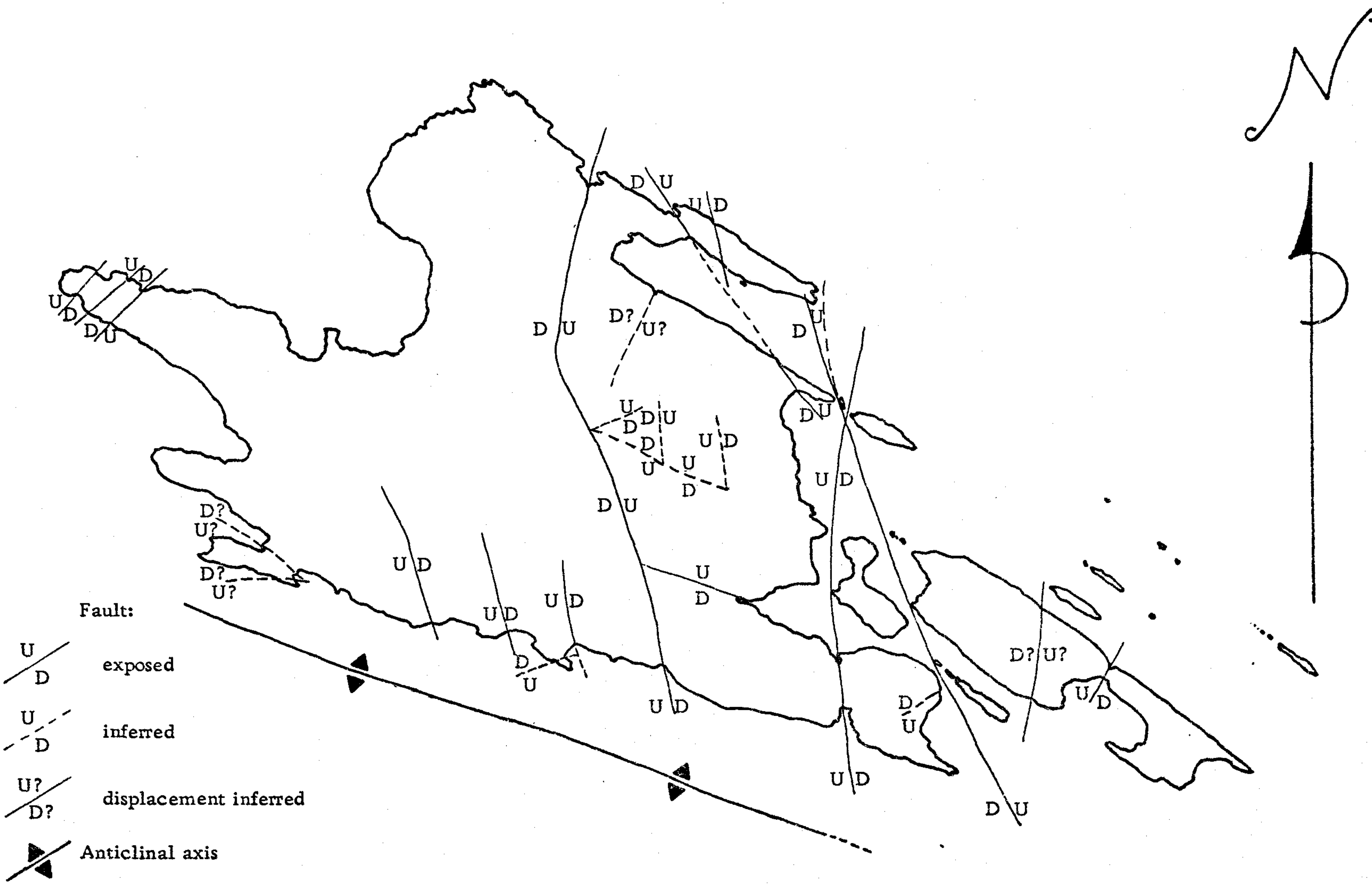



Figure 59. Structural features of thesis area (modified from Plate 1).

Figure 60. Looking northwest through Navy Channel and along the axis of the breached Trincomali Anticline--the major fold that affected the thesis area. On the left, cuestas of Pender Island dip southwesterly (left). Those on Mayne to the right dip oppositely.

## Faults and Joints--General

In the area covered by this study, faulting is the dominant tectonic feature (cf. Fig. 59 or Plate 1). Because the surface expression is commonly very subtle, nine diagnostic properties were used, in combination wherever possible, to facilitate recognition. These include: 1) observable offset of normally continuous strata or topography, 2) slickensides, 3) valleys or zones of fracture or shear cross-cutting resistant units, 4) drag features, 5) abrupt change in attitude, 6) linear fault scarps, 7) stratigraphic repetition or omission, 8) truncation of strata, and 9) lineations on aerial photos.

In the field, poorly developed bedding commonly makes it difficult to ascertain fault displacement. Joint surfaces are often locally indistinguishable from a more continuous fault pattern. There is also the problem of weeding out spurious photo lineations from those produced by faulting. During this study, predominant joint orientations were recorded at many localities. This practice was helpful in identifying and determining the continuity of faults. Thus, in addition to the nine properties listed above, aligned systems of subparallel joint planes were considered as supporting evidence of fault activity. It was also hoped that the joint pattern might show some relationship to the conjectural basement faulting. Graphical summary of these data on a contour diagram (Fig. 61) reveals that

