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Title: BEDROCK GEOLOGY OF THE NORTH SAANICH-COBBLE HILL AREAS, BRITISH COLUMBIA, CANADA

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The bedrock of the North Saanich-Cobble Hill areas consists of igneous and sedimentary rocks of Early Jurassic through Late Cretaceous age. Early Jurassic andesitic Bonanza Volcanics are intruded by Middle Jurassic Saanich Granodiorite plutonic rocks and dikes. Late Cretaceous Nanaimo Group clastic rocks nonconformably overlie these Jurassic units. The four oldest formations of the group (Comox, Haslam, Extension-Protection, and Cedar District) are exposed within the study area.

The Nanaimo Group formations were deposited within a subsiding marine basin (the Nanaimo Basin) located to the east of southern Vancouver Island. Uplift of pre-Late Cretaceous basement rocks on Vancouver Island to the west and on mainland British Columbia to the east of the basin created rugged, high-relief source areas that were chemically weathered in a warm tropical climate and mechanically eroded by high-energy braided stream systems.

The Comox and Haslam sediments were deposited in response to a continual transgression of a Late Cretaceous seaway over this rugged terrain. Braided stream systems trending north-northwest into the basin deposited Comox (Benson Member) gravels and sands onto a high-energy, cliffed shoreline. Erosion of the highlands and transgression of the marine seaway resulted in subdued topographic relief and the deposition of sediments by low-energy meandering streams within a river traversed coastal plain, followed by silt and clay deposition in tidal flat and lagoonal environments, and finally by sand deposition in a higher energy barrier bar environment. Continued marine transgression resulted in the deposition of massive marine mudstones and cyclic sandstone to mudstone sequences of the Haslam Formation.

Localized uplift within the basin elevated these units prior to complete lithification and possibly caused soft sediment deformation of upper Haslam Formation strata. An eroded surface developed on the top of the Haslam on which basal conglomerates of the Extension-Protection were deposited. Extension-Protection units represent cycles of basin deepening, delta progradation and apparent marine regression, and a resumption of marine transgression. Lower energy regimes and subdued topography are reflected by the finer grained sediments deposited from late Extension-Protection through early Cedar District time. Shallow- to intermediate-marine silts and muds deposited during early Cedar District time may represent distal turbidite flows of a prodelta environment. As the delta prograded seaward, these sediments were overlain by proximal turbidites. Delta progradation probably continued through early DeCourcy time.

The structure within the study area apparently is controlled by regional north-south compressional stresses. Strata dip from 20 to almost 90 degrees to the north and northeast, with vertical and overturned, southward-dipping beds common at some locations. Fault block tilting and drag of bedding along fault planes rather than folding probably are responsible for these attitudes. Northwest-striking faults cut Nanaimo Group strata perpendicular to almost parallel to strike. Structure is complicated by northeast-striking splays of the San Juan fault system which are interpreted as imbricate and reverse faults.

Sandstones within the formations contain little or no porosity and thus cannot be considered as reservoir rocks. Diagenetic alteration of mafic minerals to clays, calcite and silica precipitation, and prehnite formation have reduced porosity within these units to this minimum.

Bedrock Geology of the North Saanich-Cobble Hill Area, British Columbia, Canada

by

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TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page
18.	Chevron folding within Haslam Formation.	48
19.	Conglomerate channel-fill within Extension-Protection Formation.	48
20.	Extension-Protection Formation distribution and sample localities for modal analyses and pebble counts.	50
21.	Cedar District Formation distribution and sample localities for modal analyses and X-ray diffractions.	57
22.	Cyclic nature of Cedar District sandstone-siltstone-mudstone sequences.	59
23.	_Inoceramus_ molds sampled from Cedar District Formation.	59
24.	Photomicrograph of Saanich Granodiorite tonalite.	65
25.	Photomicrograph of Comox lithic arenite.	69
26.	Photomicrograph of Comox lithic arenite.	71
27.	Photomicrograph of Extension-Protection lithic arenite.	72
28.	Photomicrograph of Extension-Protection subfeldspathic lithic arenite.	78
29.	Photomicrograph of Haslam feldspathic wacke.	78
30.	Classifications of Comox, Haslam, Extension-Protection, and Cedar District sandstones.	87
31.	Photomicrograph of Benson conglomerate matrix.	89
32.	Pebble count data for Comox and Extension-Protection Formations.	91
33.	Diffractograms of clay mineralogy for the Haslam Formation mudstones.	96

LIST OF PLATES

BEDROCK GEOLOGY OF THE NORTH SAANICH-COBBLE HILL AREAS, BRITISH COLUMBIA, CANADA

INTRODUCTION

Purposes

The major purposes of this study are: (1) to map the bedrock geology of the North Saanich-Cobble Hill areas; (2) to determine the stratigraphic relationships between the Early to Middle Jurassic Bonanza Volcanics, the Middle to Late Jurassic Island Intrusions (Saanich Granodiorite), and the four oldest formations of the Late Cretaceous Nanaimo Group (Comox, Haslam, Extension-Protection, Cedar District); (3) to examine the petrology of the sedimentary and igneous rocks; (4) to determine depositional environments of the Late Cretaceous sequence; (5) to compare local folding and faulting to the regional structure; and (6) to determine the hydrocarbon reservoir potential of the Nanaimo Group clastics in the thesis area. The experience and knowledge attained and the completion of a Master of Science Degree in Geology must also be considered as important objectives of this study.

Location and Accessibility

The North Saanich Peninsula and Cobble Hill areas are located on southern Vancouver Island, British Columbia, at 48°40' N. latitude and 123°30' W. longitude. Access to Vancouver Island is possible via either the MV Coho ferry from Port Angeles, Washington, to Victoria, British Columbia, or the Washington State Ferries from Anacortes, Washington, to Sidney, British Columbia. Ferry schedule and prices vary seasonally. The MV Coho trip takes approximately 90 minutes, while the Washington State Ferry trip is a leisurely four hour tour through the San Juan Islands. The study area, which also includes Knapp, Pym, Fernie, Goudge, Piers, and Coal Islands immediately north-northeast of the North Saanich Peninsula, covers approximately 20 square miles (Figure 1).

The Cobble Hill area is separated from the North Saanich Peninsula by Saanich Inlet, a body of water about three miles wide and 15 miles long The inlet narrows to the south before terminating at Finlayson Arm, some six miles farther south. Travel to and from each area, when limited to automobile, is possible via highways 1 and 17, a total distance of approximately 45 miles. A ferry crosses the Saanich Inlet, but only saves about 20 miles and was not found to be economically beneficial. A small dinghy and a rented power boat were used to travel to and from the small islands in the North Saanich area.

Both localities are heavily populated, and development is continuing at a high rate. A fine network of paved and gravel roads transects the areas, aiding in the field studies. New subdivisions

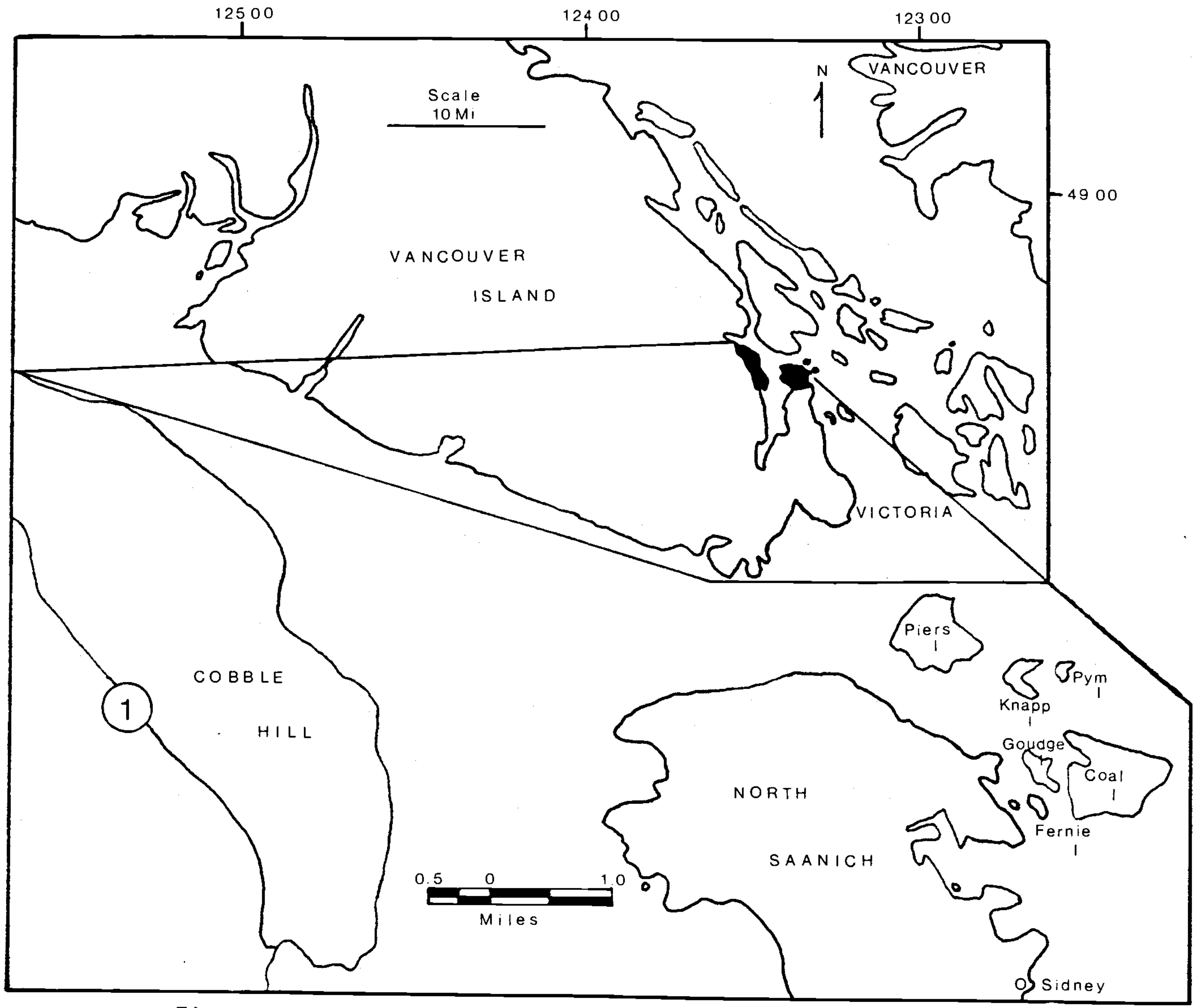


Figure 1: Index map showing location of study area.

have added additional roads which do not appear on recent aerial photos or topographic maps. Therefore, although heavily vegetated, numerous exposures in the form of road cuts do exist in the study area.

Geomorphology, Vegetation

The principal topographic features in the study area consist of intricate inlets, sea cliffs, small islands, tidal mudflats, rolling farmland, marshes, and cuestas. The degree of resistance of the bedrock to erosion, wave action, and glacial scour has resulted in the present topography common to both Cobble Hill and North Saanich.

Major embayments include Boatswain Bank and Mill Bay in the Cobble Hill area and Patricia Bay, Towner Bay, Deep Cove, Swartz Bay, Canoe Bay, and Tseum Harbor in North Saanich. Cherry and Hatch Points in Cobble Hill and Coal, Moses, Curteis, Nymph, Thumb, Armstrong, and Roberts Points in North Saanich are resistant sea cliffs of exposed bedrock. In addition to the larger, named islands mapped in the thesis area, numerous, unnamed islets and reefs are scattered off the North Saanich shoreline. The Blue Heron Basin and inner Tseum Harbor are large tidal mudflats that have been dredged in part for wharves and yacht clubs, although part of the Blue Heron Basin is a bird sanctuary. In the Cobble Hill area, Boatswain Bank is a large mudflat that becomes exposed at very low tides.

Inland, flatlands and marshes are noted where less resistant bedrock units are presumed to occur. The resistant Comox sandstones form cuestas at Horth and Cloake Hills in North Saanich, as well as a smaller, unnamed cuesta along Telegraph road in the Cobble Hill area.

Glacial till covers much of the thesis area. Beaches and wave-cut benches are overlain by rounded glacial erratics up to 15 feet in diameter. At Cobble Hill, the glacial deposits are of widest extent, reaching a thickness of over 100 feet. Numerous gravel pits are in operation in Cobble Hill, exposing large scale cross-bedding, laminated muds, and gravel stream channels within these deposits. Some of the outcrops in the North Saanich area are striated, with directions indicating a generally north to south ice movement. Mass wasting and slumping of the unconsolidated glacial sediments have caused erosion of the hillsides and generally unstable conditions. This is especially true immediately east of Dougan Lake where Highway 1 cuts through the deposits and also near the shoreline north of Cherry Point.

Silty to gravelly, sandy loam soils cover most of the Cobble Hill area, while clay and sandy loams are most common in North Saanich. Where bedrock is exposed, a veneer of rocky, poorly developed soil dominates. Clay soils apparently coincide with mudstone units of the Nanaimo Group, whereas sandy soils are more common in areas with sandstone bedrock.

Forests are of the Douglas Fir, Arbutus, western red cedar, red alder, and lodgepole pine varieties, with arbutus most common in rocky areas with poor soil development. A wide variety of grasses, ferns, and wildflowers are also noted in the thesis area.

Climate

The climate of southern Vancouver Island is classified as cool marine (Papadakis, 1958). Cool, wet winters and dry, warm summers are common to the area, with a short summer drought occurring each year. The climates of the Cobble Hill and North Saanich areas are quite similar, with average mean annual temperatures at approximately 49 degrees Fahrenheit and mean annual maximums of 57 degrees and minimums of 41.5 degrees. Extreme maximum and minimum temperatures are 97 and 4 degrees respectively. A mean total precipitation of about 40 inches accumulates annually, with a mean total snowfall of less than 20 inches each year. Southeast winds dominate in the winter while northwest winds are more common in the summer months.

Study Methods

A March 1977 visit was made as an introduction to the geology and people of the thesis area, and also to make any necessary arrangements for the summer. Field work was initiated on June 14, 1977 and completed on September 7, 1977.

After a reconnaissance of the area in early June, detailed field mapping was accomplished on 1:15,840 scale, 100 foot contour interval topographic maps with the aid of aerial photographs (1inch = 0.25 mile), ten foot contour interval topographic maps (1 inch = 400 feet), and a Brunton compass. The topographic maps and aerial photographs were purchased from the Surveys and Mapping Branch of the British Columbia Department of Lands, Forests, and Water Resources.

Field lithologic descriptions were made with the aid of a 10X hand lens, dilute hydrochloric acid, a GSA Rock-Color Chart, a sand gauge chart, and Power's (1953) Roundness Chart. Sedimentary structures and paleocurrents were measured using the method described by Briggs and Cline (1967). When necessary, some paleocurrent data was rotated in the laboratory to apparent original depositional position using a stereonet. The Jacob's staff and Abney level were used to measure representative stratigraphic sections of the Nanaimo Group formations. Slides, photographs, and samples were taken of the units on a regular basis. All field observations were recorded in a field notebook and Compton's (1962) field manual was used as a guide when necessary. Dr. Keith F. Oles made a field check on August 27, 1977 to determine progress and provide any needed advice and assistance.

Petrographic thin sections of 27 samples were examined microscopically with a total of 12 thin sections pointed counted. The Michel-Levy method was used for plagioclase determination and alkali feldspars were identified by selective staining (Bailey and Stevens, 1960). The Comox and Extension-Protection conglomerate units were sampled for pebble counts, and pebble lithologies were identified with the aid of a 10X hand lens and a binocular microscope. A rotary drilled water well cuttings sample was also examined through the binocular microscope. X-ray diffraction of clay fractions from mudstone units was accomplished to determine clay mineralogy (complete discussion of the diffraction methods is given in the Petrology section).

Paleocurrent data were plotted on rose diagrams, with the mean and standard deviations calculated, and from them the dispersal patterns and source areas interpreted.

Previous Studies

The Hudson's Bay Company became interested in the coal of the Nanaimo area sedimentary rocks in 1850 (Usher, 1952) and began mining coal from them in 1854 (Hector, 1861). In 1857, the fact that these rocks were Cretaceous was determined by F. B. Meek's identifications of Dr. J. S. Newberry's collections (Usher, 1952). Bauermann (1859) discussed the Cretaceous rocks at Nanaimo noting that ammonites, baculites, and Inoceramus are common to the concretionary and nodular "coal bearing grits."

The Nanaimo District was visited by geologists prior to the 1850's also, but the first real geological examination of major importance was made in 1860 by Sir James Hector of the Government Exploration Expedition (England) under the command of J. Palliser (Clapp, 1912). Hector (1861) wrote of geologic observations at Nanaimo and Victoria, mentioning the sandstone and conglomerate sea cliffs, intricate inlets, and the metamorphic basement rocks south of the North Saanich area. He stated that the sandstones are highly weathered, with wave action forming caves and hollows, and that the conglomerates form the highest beds of the sedimentary series and are of immense thickness.

In 1861, Meek accumulated additional paleontological evidence for a Cretaceous age for the clastic deposits, while Newberry (1863) described several plant species also common to these rocks (Usher, 1952).

Macfie (1865) gave a brief account of the geology of Vancouver Island, describing the sedimentary rocks as carbonaceous sandstone, grit, and shale of Cretaceous age that fringe the eastern part of the island and form a large part of the numerous small islands in the Gulf of Georgia. The coalfields at Nanaimo were described as having undergone extensive faulting and "numerous changes in level."

A major geologic study of Vancouver Island was accomplished by Richardson (1872, 1873), forming the basis for additional detailed studies of the stratigraphy, structure, and paleontology of the Cretaceous rocks by dividing the basins of deposition into Comox, Nanaimo, Cowichan (Usher, 1952). The Nanaimo Group was formally named by Dawson in 1890. He deduced that the group might be time correlative to the Chico Group of California.

Clapp (1912, 1914) and Clapp and Cooke (1917) analyzed the Cretaceous and older rocks of eastern Vancouver Island, noting the lithology of the volcanic, granitic, and sedimentary rocks while mapping the geology of the Nanaimo, Duncan, and Victoria areas. They noted that the Nanaimo Group thickens to the south from Nanaimo and recognized the group as a series of non-marine to marine clastics in erosional contact with the older basement rocks. Clapp (1914) further described the lateral variability of the Nanaimo Group section and the resulting hindrance to stratigraphic correlation.

Buckham (1947) measured and described a 7,600 foot section of the Nanaimo Group and determined that the principal structures at Nanaimo are a series of northwest-trending thrust (sic) faults. In 1952, Usher refined the early work of Clapp (1914) by defining extensive ammonite zones for the Nanaimo Group. This work became the basis for correlation of the units between the depositional basins.

Fyles (1955) studied the geology of the Cowichan Lake area to the northwest of Cobble Hill, giving fairly detailed petrographic descriptions of the Vancouver Group volcanics and the Island Intrusions. These were further described and mapped by Muller and Carson (1969), Muller (1971, 1975), Carson (1973), and Muller and others (1974).

Bell (1957), after examining the Late Cretaceous flora, suggested that a warm, temperate climate existed at the time of deposition of the Nanaimo Group sediments. Foraminiferal studies by McGugan (1962, 1964), and palynological studies of Crickmay and Pocock (1963) further delineated the relative ages of the Nanaimo Group formations.

The most recent, detailed work on the stratigraphy of the Nanimo Group was initiated by J. E. Muller of the Geological Survey of Canada in 1963. J. A. Jeletzky supported the field work of Muller by studying the paleontology of the Nanaimo Group. The Cretaceous ammonite zonations of Usher (1952) and the Nanaimo stratigraphy were refined by Muller and Jeletzky in 1967. A detailed analysis of the Nanaimo Group plus a 1:250,000 scale reconnaissance map of the geology of eastern Vancouver Island and the Gulf Islands was published in 1970 (Muller and Jeletzky, 1970). Additional mapping and study of the Nanaimo Group by the Canadian Geological Survey has continued to the present time.

A number of Oregon State University Master's and Doctoral degree candidates, under the direction of Dr. Keith F. Oles, have also described and mapped the Nanaimo Group strata noting the stratigraphy, structure, paleoenvironments, and petrography in great detail (Packard, 1972; Rinne, 1973; Hudson, 1975; Sturdavant, 1975; Hanson, 1976; Stickney, 1976; Carter, 1976; Fiske, 1977; and Allmaras, 1978).

Regional Geologic Setting

Vancouver Island is located within the southeastern part of the Insular Belt (Figure 2), a region of related tectonic events and rock units lying off the west coast of Canada between mainland British Columbia and the continental slope. The stratigraphy and structure of the southern Insular Belt are most complex (Figure 3), bringing together a variety of Paleozoic, Mesozoic, and Tertiary volcanic, intrusive, sedimentary, and metamorphic rocks (Muller, 1975). The oldest rocks of southern Vancouver Island consist of late Paleozoic to early Mesozoic eugeosynclinal volcanic and sedimentary rocks unconformably overlain by two major groups of clastic sediments laid down in shallow marine or continental basins during the late Mesozoic and early Tertiary (Muller and Carson, 1969).

The oldest exposed rocks of Vancouver Island are composed of up to 13,000 feet of volcanic breccias, tuffs, argillites, greenstones, andesites, cherts, graywackes, and minor limestones of the Sicker Group. These Pennsylvanian through early Permian rocks

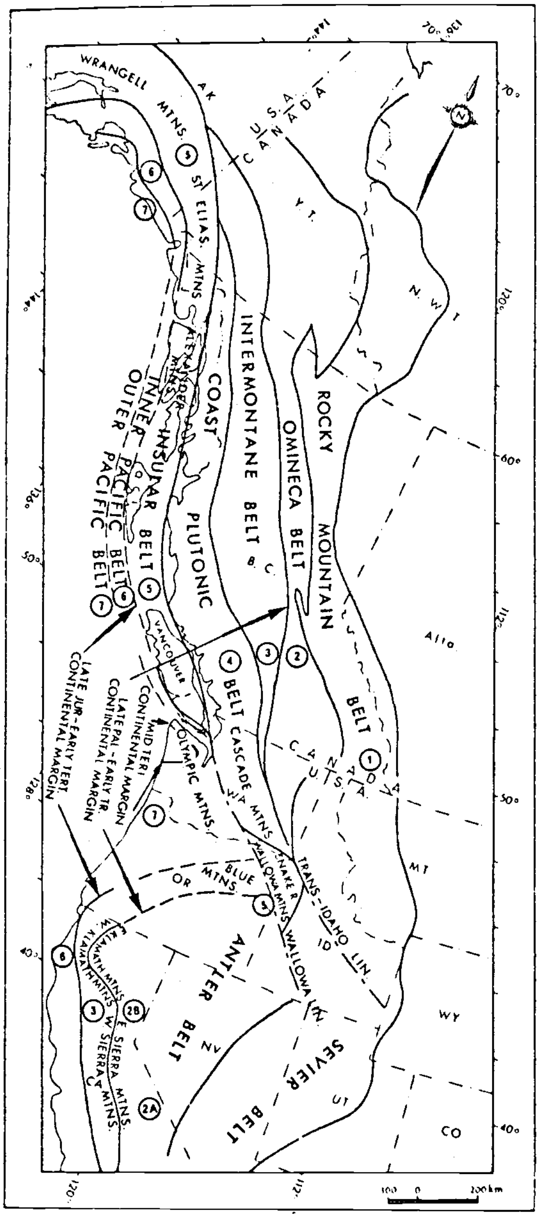
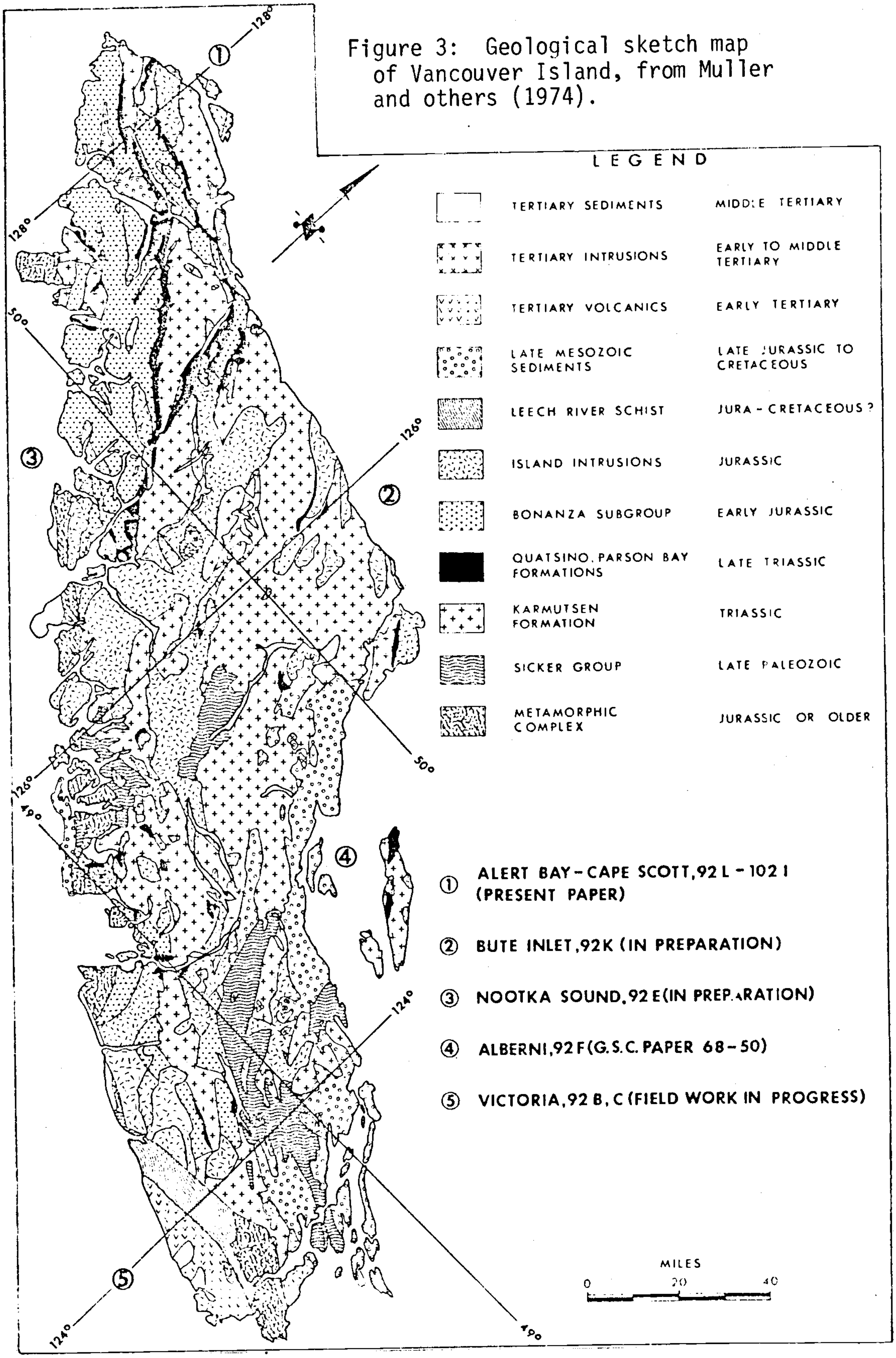


Figure 2: Outline map of Cordilleran Belts (note location of Insular Belt), from Muller (1977).

Figure 3: Geological sketch map of Vancouver Island, from Muller and others (1974).



extend from the Chemainus River to Alberni on northern Vancouver Island, along several northwest-trending outcrop belts north of the San Juan fault system, at Buttle Lake, and on Saltspring Island (Muller and Carson, 1969). No Sicker Group rocks are found in the North Saanich-Cobble Hill areas.

The Late Triassic through Early Jurassic Vancouver Group unconformably overlies the Paleozoic Sicker Group. The Vancouver Group is subdivided into the Karmutsen Formation, consisting of pillow basalts and breccias, the Quatsino Formation, consisting of massive to thickly bedded limestone, and the Bonanza Subgroup, consisting of limestone, argillite, and andesitic to dacitic breccias, tuffs, and lava flows. Only the volcanic rocks of the Bonanza Subgroup crop out in the thesis area.

Intruding the Vancouver Group are the Middle to Late Jurassic Island Intrusions (also known as the Saanich Granodiorite). These intrusive rocks are plutonic granodiorites and quartz diorites with dacitic to dioritic dike systems. The pluton, dikes, and the intrusive contacts with the older Bonanza Volcanics are exposed in the North Saanich and Cobble Hill areas.

Nonconformably overlying the Island Intrusions is the Late Cretaceous Nanaimo Group, a series of conglomerates, sandstones, siltstones, mudstones, and coals. The Nanaimo Group, deposited in the Comox and Nanaimo Basins east of Vancouver Island, represents cyclic deltaic to marine assemblages that are divided into four depositional phases and nine formations (Comox, Haslam, Extension-Protection, Cedar District, DeCourcy, Northumberland, Geoffrey, Spray, and Gabriola). The Gabriola Formation is the non-marine part of an incomplete fifth cycle. The two oldest depositional cycles and the four oldest formations of the Nanaimo Group are recognizable in the thesis area.

Pleistocene glacial deposits cover much of Vancouver Island, especially the topographically lower areas. The mantle of clays, silts, sands, and gravels masks the bedrock, limiting outcrop exposures mainly to cuestas, road cuts, and shorelines in the study area.

PRE-CRETACEOUS STRATIGRAPHY

Bonanza Volcanics

Nomenclature

The Bonanza Volcanics belong to the Bonanza Subgroup of the Vancouver Group. The Vancouver Group, originally named the Vancouver Series by Dawson (1887), consists of Triassic through Early Jurassic volcanic and sedimentary rocks. The group includes basal carbonate and basaltic rocks of the Karmutsen Formation, overlying Quatsino Formation limestone, and the uppermost Bonanza Subgroup, consisting of carbonates and andesitic volcanics. The name Bonanza Group was introduced by Gunning (1932) for the assemblage of sedimentary and volcanic rocks exposed above the Quatsino Formation, on the upper slopes west of Bonanza Lake (Muller and Carson, 1969). The group was divided into a lower sedimentary division and an upper volcanic division by Hoadley (1953) and Jeletzky (1954).

Areal Extent, General Description

The Bonanza Volcanics crop out at five locations in the North Saanich area (Figure 4, Plate 1). At Armstrong and Thumb Points, the volcanics are nonconformably overlain by the Late Cretaceous

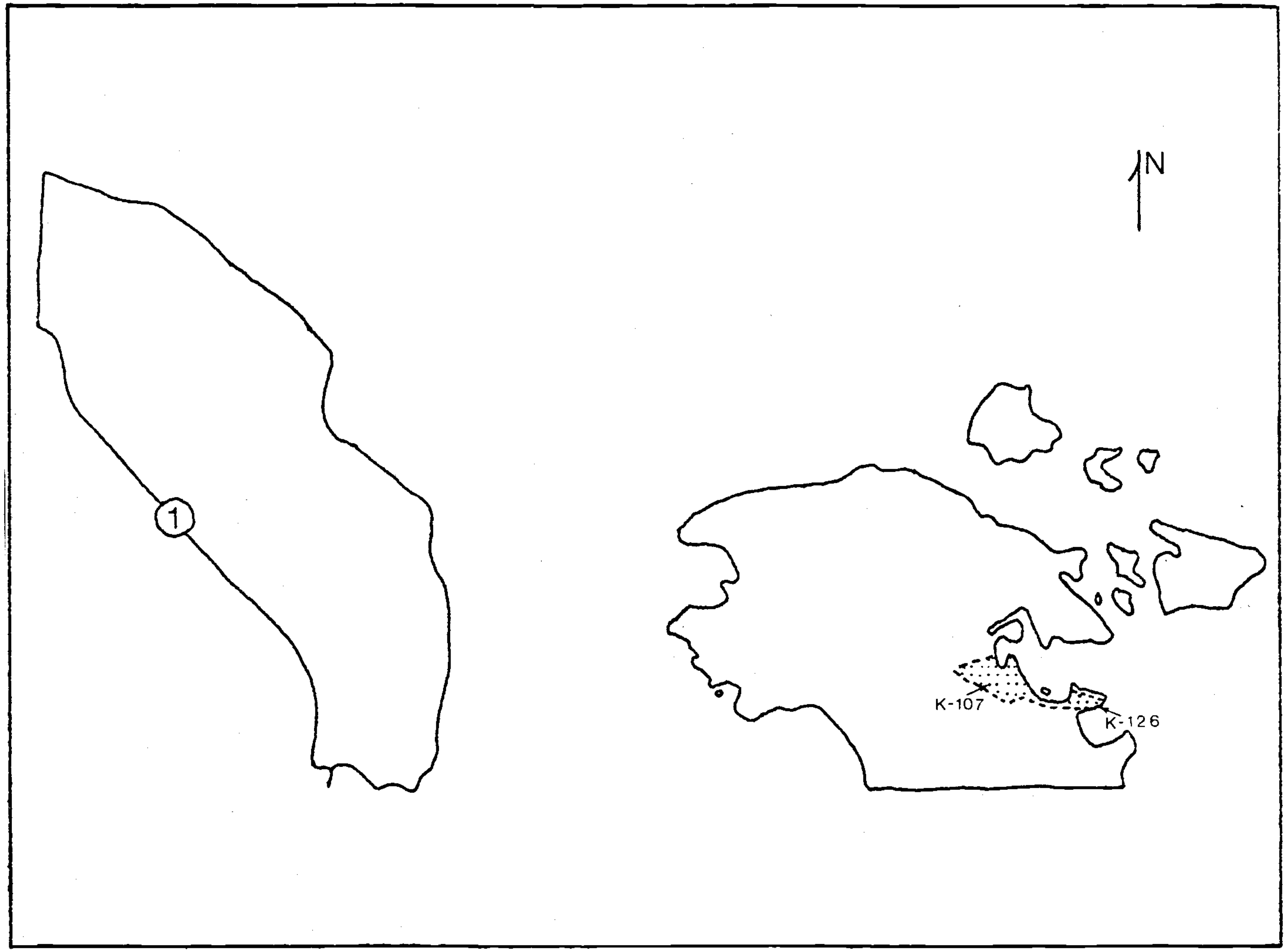


Figure 4: Bonanza Volcanics distribution and sample localities.

Comox Formation (for a description, see Stratigraphy section of the Comox Formation). The small island on which Rest Haven Hospital is located is composed of Bonanza Volcanics, as well as the peninsula at Mill Point to the northwest. Highway 17 cuts through Bonanza Volcanics 0.6 miles west of All Bay. No Bonanza Volcanics occur in the Cobble Hill area.

The Late Triassic through Early Jurassic volcanics are intruded by the Middle to Late Jurassic Island Intrusions. This intrusive contact can best be studied along the northern shoreline of Roberts Bay immediately to the south of Armstrong Point. The volcanics are cut by numerous small (less than 1 foot wide) dioritic to dacitic dikes and stringers. The dike material likely cooled fairly rapidly because of the thin nature of the dikes and the fact that no alterations of the volcanics at the contacts with the dikes are observed. The dikes apparently are associated with the general fracture and fault systems in the area, as most dikes have either northwest or northeast trends. The volcanics are hydrothermally altered at one location along the intrusive contact where they are brecciated and infilled by silica and calcite. The volcanics are generally low rank, greenschist facies metamorphosed, as evidenced by their platy nature and chloritic composition. The metamorphism apparently is the result of increased pressures and temperatures associated with the intrusions.

The Bonanza Volcanics generally are altered to chlorite and epidote and have the general appearance of greenstones. Fresh surfaces, although difficult to obtain, are dark greenish gray (5G 4/1). The volcanics have weathered surfaces that range in color from greenish black (5G 2/1) to grayish red (10R 4/2). They mainly are of an andesitic composition, with finely crystalline plagioclase feldspar and hornblende phenocrysts in a finely crystalline to aphanitic feldspathic groundmass. At some locations the volcanics are fractured to brecciated. A more detailed analysis of the petrography of the Bonanza Volcanics is given in the Petrology section.

Outcrops of the Bonanza Volcanics are non-resistant because of alteration and fracturing. The rocks weather to thin, chloritic plates and larger (to 8 inches) talus blocks. They usually break along preexisting fractures when hit with a geologic hammer, making fresh surfaces difficult to obtain in the field. Topographically low areas and tidal mud flats in the study area tend to coincide with Bonanza Volcanics bedrock localities.

Island Intrusions (Saanich Granodiorite)

Nomenclature

Eastwood (1965) classified all granitic intrusions exposed on Vancouver Island as Island Intrusions. The irregularly shaped intrusive bodies are mainly composed of quartz diorite and granodiorite, grading laterally to quartz monzonite at some localities (Muller, 1975). K-Ar radiometric age dating indicates the time of intrusion of these plutonic bodies at about 159 million years ago (Symons, 1971), or Middle to early Late Jurassic. The Island Intrusions have been correlated to the Coast Intrusions of mainland British Columbia (Fyles, 1955, and Muller and Carson, 1969). The intrusions of southern Vancouver Island, including the North Saanich and Cobble Hill areas, were originally named the Saanich Granodiorite by Clapp (1914) and Clapp and Cooke (1917). Fyles utilized this name in describing the intrusions of the Cowichan area, and this paper will also refer to the intrusive rocks in the study area as the Saanich Granodiorite.

Areal Extent, General Description

Within the thesis area the Saanich Granodiorite has, next to the Comox Formation, the greatest areal extent (Figure 5, Plate 1). In the Cobble Hill area, the granodiorite is exposed along several road cuts along Highway 1 and also along the shoreline north from Hill Point to about 0.5 miles south of Hatch Point. In North Saanich, the intrusions are exposed at numerous localities. The shoreline from Patricia Bay to Towner Bay, the point 0.6 miles southeast of Coal Point, and the shoreline from Roberts Point to the northern shoreline of Roberts Bay are composed of Saanich Granodiorite and

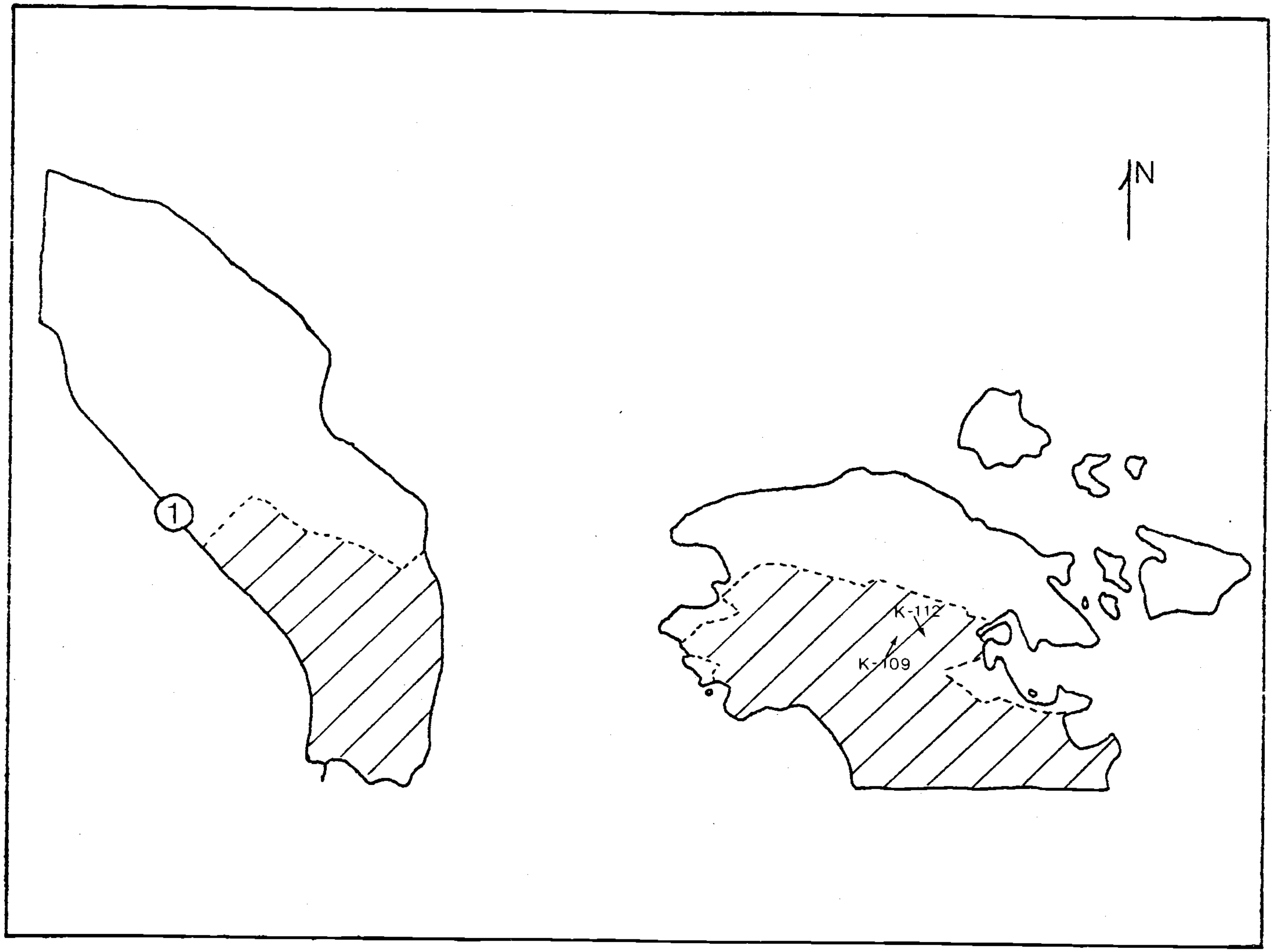


Figure 5: Saanich Granodiorite distribution and sample localities.

associated dioritic to dacitic dike systems. Inland, road cuts around McDonald Provincial Park and along Wain and Tatlow Roads expose Saanich Granodiorite, and the hills southeast of Deep Cove are also composed of granodiorite outcrops. Other Saanich Granodiorite locations have been determined from water well log data supplied by the North Saanich Municipality and from isolated outcrops and road cuts throughout the study area.

The intrusive contact with the Bonanza Volcanics has been described in the previous section, and the upper nonconformable contact with the overlying Comox Formation is described in the Comox Stratigraphy section. These contact relations show the relative age of the granodiorite, as the plutonic rocks intrude rocks of Early Jurassic age and are nonconformably overlain by Late Cretaceous sediments. The Saanich Granodiorite is thus younger than the Bonanza Volcanics but was a cooled mass undergoing erosion during the Late Cretaceous.

Although the Saanich Granodiorite is broken by numerous cross-faults and is highly jointed and fractured, no measurements of these patterns were taken in the field area. The fractured pattern of the granodiorite is readily seen in outcrop, with slickensides observed along some joints, as at one location east of Deep Cove. These fractures and joints aid in the weathering of the granitic rocks making fresh samples difficult to locate. Surprisingly, because of its fractured nature the granodiorite is a fairly good water reservoir, with numerous water wells passing through the generally impermeable Comox sandstones and tapping the underlying Saanich Granodiorite in the North Saanich area.

Fresh surfaces of the granodiorite range in color from light gray (N 7), to medium light gray (N 6), to pinkish gray (5YR 8/1). At some locations, especially south of Deep Cove, the granodiorite is medium bluish gray (5B 5/1) in color. When weathered, the Saanich Granodiorite is very light gray (N 8), yellowish gray (5Y 8/1), or greenish gray (5GY 6/1). Associated dacitic dikes are greenish gray (5G 6/1) weathering to greenish gray (5GY 6/1). Fresh surfaces of the dioritic dikes are light gray (N 7) but weather to a moderate brown (5YR 4/4) color, probably due to iron oxide staining.

The composition of the Saanich Granodiorite varies throughout the study area. Generally, it is composed of medium-crystalline quartz, plagioclase feldspar, potassium feldspar, hornblende, and biotite. At some localities the granodiorite is porphyritic, with plagioclase and pink potassium feldspar crystals up to 3 inches long. Along the shoreline north of Mill Bay in the Cobble Hill area, the granodiorite is cut by greenish gray (5GY 6/1), quartz-rich felsite veins ranging in size from 0.5 to 2 inches across. The dacitic dikes of the Island Intrusions contain euhedral, medium-crystalline plagioclase phenocrysts in an aphanitic feldspathic groundmass. A complete petrographic description of the Saanich Granodiorite is given in the Petrology section.