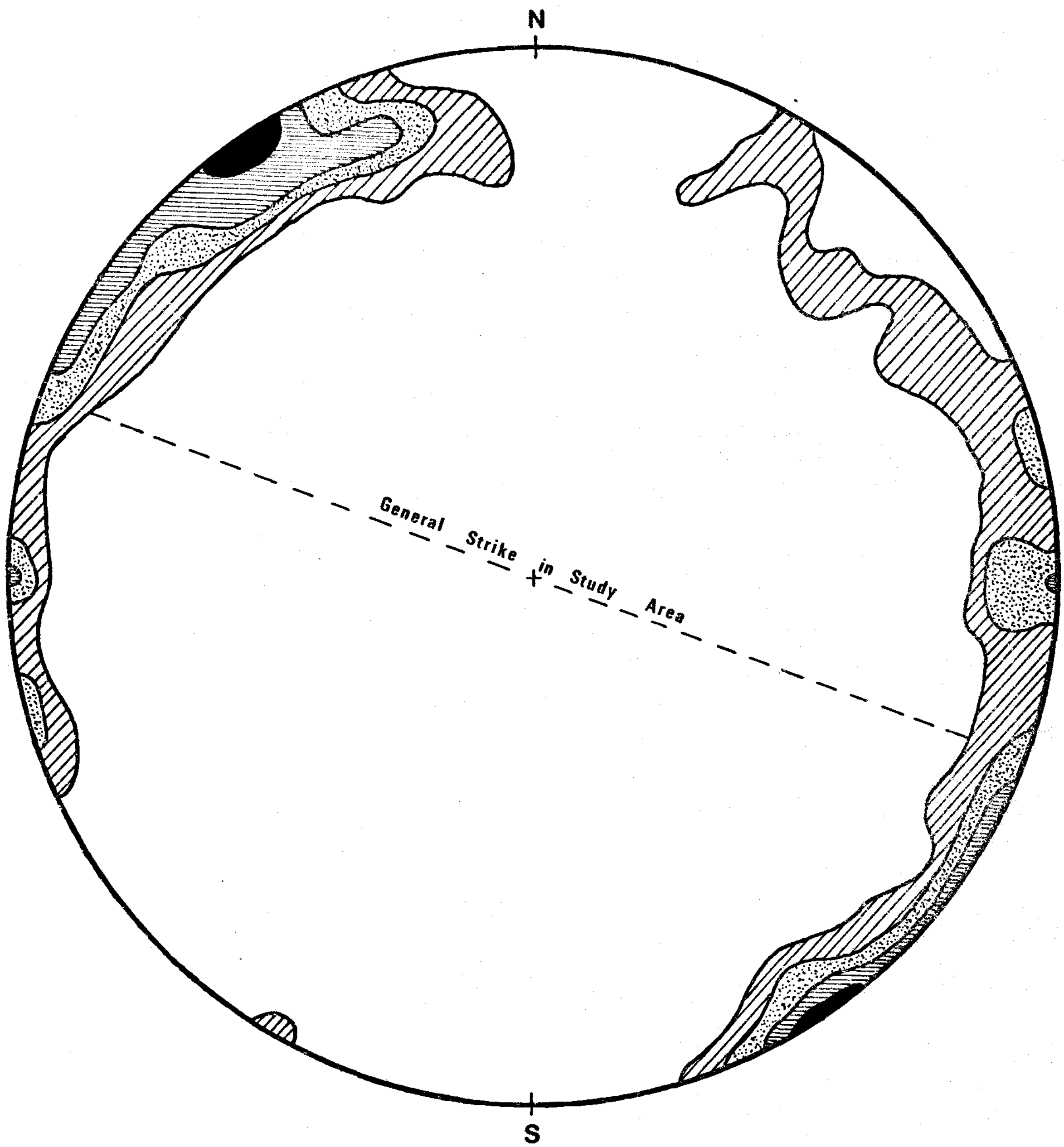



Figure 61. Contour Diagram Showing Poles to Dominant Fault and Joint Planes in Study Area. Reflects Overall Local Pattern Transverse to Strike (based on 956 readings). Contours 2-3-4-5% per 1% area, maximum 6%.

within the study area, transverse joints and faults are most prominent. Thus, no obvious connection with longitudinal basement faults is indicated. It was separately concluded that regarding all faulting in general, senses of displacement do not fit an overall pattern discernible on a local scale.

## Longitudinal Faults

Strike faults are the least common of those mapped. Because they are not associated with topographic offset, the magnitude and sense of their displacement is more subjective. This type is characterized by the examples discussed below.

Along the south shore of Mayne Island, especially in the stretch between Conconi Reef and Dinner Point (Plate 1) strike faults are particularly well-exposed. They only appear in the resistant sandstone and conglomerate units where broad surfaces, covered with dip-oriented slickensides cannot escape attention (Fig. 62). Such surfaces are also conspicuous on the south-facing slope of Mt. Parke near the summit and elsewhere. The discontinuous bedding in these rocks is of little to no help in ascertaining relative offset. It is easily demonstrated that during crustal warping, a shear couple develops normal to a fold axis. Uppermost beds on the anticlinal flank will tend to translate toward the axial region, while those beneath will move away from it. Therefore, the faults observed

Figure 62. Dip-oriented slickensides on the undersurface of a conglomerate bed within the DeCourcy Formation. They were produced by bed-on-bed sliding during flexure of the Trincomali Anticline. Located adjacent to Navy Channel on Mayne Island 0.4 mi. west of the Conconi Reef navigation light. At center there is a light-colored fieldbook for scale.

probably formed in response to folding of the Trincomali Anticline. If so, this evidence indicates dip-slip, reverse movement (i. e., north block up).

Eastward along strike from Village Bay, thickness of the Northumberland Formation remains fairly constant to within one mile of Horton Bay. There it is nearly doubled abruptly. A small, intermittent stream emptying into the head of Horton Bay has carved a deep, elongate channel parallel to strike. An interpretation, based on these observations, is that additional Northumberland reached the surface on the upthrown north block of a strike fault. The stream erodes more rapidly along the zone of weakness created by the faulting. The sense of displacement here is consistent with those mentioned above. Although not necessarily, this fault could also be related to the folding.

Cedar District rocks are exposed between Dinner Bay and the small cove on the east side of the peninsula. Judging from the outcrop pattern mapped by Hudson (1975) on Pender, the same rocks are generally thicker there. Despite some evidence for lateral thinning on Mayne, a strike fault here, with the south block elevated, may also have omitted part of the Cedar District Formation. Presence of a wide crush zone and possible drag features support this inference. Orientation of slickensides also indicates a strike-slip component.

Other longitudinal faults are less prominent and the minor deviations from strike, where they occur, are all less than 30°.

Transverse Faults

By observing topographic or structural discontinuities and peculiar shoreline indentations, numerous transverse faults become apparent. Stratigraphic throw on the largest one, which truncates the east end of Mt. Parke (the west block) is on the order of 700 feet. The raised east block exposes Geoffrey sandstones and conglomerates several hundred feet to the north. Although not clearly demonstrable, aerial photo lineations, joint patterns, and topography suggest that this fault emerges farther north at David Cove. Its southerly extension created a narrow valley through the resistant DeCourcy Formation bordering Navy Channel. Here the west side is raised. Such displacement is anomalous compared to the central section just described. A possible explanation might be scissor-type motion; however, lack of exposure along the fault precludes a more definite interpretation. Similarly trending faults, the positions of which are likewise defined by narrow valleys, divide this once-continuous DeCourcy ridge into several fault blocks. These are illustrated by Deacon and Heck Hills and others to the east that are unnamed. The west blocks are uplifted in each case, but relative displacements are estimated to be quite small.

The peninsula north of Campbell Bay is crossed by two faults which are separated by an upthrown, wedge-shaped block. Where each one would ordinarily be completely obscured by vegetation, a small col has developed by differential erosion along the zone of weakness. Of these two faults, the western one has the greater offset and is also responsible for the northernmost shoreline indentation in Campbell Bay. A fault of similar orientation and displacement was noted in the northwest corner of Bennett Bay. Aerial photo lineation and joint patterns suggest the two are continuous.

A pair of faults is postulated to lie within the channels on the east end of Mayne Island. Both pass between Campbell Point and Georgeson Island. One of these is continuous with the fault underlying the valley at the south end of Horton Bay. Its elevated west block was mentioned above. A slight (less than 5$^{\circ}$), but abrupt change in strike was observed between Mayne and Georgeson. Such a change in attitude from Mayne to Curlew Island was also noted for the prominent Northumberland sandstone beds at Aitken Point. The contact between the Geoffrey and Northumberland Formations on Curlew is displaced noticeably south relative to its position on Mayne. All these previously enigmatic field observations are unified into a consistent pattern by this interpretation.

The second of these two faults separates Curlew and Samuel Islands and also follows the channel between Mayne and Lizard

Islands. Similar lines of evidence substantiate its existence. On Lizard and Samuel, strikes are generally consistent, but are at variance by at least 10° with those recorded close by on Mayne or Curlew. A corresponding disparity is also apparent for dip measurements. A smooth line connecting the Geoffrey-Northumberland contact on Mayne and Curlew is deflected northward when carried onto Samuel Island. These considerations are ascribed to a fault with an upthrown east block and possibly a rotational component of displacement as suggested by dip readings. It is also worthy of mention that joint plane orientations along both of these conjectural faults corroborate the interpretations advocated here.

The above examples are meant to show some of the features that typify the style of transverse faulting in the study area. Several more were mapped which exhibit similar characteristics. Trends range from N. 26° W. to N. 13° E.

# ECONOMIC GEOLOGY

## Coal

The Nanaimo and Comox coal fields yielded approximately 72 million long tons (Muller and Atchison, 1971) during a 114 year period. Closure of the Tsable River Mine near Comox in 1966 terminated production which had become economically unfeasible. There remains potential for renewal of activity as demanded by changing energy requirements and increased market value. The Extension-Protection Formation was the major coal-producing unit in the Nanaimo Basin, but very little of this formation is exposed in the study area (Fig. 4 and Plate 1). Clapp (1914b) suggests that coal beds may lie underwater along the axis of the Trincomali Anticline in Navy Channel. These strata, even if coal-bearing, dip northeasterly well beneath the surface along the south shore of Mayne Island and economical recovery is unlikely.