At numerous localities the Saanich Granodiorite contains rounded mafic inclusions ranging in size from less than 0.5 to over 3 inches long. These inclusions are dusky yellow green (5GY 5/2) to medium dark gray (N 4) in color and are composed either of irregularly oriented, elongated crystals of hornblende or hornblende and plagioclase phenocrysts in an aphanitic groundmass. These small mafic inclusions and fragments can be regarded as remnants of stoped blocks or incorporated wallrock (Fyles, 1955).

LATE CRETACEOUS STRATIGRAPHY

General Statement

The four oldest formations of the Nanaimo Group crop out in the thesis area. The Comox, the oldest formation of the group, consists of fluvial to lagoonal conglomerates, sandstones, siltstones, mudstones, and coals overlain by marine mudstones, siltstones, and fine-grained sandstones of the Haslam Formation. These two formations apparently comprise a continuous, transgressive depositional cycle, beginning with the basal, erosional contact between fluvial conglomerates and sandstones of the Benson Member of the Comox and the underlying Jurassic igneous rocks, continuing through the gradational contact between the lagoonal to shallow marine Comox sandstones and siltstones and the marine mudstones of the Haslam Formation, and finally to the upper disconformable contact with the overlying, coarser grained units of the Extension-Protection Formation. Above this disconformity begins a second depositional cycle consisting of deltaic to lagoonal conglomerates, sandstones, mudstones, and coals of the Extension-Protection Formation overlain by marine mudstones, siltstones, and fine-grained sandstones of the Cedar District Formation, again in gradational contact with each other. Because a complete section of the Cedar District Formation is not present in the study area, these two formations do not represent a complete depositional cycle in this location.

The recent studies by Oregon State University students under the direction of Dr. Keith F. Oles have revealed that these successions possibly represent upward-coarsening cycles of delta progradation. This is in contrast to the cyclic depositional sequence hypothesis of Muller and Jeletzky (1970) and also to the generally fining upward trend of the Comox to Haslam Formations and the disconformable contact between the Haslam and the Extension-Protection Formations observed in the field in the study area. The younger formations of the Nanaimo Group may indeed be upward-coarsening cycles of delta progradation, but at least the three oldest formations of the group probably are not. This subject is discussed in more detail in the Geologic History section.

Comox Formation

Nomenclature

The Comox Formation was first named by Clapp (1912) for the sandstone-siltstone-coal sequence common to the Comox Basin near Comox, Vancouver Island. The basal Benson conglomerates at Nanaimo were at first considered to be noncorrelative to the Comox sequence, but later were included as a member of the Comox Formation (Muller and Jeletzky, 1970).

Stratigraphy

The Comox Formation crops out over a large part of the thesis area (Figure 6, Plate 1). In the Cobble Hill area, a continuous outcrop of the Comox, dipping about 45 degrees northeast, forms a large part of the shoreline of Hatch Point. Inland to the northwest, sections of the Comox are exposed on the antidip slope of a cuesta extending about a mile along Telegraph Road. More continuous sections of the Comox are exposed in the North Saanich area. A fairly continuous outcrop of the Comox extends north from Towner Bay, around Coal Point, into Deep Cove, around Moses Point, and eastward along the north shoreline of the peninsula. The eastern shoreline of the peninsula from Nymph Point to Swartz Bay is also composed of Comox rocks, as well as the entire shoreline of Fernie and Goudge Islands and the southern shoreline of Coal Island. Inland on the peninsula, the Comox Formation can be studied in road cuts along Lands End Road and Patricia Bay Highway and at outcrops on the antidip slopes of the northeast-dipping Cloake and Horth Hill cuestas. At most other locations, only small, isolated outcrops are exposed among the widespread glacial deposits.

Most outcrops along the shorelines are accessible at low tides; however, some difficulty arises when hiking beneath sea cliffs and along wave-cut benches during high tides. If the tide covers the

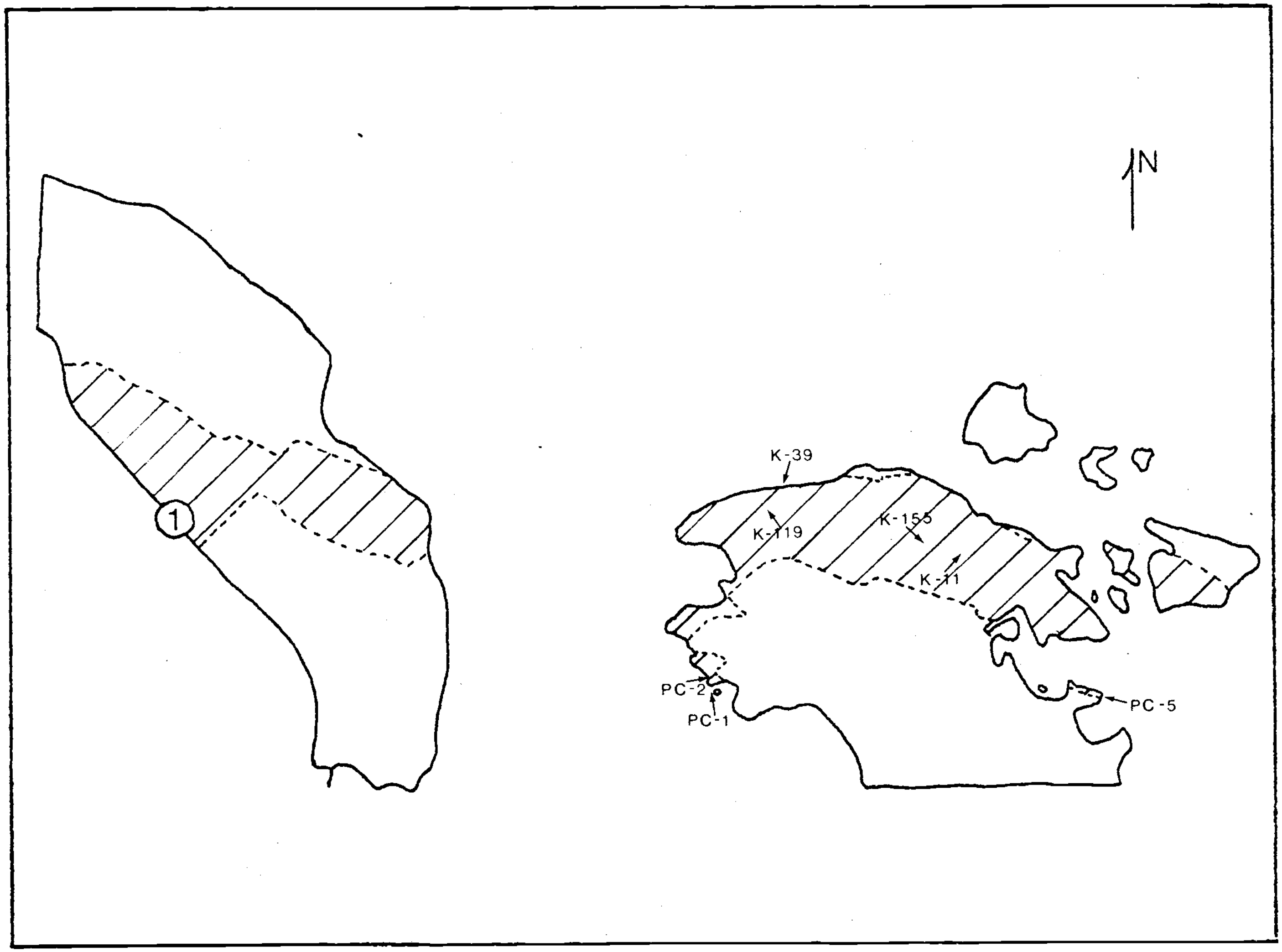


Figure 6: Comox Formation distribution and sample localities for modal analyses and pebble counts.

wave-cut benches, passage along smooth, wet bedding planes parallel to strike can be hazardous as most strata dip at angles greater than 45 degrees into the water. When examining outcrops perpendicular to strike, numerous embayments, representing the less resistant interbedded siltsontes and mudstones of the Comox, are encountered. The more resistant sandstones extend outward from the shoreline, acting as natural groins for sediment capture and beach formation and forming protective coves used for boat landings and wharves.

The basal Benson Conglomerate Member of the Comox Formation, because of clast compositional and matrix size variability, weathers and erodes more rapidly than the sandstone units. At some locations, where the contact between the Comox Formation and the underlying igneous rocks is inferred and Benson Conglomerate is expected, embayments and valleys are noted. For example, in the Cobble Hill area, the basal contact of the Comox is covered inland and forms a small bay to the south of Hatch Point. In North Saanich, this contact is interpreted to occur at the southwest base of the Horth and Cloake Hill cuestas, but does crop out immediately southeast of Deep Cove and along the shoreline north of Towner Bay and at Armstrong Point.

Immediately north of Towner Bay, the Benson Conglomerate is in direct contact with the Jurassic Saanich Granodiorite. This contact consists of a nonconformable, erosional surface of the granodiorite having as much as three feet of relief. The sandstones and conglomerates of the Benson infill basement bedrock irregularities, indicating that the Saanich Granodiorite was possibly a topographic high undergoing erosion during the initial Late Cretaceous transgression. Pebbly sandstone forms the base of the Benson, coarsening upward to a thick conglomerate unit (Figure 7). Alternating beds of conglomerate and sandstone yield upsection to pebbly sandstones, sandstones, and siltstones. Some sandstone beds are finely laminated and grade normally to siltstone and mudstone laminae. Mud rip ups and flame structures (Figure 8) are also observed upsection from the contact, indicating cohesion of the muds during calm flow regimes disrupted by an influx of coarser sediments at higher energy flows. The conglomerate units are firmly indurated, with most clasts well-cemented within the matrix but breaking loose as a result of weathering and wave activity. The clasts consist of subrounded granitic, metamorphic, volcanic, and quartzitic pebbles, cobbles, and boulders, as well as subangular cobbles and boulders of granodiorite having dimensions of up to three feet in diameter. Some of the subangular boulders disrupt bedding, having apparently fallen from cliffs and outcrops into noncohesive sediments, and then buried by additional finer grained material.

The Benson Conglomerate is also exposed at Armstrong Point (Figure 9), again in erosional, nonconformable contact with the

Figure 7. Overturned, nonconformable contact between Benson conglomerate and underlying Saanich Granodiorite. Note the fractured granodiorite, erosional depositional surface, and pebbly sandstone base of the Benson. Unnamed point immediately north of Towner Bay.

Figure 8. Flame structures, parallel laminations, and convolute laminations within Benson Member sandstone unit. Sampled 50 feet upsection from overturned basal contact (Figure 7). Note slickensided bedding surface. Sample actually overturned from stratigraphic position.

underlying Jurassic rocks (Bonanza Volcanics). The volcanics were likely also topographic highs undergoing erosion in the Late Cretaceous, as evidenced by the eroded bedrock surfaces trapping coarse sediments on the upstream side of these relief features and causing finer sediments to settle out on the leeward side. The base of section A-B, which begins at this contact, consists of 35 feet of Benson Conglomerate strata. Hanson (1976) determined a thickness of 46 feet for the Benson at Lake Maxwell on Saltspring Island, some eight miles northwest of Armstrong Point. Muller and Jeletzky (1970) note that the Benson Conglomerate is quite variable in thickness, depending on the local conditions of deposition.

Sedimentary structures within the conglomerate units of the Benson are rare, with pebble alignment noted at only a few locations and pebble imbrication generally nonexistent. Pebble lithology from the individual conglomerate beds and matrix petrography is discussed in detail in the Petrology section. The conglomerates are locally hematite stained and generally occur in continuous sheets less than 15 feet thick. Matrix color ranges from light olive gray (5Y 5/2) to medium light gray (N 6) fresh to grayish olive (10Y 4/2) weathered.

The contact between the Comox and the overlying Haslam is best exposed on the extreme northern point of the North Saanich Peninsula. This contact, separating the generally coarse-grained strata of the Comox from the mudstones, siltstones, and fine-grained sandstones of the Haslam, is gradational over about 15 feet as sandstone grades to siltstone and finally to structureless mudstone. Calcareous concretions from two to eight inches in diameter are abundant in both formations at the contact. Exfoliation and chippy weathering units prevail east of the contact in contrast to sea cliffs and dip slopes of sandstone to the west. The Haslam Formation grades from mudstone to interbedded sandstone-siltstone-mudstone upsection from the contact.

Four reference sections were measured to determine the stratigraphic character and approximate thickness of the Comox in the study area. A basal section including the Benson Member is presented in Appendix I. Because of faulting and cover, neither the actual thickness nor a complete section of the Comox could be obtained; however, a total thickness, calculated from available outcrop position, cumulative measured sections, and stratigraphic position, is approximately 2,200 feet. This is somewhat thicker than the 1,300 feet measured by Hanson (1976) for the Comox on Saltspring Island. In 1913, a mining company with German interests drilled a well southwest of Cloake Hill in search of coal measures. The well penetrated 1,086 feet of strata dipping 45 degrees northeast, or approximately 800 feet of the Comox Formation. A fairly detailed log was kept during drilling and was made available by the North Saanich Municipality. Because the underlying bedrock was not encountered

Figure 9. Nonconformable contact between Jurassic Bonanza Volcanics and overlying Late Cretaceous Comox Formation (Benson Member conglomerate). Armstrong Point, North Saanich Peninsula.

Figure 10. Trough cross-bedding within Comox sandstone. Note honeycomb-weathered surface. Immediately north of Hatch Point, Cobble Hill area.

and the overlying Haslam Formation is not present at the drill site, this log only represents another incomplete section for part of the Comox Formation.

Sandstones compose the bulk of the Comox Formation. Generally medium gray (N 6) fresh, they weather to greenish gray (5GY 6/1) and olive gray (5Y 4/1). The angular to subangular grains are composed of quartz, feldspar, chert, rock fragments, and biotite. Selective removal of less resistant, finer grained minerals from weathered outcrop gives an appearance of a coarser grained, better sorted sandstone when weathered than when fresh. Silica, calcite, and clay minerals generally infill likely pore spaces, reducing porosity to almost zero. Fractures common to the sandstone units usually are elevated from outcrop surfaces, because of the selective calcite cementation along fracture surfaces which makes them more resistant to weathering and wave activity. Honeycomb weathering of the sandstone surfaces (Figure 10) usually occurs along the shoreline and sea cliffs and is presumably the result of weathering by salt water spray. Gallery structures (Figure 11) are also common along the shoreline. Described by Stickney (1976), these galleries are possibly the end result of removal of concretions by weathering activity and enlargement of the cavities by continued erosion. The smooth, recessed surfaces in galleries generally exhibit sedimentary structures which usually are masked on weathered outcrop surfaces.

The finer grained units of the Comox Formation are less resistant to erosion than the coarser sandstones and conglomerates. Topographic lows, talus slopes, and embayments are noted to coincide with siltstone and mudstone strata. Siltstone outcrops exhibit onion-skin weathering; the exfoliation occurs in oval sheets less than 0.25 inches thick which break away from a central spheroid and have a veneer of manganese and iron oxide between the individual sheets (Figure 12). Carbonized wood and plant debris and discontinuous coal veins are also common to the siltstones and mudstones of the Comox. Generally dark gray (N 3) fresh, the mudstones weather to light gray (N 7), olive gray (5Y 4/1), and grayish red (10R 4/2). The reddish mudstones weather to brittle chips and apparently contain large amounts of iron.

Many beds of the Comox contain fossils and concretions. Fossil leaves are most abundant along bedding planes in thinly bedded sandstone units and in carbonaceous pods common to the mudstone units. Wood fragments, ranging from less than an inch to over a foot long, also occur along bedding planes in many localities. Bivalves, including large, thick shelled Inoceramus fragments, are usually disarticulated and broken. Trace fossils, similar to Planolites noted by Hanson (1976), are common to bedding surfaces in the Hatch Point area. A single echinoid was sampled from a silty, carbonaceous unit of the Comox cropping out along Lands End

Figure 11. Gallery structure within Comox sandstone exposing cross-laminations. Note elevated fracture surfaces. 0.25 miles north of Hatch Point, Cobble Hill area.

Figure 12. Concretions sampled from Comox Formation. Note exfoliation and manganese and iron oxide staining of concretion on left and hash of bivalves within concretion on right.

Road in North Saanich. Gastropods also are common to the Comox, usually in association with bivalves in fossiliferous units. Elongate, oval, and spheroidal concretions generally lie parallel to bedding surfaces. When broken, they contain a hash of bivalves, carbonized wood fragments, iron oxide staining, or nothing.

Discontinuous coal seams are noted immediately south of Coal Point, at Nymph and Kingfisher Points, and at 39 feet on Section C-D and 365 feet on Section E-F. The coal is generally low rank, brittle, sooty, and limited to seams ranging from 0.25 to 3 inches thick that pinch out over distances of less than five feet. In some instances, the coal seams extend from a central carbonaceous mass, as shown in Figure 13.

Sedimentary structures common to the Comox Formation include local pebble imbrication and alignment, asymmetrical ripples, symmetrical ripples, interference ripples, festoon cross-lamination, laminated bedding, flame structures, mud rip ups, channeling, graded bedding, loading features, and large-scale cross-bedding. Paleocurrent directions and a discussion of the dispersal patterns are given in the Geologic History section.

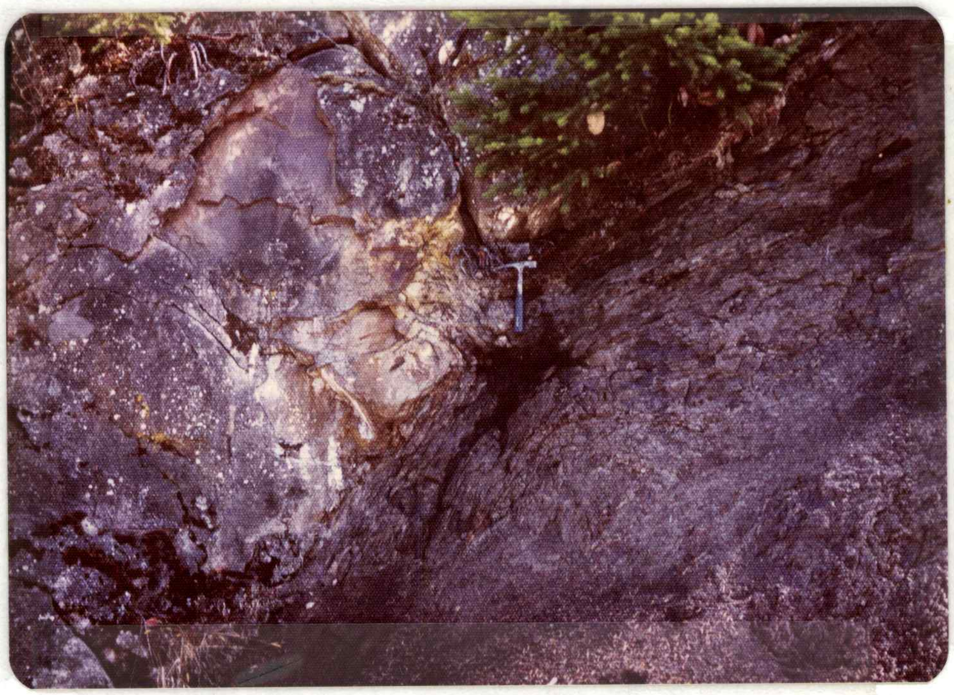


Figure 13. Loading phenomenon within Comox Formation. Note siltstone compaction by and projection into overlying sandstone. Note also discontinuous coal veins extending from central coaly mass hear hammer. Raod cut 0.6 miles southwest of Swartz Bay along Highway 17.

Figure 14. Sharp contact between topmost siltstone unit and overlying basal sandstone unit of normally graded Comox sandstone to siltstone sequences. Road cut 0.5 miles southwest of Swartz Bay along Highway 17.

Haslam Formation

Nomenclature

The name, Haslam Formation, was proposed by Clapp (1912a) for the mudstones near Nanaimo at Haslam Creek. Clapp (1912b) also originally named the basal mudstone section of the Comox Basin the Trent River Formation and correlated it to the Cedar District Formation of the Nanaimo Basin. However, Muller and Jeletzky (1970), using molluscan faunas, determined that the Trent River and Haslam mudstones are time-correlative and proposed that the name Haslam be adopted for both sections.

Stratigraphy

The Haslam Formation is a non-resistant mudstone, siltstone, and fine-grained sandstone unit overlying the coarser grained Comox Formation. Because it is readily eroded, exposures of the Haslam are scarce in the study area, limiting field mapping to isolated outcrops, geomorphic and aerial photo interpretation, and stratigraphic position.

The Haslam Formation crops out along the shoreline immediately north of Hatch Point in the Cobble Hill area, along the northernmost point of the North Saanich Peninsula, along the shoreline west of Swartz Bay, and along the southern shorelines of Piers and Knapp

Islands (Figure 15, Plate 1). Valleys, coastal embayments, and topographic lows generally coincide with predicted Haslam Formation positions. For example, the central valleys trending northwest from Boatswain Bank in the Cobble Hill area and those of Coal Island are interpreted localities of Haslam Formation bedrock. The Haslam dips approximately 50 to 60 degrees to the northeast in the Cobble Hill area and on the North Saanich Peninsula, but attains dips of up to 85 degrees northeast on Piers and Knapp Islands.