## Gravel and Brick

During the field season, gravel production was increased for new road-building and reconditioning activity. Ordinarily, very little is used. The main source is glacio-fluvial debris that is concentrated adjacent to areas of higher relief on Mayne Island.

Circa 1912, the Franco Canadian Company built a brick plant, ostensibly to utilize Spray Formation mudstones and sandstones, on the east side of Mayne Island. The Mayne Inn, also constructed then, was originally intended to house company employees. The interruption of World War I brought the operation to an end before it became commercial and it has not since been pursued (Evans, 1971).

## Water

The proximity of Mayne Island to Vancouver and Victoria, B. C. and the ease of access have encouraged accelerated home-building and tourism. The resulting drain on local water resources is graphically demonstrated by the necessary inconvenience of summer rationing in places. Fracture porosity is the dominant avenue for collection of groundwater, yet its escape is not sufficiently impeded. Construction of cisterns to capture and store run-off waters for periods of shortage has not yet become popular. As the catchment area is too small to support unlimited use by the expanding population, more stringent conservation measures, hopefully self-imposed, will be necessary.

At the risk of casting aspersions on a popular story, a Mt. Baker source for the groundwater supply in the study area does not appear to be consistent with the present geologic investigation. Problems which confront such a hypothesis are the depth of the cleft which contains the Strait of Georgia and the northeast dip of the strata here.

## Petroleum

The fine-grained marine formations exposed in the area superficially appear to have potential as hydrocarbon source rocks. The abundant fossils, even though not well-preserved, show there to have been considerable organic matter present. Similarly, thicknesses estimated for the Nanaimo Group indicate that burial was sufficient for generation to have occurred. The main problem is that of an adequate reservoir. In hand sample, the coarser deltaic sandstones interbedded with the marine strata seem to satisfy this requirement. However, microscopic examination shows they are replete with diagenetic matrix and calcareous cement in many cases. Also, depositional porosity was reduced significantly by compaction. Therefore, despite favorable structural conditions flanking the Trincomali Anticline, with possibilities of stratigraphic traps where sandstones pinch out to mudstones up-dip, the picture is not encouraging. Comparable findings are reported in nearby studies (Hudson, 1975; Sturdavant, 1975; Hanson, 1976).

## SELECTED REFERENCES

Atmospheric Environment Service, 1974a, Annual Meteorological Summary, Vancouver International Airport--Vancouver City, British Columbia: Distrib. by Regional Climate Data Centre, Victoria, B. C., 37 p.

_____________, 1974b, Annual Meteorological Summary of Victoria and Area, British Columbia: Distrib. by Regional Climate Data Centre, Victoria, B. C., 144 p.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. America Bull., v. 81, p. 3513-3536.

Bailey, E. H. and Stevens, R. E., 1960, Selective staining of potassium feldspar and plagioclase on rock slabs and thin sections: Amer. Mineralogist, v. 45, p. 1020-1025.

Bell, W. A., 1957, Flora of the Upper Cretaceous Nanaimo Group of Vancouver Island, British Columbia: Geol. Survey Can., Memoir 293, 84 p.

Blatt, H. et al., 1972, Origin of Sedimentary Rocks: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 634 p.

Bouma, A. H., 1962, Sedimentology of Some Flysch Deposits: Amsterdam, Elsevier Pub. Co., 168 p.

Briggs, G. and Cline, L. M., 1967, Paleocurrents and source areas of late Paleozoic sediments of the Ouachita Mountains, southeastern Oklahoma: Jour. Sed. Pet., v. 37, p. 985-1000.

Buckham, A. F., 1947, The Nanaimo Coal Field: Canadian Inst. of Mining and Metallurgy, Transactions, v. 50, p. 460-472.

Carroll, D., 1970, Clay minerals: A guide to their X-ray identification: Geol. Soc. America Sp. Paper 126, 80 p.

Carter, J., in preparation, The stratigraphy, structure, and sedimentology of the Cretaceous Nanaimo Group, Galiano Island, British Columbia, A masters thesis, Oreg. State Univ., Corvallis, Oreg.

Carter, J., 1976, Oregon State University graduate student, Pers. commun.

Chamberlain, K. C., 1975, Assistant Professor of Geology, Ohio University, Athens, Ohio, Written communication with W. B. Hanson and C. D. Sturdavant, 3 Mar. 1975.

Clapp, C. H., 1912, Geology of Nanaimo sheet, Nanaimo Coal-Field, Vancouver Island, British Columbia: Geol. Survey Can. Summary Rprt., 1911, p. 91-105.

____________, 1914a, Geology of the Nanaimo map-area: Geol. Survey Can. Memoir 51, 135 p.

____________, 1914b, Coal formation on Galiano, Mayne, and Saturna Islands: B. C. Minister of Mines, Ann. Rprt., 1913, p. K292-299.

____________ and Cooke, H. C., 1917, Sooke and Duncan map-areas, Vancouver Island: Geol. Survey Can. Memoir 96, 445 p.

Clifton, H. E., 1973, Pebble segregation and bed lenticularity in wave-worked versus alluvial gravel: Sedimentology, v. 20, p. 173-187.

Coleman, J. M. and Gagliano, S. M., 1964, Cyclic sedimentation in the Mississippi River deltaic plain: Gulf Coast Assoc. Geol. Soc. Trans., v. 14, p. 67-80.

____________ and Wright, L. D., 1975, Modern river deltas: variability of processes and sand bodies: in Deltas, M. L. Broussard, ed., Houston Geol. Soc., p. 99-149.

Compton, R. R., 1962, Manual of Field Geology: New York, John Wiley & Sons, Inc., 378 p.

Crickmay, C. H. and Pocock, S. A. J., 1963, Cretaceous of Vancouver, British Columbia, Canada: Am. Assoc. Petrol. Geol. Bull., v. 47, p. 1928-1942.

Crosson, R. S., 1972, Small earthquakes, structure, and tectonics of the Puget Sound region: Seismolog. Soc. Amer. Bull., v. 62, p. 1133-1171.

Curray, J. R., 1956, The analysis of two-dimensional data: Jour. Geol., v. 64, p. 117-131.

Dawson, G. M., 1890, Notes on the Cretaceous of the British Columbia Region--The Nanaimo Group: Am. Jour. Sci., v. 39, p. 180-183.

Deevey, E. S. Jr., 1952, Radiocarbon dating: Sci. Amer., v. 186, no. 2, p. 24-28.

Dott, R. H. Jr., 1963, Dynamics of subaqueous gravity depositional processes: Am. Assoc. Petrol. Geol. Bull., v. 47, no. 1, p. 104-128.

____________, 1966, Eocene deltaic sedimentation at Coos Bay, Oregon: Jour. Geol., v. 74, no. 4, p. 373-420.

____________ and Howard, J. K., 1962, Convolute lamination in non-graded sequences: Jour. Geol., v. 70, p. 114-121.

Easterbrook, D. J., 1963, Late Pleistocene glacial events and relative sea level changes in the Northern Puget Sound Lowland, Washington: Geol. Soc. America Bull., v. 74, p. 1465-1484.

____________, 1969, Pleistocene chronology of the Puget Lowland and San Juan Islands, Washington: Geol. Soc. America Bull., v. 80, p. 2273-2286.

Eis, S. and Oswald, E. T., 1975, Highland landscape: Canadian Forestry Service Dept. of Environment Report BC-X-119, 36 p.

Evans, G., 1971, The Mayne Inn: in Mayne Island Fall Fair pamphlet, Jesse Brown, ed., local public., publisher unlisted.

Flint, R. F., 1947, Glacial Geology and the Pleistocene Epoch: New York, John Wiley & Sons, Inc., 589 p.

Folk, R. L., 1951, Stages of textural maturity in sedimentary rocks: Jour. Sed. Pet., v. 21, no. 3, p. 127-130.

____________, 1962, Spectral subdivision of limestone types: in Classification of Carbonate Rocks, W. E. Ham, ed., Am. Assoc. Petrol. Geol. Memoir 1, p. 62-84.

Foster, M., 1966, Mayne Island--historical notes: in A Gulf Islands Patchwork: Peninsula Printing Co., Ltd., Sidney, B. C., p. 45.

Freeman, B. J. S., 1966, Saturna Island place names: in A Gulf Islands Patchwork: Peninsula Printing Co., Ltd., Sidney, B. C., p. 158.

Fyles, J. G., 1963, Surficial geology of Horn Lake and Parksville map-areas, Vancouver Island, British Columbia: Geol. Survey Can., Memoir 318, 142 p.

Galloway, W. E., 1975, Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems: in Deltas: M. L. Broussard, ed., Houston Geol. Soc., p. 87-98.

Geological Survey of Canada, 1962, Geologic map of British Columbia, map 932A, Dept. of Mines and Tech. Surveys, Ottawa, Can.

Goddard, E. N. et al., 1970, Rock-Color Chart: G. S. A., Boulder, Colo., n. p.

Gould, H. R., 1970, The Mississippi delta complex: in Deltaic Sedimentation Modern and Ancient: J. P. Morgan, ed., Soc. Econom. Paleontol. and Mineralogists, Spec. Pub. no. 15, p. 3-30.

Graham, S. A. et al., 1975, Himalayan-Bengal model for flysch dispersal in the Appalachian-Ouachita system: Geol. Soc. America Bull., v. 86, p. 273-286.

Hanson, B. S. and Easterbrook, D. J., 1974, Stratigraphy and palynology of Late Quaternary sediments in the Puget Lowland, Washington: Geol. Soc. America Bull., v. 85, p. 587-602.

Hanson, W. B., 1976, Stratigraphy and sedimentology of the Cretaceous Nanaimo Group, Saltspring Island, British Columbia: Unpub. doctoral thesis, Oreg. State Univ., Corvallis, Oreg.

____________, 1976, Geologist, Amoco Production Co., Denver, Colo., Pers. commun.

Harms, J. C. and Fahnestock, R. K., 1965, Stratification, bed forms, and flow phenomena (with an example from the Rio Grande): in Primary Sedimentary Structures and Their Hydrodynamic Interpretation: G. V. Middleton, ed., Soc. Econom. Paleontol. and Mineralogists, Spec. Pub., no. 12, p. 84-115.

Hass, W. H. et al., 1962, Treatise on Invertebrate Paleontology, Part W., Miscellanea: Geol. Soc. America and Univ. of Kansas Press, New York, 259 p.

Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record: in Recognition of Ancient Sedimentary Environments: J. K. Rigby and W. K. Hamblin, eds., Soc. Econom. Paleontol. and Mineralogists, Spec. Pub. no. 16, p. 215-225.

Hudson, J. P., 1975, Stratigraphy and Paleoenvironments of the Cretaceous Rocks, North and South Pender Islands, British Columbia: Unpub. masters thesis, Oreg. State Univ., Corvallis, Oreg.

Hunt-Sowrey, W. W., 1975, Mayne Isl. Precip. Sta. Observer for Regional Climate Data Centre, Atmospheric Environment Service, Victoria, B. C., Pers. commun.

Jeletzky, J. A., 1965, Age and tectonic nature of the Strait of Georgia Seaway (abstr.): Geol. Survey Can., Paper 65-2, p. 72.

Kummel, B. and Raup, D., eds., 1965, Handbook of Paleontological Techniques: San Francisco, W. H. Freeman and Co., 852 p.

Mallory, V. S., 1976, Curator and Chairman, Geol. and Paleontol. Div., Burke Memorial Wash. State Museum, Univ. of Wash., Seattle, Wa. Written communications, 8 Mar. 1976 and 24 Mar. 1976.

Mayers, I. R. and Bennett, L. C. Jr., 1973, Geology of the Strait of Juan de Fuca: Marine Geology, v. 15, p. 89-117.

McBride, E. F. et al., 1975, Deltaic and associated deposits of Difunta Group (Late Cretaceous to Paleocene), Parras and La Popa Basins, northeastern Mexico: in Deltas: M. L. Broussard, ed., Houston Geol. Soc., p. 485-522.

McGugan, A., 1964, Upper Cretaceous zone Foraminifera, Vancouver Island, British Columbia, Canada: Jour. Paleontol., v. 38, no. 5, p. 933-951.

____________, 1976, Professor of Geology, Univ. of Calgary, Calgary, Alberta. Written communications, 13 Feb. 1976 and 1 Mar. 1976.

McKee, E. D., 1965, Experiments on ripple lamination: in Primary Sedimentary Structures and Their Hydrodynamic Interpretation: G. V. Middleton, ed., Soc. Econom. Paleontol. and Mineralogists, Spec. Pub., no. 12, p. 66-83.

____________ and Weir, G. W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, no. 4, p. 381-389.

McLellan, R. D., 1927, Geology of the San Juan Islands: Univ. of Washington, Public. in Geology, v. 2, 185 p.

Middleton, G. V. and Hampton, M. A., 1973, Sediment gravity flows: Mechanics of flow and deposition: in Turbidites and Deep-Water Sedimentation: Soc. Econom. Paleontol. and Mineralogists, Pacif. Sec., Short Course, Anaheim, Part I, p. 1-38.

Miller, G. M. and Misch, P., 1963, Early Eocene angular unconformity at western front of northern Cascades, Whatcom County, Washington: Am. Assoc. Petrol. Geol. Bull., v. 47, p. 163-174.

Milner, H. B., 1962, Sedimentary Petrography: London, George Allen & Unwin Ltd., v. 2, 715 p.

Monger, J. W. H. et al., 1972, Evolution of the Canadian Cordillera: A plate tectonic model: Am. Jour. Sci., v. 272, p. 577-602.

Moore, R. C. et al., 1952, Invertebrate Fossils: New York, McGraw-Hill Book Co., Inc., 766 p.

Morgan, J. P., 1970, Deltas--A resumé: Jour. of Geol. Educ., v. 18, no. 3, p. 107-117.

Muller, J. E., 1974, Victoria map-area, (92B, C), Pacific Rim National Park, Vancouver Island, B. C.: Geol. Survey Can., Paper 74-1, Part A, p. 21-23.

____________, 1975, Victoria map-area, British Columbia (92B): Geol. Survey Can., Paper 75-1, Part A, p. 21-26.

____________, 1976, Cape Flattery map-area, British Columbia (92C): Geol. Survey Can., Paper 76-1A, p. 107-112.

____________ and Atchison, M., 1971, Geology history and potential of Vancouver Island coal deposits: Geol. Survey Can., Paper 70-53, 50 p.

____________ and Carson, D. J. T., 1969, Geology and mineral deposits of Alberni map-area, British Columbia (92F): Geol. Survey Can., Paper 68-50, 52 p.

____________ and Jeletzky, J. A., 1967, Stratigraphy and biochronology of the Nanaimo Group, Vancouver Island and Gulf Islands, British, Columbia: Geol. Survey Can., Paper 67-1, Part B, p. 39-47.

____________ and Jeletzky, J. A., 1970, Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia: Geol. Survey Can., Paper 69-25, 77 p.

____________ et al., 1974, Geology and mineral deposits of Alert Bay--Cape Scott map-area, Vancouver Islands, British Columbia: Geol. Survey Can., Paper 74-8, 77 p.

Nelson, C. H. and Kulm, L. D., 1973, Submarine fans and deep-sea channels: in Turbidites and Deep-Water Sedimentation: Soc. Econom. Paleontol. and Mineralogists, Pacif. Sec., Short Course, Anaheim, Part II, p. 39-78.

Packard, J. A., 1972, Paleoenvironments of the Cretaceous Rocks, Gabriola Island, British Columbia: Unpub. masters thesis, Oreg. State Univ., Corvallis, Oreg.