The basal contact of the Haslam Formation with the underlying Comox Formation has been described in the previous section. The upper contact with the overlying Extension-Protection Formation is best exposed on Piers and Knapp Islands (Figure 16). On Piers Island, the Haslam crops out as a normally graded silty sandstone to mudstone sequence dipping approximately 81 degrees northeast. The disconformable surface between these two units is planar, showing no erosional relief between the two units. On the disconformity lie the basal conglomerates of the Extension-Protection Formation, containing no apparent Haslam mudstone rip ups. A direct measurement of the attitude of the conglomerate beds was not possible at the contact because of a lack of distinctive bedding; however, interbedded sandstones in the Extension-Protection conglomerates dip initially at about 70 degrees and finally at about 64 degrees northeast farther upsection. On Knapp Island, the continuous silty sandstone to

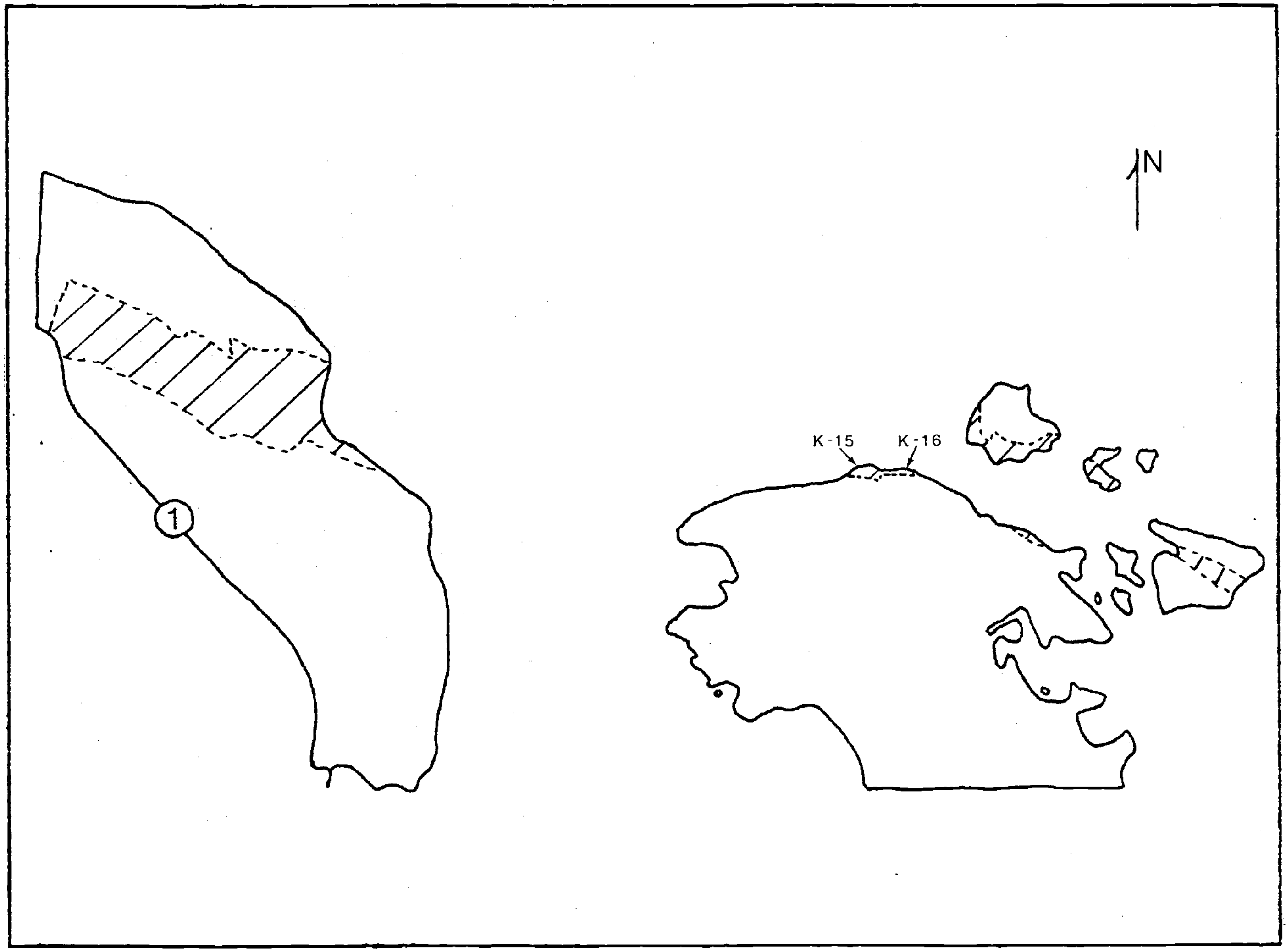


Figure 15: Haslam Formation distribution and sample localities for modal analyses and X-ray diffractions.

mudstone sequences also are abruptly overlain by Extension-Protection conglomerates, but the disconformable surface is more irregular, with Haslam Formation mudstone rip ups and inclusions incorporated within the Extension-Protection conglomerates.

Because of the erosive nature of the Haslam Formation, a complete section is not present within the thesis area; however, from its stratigraphic positions and the dips of exposed units, a total thickness of 550 feet is estimated. Muller and Jeletzky (1970) gave a thickness of 400 feet for the Haslam on Saltspring Island; this was refined by Hanson (1976) to 600 feet from a measured section at Maxwell Creek.

The mudstones of the Haslam are medium dark gray (N 4) to dark gray (N 3), both fresh and weathered. Silty sandstone units are medium light gray (N 6) fresh to light olive gray (5Y 6/1) or dark yellowish brown (10YR 4/2) weathered. The clay mineralogy and petrography of the Haslam Formation units are described in detail in the Petrology section. Sandstone beds generally have groove marks or mudstone rip ups at their base, contain internal flaser laminae, and grade normally to laminated siltstone and then to laminated mudstone. The sand grains are subangular to rounded quartz, plagioclase, and biotite, with calcite cement and a clay matrix.

Both the sandstone and the mudstone units of the Haslam Formation contain concretions. Within the mudstones, they usually

Figure 16. Contact between Haslam Formation and overlying basal conglomerates of Extension-Protection Formation. Note cyclic nature of the silty sandstone to mudstone units within the Haslam Formation. Easternmost shoreline of Piers Island.

Figure 17. Convolute laminations within Haslam Formation silty sandstone units. Sampled from southeastern shoreline of Piers Island.

are elongate to oval, up to 18 inches long by 6 inches wide, and aligned parallel to bedding. The concretions generally are medium dark gray (N 4) fresh, weathering to light gray (N 7). When fractured, many yield a variety of disarticulated bivalves, whole and broken ammonites, thick-shelled Inoceramus fragments, gastropods, carbonized wood, and finely disseminated pyrite. Many of the fossils are well preserved and still display original mother-of-pearl surfaces. Many concretions contain no obvious organic remains, only sparry calcite veins which are likely the result of remobilization of calcite from dissolved calcite tests. This is most common in the concretions in the sandstone units.

Haslam Formation mudstones usually weather to small, flattened chips less than one inch in diameter. At one locality, the mudstone has weathered to elongate, diamond-shaped chips about one inch long by a half inch wide. The silty units are exfoliated, with oval plates separating from a centralized mass, as described for the Comox siltstone units. Calcareous concretions are more resistant than the mudstones in which they are incorporated and thus weather from outcrops and fall below. Wave-cut benches of the Haslam are usually overlain by loose concretions as current action has removed the smaller, weathered chips of mudstone. Where wave activity is less intense, rounded mudstone chips less than 0.5 inch in diameter accumulate as beach deposits on Haslam outcrop locations.

The cyclic nature of the silty sandstone to mudstone units of the Haslam is best observed on Piers Island along wave-cut benches and sea cliffs (Figure 16). The sandstone beds, being more resistant to erosion, extend outward between the eroded mudstone beds. Soft sediment deformation in the form of ball and pillow structures and small-scale internal slumping features similar to convolute laminations (Figure 17) are noted within the sandstone units, and are likely the result of syn- and/or post-depositional slump or creep down the paleoslope. Most of these features are either non-directional or bidirectional and thus were not useful in the determination of the paleoslope. Selective weathering of the internal laminae make them quite noticeable in outcrop. Cross-laminations formed by migrating ripples were also observed in many of the sandstone units. Sandstone strata within these sandstone to mudstone to mudstone sequences range from two to eight inches thick, whereas interbedded mudstones attain thicknesses of up to 12 inches.

Soft sediment deformation of the Haslam Formation sequences is noted on a large scale on Piers Island (Figure 18). The silty sandstone to mudstone sequences are folded into tight chevrons in sets greater than eight feet thick. This may also be the result of large-scale downslope creep of the semi-coherent units before lithification. These features, combined with the fact that the strata dip

Figure 18. Large-scale, soft sediment deformation in the form of chevron folds within Haslam Formation. Southeasternmost shoreline of Piers Island.

Figure 19. Conglomerate channel-fill within Extension-Protection Formation. Note crude pebble alignment. Easternmost shoreline of Piers Island.

almost vertically in the area, may also have been caused by post-depositional faulting and drag.

Extension-Protection Formation

Nomenclature

Originally subdivided into the East Wellington, Extension, Newcastle, and Protection Formations by Clapp (1912a) to describe the strata near Nanaimo, these formations were grouped into one by Muller and Jeletzky (1970). The name, Extension-Protection, is derived from the town of Extension, where conglomerates of the formation occur, and Protection Island in Nanaimo Harbor, where a section of the sandstones of the formation crops out.

Stratigraphy

The Extension-Protection Formation is best studied along beach exposures and at a few isolated inland outcrops in the thesis area. In the Cobble Hill area, the only outcrop of the formation occurs at Cherry Point; however, the east and west shorelines of Piers Island and the north shorelines of Knapp and Coal Islands are comprised entirely of Extension-Protection Formation strata (Figure 20, Plate 1). The ridge trending northwest-southeast from Fir Cone to Charmer Points on Coal Island is a northeast-dipping hogback of

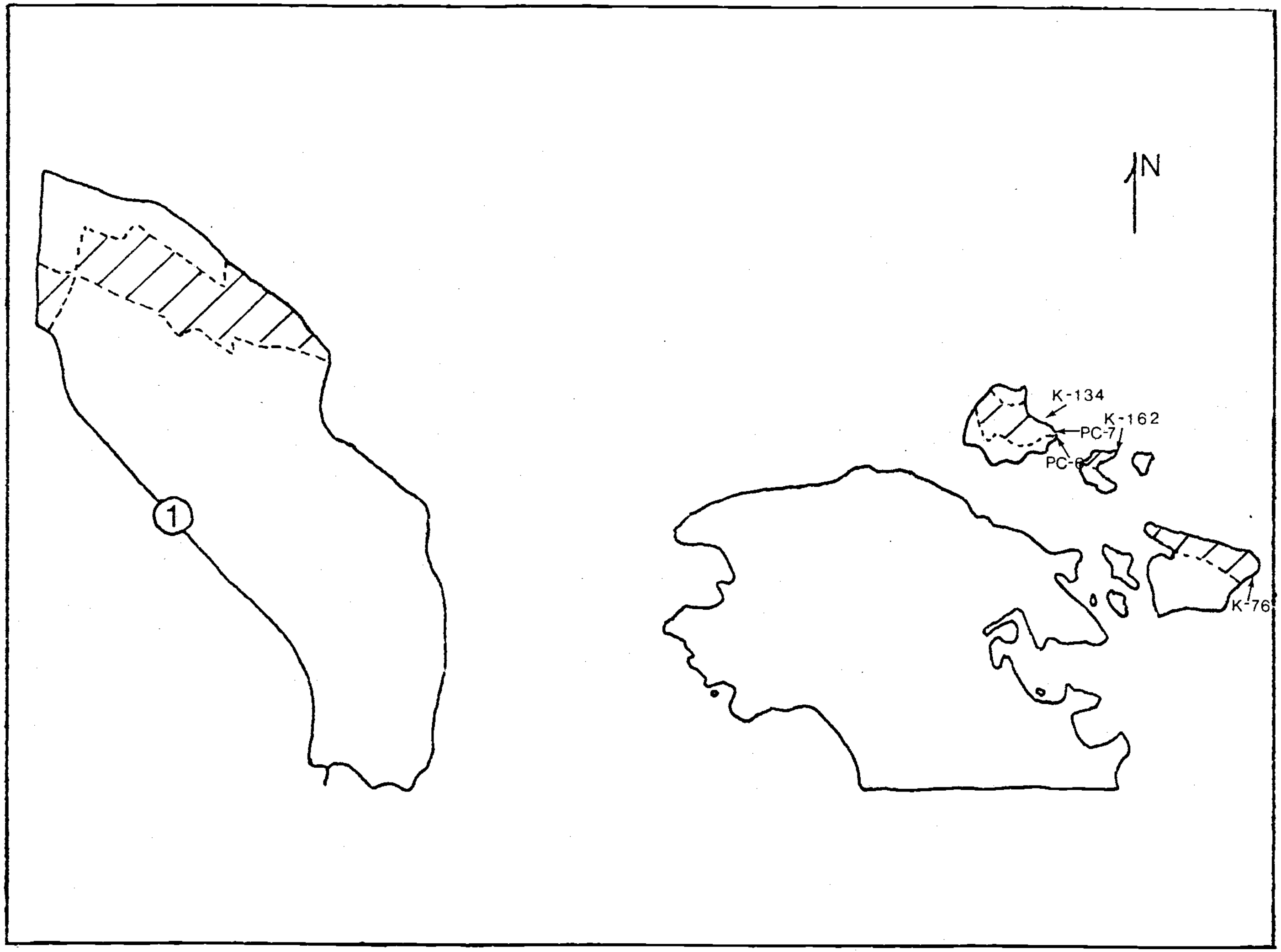


Figure 20: Extension-Protection Formation distribution and sample localities for modal analyses and pebble counts.

the formation. The Extension-Protection dips from approximately 45 degrees northeast at Cherry Point to 80 degrees northeast on Coal Island.

The basal contact with the underlying Haslam Formation has been described in the previous section. The upper contact, separating the coarser grained strata of the Extension-Protection from the finer grained silty sandstones, siltstones, and mudstones of the Cedar District Formation, is conformable and gradational over about 50 feet. This is best observed along the northeast shoreline of Piers Island, where sea cliffs and dip slopes of the Extension-Protection give way to the wave-cut benches, embayments, and beaches more common to the Cedar District Formation.

A representative section of the Extension-Protection Formation was measured and described on Piers Island (Appendix I-a). The formation was noted to undergo numerous lithological changes laterally within the section; conglomerates grade laterally into sandstones parallel to strike whereas sandstones contain numerous discontinuous channels and scour-and-fill structures that range in size from 5 to 15 feet across. The formation initially fines upward from conglomerates, pebbly sandstones, and channel sandstones to sandstones, siltstones, and mudstones. A second fining upward sequence overlies the first; it begins with an erosional disconformity between the underlying mudstones and the overlying sandstones and conglomerates, grades to channel conglomerates (Figure 19), coarse- to medium-grained, medium-bedded sandstones, pebbly sandstones, and finally to medium- to fine-grained, thinly bedded sandstones and laminated siltstones. The Extension-Protection then grades from siltstones to mudstones of the Cedar District Formation. A total thickness of 580 feet was measured for the Extension-Protection at this location, with a combined thickness of 1,250 feet approximated for the formation in the study area. Although Muller and Jeletzky (1970) estimate a total thickness of 1,900 feet for the formation in the Nanaimo area, Hanson (1976) measured thicknesses of between 180 and 1,300 feet for the Extension-Protection on Saltspring Island, some five miles to the northwest of Piers Island.

The basal conglomerates of the Extension-Protection have a total thickness of about 90 feet, are thickly to very thickly bedded, and have a matrix color ranging from medium gray (N 5) to medium dark gray (N 4) fresh to greenish gray (5GY 6/1), dark greenish gray (5GY 4/1), and light olive gray (5Y 5/2) weathered. The conglomerate clasts are elongated, subrounded to angular granitic, volcanic, quartzitic, chert, greenstone, mudstone, and sandstone pebbles, cobbles, and boulders. The well-indurated conglomerates interfinger with medium-bedded, coarse-grained sandstones that pinch out laterally over distances of less than ten feet. Both the interfingering sandstones and the conglomerate matrix are composed of angular to subrounded quartz, feldspar, rock fragments, and biotite in a fine-grained, clay and silica matrix that at places is cemented by calcite.

Upsection from the basal conglomerates and channel sandstones lie pebbly sandstones, channel conglomerates, medium- to coarse-grained medium-bedded sandstones, concretionary sandstones, pebbly siltstones, siltstones, and mudstones. The rhythmic, normally graded sandstone to carbonaceous siltstone sequences common to the Comox Formation are absent in the Extension-Protection on Piers Island. Conglomerates are more dominant within the formation than siltstones and are noted to occur in the upper part of the section, not just as a basal unit as in the Comox Formations. Disconformities between underlying mudstones and overlying sandstones also occur within the formation, as well as minor coarsening upward sequences of sandstones to conglomerates. Thickly bedded, medium-grained sandstones with conglomerate channels dominate upsection, at places grading to siltstones and finally to the overlying silty sandstone, siltstone, and concretionary mudstone sequences of the Cedar District Formation.

The sandstones of the Extension-Protection Formation are composed mainly of angular to subrounded grains of quartz, chert, plagioclase feldspar, biotite, muscovite, and volcanic and low-grade metamorphic rock fragments. They generally are well-indurated and cemented by calcite and range in color from medium gray (N5) fresh to light olive gray (5Y 6/1) weathered. The siltstones and mudstones of the formation exhibit onionskin weathering and are colored medium gray (N 5) to medium light gray (N 6), both fresh and weathered. Complete petrography of the Extension-Protection Formation units is given in the Petrology section.

Calcareous concretions are common to both the sandstones and mudstones of the formation, ranging in color from medium gray (N 5) to dark gray (N 4) fresh to light gray (N 7) weathered. Broken Inoceramus tests and wood fragments are found within the concretions, but generally they contain nothing. Most concretions are elongate to oval, attain dimensions of up to ten inches long by three inches wide, and lie parallel to bedding.

Fossils are less common to the Extension-Protection than the Comox. Carbonized wood fragments, 0.5 to 1 inch thick, discontinuous coal seams, gastropods, and disarticulated Inoceramus shells are the only organic remnants noted within the formation. Both the wood fragments and the coal seams generally lie along bedding surfaces.

On the whole, the strata of the Extension-Protection Formation exhibit the same weathering characteristics as the Comox Formation. Honeycomb and gallery structures, as well as elevated fracture ribs such as those described in the Comox Stratigraphy section are somewhat common to the Extension-Protection. Sandstones erode to sea cliffs, cuestas, and hogbacks, whereas the siltstones and mudstones become coastal embayments and topographic lows. Conglomerate units generally are fairly resistant to erosion, especially when occurring as channel fills. The sandstones are extensively fractured and break off into 0.5 inch thick flags when weathered. Mudstones weather to chips less than 1 inch in diameter with the more resistant concretions weathering out from outcrops and falling below.

Asymmetrical and symmetrical ripple marks are the dominant sedimentary structures of the sandstone strata, with pebble alignment (Figure 19), pebble imbrication, scour-and-fill, and channel structures more common in the conglomerates and coarser grained sandstone units of the Extension-Protection Formation. Most paleocurrent data measurements taken were thus bidirectional for the formation, with unidirectional measurements commonly taken in the upper units of the formation. Paleocurrent data and postulated source areas are described in the Geological History section.

Cedar District Formation

Nomenclature

The marine mudstones overlying the coal deposits in the Nanaimo Basin were formally named the Cedar District Formation by Clapp and Cooke in 1917. Muller and Jeletzky (1970) consider the section exposed along the shoreline south of Dodd Narrows as the type section for the formation.

Stratigraphy

The Cedar District Formation is of limited extent in the thesis area (Figure 21, Plate 1). The northern shoreline of Piers Island and all of Pym Island are composed of Cedar District strata. Although no Cedar District Formation rocks crop out in the Cobble Hill area, the southeast- to northwest-trending valley lying north of Cherry Point and into Cowichan Bay is interpreted as being underlain by Cedar District Formation strata. Inland, interpreted Cedar District localities are overlain by a mantle of glacial deposits. On Piers and Pym Islands, the strata dip from over 80 degrees to 90 degrees, with some beds of the formation apparently slightly overturned, dipping 85 degrees to the southwest.

The lower contact of the Cedar District with the underlying Extension-Protection Formation has been described in the previous section. This contact is exposed on Piers Island, where outcrops of the Cedar District are discontinuous, having been eroded into embayments and overlain by glacial and beach sediments. On Pym Island, a more continuous Cedar District section crops out; however, the lower contact is not exposed here. Because the overlying

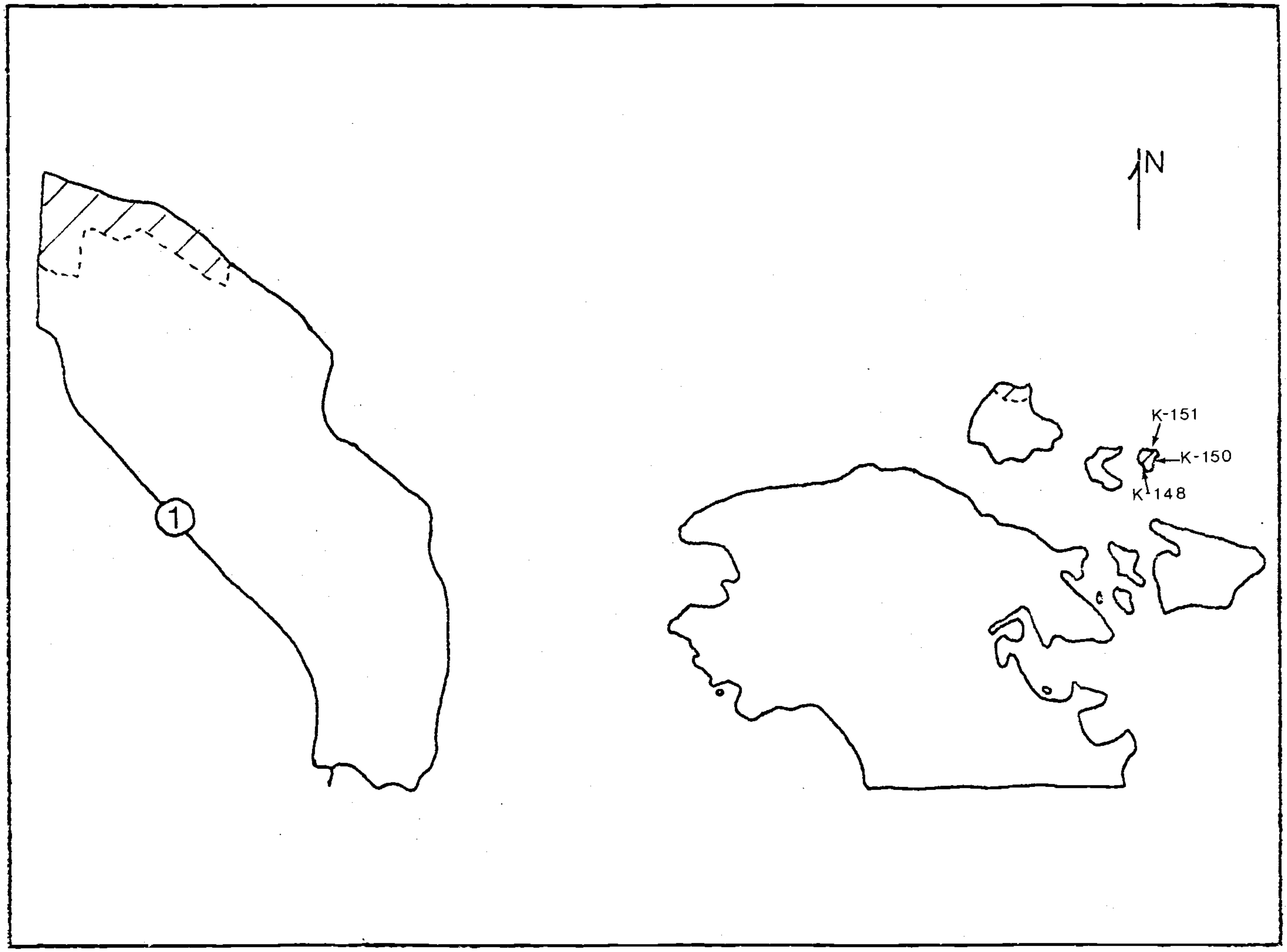


Figure 21: Cedar District Formation distribution and sample localities for modal analyses and X-ray diffractions.