Pettijohn, F. J., 1957, Sedimentary Rocks: New York, Harper & Row, Inc., 718 p.

Powers, M. C., 1953, A new roundness scale for sedimentary particles: Jour. Sed. Pet., v. 23, p. 117-119.

Richardson, J., 1872, Coal fields of the east coast of Vancouver Island: Geolog. Survey of Can. Rprt. of Progress 1871-1872, Part 3, p. 73-100.

____________, 1878, Coal fields of Nanaimo, Comox, Cowichan, Burrard Inlet and Sooke, British Columbia: Geol. Survey Can. Rprt. of Progress 1876-1877, Part 7, p. 160-192.

Rinne, R. W., 1973, Geology of the Duke Point-Kulleet Bay area, Vancouver Island, B. C.: Unpub. masters thesis, Oreg. State Univ., Corvallis, Oreg.

Royse, C. F. Jr., 1970, An Introduction to Sediment Analysis: Tempe, Arizona, Royse, 180 p.

Selley, R. C., 1970, Ancient Sedimentary Environments: Ithaca, New York, Cornell University Press, 237 p.

Simmons, M. L., 1973, Stratigraphy and paleoenvironments of Thetis, Kuper, and adjacent islands, British Columbia: Unpub. masters thesis, Oreg. State Univ., Corvallis, Oreg.

Sliter, W. V., 1973, Upper Cretaceous foraminifers from the Vancouver Island area, British Columbia, Canada: Jour. Foraminiferal Research, v. 3, no. 4, p. 167-186.

Sturdavant, C. D., 1975, Sedimentary Environments and Structure of the Cretaceous Rocks of Saturna and Tumbo Islands, British Columbia: Unpub. masters thesis, Oreg. State Univ., Corvallis, Oreg.

Sullwold, H. H., 1961, Turbidites in oil exploration: in Geometry of Sandstone Bodies: J. A. Peterson and J. C. Osmond, eds., Am. Assoc. Petrol. Geol. Symposium, Tulsa, p. 63-81.

Sutherland-Brown, A., 1966, Tectonic history of the Insular Belt of British Columbia: in Canadian Institute of Mining and Metallurgy, Sp. v. 8, p. 83-100.

Thornbury, W. D., 1961, Principles of Geomorphology: New York, John Wiley & Sons, Inc., 618 p.

Usher, J. L., 1949, Stratigraphy and Paleontology of the Upper Cretaceous Rocks of Vancouver Island, British Columbia: Unpub. Ph. D. thesis, McGill Univ., Montreal, Quebec, Canada.

Usher, J. L., 1952, Ammonite faunas of the Upper Cretaceous rocks of Vancouver Island, British Columbia: Geol. Survey Can., Bull. 21, 182 p.

Visher, G. S., 1965, Use of vertical profile in environmental reconstruction: Am. Assoc. Petrol. Geol. Bull., v. 49, no. 1, p. 41-61.

Walker, R. G., 1975, Conglomerate: Sedimentary structures and facies models: in Harms, J. C. et al., Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences: Soc. Econom. Paleontol. and Mineralogists Short Course, no. 2, Dallas, ch. 7, p. 133-161.

__________ and Mutti, E., 1973, Turbidite facies and facies associations: in Turbidites and Deep-Water Sedimentation: Soc. Econom. Paleontol. and Mineralogists, Pacif. Sec., Short Course, Anaheim, Part IV, p. 119-157.

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Jour. Geol., v. 30, p. 377-392.

Wilkinson, W. D. and Oles, K. F., 1968, Stratigraphy and paleoenvironments of Cretaceous rocks, Mitchell Quadrangle, Oreg.: Am. Assoc. Petrol. Geol. Bull. 52, p. 129-161.

Williams, H. et al., 1954, Petrography: San Francisco, W. H. Freeman and Co., 406 p.

Wilson, J. T., 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, no. 4995, p. 343-347.

# APPENDICES

# APPENDIX A

## MEASURED SECTION X-Y, NORTHUMBERLAND FORMATION

Section X-Y was measured with a five-foot Jacob's staff and a mounted Abney level. Dip corrections were obtained from a Brunton compass. For standardization, a sand gauge and the Geological Society of America Rock-Color Chart (Goddard et al., 1970) were used. A 10X hand lens and (0.1N) hydrochloric acid facilitated descriptions.

Section X-Y includes only the westernmost exposure of the Northumberland Formation in Village Bay on Mayne Island. The reasons for measuring this section were: 1) to obtain an accurate thickness where contacts are least obscured and 2) to describe a "representative interval" typical of the less resistant units exposed in the thesis area (cf. interval from 257.5 to 262.5 feet above base of section X-Y).

Terminal point (Y, Plate 1) is located on the beach at the center of the S.E. 1/4 of the S.W. 1/4 of the N.W. 1/4 of the N.E. 1/4 of the N.W. 1/4 of section 6. This point was arbitrarily selected at the break in slope adjacent to a very large (several tens of feet thick), prominent boulder which has several well-established fir trees growing on top. This boulder forms a noticeable shoreline salient on bearings of N. 83° E. from the Enterprise Reef navigational marker and N. 10° W. from the tallest steel framework member of the Village Bay ferry terminal loading ramp.

Contact at Y: Northumberland Formation graded beds are overlain by coarser grained sandstones of the Geoffrey Formation. When this section was measured, the actual contact was covered with beach sand or debris that shifts seasonally. The interval of transition, noted by a change to boulder talus up-section, is less than 20 feet thick (true).

| Interval (feet) | Description |
|---|---|
| Northumberland Formation | |
| 633-646 | Graded beds typical of section are mostly covered. Contorted blocks of coarse Geoffrey Formation sandstone occur within uppermost 8 feet of interval. |
| 608-633 | Typical of section. |
| | Attitude: N. 75° W., 14° N.E. Proceed N. 15° E. up-section to break in slope at upper contact. |
| 573-608 | Typical of section. |
| | Offset N. 63° W. approximately 100 feet to equivalent stratigraphic position. Bedding partly obscured by beach cover. Attitude: N. 79° W., 22° N.E. Proceed N. 11° E. up-section. |

Appendix A. (Continued)

| Interval (feet) | Description |
|---|---|
| 544.5-573 | Typical of section. Increasing sand content, same as next lower interval. |
| | Offset N. 59° W. approximately 60 feet to same stratigraphic position to skirt sea cliff and beach cover. Attitude: N. 65° W., 22° N.E. Proceed N. 35° E. up-section. |
| 541.5-544.5 | Typical of section, except sand content increasing. Not as apparent in overall aspect as in greater resistance to erosion forming elevated bench here. |
| | Offset N. 58° W. approximately 100 feet to equivalent stratigraphic position to avoid sea cliff. Attitude: N. 69° W., 26° N.E. Proceed N. 31° E. up-section. |
| 523.5-541.5 | Typical of section. |
| 503.5-523.5 | Typical of section. |
| | Offset N. 71° W. 25 feet to same stratigraphic position avoiding sea cliff. Proceed N. 10° E. up-section. |
| 462.5-503.5 | Typical of section. |
| | Offset N. 68° W. approximately 50 feet to equivalent stratigraphic position. Attitude: N. 80° W., 20° N.E. Proceed N. 10° E. up-section. |
| 442.5-462.5 | Typical of section. |
| | Offset N. 57° W. 25 feet to same stratigraphic position to avoid beach cover. Attitude: N. 76° W., 18° N.E. Proceed N. 24° E. up-section. |
| 441-442.5 | Sandstone. Ledge-former, medium-grained, moderately sorted, with angular to subangular particles. |
| | Especially well-cemented with $CaCO_3$. Light gray (N7) to light olive gray (5Y 7/1) weathered, olive gray (5Y 4/1) fresh. Exclusively parallel laminations internally, each approximately 1 mm thick, producing very distinct bedding with planar upper and lower contacts. Incipient honeycomb weathering localized along laminae. Dominant minerals are quartz and feldspar with lesser biotite and hematite. |
| | Offset N. 56° W. approximately 35 feet to equivalent stratigraphic position to avoid beach cover. Proceed N. 31° E. up-section. |
| 429-441 | Typical of section. |
| 406-429 | Covered. |
| | Attitude: N. 69° W., 16° N.E. Proceed N. 31° E. up-section. |