DeCourcy Formation is not found in the study area, the top of the Cedar District cannot be identified in a measured section of the formation. Therefore, a representative section was not measured in the study area because of a lack of a datum or because the section is mainly covered and thus incomplete. The Cedar District Formation is approximated to be at least 1,800 feet in the study area. The type section for the formation, measured and described by Muller and Jeletzky (1970) in the Nanaimo area, is only 1,010 feet thick; however, Hanson (1976) points out that this section may only be equivalent to Hanson's upper member of the Cedar District and estimates a total thickness of over 3,500 feet for the formation on Saltspring Island. The actual total thickness apparently varies according to where within the depositional basin the formation was deposited.

The rocks of the Cedar District are mainly composed of alternating beds of normally graded, fine-grained sandstone, siltstone, and mudstone. These sequences are continuously repeated upsection, with some localities having either thicker mudstone or sandstone units. Because the alternating sandstones are more resistant to erosion than the finer grained siltstones and mudstones, the cyclic strata of the Cedar District form continuous ribs along wave-cut benches and sea cliffs (Figure 22).

Cedar District Formation lithology shows little variation over

Figure 22. Cyclic nature of Cedar District sandstone-siltstone-mudstone sequences exposed along wave-cut benches. Note thickening of sandstone strata to right (north). Note also rounded cobble and boulder glacial erratics. Northeasternmost shoreline of Piers Island.

Figure 23. Inoceramus molds sampled from Cedar District Formation siltstone unit, Harry Point, Piers Island.

the thesis area. The fine-grained sandstones are subangular to subrounded, moderately sorted, thinly laminated, and normally graded. They are composed of quartz, plagioclase, rock fragments, biotite, muscovite, chlorite, carbonaceous debris, and a clay matrix. Locally, the sandstones contain skeletal calcite or are cemented by calcite. The sandstones, ranging in color from medium gray (N 5) to dark gray (N 3) fresh to olive gray (5Y 4/1) and dark yellowish brown (10YR 4/2) weathered, grade to siltstones and mudstones that are medium dark gray (N 4) and weather to medium gray (N 5) and dark yellowish brown (10YR 4/2). The finer grained units weather to conchoidal chips that range in size from 0.25 to 2 inches in diameter. A complete discussion of the lithology of the sandstones and the clay mineralogy of the mudstones is given in the Petrology section.

The mudstones of the Cedar District contain concretions that range in size from 0.5 to 30 inches long by 0.25 to 6 inches wide and lie parallel to bedding. These calcareous concretions are firmly indurated, break conchoidally, and usually yield carbonized wood chips less than 0.25 inch in diameter, broken Inoceramus tests, or nothing. They range in color from medium dark gray (N 4) to medium gray (N 5), both fresh and weathered.

Individual graded fine-grained sandstone to mudstone units are 4 to 18 inches thick, have sharp bottom contacts with basal groove and load casts at some locations, and grade to mudstones over a distance of one to two inches. Parallel laminations, ripple laminations, and cross-laminations are the common sedimentary structures of the sandstones and and siltstones, possibly representing B, C, and D subdivisions of incomplete Bouma sequences (Bouma, 1962).

Well-preserved Inoceramus and molds of Inoceramus are the dominant fossils sampled from the Cedar District (Figure 23). Isolated beds of siltstone and mudstone are highly fossiliferous, with Inoceramus tests lying side-by-side over the entire bedding surface over large areas. Fossiliferous mudstone beds such as these are noted at Harry Point on Piers Island and along the western shoreline of Pym Island. Horizontal burrows are also noted along the western shoreline of Piers Island.

While traversing upsection on Pym Island, the sandstone units of the Cedar District sandstone-siltstone-mudstone cycles are noted to begin to dominate and thicken from six inches to over one foot thick. Along the northern shoreline of the island, the sandstone beds are over 2.5 feet thick and the siltstone and mudstone units generally absent. This may represent the gradational contact between the Cedar District and the overlying, coarser grained DeCourcy Formation as described by Hudson (1974), Hanson (1976), and Allmaras (1978).

PETROLOGY

Igneous Rocks

Bonanza Volcanics

Two thin sections of Bonanza Volcanics were examined to determine mineralogies and rock types. Fresh samples of the volcanics could not be obtained in the field because of three factors: (1) limited exposures of these Early to Middle Jurassic volcanics; (2) their proximity to intrusions of the Middle Jurassic Saanich Granodiorite and the related dikes; and (3) deep weathering. The samples studied consist of finely crystalline groundmass material much altered to chlorite epidote, green clays, and sericite. Incorporated within the groundmass material are euhedral to subhedral phenocrysts of green hornblende and augite that are partly altered to chlorite, as well as unaltered, medium to finely crystalline anhedral quartz (less than 10 percent). A few plagioclase microlites were noted "floating" within the altered groundmass; however, because of the small number and minute crystal size of the plagioclase microlites, no accurate estimation of their composition was possible.

Volcanic clasts and rock fragments occurring within the Nanaimo Group clastics have been determined from thin section analysis to be of andesitic composition (see Sandstones and

Conglomerates Petrology sections). Bonanza volcanics to the west and north of the study area have also been classified as andesites by Muller and Carson (1969) and Muller (1975). The volcanics in the North Saanich area underlying the Cretaceous Nanaimo Group therefore are also possibly of an original andesitic composition.

Saanich Granodiorite

Three thin sections of the Saanich Granodiorite were examined for classification purposes. Two of these samples were point counted with a minimum of 300 counts taken per slide. From the resulting mineral percentages, each sample was named according to the IUGS classification (Streckeisen, 1975). The point count data are presented in Appendix II.

As noted by Fyles (1955) and Muller and Carson (1969), the Saanich Granodiorite is of a variable composition, with the term, granodiorite, used only as a collective name to describe these plutonic rocks. This variability is readily noted in analyses of both hand samples and thin sections of the granodiorite. For example, sample K-109, plotting as a quartz monzonite on the IUGS chart, was collected less than 0.5 miles west of sample K-112, which plots as a tonalite (equivalent to a quartz diorite). Along the shoreline in the Cobble Hill area, the Saanich Granodiorite is of a granitic composition, consisting mainly of alkali feldspar and quartz and containing pink potassium feldspar phenocrysts almost three inches long.

Sample K-109 consists of coarsely crystalline anhedral to euhedral light brown to green hornblende (9.3 percent), plagioclase (55.2 percent), alkali feldspar (9 percent), and quartz (3.6 percent) phenocrysts in a finely crystalline quartz and feldspar groundmass (16 percent). Quartz mainly occurs as an anhedral interstitial material or as an intergrowth with alkali feldspar (micrographic texture) and plagioclase (myrmekite). Radiating crystals of epidote are somewhat common (2.3 percent) and may either be of a secondary hydrothermal origin or the result of chemical weathering. The hornblende phenocrysts are commonly fresh or altered to chlorite and epidote. Feldspars, altered to sericite and epidote, consist of microcline (less than one percent), zoned plagioclase (An_{64} cores with An_{38} rims), and unzoned plagioclase (An_{40}). Euhedral magnetite occurs as a minor constituent (less than one percent) and is usually altered to hematite.

Sample K-112 (Figure 24), a tonalite, is composed of 54 percent plagioclase (An_{38}), 24.6 percent quartz, 11 percent brown-green hornblende, and only three percent alkali feldspar (orthoclase and microcline). The remaining constituents are magnetite (one percent) and augite (0.3 percent) as well as secondary chlorite (4.3 percent) and epidote (1.3 percent). Quartz occurs as anhedral interstitial material surrounding subhedral zoned (An_{58} cores with

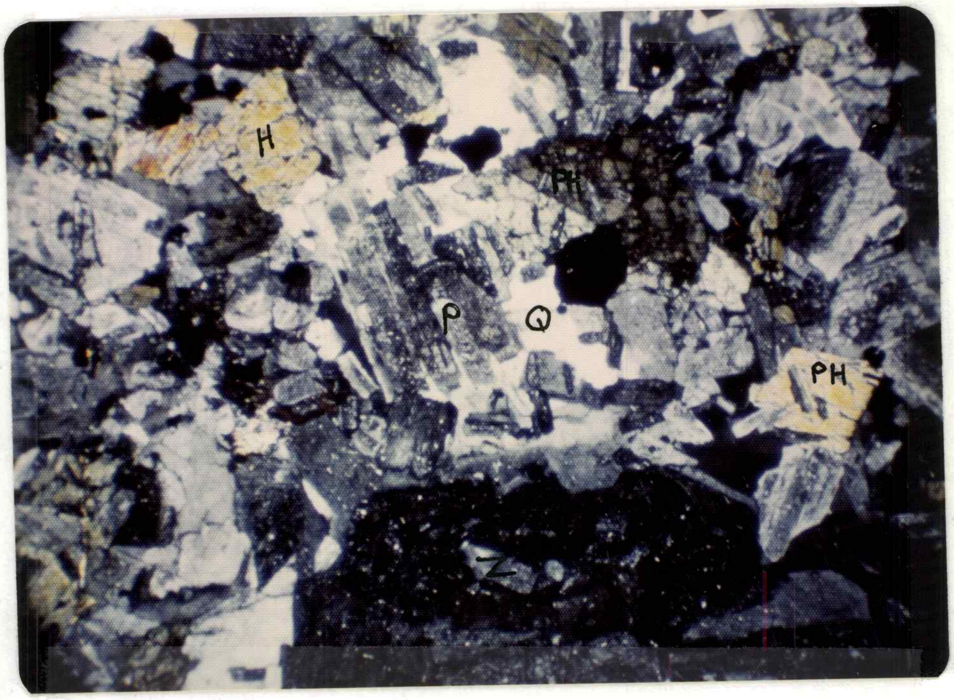


Figure 24. Photomicrograph of Saanich Granodiorite tonalite. Note interstitial quartz (Q), zoned (Z) and unzoned (P) plagioclase, and hornblende (H). Note also poikilitic hornblende (PH). Width of field is four millimeters. Sample K-112, Saanich Granodiorite.

An_{36} rims) and unzoned plagioclase, hornblende (altered to chlorite), and microcline. Poikilitic texture with both hornblende containing crystals of plagioclase and plagioclase enclosing hornblende is common. Liquid inclusions occur within the quartz crystals, exhibiting Brownian movement when examined under 300X power.

Sandstones

Introduction

A total of 21 thin sections of Nanaimo Group clastics were examined utilizing a Leitz petrographic microscope under 40X, 100X, and 200X. A minimum of 300 non-opaque framework grains were identified and point counted from each of ten petrographic thin sections. Data from the point counts are given in Appendix II-a. Opaque minerals were identified utilizing an overhead lamp, whereas feldspar differentiation was determined from the examination of nine selectively stained (method of Bailey and Stevens, 1960) billets through a binocular microscope.

Textures

The Nanaimo Group sandstones in the thesis area generally are texturally submature to immature, based on Folk's (1951) classification. They usually contain two to ten percent clay-sized matrix material, are poorly to only moderately sorted, and consist of angular to subrounded grains. The more resistant grains, such as quartz, generally are angular, whereas grains consisting of less resistant rock fragments and ferromagnesium minerals are subrounded to subangular. Chert grains vary in their degree of roundness, reflecting the degree of reworking or the transport distance from the source area. Feldspar grains usually are subangular to angular, indicative of a relatively close source area, as feldspars are highly susceptible to weathering and erosion during transport. Biotite and muscovite, because of density, crystal shape, and cleavage habits, occur as elongate and angular flakes.

Framework Grains

Quartz. Quartz is the most abundant (26 to 57 percent) constituent of the Nanaimo Group sandstones. Both monocrystalline and polycrystalline strained and unstrained quartz varieties occur in varying percentages from sample to sample. Monocrystalline strained quartz, averaging 60 to 78 percent of the total quartz, is the most common type of quartz noted in the Comox and Extension-Protection Formations. Such quartz grains are equant to elongate and possess an undulatory or a wavy extinction, becoming completely extinct over a five to 25 degree rotation of the petrographic microscope stage. In some coarser grained sandstone units, polycrystalline strained and unstrained quartz is abundant, totaling almost 28 percent of the quartz present within the samples. In polycrystalline strained quartz, the grains are elongate and fractured, with each fracture unit within the grain displaying strained extinction independent of the other fracture units (Figure 25). Fine-grained sandstones such as those common to the Haslam and Cedar District Formations generally contain higher percentages of monocrystalline unstrained quartz (25 to 35 percent of the total quartz), whereas this type of quartz generally is rare in coarser grained sandstones (less than five percent).

The percentages of each variety of quartz for individual samples are probably related to the grain sizes of the sandstones and the stability of each type of quartz. Polycrystalline strained quartz grains probably break along fractures into monocrystalline strained quartz grains; therefore, some finer grained monocrystalline quartz grains in fine-grained sandstones and siltstones may have their origin from separated polycrystalline quartz grains.

Inclusions within quartz are fairly common. Many quartz varieties contain minute mica flakes or tourmaline needles. Both gas- and liquid-filled spherical bubbles also occur within some of the quartz. A grain showing graphic intergrowth of quartz and feldspar was noted in sample K-119 of the Comox Formation.

Chert. Chert is a common element of the sandstone units,

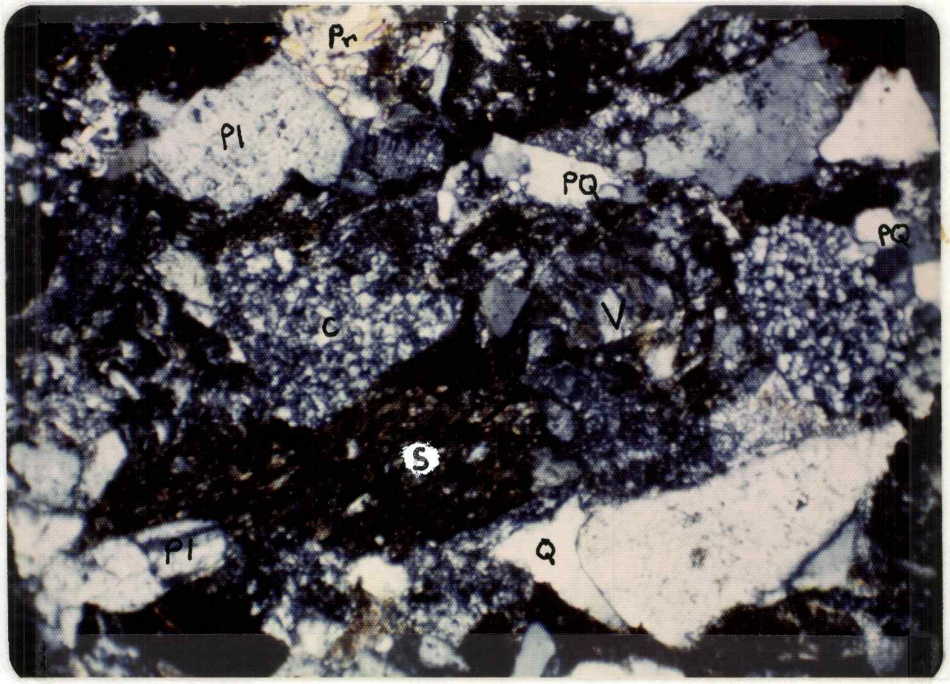


Figure 25. Photomicrograph of Comox lithic arenite. Note general angularity of grains and lack of porosity. Note also monocrystalline quartz (Q), polycrystalline quartz (PQ), plagioclase altered to sericite (Pl), schist rock fragment (S), chert (C), altered volcanic rock fragment (V), and prehnite (Pr). Width of field is 1.5 millimeters. Sample K-119, Comox sandstone.

averaging from 10 to 15 percent of the whole-rock composition in both the Comox and Extension-Protection Formations. The chert grains generally are subrounded to well rounded, although some are elongate and angular, possibly representative of recrystallized volcanic glass shards derived from a fairly close source area.

Chert grains consist of microcrystalline quartz aggregates that exhibit a glittering appearance upon rotation of the petrographic microscope stage under crossed nicols (Figure 25). The chert ranges in color from clear to green or red. Green chert may be a form of recrystallized volcanic glass, containing green earth minerals common to altered volcanic glass. The red varieties apparently are iron-oxide stained, with the iron oxide dispersed among the microcrystalline quartz.

Rock Fragments. Four types of rock fragments occur within the sandstones: volcanic, metamorphic, granitic, and sedimentary. All rock fragments generally are subrounded, reflecting their susceptibility to wear and chemical breakdown.

Volcanics generally are the most common type of rock fragments of the Comox and Extension-Protection Formations (Figures 25 and 26), and average from eight to 26 percent of the framework grains. Fresher samples usually contain higher percentages of the volcanic rock fragments, whereas altered sandstones contain a greater percentage of clay matrix and less volcanics; this is probably

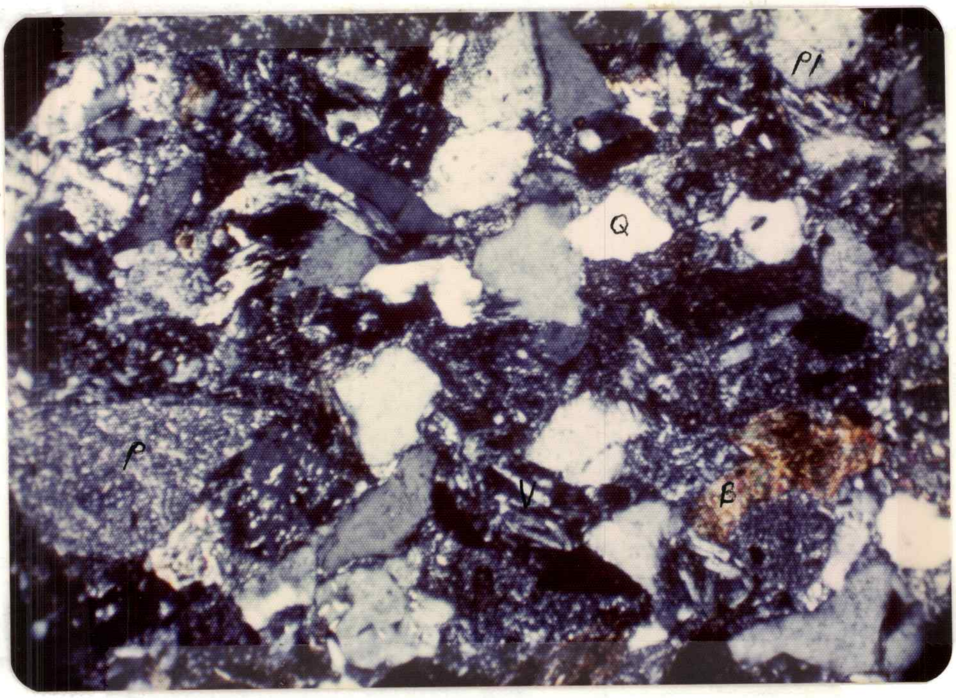


Figure 26. Photomicrograph of Comox lithic arenite. Note compacted biotite grain (B). Note also volcanic rock fragment (V), plagioclase replaced by calcite (Pl), monocrystalline unstrained quartz (Q), and phyllite fragment (P). Width of field is 1.5 millimeters. Sample K-119, Comox sandstone.

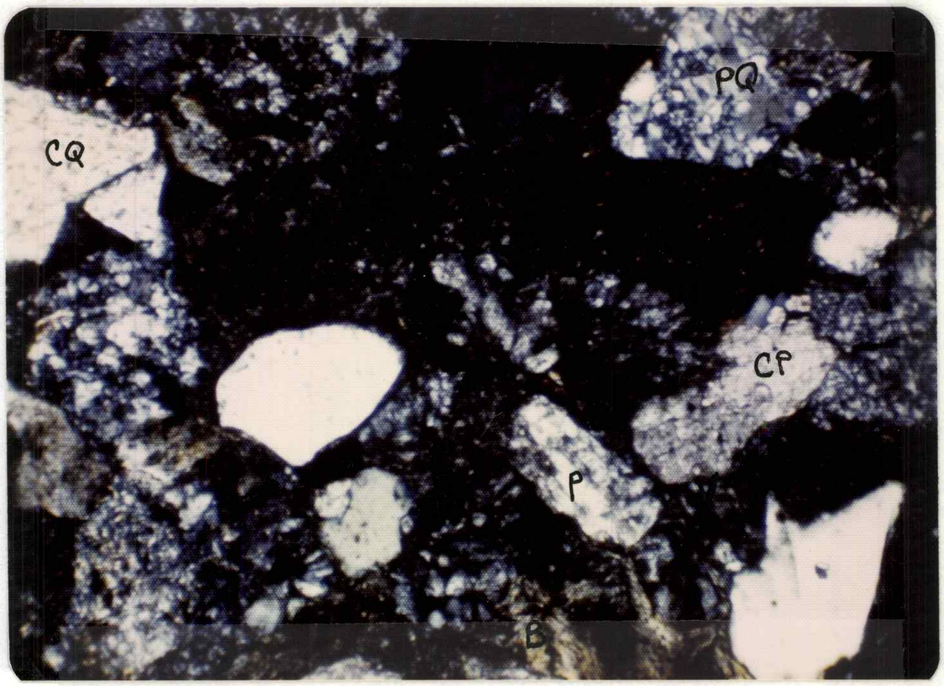


Figure 27. Photomicrograph of Extension-Protection lithic arenite. Note secondary calcite replacement of quartz (CQ) and plagioclase (CP). Note also polycrystalline quartz (PQ), plagioclase (P), and biotite altering to chlorite (B). Width of field is 1.5 millimeters. Sample K-76, Extension-Protection sandstone.

because volcanic fragments are chemically unstable and are composed of ferromagnesium minerals and feldspars that readily alter to clay minerals. In sample K-11, which is composed of only eight percent volcanic fragments and almost nine percent clay matrix, plagioclase microlites are noted to "float" in the clay matrix, probably indicative of a finely-crystalline volcanic framework chemically altered to matrix material. Difficulty arises in determining the composition of the volcanics because of the finely crystalline size of the plagioclase; however, most microlites are of an andesine to oligoclase composition, and therefore most of the fragments likely are dacite or andesite.