Appendix A. (Continued)

| Interval (feet) | Description |
|---|---|
| 401-406 | Covered.<br><br>Offset N. 75.5$^\circ$ W. 20 feet along strike. Proceed N. 14.5$^\circ$ E. up-section. |
| 386-401 | Covered.<br><br>Offsets required here to avoid sea cliff and covered interval at ferry terminal loading ramp. Because of attitude disparity between north and south side of covered interval (i.e., N. 69$^\circ$ W., 16$^\circ$ N.E. and N. 82$^\circ$ W., 13$^\circ$ N.E. respectively) the average was used to calculate true thickness (i.e., N. 75.5$^\circ$ W., 14.5$^\circ$ N.E.).<br><br>Note that up-section from base of covered interval there are two thick sandstone beds which are not accessible for accurate measurement. Approximate distance to base of lowest one is 10 feet. The sandstone bed is itself 1.5 feet thick. From its upper surface it is 4 more feet to the next higher sandstone bed which is approximately 1 foot thick. The intervening graded packets are typical of the section.<br><br>Offset N. 75.5$^\circ$ W. approximately 500 feet along strike to a point circa 100 feet S.E. of the steel framework of the ferry terminal loading ramp. Proceed N. 14.5$^\circ$ E. up-section. |
| 350.5-386 | Typical of section.<br><br>Offset N. 67$^\circ$ W. approximately 60 feet to avoid cliff. Attitude: N. 81$^\circ$ W., 11$^\circ$ N.E. Proceed N. 9$^\circ$ E. up-section. |
| 348.5-350.5 | Sandstone. Ledge- to rib-former. Fine- to very fine-grained, moderately sorted, with subangular particles. Light gray (N7) fresh, olive gray (5Y 4/1) weathered. Bedding well-defined. Internally, parallel laminations give way to indistinct festoon (?) cross-laminae in uppermost 6 inches where surface grades imperceptibly to mudstone. The lower bedding surface is sharp and planar to slightly undulating with less than 1/2 inch of relief. Minerals include quartz, feldspar, biotite, muscovite, and limonite.<br><br>Attitude: N. 73$^\circ$ W., 19$^\circ$ N.E. Proceed N. 17$^\circ$ E. up-section. |
| 338.5-348.5 | Typical of section.<br><br>Offset N. 65$^\circ$ W. approximately 450 feet to equivalent stratigraphic position at base of thick sandstone bed exposed on beach. Proceed N. 14$^\circ$ E. up-section. |
| 298.5-338.5 | Typical of section.<br><br>Offset N. 56$^\circ$ W. approximately 100 feet to equivalent stratigraphic position avoiding cliff and covered interval. Proceed N. 14$^\circ$ E. up-section. |

Appendix A. (Continued)

| Interval (feet) | Description |
|---|---|
| 297-298.5 | Sandstone. Rib-former, fine-grained, moderately sorted, with subangular to subrounded particles. Fresh surface very light gray (N8), light olive gray (5Y 6/1) weathered. Bedding indistinct. Lowermost 4 inches show parallel laminations that are succeeded by poorly defined festoon cross-laminae. Incipient honeycomb weathering features present. Lower contact shows scour-and-fill with underlying mudstone and the upper contact is gradational into mudstone above. Quartz, feldspar, and mica represent the dominant minerals. |
| | Attitude: N. 76° W., 18° N.E. Proceed N. 14° E. up-section. |
| 277.5-297 | Typical of section. |
| 262.5-277.5 | Typical of section. |
| | Offset N. 59° W. approximately 100 feet to equivalent stratigraphic position to avoid sea cliff. Proceed N. 13° E. up-section. |

Top of "representative interval" is 262.5 feet above base of section.

| | |
|---|---|
| 262.1-262.5 | Graded packet. Sandstone member is 2.5 inches thick and structureless internally. Grades imperceptibly into overlying mudstone. |
| 261.5-262.1 | Graded packet. As below. Sandstone member is 2 to 3 inches thick with undulating upper surface caused by presence of oblate ellipsoidal concretions identical to those in underlying packet. |
| 260.8-261.5 | Mudstone. Finer grained member of graded packet that includes underlying sandstone. Interjacent contact is gradational. Sand content beginning to increase slightly up-section. |
| 260.1-260.8 | Sandstone bed nearly 8 inches thick. Ledge-former. Fine-grained, moderately sorted. Particles subangular. Fresh surface is medium gray (N5) and light olive gray (5Y 6/1) weathered. Well-developed bedding and parallel laminations give way to festoon cross-laminae in uppermost 2 inches. Lower surface nearly planar with very slight, load-produced indulations. |
| 259.5-260.1 | Graded packet. Sandstone member is 1 inch thick with festoon cross-laminae 1 to 3 inches wide that have less than 1/4 inch of relief. Grades into overlying mudstone part of interval which contains a straight ammonite 1 inch in diameter. |
| 259.1-259.5 | Graded packet which is 5 inches thick. Sandstone part is 1.5 inches thick and the remainder is mudstone. Character as below. |
| 258.5-259.1 | The fine-grained sandstone part is 3.5 inches thick and the rest is gradationally overlying the mudstone. |
| 257.9-258.5 | Graded packet. Sandstone part is 3 inches thick and parallel laminations are succeeded by festoon cross-laminations in the uppermost inch of sandstone. The |

Appendix A. (Continued)

| Interval (feet) | Description |
|---|---|
| | remainder of the packet grades normally into siltstone with the same features described below except it weathers to chips only 1/4 inch long. Undulating contact with superjacent packet is caused by presence of oblate ellipsoidal micritic concretions parallel to the bedding. They range from 3 inches to 2 feet in diameter and they are 1 to 3 inches thick. Enclosing strata are compacted around them. |
| 257.5-257.9 | Sandstone to mudstone graded packets dominate this described interval. The basal packet is 5 inches thick. |
| | Nonresistant mudstone forms the uppermost 1 inch of this packet. Because it lacks a gritty feel, it is probably composed of very fine silt- and clay-size particles. It is medium gray (N5) on the deeply weathered surface. No fresh sample was obtainable. The upper surface is sharp and planar where it is succeeded by the parallel laminae of the overlying sandstone. This mudstone weathers to powder that is finer than materials normally found throughout this section. |
| | A siltstone interval approximately 3.5 inches thick overlies sandstone below. Particle size is not determinable but it feels only slightly gritty to the teeth. It is a slope-former which is dusky blue (5PB 3/2) to light gray (N7) weathered, and medium dark gray (N4) fresh. Internally structureless with gradational upper and lower surfaces. Weathers to angular chips from 1/2 to 1 inch long and from 1/8 to 1/2 inch thick. |
| | The lowest 1/2 inch of this packet is a minor, rib-forming sandstone. It is moderately sorted with angular particles. Fresh color is medium light gray (N6) and light gray (N7) when weathered. Bedding is moderately well-defined. Internally it has festoon cross-laminations with 2 to 3 laminae per millimeter. The festoons are from 1 to 3 inches wide with less than 1/4 inch of relief creating an undulating upper surface that grades into the siltstone above. The base of the sandstone shows scour-and-fill with the underlying mudstone. Unidentified horizontal worm burrows occur on the upper surface of the sandstone preserved as hyporeliefs. Minor $CaCO_3$ present, probably as cement. Very irregular small joints developed with no obvious pattern. Limonite stains the weathered surface in places. |
| | Offset N. 56° W. approximately 30 feet to equivalent stratigraphic position. Attitude: N. 77° W., 24° N.E. Proceed N. 13° E. up-section. |

Base of "representative interval" is 257.5 feet above base of section.

| | |
|---|---|
| 236-257.5 | Bedrock typical of section. |
| | Offset N. 43° W. approximately 25 feet to equivalent stratigraphic position to avoid cliff. Proceed N. 20° E. up-section. |

Appendix A. (Continued)

| Interval (feet) | Description |
|---|---|
| 41.5-236 | Covered by bayhead beach. |
| | Offset S. 71° E. approximately 150 feet along strike to intercept lowest exposed bedrock. Attitude: N. 70° W., 20° N.E. Proceed N. 20° E. up-section. |
| 36.5-41.5 | Same as described below. |
| | Offset S. 70° E. to S.E. part of shore at bayhead. Attitude: N. 71° W., 21° N.E. Proceed N. 19° E. up-section. |
| 30.5-36.5 | Same as described below. |
| | Offset S. 70° E. approximately 100 feet along strike. Attitude: N. 71° W., 22° N.E. Proceed N. 19° E. up-section. |
| 15.5-30.5 | Overall character same as described below except sandstone beds slightly thicker--mostly 1-3 inches and medium- to fine-grained. Apparent BC Bouma sequences common as festoon cross-laminations become more abundant in the sandstone. The siltstone-mudstone intervals are also slightly thicker (2 to 6 inches). On the upper surfaces of the sandstone beds, there are abundant contorted bedding features and many straight and Y-branching burrows much like Thalassinoides. |
| | Offset S. 70° E. approximately 50 feet along strike. Attitude: N. 70° W., 23° N.E. Proceed N. 20° E. up-section. |
| 10-15.5 | This interval contains somewhat thicker (6 inches to 1 foot) sandstone beds interspersed with the typical graded packets as described below. These sandstone beds are fine-grained with apparent BC Bouma sequences. |
| 0-10 | Graded packets typical of the section. Sandstone is interbedded with siltstone or mudstone. The sandstone beds range from 1/2 to 6 inches with most between 1 and 2 inches thick. They grade normally to siltstone or mudstone over 1 to 3 inches. Locally contorted bedding results from loading. Parallel laminations are most common in the coarser grained sandstone beds of the graded packets, but thinner and finer grained beds show festoon cross-laminae which are usually 1 to 3 inches wide with less than 1/2 inch of relief. |
| | Offset S. 75° E. approximately 400 feet along strike to equivalent stratigraphic position. Attitude: N. 70° W., 23° N.E. Proceed N. 20° E. up-section. |

Initial point (X, Plate 1) is located at the center of the N.W. 1/4 of the S.W. 1/4 of the S.W. 1/4 of the S.E. 1/4 of the N.W. 1/4 of section 6. Here a small sandy to pebbly beach opens toward Galiano Island. The north side of this beach is flanked by a sandstone bed approximately 6 feet thick. The uppermost surface of this bed at its westernmost extremity is the initial point. It lies on a bearing of S. 13° W. from the highest part of the steel framework structure at the Village Bay ferry terminal loading ramp. It is also crossed by a second bearing of S. 42° E. from the high tide mark on the westernmost visible extremity of land at Helen Point. The attitude here is N. 75° W., 23° N.E. The section is measured stratigraphically up heading N. 15° E.

Appendix A. (Continued)

Contact at X: At initial point X, described above, there occurs a graded interval of Northumberland aspect approximately 10 to 15 feet thick. Farther down-section, graded interbeds that separate typical coarser grained units of the DeCourcy Formation are much thinner. For this reason, the basal contact of the Northumberland Formation is arbitrarily chosen at point X.

# APPENDIX B

## MODAL ANALYSES OF SELECTED SANDSTONE SAMPLES

| Mineralogy | Formation and Sample | | | | | |
|---|---|---|---|---|---|---|
| | Kep | | Kcd | Kdc | | |
| | 357-1 | 370-1 | 321-1 | 390-2 | 396-1 | 165-4 |
| Stable Grains | | | | | | |
| Normal Quartz | 14.3 | 1.8 | 1.5 | 3.2 | 1.5 | 2.0 |
| Polyxlln Quartz | 3.9 | 4.5 | 15.3 | 5.0 | 11.5 | 9.2 |
| Undulat. Quartz | 18.4 | 11.3 | 8.0 | 16.2 | 10.5 | 15.4 |
| Chert | 3.4 | 0.3 | 2.3 | 2.7 | - | 0.5 |
| Feldspar | | | | | | |
| K-spar | 11.7 | 9.3 | 6.8 | 15.1 | 11.3 | 14.2 |
| Plagioclase | 31.6 | 35.0 | 23.9 | 30.2 | 24.4 | 31.3 |
| Rock Fragments | | | | | | |
| Igneous | T | T | 0.5 | - | 7.3 | 0.7 |
| Volcanic | 1.4 | 0.8 | 4.8 | 6.1 | 9.0 | 6.2 |
| Metamorphic | 0.8 | 1.8 | - | 1.6 | 0.7 | 0.7 |
| Heavy Minerals | | | | | | |
| Apatite | T | - | T | - | - | T |
| Epidote | 0.6 | 0.5 | 1.5 | T | 0.5 | 0.2 |
| Garnet | T | 0.3 | - | T | 0.2 | 0.2 |
| Hematite | 1.1 | 1.0 | T | - | T | - |
| Hornblende | - | - | - | - | - | - |
| Ilmenite | 0.3 | 0.5 | 0.5 | - | - | - |
| Leucoxene | 0.8 | 0.8 | 0.3 | - | - | - |
| Magnetite | T | T | 1.3 | T | 0.2 | 0.5 |
| Sphene | T | - | T | 0.8 | 0.2 | T |
| Zircon | T | 0.3 | - | - | - | 0.2 |
| Mica | | | | | | |
| Biotite | 7.3 | 5.5 | 4.5 | 6.1 | 2.9 | 6.2 |
| Chlorite | 0.6 | 0.8 | 2.0 | T | 1.2 | T |
| Muscovite | 3.1 | 2.5 | 1.3 | 1.1 | 1.7 | 0.5 |
| Matrix | 0.8 | 22.7 | 17.1 | 11.9 | 16.9 | 11.4 |
| Cement | | | | | | |
| Calcite | - | - | 9.8 | - | - | 0.2 |
| Laumontite | - | - | - | - | - | - |

Appendix B. (Continued)