Metamorphic rock fragments consist of phyllite, schist, and quartzite. These fragments are subrounded to angular; the schist and phyllite grains generally are elongate, whereas quartzite grains are irregularly shaped and more angular. Phyllite fragments are foliated and marked by alternations of muscovite, clays, quartz, and dark, carbonaceous stringers. They generally are very finely crystalline and some show aggregate extinction. Schist fragments are also foliated, but are more coarsely crystalline and contain no more quartz than phyllites. The schist fragments apparently are of a low-rank nature, containing muscovite, quartz, chlorite, and some biotite, and probably are best classified as quartz mica schists. Quartzite fragments are mainly composed of elongate quartz crystals either intergrown and in "sawtooth" contact or separated by finely crystalline, flattened micas.

Granitic fragments are rare within the sandstone units (less than one percent) and generally are non-existent in the finer grained sandstones and siltsontes, possibly because of disaggregation during transport and chemical instability. Where still intact, the granitic fragments are coarsely crystalline, subangular, and composed of microcline, plagioclase, muscovite, and quartz. These fragments possibly are representative of the local granodiorite source area.

Mudstones and siltstones comprise the bulk of the sedimentary rock fragments of the sandstone units but are only of a small percentage (less than one percent) of the total framework grains. The mudstone fragments generally are subrounded, silicified, and composed of very fine-grained clay minerals, silica, and opaques. Mudstone rip ups are common in some of the samples (Figure 29). Siltstone fragments are coarser grained than the mudstones but contain finer grained quartz grains than those common to the sandstones in which they are incorporated. Siltstone fragments are usually best observed under plane light where the aggregation of the fine-grained quartz and clay are most noticeable as a continuous unit.

Feldspars. Feldspar grains (Figure 27) are angular to subangular and euhedral, generally fresh and clear or altered to kaolinite or sericite, and are of a variable composition within the

Nanaimo Group sandstones. Framework percentages of the feldspars range from 10 to 17 percent. Only a minor percentage (less than two percent) of the feldspars are of the alkali variety, whereas andesine and subordinate oligoclase and albite are more dominant. Alkali feldspars were identified from their optical properties and colors on stained billets. Plagioclase feldspars appear to form a higher percentage (from 30 to 40 percent of the whole-rock composition) in stained billets than in thin sections because of the likelihood of staining volcanic rock fragments along with the plagioclase grains.

Plagioclase grains generally exhibit both Carlsbad and albite twinning, possess large axial angles, and have a fairly low birefringence. Polysynthetic twinning common to microcline gives these grains the noticeable quadrille structure in thin section. Orthoclase grains are biaxial negative, have a large optic angle (approximately 70 degrees), and are stained yellow by the cobalnitrate solution on stained billets.

Micas. Mica grains range from three to 13 percent of the framework constituents. Although mainly consisting of biotite, chlorite occurring as an alteration product of biotite and as singular grains totals almost three percent of the framework grains in some samples. Muscovite generally is present only in trace amounts or as a diagenetic product from the alteration of plagioclase to sericite. The elongate, cleaved flakes of brown, pleochroic biotite usually possess a characteristic wavy form, likely the result of depression by harder grains under intense pressures and packing (Figure 26). Chlorite grains are light green and pleochroic but exhibit a purplish-brown color under crossed nicols.

Mafic Minerals. Clinopyroxenes (augite), epidote, and hornblende are the most common mafic minerals of the sandstones, but only represent a minor percentage (less than two percent) of the framework grain total. The grains usually are subrounded because of chemical solution and mechanical wear during transport.

Augite is the apparent clinopyroxene present in the sandstones, because it is optically positive, has a 2V of approximately 60 degrees, and has an extinction angle of about 30 degrees. Hornblende is pleochroic from green to brown, is optically negative, and becomes extinct from between 12 to 30 degrees. Epidote is distinguished from augite by its 2V (70 to 89 degrees), parallel extinction, and light greenish color.

Opaques. Depending upon the sample, opaque minerals range from two to 11 percent of the framework grains of the sandstones. Black, carbonaceous stringers, cubic and botryoidal pyrite, and leucoxene are the dominant opaques, of which carbonaceous debris is most common. Pyrite grains generally are dispersed among the carbonaceous material, reflecting the reducing conditions present during the chemical breakdown of the organic material. Leucoxene, an alteration product of ilmenite, is a white opaque disseminated throughout most of the samples.

Skeletal Calcite. Usually representing less than one percent of the framework grains, skeletal calcite is noted in many samples. This type of calcite generally is in the form of bivalve tests composed of fibrous or layered calcite or aragonite (Figure 28).

Matrix

The percentage of matrix in the Nanaimo Group sandstones ranges from two to 15 percent of the whole-rock compositions. Clay- and silt-sized fragments are considered as matrix in the sandstones (Williams, Turner, and Gilbert, 1954). As stated earlier, the matrix percentage is dependent upon the freshness of the sample, as altered rocks are composed of a diagenetic matrix derived from chemically unstable minerals and rock fragments. The matrix generally is composed of greenish clay minerals, microcrystalline quartz, fine-grained muscovite, and powdery hematite.

The matrix material usually infills pore spaces, with framework grains generally in framework support. In samples with framework grains suspended in matrix material, it is usually assumed that the matrix is diagenetic and not depositional. Hematite occurs as a powdery grain coating or as a finely disseminated fracture filling.

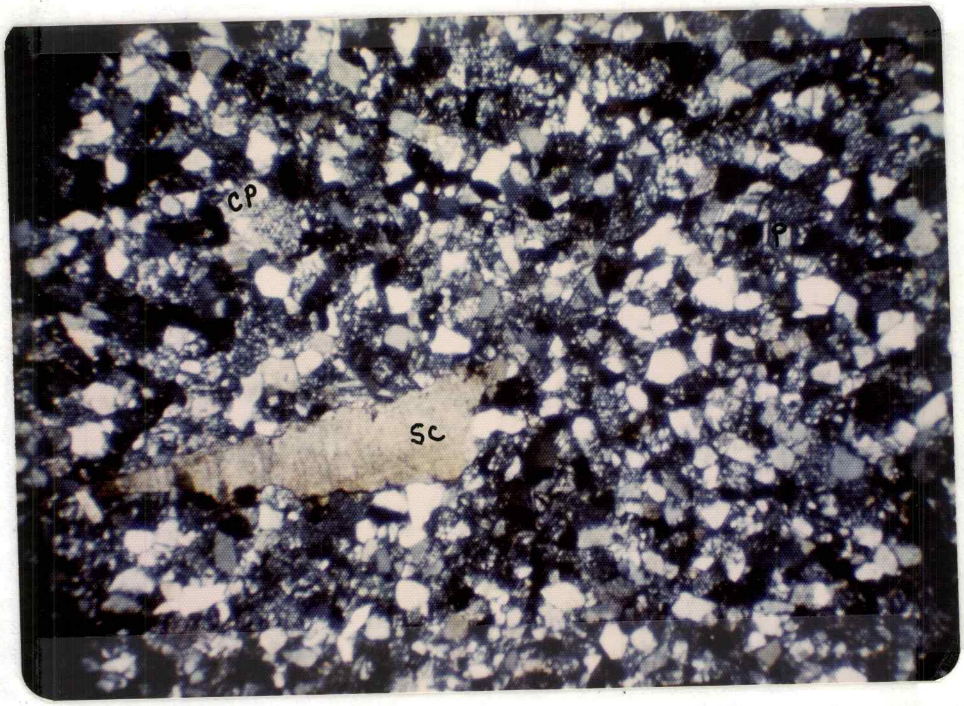


Figure 28. Photomicrograph of Extension-Protection subfeldspathic lithic arenite. Note skeletal calcite (SC), twinned plagioclase (P), and calcite replacing plagioclase (CP). Width of field is four millimeters. Sample K-134, Extension-Protection sandstone.

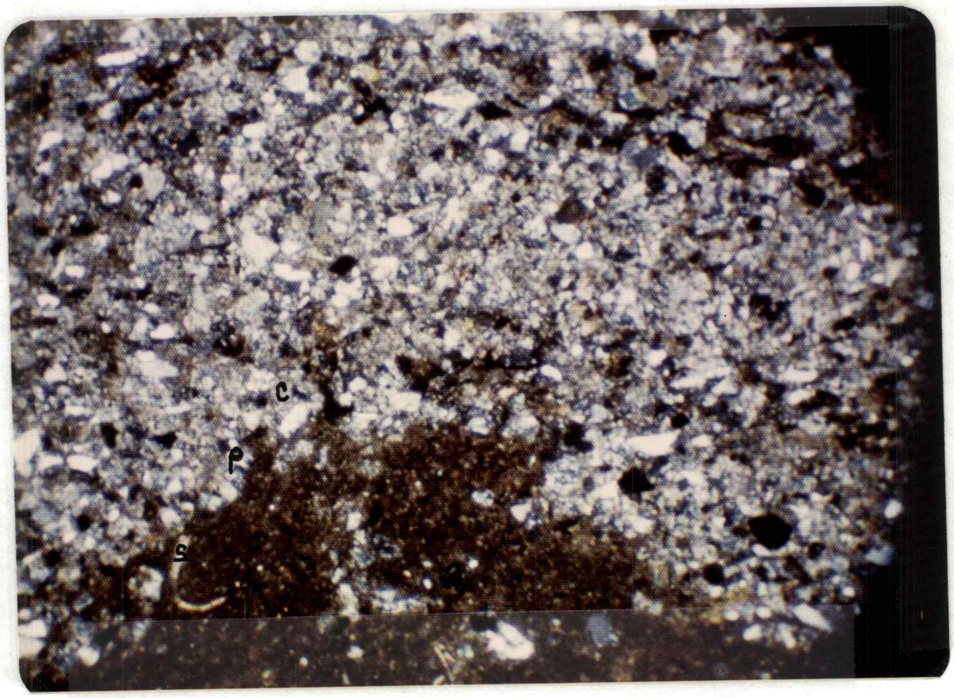


Figure 29. Photomicrograph of Haslam feldspathic wacke. Note mudstone rip up at base with incorporated skeletal calcite (S). Note also twinned plagioclase (P) and calcite cement (C). Width of field is four millimeters. Sample K-15, Haslam fine-grained sandstone.

Cements

Calcite and quartz are the most common cements of the sandstones, of which calcite can be fairly abundant, ranging from two to 24 percent of the whole-rock compositions. Calcite occurs as a pore-filling sparry cement, as a fracture and vein filler, or as a replacement product of quartz and feldspar (Figure 27). Its origin is discussed in the Porosity and Diagenesis section. Silica cement is intermixed among the fine-grained clay matrix, is usually microcrystalline, and generally is only a minor cementing agent, having probably been replaced by calcite or recrystallized to chert in many samples.

Prehnite is a less common cement of the sandstones (Figure 25), averaging less than one percent of the whole-rock composition. It is a micaceous mineral that occurs as radiating aggregates, commonly called "bow tie" structure, and usually infills void spaces.

Porosity and Diagenesis

The diagenetic history of the Nanaimo Group clastic rocks possibly has had an effect on the porosity of these sandstones. Porosity in all sandstones observed represents less than one percent of the whole-rock total. Calcite and silica precipitation, prehnite formation, and unstable grain alterations have reduced porosity to this minimum. In many samples, porosity is almost completely absent.

Chemical alterations of unstable grains to clay matrix material has decreased the degree of sorting in many sandstones and thus also has reduced porosity. Cummins (1962) gave support for the theory of a diagenetic orign for the matrix in sandstones. After burial, unstable mafic minerals and rock fragments may alter to clay minerals as a result of one or more processes: (1) chemical alteration in a weathered zone; (2) alteration from increased temperature and pressure during deep burial; and (3) low-grade metamorphism because of shearing in a tectonically active area, mechanically transferring unstable minerals to clays (a cataclastic or a mylonitic process). The first two of these processes may have been possible mechanisms for the origin of the matrix in the Nanaimo Group sandstones.

Hydrothermal alteration could possibly have occurred within these clastic rocks. Hydrothermal solutions may kaolinize feldspars, or they may result in the precipitation of silica and prehnite or the formation of zeolites (such as laumontite reported by Hanson, 1976). This diagenetic process may only have been of a localized nature but possibly did have a role in porosity reduction.

Carbonate cementation and replacement are the most common diagenetic occurrences within the sandstones. The carbonate cement may have been an early diagenetic precipitate if the sand was deposited in a favorable (marine) environment for calcite precipitation (Pettyjohn and others, 1973). Garrison and others (1969) concluded that carbonate shell material can be dissolved by interstital pore waters and reprecipitated under increased pressures during compaction of the sediments. The temperature, pH, and partial pressure of carbon dioxide within a system affects the silica-calcite equilibrium (Garrels and Christ, 1965). As the pH of a solution increases from acidic to basic, the solubility of calcite decreases whereas the solubility of silica increases. An increase in temperature can facilitate the release of carbon dioxide from a system, decreasing the solubility of calcite. Sillen (1961) points out that the pH of sea water is about eight, or slightly basic, and that sediments deposited in a marine environment may have interstitial pore waters with a similar pH if there is no exchange with groundwater from outside the system. With relatively rapid burial, the combined effect of a high pH and increased temperature can therefore result in the solution of silica and the precipitation of calcite as a cement or as a replacement product of silicate minerals. Uplift of a calcite-cemented sandstone may cause the localized solution and remobilization of calcite by acidic ground and surface waters and its reprecipitation along surface fractures and joints, a feature observed in both Comox and Extension-Protection Formation outcrops.

Calcareous concretions present in the Nanaimo Group units are also likely an early diagenetic product. Weeks (1953) points out that carbonate concretions can form under the alkaline conditions created during post-depositional decay of organic matter. This increase in pH causes the solubility of calcite to decrease and results in its precipitation from interstitial pore waters. Both the high percentages of pyrite and the carbonaceous plant debris present in the formations, and within the concretions, are suggestive of such a reducing environment. Increased temperature of burial should aid in carbonate precipitation, as stated above. The facts that calcareous concretions disrupt bedding, contain fresh or replaced chemically unstable minerals, and weather out from outcrops as independent units are also indicative of their pre-uplift origin.

Classifications

Introduction. The Nanaimo Group clastic rocks present in the thesis area are classified according to Gilbert's (Williams, Turner, and Gilbert, 1954) classification. This classification was chosen for five reasons: (1) it is relatively simple (utilizes limited nomenclature); (2) it is widely accepted among geologists; (3) it introduces the term wacke (eliminates the non-definitive, often misused term "greywacke"); (4) it differentiates between a rock with less than ten percent matrix (texturally mature arenite) and a rock with more than ten percent matrix (texturally immature wacke); and (5) it allows the concept of compositional maturity to be readily noted from the classification by utilizing a ternary subdivision of stable grains (quartz, chert, and quartzite), relatively abundant, yet semi-unstable grains (feldspars), and very unstable grains (mafic minerals and rock fragments).

Comox Formation. Ten thin sections of Comox Formation sandstones were examined petrographically, of which four were point counted for classification purposes. All four samples plot as lithic arenites, but are spread out over the entire lithic arenite field (Figure 30). Sample K-11, which is more altered and contains more matrix (nine percent) than the other samples, plots near the feldspathic arenite field. As discussed previously, the chemical breakdown of unstable mafic minerals and rock fragments to matrix material can possibly cause this shift away from the lithic arenite region.

Polycrystalline strained quartz ranges from 22 to 27 percent of the quartz in Comox samples; however, it is less common than monocrystalline strained quartz (69 to 72 percent). Rock fragments are divided between metamorphic and volcanic varieties, with volcanics more dominant in most samples. Biotite grains are fairly common, whereas chlorite is less so. Feldspars range from 10 to 16 percent of the framework total and are composed mainly of andesine.

From the classification, it can be noted that the Comox

Formation sandstones are compositionally immature, indicative of little transport distance and almost no reworking of the grains prior to rapid deposition and burial. A dominance of mechanical over chemical weathering can also result in the deposition of immature sediments. The textural submaturity of these rocks, determined from clay content, sorting, and grain angularity, further supports these hypotheses.

Haslam Formation. Because of the lack of exposures of sandstone units within the Haslam Formation in the study area, only one thin section of the Haslam was petrographically examined and point counted. Plotting as a feldspathic wacke (Figure 30), this sandstone is texturally immature and compositionally immature to submature.

Monocrystalline strained and unstrained quartz grains (96 percent of the quartz) far outnumber polycrystalline quartz grains (four percent) in this Haslam sample; together, these quartz grains comprise 51 percent of the total framework grains. Chert (18 percent) is the next abundant constituent, followed by plagioclase (17.6 percent) and then by biotite (4.5 percent), muscovite (2.7 percent), and chlorite (1.7 percent). Opaques total about seven percent of the whole-rock composition, whereas less than two percent is unstable rock fragments. Calcite as a replacement product, as a cement, or as biotics totals about five percent of the sample. Almost 25 percent of the total composition consists of matrix material. Mudstone rip ups, composed of clay minerals, carbonaceous debris, and skeletal calcite, occur at the base of this oriented Haslam Formation thin section (Figure 29).

Extension-Protection Formation. Three of the nine Extension-Protection Formation samples examined were point counted and classified (Figure 30). The sandstones have compositions similar to Comox samples, plotting as lithic arenites over a wide field. Sample K-76 is rich in volcanic rock fragments (over 26 percent) and fairly low in quartz (26 percent), whereas the other two samples contain less than 20 percent volcanics and almost 40 percent quartz. Chert ranges from 12 to 18 percent of the framework grains and matrix material accounts for less than five percent of the total compositions.

Although texturally submature, these sandstones are compositionally immature because they contain abundant lithic fragments and feldspars. The distance of transport was likely fairly short with rapid burial, allowing for little or no reworking of the sediments. The energy of the transporting medium had to be great enough to winnow clay-sized material and thus to increase the degree of sorting in these samples. As with the Comox Formation, a dominance of mechanical over chemical weathering, or the combined effect of both intensive mechanical weathering and rapid burial, can result in the deposition of a compositionally immature sediment.

Cedar District Formation. Two thin sections of Cedar District Formation sandstones were petrographically examined and point counted. Sample K-150, plotting as a subfeldspathic, lithic wacke, was sampled from within the middle Cedar District sandstone to mudstone sequences, whereas sample K-151, plotting as a lithic arenite, was sampled upsection in the formation along the northern-most shoreline of Pym Island. The two sandstones are characteristically different, and probably were deposited within different depositional environments.

Sample K-150 contains abundant quartz (58 percent of the framework total) and chert (11.6 percent) grains. Plagioclase feldspar (andesine) accounts for only 13 percent of the framework total. Biotite (9.6 percent), volcanic rock fragments (3.6 percent), and chlorite comprise the remaining non-opaque constituents. Over 22 percent of the rock is composed of clay matrix and calcite cement.

Volcanic rock fragments (27.7 percent of the framework total) are the most abundant constituents of sample K-151. Quartz (25.7 percent), plagioclase (15.3 percent), and chert (12.3 percent) grains are also fairly common. Polycrystalline strained quartz grains comprise 23 percent of the quartz total, whereas 67.5 percent is monocrystalline strained and five percent monocrystalline unstrained. Micrographic quartz (3.4 percent of the total quartz) is somewhat common, as are granitic rock fragments (5.2 percent of the framework

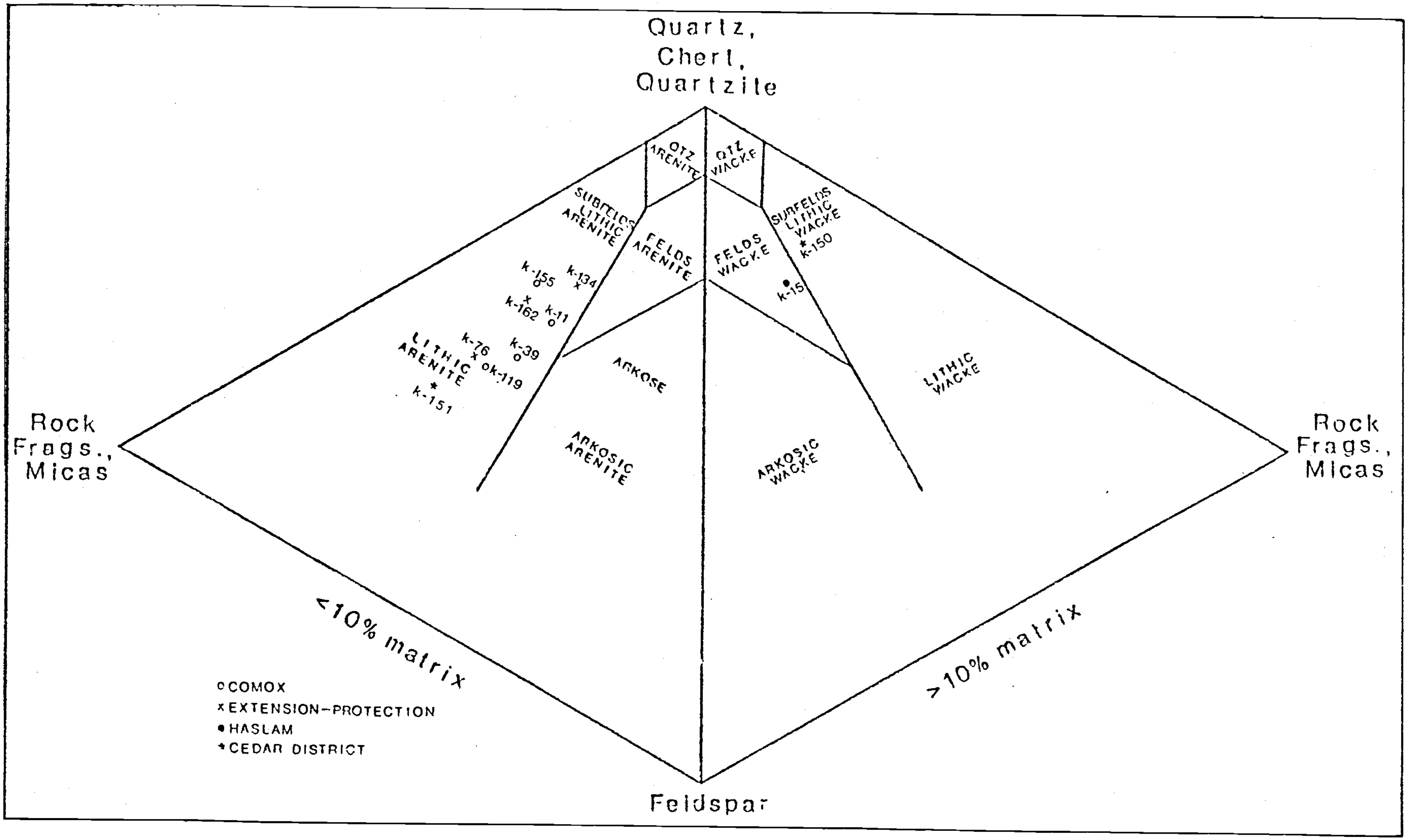


Figure 30: Classifications of Comox, Haslam, Extension-Protection, and Cedar District sandstones (after Gilbert, 1954).

total) and metamorphic rock fragments (4.7 percent). Only 2.7 percent of the rock consists of matrix material.

A shift from a low energy environment to a higher energy environment is suggested from the differences between these two samples. Sample K-151 is compositionally more immature than Sample K-150, possibly indicative of a dominance of mechanical weathering within the source area, a short transport distance, and rapid deposition and burial.

Conglomerates

Introduction

Conglomerate units in the thesis area are limited to the Benson Member of the Comox Formation and to the Extension-Protection Formation. A minimum of 100 pebbles and small cobbles were randomly marked and removed from five conglomerate outcrop locations and returned to the laboratory for identification purposes. Numerous large samples of conglomerate material were returned to the laboratory for crushing and clast removal. Both wetted and freshly fractured surfaces of the conglomerate clasts were observed through a binocular microscope and a 10X hand lens to aid in rock identification. One thin section of a Benson Member conglomerate was studied to determine matrix mineralogy (Figure 31). The

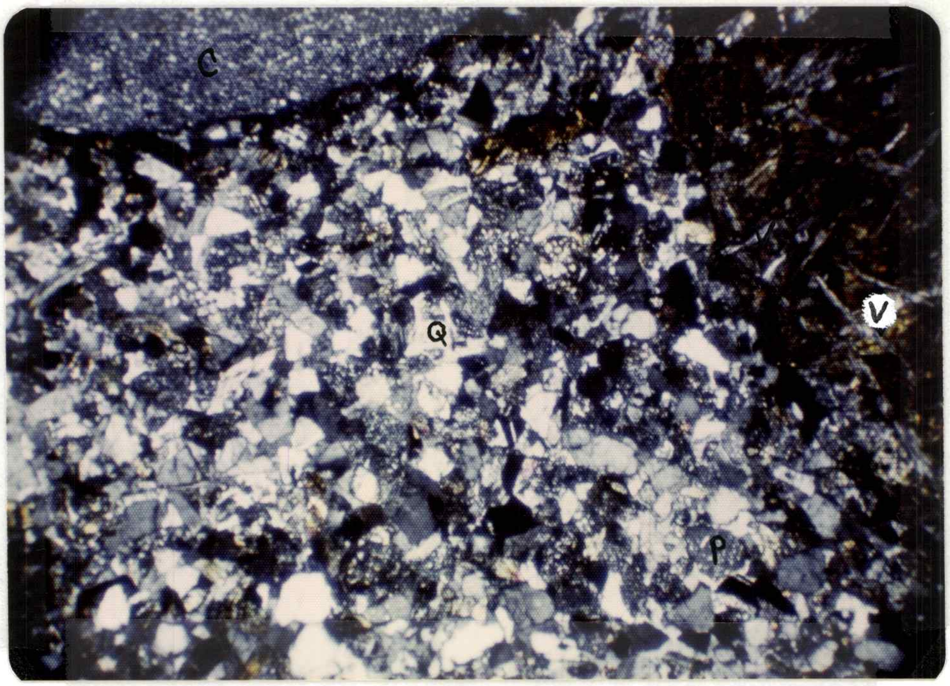


Figure 31. Photomicrograph of Benson conglomerate matrix. Note chert (C) and volcanic (V) clasts. Note also quartz (Q) and plagioclase altered to sericite (P). Width of field is four millimeters. Sample K-147, Benson Member conglomerate.

results of the pebble counts for the two formations are presented in Figure 32.

Comox Formation

The conglomerates of the Comox Formation are composed of subrounded to well rounded, pebble- to small boulder-sized (0.25 to 10 inches in diameter) clasts of basalt, andesite, chert, granodiorite, quartzite, quartz mica schist, phyllite, greenstone, mudstone, and sandstone in a moderately sorted, medium- to coarse-grained sand matrix. Volcanics, granitics, and low-grade metamorphics (especially greenstones) are the most common types of clasts occurring within the conglomerates. The granitic clasts are of a larger size (cobbles to boulders) and are more angular than the other varieties.

The matrix of the Benson conglomerates is similar to the Comox Formation sandstones in both texture and mineralogy. The subangular to angular, moderately sorted grains of the conglomerate matrix are composed of quartz, chert, plagioclase, microcline, volcanic rock fragments, biotite, augite, hornblende, and chlorite. The matrix is arenitic, consisting of less than two percent clay- and silt-sized material. Cement is of a silica-clay composition and porosity is virtually absent. Powdery hematite coats the clasts and infills fractures within the matrix. Alteration products include

Lithology	Comox	Extension-Protection
Quartz	5%	3%
Granitic	14%	8%
Greenstone	8%	2%
Chert	17%	16%
Andesite	21%	26%
Phyllite, quartzite, quartz mica schist	2%	1%
Basalt	24%	25%
Sandstone	7%	11%
Rhyolite, dacite	2%	7%
Mudstone	-	1%

Figure 32. Pebble count data for Comox and Extension-Protection Formations.

sericite, chlorite, green earth minerals, kaolinite, hematite, and leucoxene.

Extension-Protection Formation

The lithology and textures of the Extension-Protection Formation conglomerates are similar to those of the Comox Formation conglomerates. However, as noted from pebble count data, more basaltic, andesitic, and sedimentary clasts apparently occur within the Extension-Protection than within the Comox conglomerates.

These differences can be attributed to a variety of reasons: (1) inaccuracies in field collections; (2) the susceptibility of certain clasts to weathering; or (3) a shift in lithology of the source area. Because of the firmly indurated nature of the conglomerates, most clasts were removed from the matrix only after intensive pounding of the outcrops with a geologic hammer, possibly resulting in the selective collection of harder or more easily obtained clasts. Softer clasts, such as mudstones and phyllites, may be less abundant because of selective weathering and removal from the more firmly indurated conglomerate matrix material. A shift in the source area away from a low-rank metamorphic and volcanic terrane to one composed mainly of volcanic and sedimentary rocks is also a possible cause for the differences in the clast compositions between the two formations. A decrease in granitic clasts is also noted within the

Extension-Protection conglomerates compared to the Comox Formation conglomerates, reflecting either the covering of the granodiorite by sediments or a shift in transport directions during deposition of the Extension-Protection Formation.

Clay Mineralogy

Procedure

Two mudstone samples (one each from the Haslam and Cedar District Formations) were collected and analyzed for clay mineralogy utilizing X-ray diffraction techniques. Care was taken in the field to obtain fresh samples to avoid collection of diagenetic, mixed layer clays. Each sample was prepared according to the following method, as described by Harward (1978):

1. Disaggregated in boiling water and by gentle grinding in a mortar and pestle;
2. Wet sieved through a 4ϕ-size sieve; saved fine silt- and clay-sized sample;
3. Air dried and disaggregated;
4. Suspended 15 grams in distilled water by gentle shaking in a centrifuge tube;
5. Centrifuged for four minutes at 750 RPM; repeated six times, each time saving the clay suspensate;

6. Centrifuged clay suspension at 6,000 RPM for ten minutes and saved clay residue;
7. Placed 2/3 of the clay residue in one centrifuge tube and 1/3 in another;
8. Added 1 N $MgCl_2$ solution to the tube with the 2/3 volume, shook, centrifuged at 6,000 RPM for ten minutes, and repeated twice (each time discarding the supernatant and washing two times with distilled water);
9. Added 1N KCl_2 solution to the other tube and repeated the same procedure as with the $MgCl_2$ solution;
10. Prepared two Mg-saturated slides and one K-saturated slide by smearing an even coating of the pastes on petrographic slides.

A total of seven runs were made of the clay fractions on a Norelco X-ray diffractometer over a range of two to 25 degrees 2θ. The instrumental settings were as follows: Radiation Cu $K\alpha$ at 35 KV and 35 MA with an Ni filter; 0.006 inch receiving slit; rate meter at 1×10^3 with a time constant of 1; scan rate of one degree 2θ per minute. The seven runs consisted of: (1) Mg-saturated at 54% RH; (2) glycerol-solvated Mg-saturated (heated at 105 degrees Centigrade for two hours) at 54% RH; (3) glycolated Mg-saturated (heated at 65 degrees Centigrade for two hours) at 54% RH; (4) K-saturated after drying at 105 degrees Centigrade at 0% RH; (5) K-saturated at 54%

RH; (6) K-saturated at 0% RH after heating at 300 degrees Centigrade for three hours; and (7) K-saturated at 0% RH after heating at 550 degrees Centigrade for three hours.

Identification Criteria and Results

From the resulting diffractograms (Figures 33 and 34), it is apparent that the clays of the Haslam and the Cedar District Formation mudstones are fairly similar. Five clay minerals were interpreted to occur within these formations: chlorite, mica (including muscovite and sericite), kaolinite, vermiculite, and chloritic intergrades.

Because of overlapping diffraction patterns, vermiculite and chloritic intergrade clays cannot be ruled out as not being present and therefore are included as possibilities. Both of these clays are of a secondary origin; mixed layer chlorites can form from the chemical weathering of muscovite whereas vermiculite can form from the chemical breakdown of chlorite.

Strong, non-mobile diffraction peaks at 10 and 14 Å are indicative of chlorite and mica clays. The characteristic intensification of the 10 Å peak upon heating, noted in mica clays as a result of the removal of interlayered water from the clay lattice, is observed in the diffractograms. The second order chlorite peak, as well as the first order kaolinite peak, occurs at 7 Å; however, kaolinite

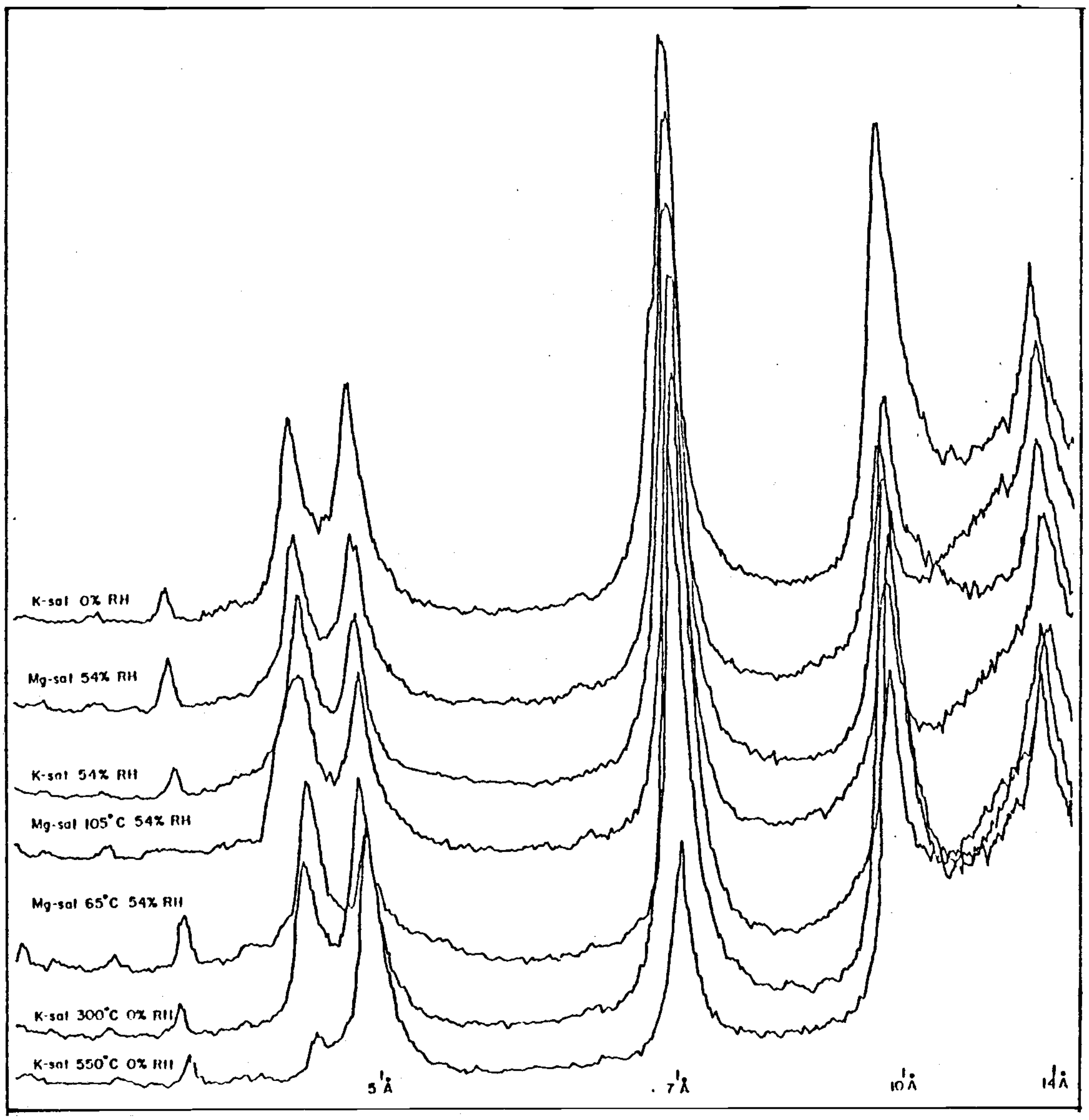


Figure 33: Diffractograms of clay mineralogy for the Haslam Formation mudstones.

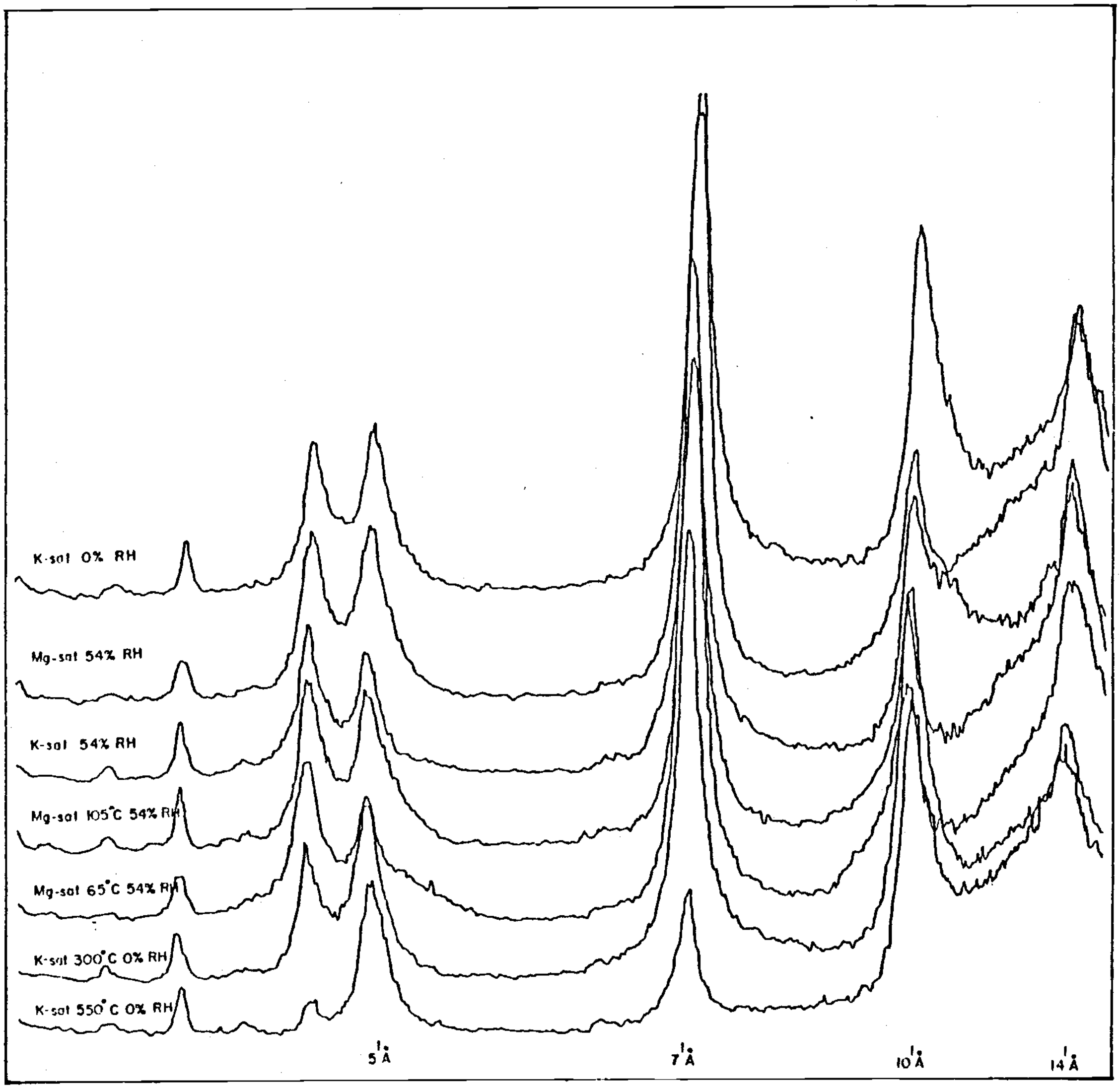


Figure 34: Diffractograms of clay mineralogy for the Cedar District Formation mudstones.

becomes amorphous when heated at temperatures above 500 degrees Centigrade and does not exhibit an X-ray diffraction peak at this d-spacing (Carroll, 1970). As noted from the 550 degree Centigrade K-saturated run, the 7 Å peak loses its intensity compared to the other runs, which is strongly indicative of the presence of kaolinite. Because neither 16 to 17 Å peaks nor a reduction in the 14 Å peak occur during the glycol or the glycerol treated runs, montmorillonite, an expanding lattice-type clay, is probably not present in either of the mudstone samples.

Diffraction peaks for quartz (3.3 Å) and gibbsite (4.85 Å) are also noted on the diffractograms. Gibbsite is assumed only because the third order chlorite peak also lies at 4.8 Å. Upon heating chlorite, the first order (14 Å) peak becomes more intense and higher orders disappear (Carroll, 1970). This is noted to occur on the 550 degree Centigrade K-saturated diffractograms; however, because the 4.8 Å peak is not completely destroyed, trace amounts of gibbsite may be present.

STRUCTURE

Regional Structure

Vancouver Island, situated between mainland British Columbia and the continental slope, lies within the Insular Belt of the Canadian Cordillera (Monger and others, 1972). This belt of related tectonic events extends north-northwestward to the Alaskan Peninsula. Within the Insular Belt, folding is a secondary response to faulting (Muller and Jeletzky, 1970). Compressed and overturned folds appear to be limited to adjustments between fault blocks, between massive panels of volcanic rocks, or adjacent to plutons (Sutherland-Brown, 1966).

The Leech River, San Juan, and Orcas fault systems (Figure 35) are the major structural elements of the southern Vancouver Island area, subdividing it into two extensive fault blocks that appear to be geologic extensions of the mainland to the south and east. Tertiary volcanic and sedimentary rocks south of the Leech River reverse fault are continuous with the Olympic Mountains, whereas Paleozoic and Mesozoic rocks lying between the eastern line of the San Juan fault and the Orcas fault zone appear to be geologically continuous to the Cascades of mainland British Columbia (Muller, 1977).