| Mineralogy | Formation and Sample | | | | | | |
|---|---|---|---|---|---|---|---|
| | Kn | | | Kg | | | |
| | 437-1 | 147-2 | 503-1 | 131-2 | 397-1 | 216-1 | 522-2 |
| Stable Grains | | | | | | | |
| Normal Quartz | 1.5 | 1.0 | 1.6 | 3.8 | - | 2.1 | 0.5 |
| Polyxylln Quartz | 3.3 | 3.7 | 2.0 | 9.0 | 3.7 | 9.8 | 6.0 |
| Undulat. Quartz | 12.6 | 19.5 | 14.4 | 16.5 | 8.1 | 17.1 | 7.2 |
| Chert | 2.0 | 0.9 | 1.2 | 1.9 | 1.1 | 0.8 | 1.4 |
| Feldspar | | | | | | | |
| K-spar | 2.9 | 6.3 | 6.6 | 9.7 | 12.0 | 12.1 | 8.2 |
| Plagioclase | 15.0 | 30.8 | 24.2 | 26.5 | 34.8 | 36.9 | 42.9 |
| Rock Fragments | | | | | | | |
| Igneous | - | - | 0.2 | 3.1 | 0.9 | - | 1.0 |
| Volcanic | 5.5 | 2.2 | 7.0 | 6.4 | 4.1 | 1.3 | 15.8 |
| Metamorphic | 0.4 | 0.5 | 0.8 | 1.6 | 3.5 | 1.9 | 1.2 |
| Heavy Minerals | | | | | | | |
| Apatite | - | - | - | 0.2 | - | - | - |
| Epidote | - | 0.5 | 0.2 | 0.9 | 0.2 | 0.5 | 0.2 |
| Garnet | T | - | T | - | - | T | T |
| Hematite | 0.7 | 0.5 | T | T | T | 0.3 | T |
| Hornblende | - | - | - | 1.2 | 1.4 | - | - |
| Ilmenite | - | - | - | - | - | - | - |
| Leucoxene | - | - | - | - | - | - | - |
| Magnetite | 6.2 | 1.4 | 0.8 | 0.2 | 1.2 | 0.5 | 1.7 |
| Sphene | - | 0.5 | T | 0.2 | - | T | T |
| Zircon | - | 0.2 | - | - | - | T | T |
| Mica | | | | | | | |
| Biotite | 6.8 | 4.9 | 3.4 | 2.1 | 3.2 | 5.6 | 4.8 |
| Chlorite | 1.3 | 11.0 | 0.4 | - | - | - | 0.2 |
| Muscovite | 0.2 | 2.2 | 0.8 | 1.4 | 0.2 | 0.5 | 1.0 |
| Matrix | 5.5 | 10.0 | 0.8 | 15.1 | 25.8 | 10.3 | 7.9 |
| Cement | | | | | | | |
| Calcite | 35.7 | 3.9 | 35.6 | - | - | - | - |
| Laumontite | - | - | - | - | - | - | - |
| Quartz | - | - | - | - | - | 0.3 | - |

Appendix B. (Continued)

| Mineralogy | Formation and Sample | | | | | | |
|---|---|---|---|---|---|---|---|
| | Ks | | | | Kga | | |
| | 425-1 | 7-3 | 213-1 | 201-1 | 426-1 | 242-1 | 193-1 |
| Stable Grains | | | | | | | |
| Normal Quartz | 0.5 | 0.7 | 1.4 | - | 0.3 | 0.2 | 1.3 |
| Polyxylln Quartz | 5.9 | 1.9 | 2.8 | 3.6 | 5.0 | 3.0 | 3.6 |
| Undulat. Quartz | 11.5 | 18.6 | 17.1 | 14.7 | 13.0 | 20.1 | 18.9 |
| Chert | 4.9 | 1.4 | 3.1 | 2.8 | 1.9 | - | 0.4 |
| Feldspar | | | | | | | |
| K-spar | 11.3 | 5.6 | 9.0 | 9.5 | 10.5 | 12.7 | 12.7 |
| Plagioclase | 41.2 | 26.3 | 30.9 | 36.7 | 44.3 | 39.4 | 42.6 |
| Rock Fragments | | | | | | | |
| Igneous | 0.5 | - | 0.6 | - | 0.2 | 0.5 | 0.4 |
| Volcanic | 14.5 | 0.7 | 2.9 | 6.9 | 9.8 | 3.2 | 1.8 |
| Metamorphic | 2.2 | - | 0.2 | 1.2 | 1.0 | 0.5 | 1.1 |
| Heavy Minerals | | | | | | | |
| Apatite | - | - | - | - | - | - | - |
| Epidote | 1.2 | 0.2 | 0.8 | 0.7 | 0.8 | 0.5 | 1.2 |
| Garnet | T | - | - | - | - | T | T |
| Hematite | T | T | 1.0 | 0.5 | - | T | T |
| Hornblende | - | - | - | - | - | - | T |
| Ilmenite | - | - | - | - | - | - | - |
| Leucoxene | - | - | - | - | - | - | - |
| Magnetite | T | 1.6 | 0.8 | 1.0 | 0.3 | 0.5 | 0.4 |
| Sphene | T | - | 0.2 | T | - | T | 0.4 |
| Zircon | T | - | - | 0.2 | 0.2 | T | - |
| Mica | | | | | | | |
| Biotite | 3.2 | 6.7 | 5.7 | 6.2 | 3.5 | 6.0 | 6.0 |
| Chlorite | T | - | - | 0.2 | 0.7 | - | 0.7 |
| Muscovite | 0.7 | 0.7 | 0.2 | 0.2 | 0.2 | 0.2 | 0.4 |
| Matrix | 2.5 | 13.7 | 2.4 | 15.4 | 8.2 | 12.9 | 8.0 |
| Cement | | | | | | | |
| Calcite | - | 21.9 | 23.8 | - | - | - | - |
| Laumontite | - | - | - | 0.2 | - | 0.3 | - |

# APPENDIX C

## PEBBLE COUNT LITHOLOGIES AND MINERALS IDENTIFIED BY X-RAY DIFFRACTION ANALYSIS

Pebble Count Lithologies

| Lithology | Formation and Sample | | |
|---|---|---|---|
| | Kep | Kdc | Kg |
| | 347-1 | 301-1 | 94-1 |
| Andesite | 0.5 | 1.5 | 2.0 |
| Basalt | 15.5 | 3.0 | 13.5 |
| Chert | 49.0 | 51.5 | 27.0 |
| Foliated metamorphics | 3.0 | 1.0 | - |
| Granitics | 15.5 | 19.0 | 29.0 |
| Quartzite | 16.5 | 23.0 | 28.5 |
| Sandstone | - | 1.0 | - |

Minerals Identified by X-Ray Diffraction Analysis

| Mineralogy | Formation | | | | | |
|---|---|---|---|---|---|---|
| | Kcd | Kdc | Kn | Kg | Ks | Kga |
| Chlorite | x | x | x | x | x | x |
| Feldspar | x | x | x | x | x | x |
| Kaolinite | x | x | x | x | x | x |
| Laumontite | | | | | | x |
| Mica | x | x | x | x | x | x |
| Quartz | x | x | x | x | x | x |

# APPENDIX D

## X-RAY PROCEDURE

Selected samples from the six youngest formations in the study area were X-rayed. The samples were pulverized and separately treated with 30% hydrogen peroxide for removal of organic matter and then with 0.1 N hydrochloric acid to dissolve carbonate cement where present. The size fraction smaller than 4.5 ϕ was separated by sieving and then mixed with Calgon plus distilled water to deflocculate the clays. By differential centrifugation, the size fraction between 0.2 and 2 microns was extracted as follows: 1) the entire suspension was spun at 700 r.p.m. for 7 minutes to remove the material larger than 2 microns (the residue); and 2) the suspensate was centrifuged at 6,000 r.p.m. for 7 minutes to recover the 0.2 to 2 micron fraction (the residue). These last two steps were repeated twice after resuspension. The desired fraction was resuspended in distilled water, placed on a slide, and air dried.

The samples were X-rayed initially and peaks were identified. The only apparent ambiguities noted were: 1) the peaks at approximately 7 Å could represent either chlorite or kaolinite; and 2) peaks at approximately 14 Å are common to chlorite and expandable lattice clays. To resolve the latter, treatment with ethylene glycol was performed and the samples were X-rayed again. Result: no shift in

Appendix D. (Continued)

the peaks indicative of lattice expansion. Conclusion: 14 Å peaks represent chlorite.

To differentiate between kaolinite and 7 Å chlorite, the samples were heated to 550°C for 30 minutes and X-rayed again. Result: nearly total obliteration of the 7 Å peak. Conclusion: A very minor amount of 7 Å chlorite could be present, but these peaks are mostly ascribable to kaolinite.

A Norelco X-ray diffractometer was used and individual scans ranged from 3° to 30° 2 θ. The following instrument settings remained unchanged:

| | |
|---|---|
| Radiation: | Copper (Cu $K_{\alpha}$) broad focus |
| KV: | 35 |
| MV: | 35 |
| Filter: | Nickel |

Rate Meter Settings

| | |
|---|---|
| Multiplier: | $5 \times 10^2$ |
| Time Constant: | 2 sec. |
| Scan Rate: | 2° 2θ/minute |