The Leech River fault is marked by the Loss, Wye, Bear Creek, Leech, and Goldstream River valleys to the southwest of the thesis area. The San Juan fault is traced along the San Juan River before

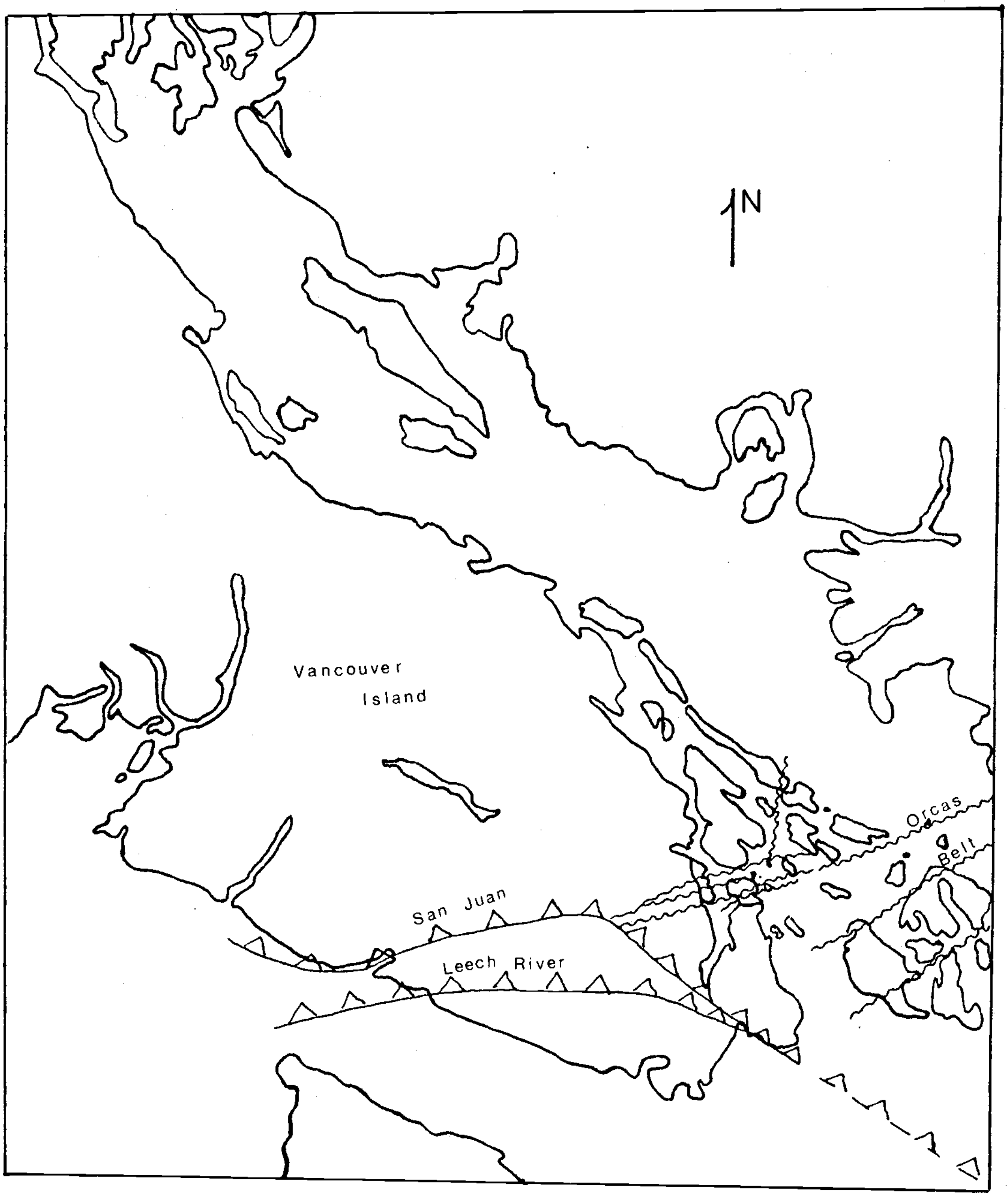


Figure 35: Southern Vancouver Island and locations of the San Juan, Leech River, and Orcas fault systems, modified from Muller (1977).

curving southeastward and joining the Leech River fault immediately east of Langford Lake (Muller, 1971). Both faults are vertical to steeply northward dipping, with units south of the faults overridden by older rocks to the north (Muller, 1971). The principal stress directions, interpreted from the fault traces and movements along them, therefore appear to be from the north and south.

Northwest of Sooke Lake, the San Juan fault splays to the northeast away from its southeast arcuate trend (Muller, 1975). These northeast-trending splays pass through the study area and continue on through and north of the San Juan Islands as the Orcas fault belt. Vance (1977) describes one of the Orcas faults passing through northern Orcas Island as a decollement thrust. He suggests that the Nanaimo Group strata may have sheared off from the underlying early Paleozoic Turtleback gabbro and quartz diorite basement and overrode it, moving southward as a decollement thrust. A better term for this occurrence on Orcas Island would be "imbricate thrust" as no true decollement zone of incompetent strata (such as shale, salt, or gypsum) exists between the two units, a common association in zones of decollement faulting (Hobbs and others, 1976).

Within the Nanaimo Basin, structure is also dominated by faulting. Northwest- to southeast-striking block faults that generally have northeast downthrows sequentially expose younger Nanaimo Group strata away from Vancouver Island. Although less common, younger northeast-striking cross faults also cut Nanaimo Group strata. These faults are older than the Leech River, San Juan, and Orcas faults. A series of northwest-trending synclines and anticlines extend through the Gulf Islands to the Georgia Strait, possibly occurring as surface expressions of movements along basement faults (Sutherland-Brown, 1966).

Areal Structure

The structure within the North Saanich and Cobble Hill areas apparently is controlled by the regional north-south compressional stresses in the southern Vancouver Island area. Strata dip from 20 to almost 90 degrees to the north and northeast, with vertical and overturned, southward-dipping beds common at some locations in North Saanich. Fault block tilting and drag of bedding along fault planes rather than folding probably are responsible for these steeply dipping attitudes. No mappable folds were noted within the study area; tight chevron folds confined to localized areas within Haslam Formation strata on Piers Island are probably either the result of soft-sediment creep down the paleoslope or stress disturbances related to the local faulting.

Faults within the study area (Figure 36, Plate 1) were plotted utilizing the following criteria: (1) fault plane and block displacements observed in the field; (2) topographic discontinuities and lineaments

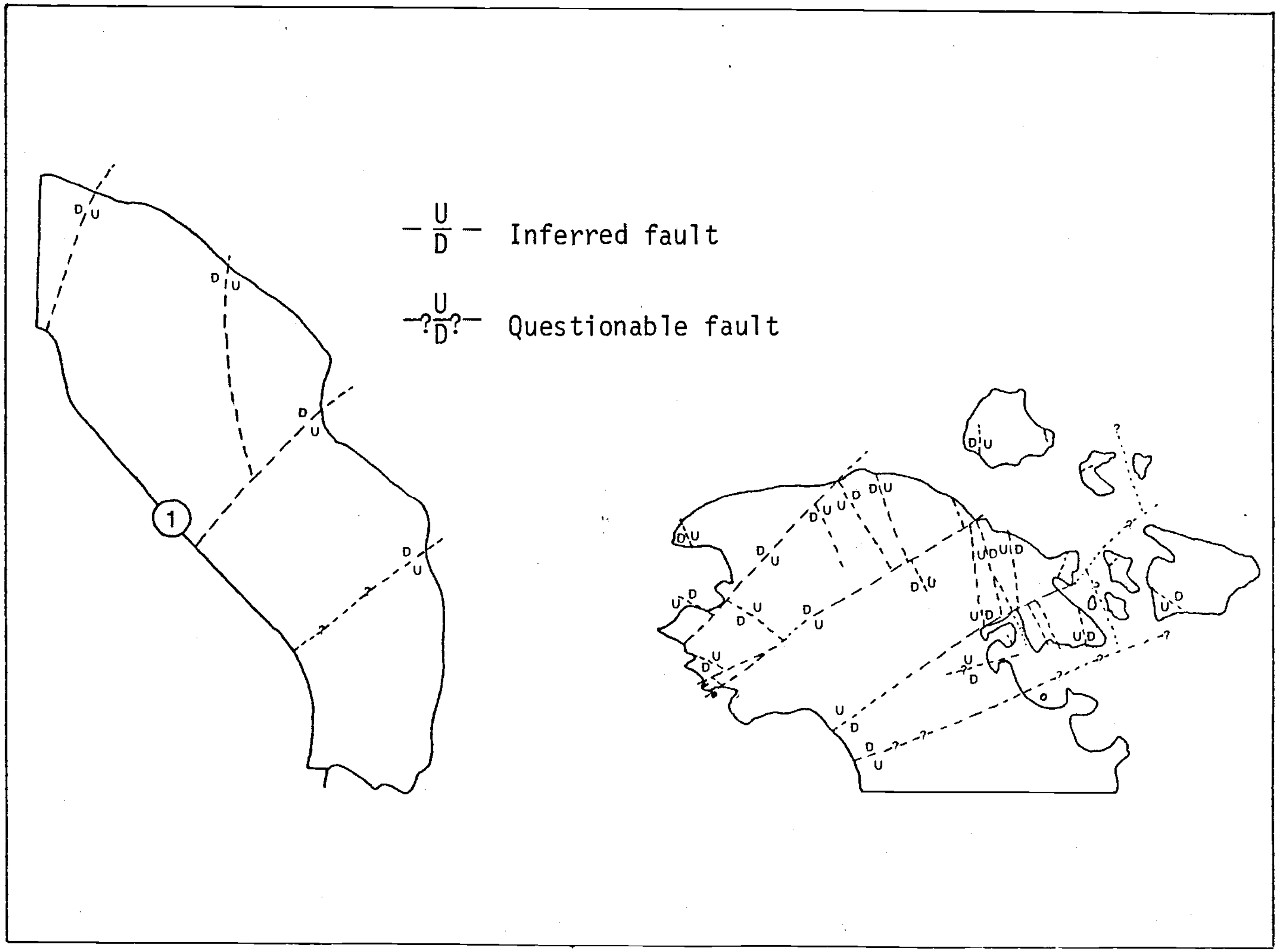


Figure 36: Faults within the North Saanich-Cobble Hill area.

traced on aerial photographs; (3) repetition of or abrupt changes in rock types; (4) abrupt changes in attitudes of the bedding; (5) location and orientation of slickensided surfaces; (6) crush and fracture zones reported in water well data; and (7) combinations of the above. Both northwest-striking block faults and traces of the northeast-trending San Juan Fault system splays are noted within the North Saanich-Cobble Hill area.

The northwest-striking block faults cut Nanaimo Group strata perpendicular to almost parallel to strike. Fault planes either are perpendicular or dip to the northeast; fault blocks to the northeast generally are downthrown with respect to those to the southwest. The Cloake and Horth Hill cuesta is disrupted by at least four of these normal faults. The saddle situated between these two hills apparently is a graben located between two upthrown blocks. At other localities, Comox Formation strata dipping north-northeastward toward the older Saanich Granodiorite are interpreted to be in fault contact with it.

Structure within the study area is complicated by a number of northeast-striking splays of the San Juan fault system. Traces of these faults are interpreted from steeply dipping, overturned, contorted, and disrupted bedding, from slickensided surfaces, and from aerial photo lineations. These splays are younger than the northwest-striking block faults that are both terminated and displaced by the splays. Along the western shoreline of the North Saanich Peninsula between Warrior and Coal Points, movements along these faults have resulted in repetitions of rock types, changes in attitudes of Comox Formation strata, and overturned bedding. The structure immediately north of Towner Bay is especially complicated. In a north to south traverse along the shoreline, the following structure is encountered: (1) Comox Formation strata dipping from 70 to 80 degrees to the north; (2) a small, sandy embayment; (3) overturned Comox Formation strata having slickensided bedding surfaces; (4) an increase in overturned dip of the strata from 38 to almost 80 degrees to the south; and (5) an overturned, nonconformable contact of the Comox Formation with the older Saanich Granodiorite. A small island composed of Comox strata dipping 57 degrees normally to the north is separated from this point north of Towner Bay by a small sandy inlet and isolated outcrops of highly contorted sandstone beds. Saanich Granodiorite crops out along the northeastern and southern shorelines of Towner Bay, separated by a broad, sandy to muddy beach. Traces of the San Juan splays probably pass through both north and south of the point north of Towner Bay and continue to the northeast to Queen Mary Bay. Other traces of these splays are plotted through Patricia Bay and northeastward based on topographic discontinuities, displaced rock units, and fracture zones noted in water well log data. An additional branch, passing through the North Saanich Peninsula from a small embayment south of Coal Point northeastward through Deep Cove and west of Cloake Hill, is plotted according to similar criteria. In the Cobble Hill area, three traces of these faults have been interpreted as continuations of northeast-trending topographic lows extending from the Koksilah and Shawnigan Rivers and a part of Shawnigan Lake located southwest of the thesis area. These traces continue northeastward and probably are responsible for the obvious bedrock discontinuities noted along the shoreline north of Cherry Point, at Boatswain Bank, and south of Hatch Point. Another part of the fault system probably passes through Mill Bay immediately south of the Cobble Hill area.

The splays of the San Juan fault system passing through Patricia and Towner Bays are interpreted as imbricate and reverse faults (Plate 1). The reverse movements along these northeast-striking fault planes may have been in response to compression from directions almost perpendicular to strike. Possible imbrication of the faulted block at Towner Bay is interpreted from the steeply overturned strata and incorporated Saanich Granodiorite noted within the fault block north of the bay. Following these initial movements, secondary normal faults probably developed within the less rigid Comox strata to the northwest which apparently "slumped" northwestward away from the upthrown basement rocks.

This interpretation of imbricate and reverse movements along the primary splays of the San Juan fault system is in general agreement with that of Vance (1977) for the Orcas faults of the San Juan Islands east of the study area, as described in the Regional Structure section.

GEOLOGIC HISTORY

Paleocurrent Data

Introduction

Numerous sedimentary structures were noted within the Nanaimo Group clastic rocks in the thesis area. The mode and direction of transport of clastic material can be determined from a study of such sedimentary structures. Paleocurrent directions were measured in the field utilizing the method described by Briggs and Cline (1967). Only data from the Comox and Extension-Protection Formations are presented in this section because of the limited number of directional sedimentary structures noted within the generally finer grained Haslam and Cedar District Formations.

The means and standard deviations of the paleocurrent data for each formation were calculated utilizing the methods described by Curray (1956), Royse (1970), and Pettyjohn and Potter (1977). Three rose diagrams were constructed for each formation showing the unidirectional, bidirectional, and modified-combined measurements. From a comparison of the unidirectional and bidirectional rose diagrams, the assumed transport directions for the bidirectional sedimentary structures plotting closest to the unidirectional mean were considered to be the true transport trends. Because the bidirectional measurements had trends fairly close to the unidirectional means, this method could be used with some degree of certainty. If the bidirectional plots were 90 degrees to the unidirectional mean, a separate statistical analysis of the bidirectional data would have been necessary to determine the true bidirectional mean. The combined-modified rose diagrams therefore consider the bidirectional measurements closest to the unidirectional mean as trending in that direction. A combined mean and standard deviation were also calculated for each formation.

Comox Formation

The Comox Formation, being of wide extent in the study area, has an abundance of sedimentary structures. These include localized pebble imbrication and alignment, asymmetrical and symmetrical ripple marks, interference ripple marks, festoon cross-lamination, large-scale cross-bedding, laminated bedding, mud rip ups, flame structures, channeling, graded bedding, and loading features. The locations of the individual measurements and the rose diagrams plotted from them are presented in Figure 37. The mean transport direction is from the south to the north, with a change in attitude of some paleocurrent directions (especially noted from asymmetrical ripple marks) recorded upsection within the formation. The standard deviation for the unidirectional data is approximately 99 degrees,

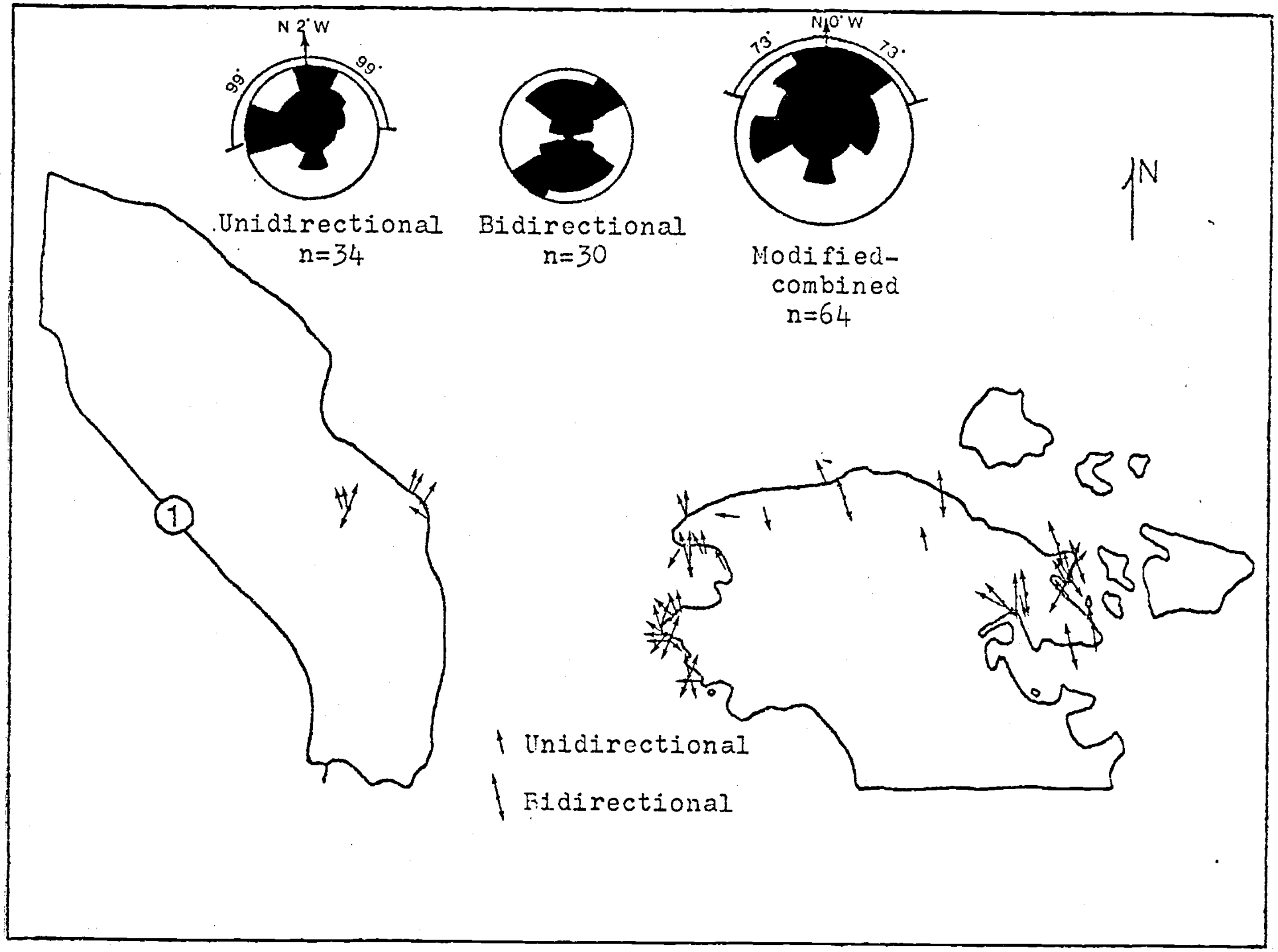


Figure 37: Paleocurrent data for Comox Formation.

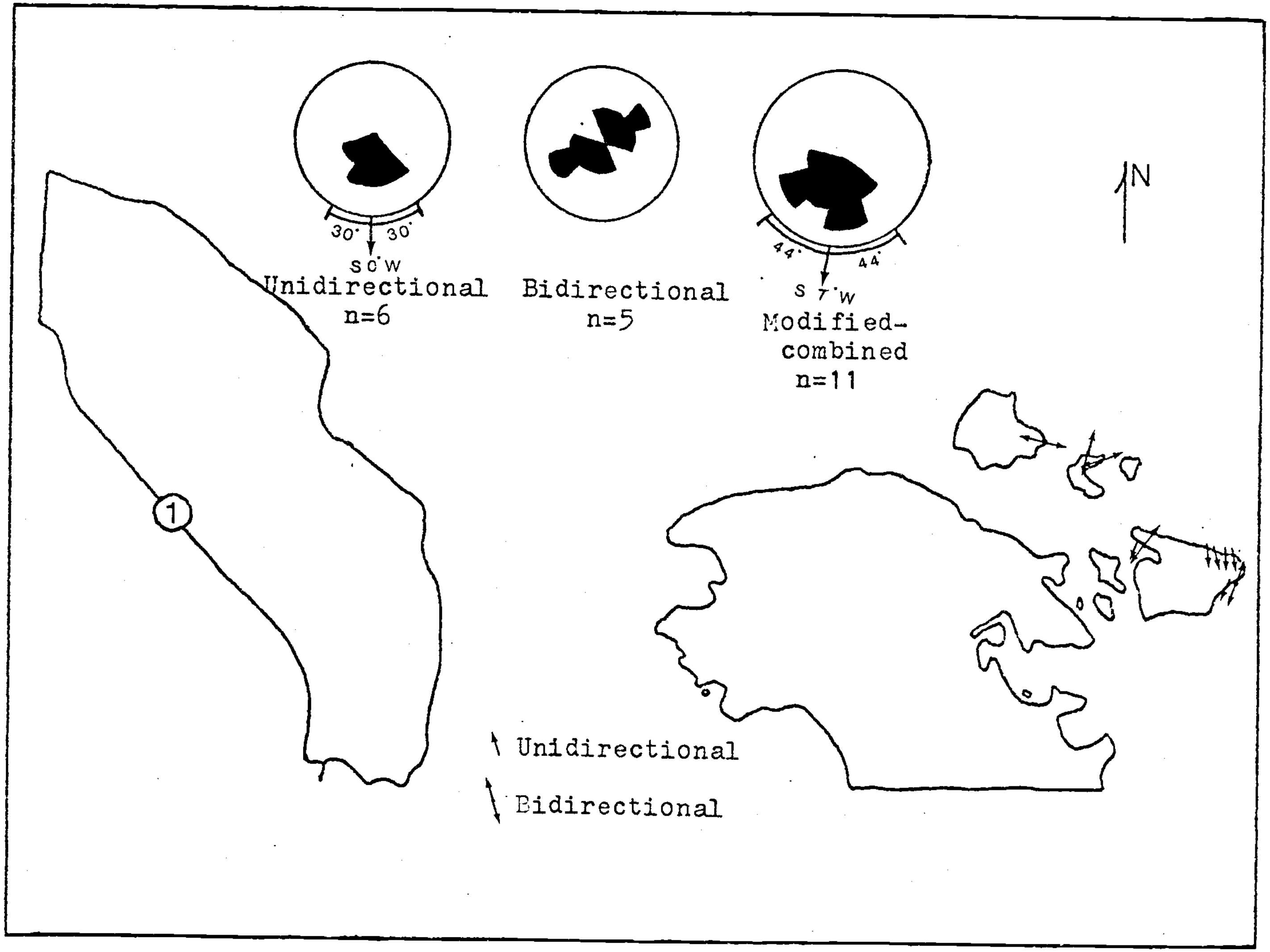


Figure 38: Paleocurrent data for Extension-Protection Formation.

whereas the combined standard deviation for the unidirectional and bidirectional data is 73 degrees. Of the 64 measurements taken, only 34 were unidirectional, with asymmetrical and symmetrical ripple marks generally the most common sedimentary structures noted within the formation.

Extension-Protection Formation

Asymmetrical and symmetrical ripple marks are the dominant sedimentary structures within the sandstones of the Extension-Protection Formation, with pebble alignment, pebble imbrication, scour-and-fill, and channeling common to the conglomerates and coarser grained units of the formation. Of the 11 measurements taken from these structures, five are bidirectional and only six unidriectional. As stated in the Extension-Protection Formation Stratigraphy section, the coarser grained units occur within the lower sections of the formation, whereas sandstones dominate upsection. Because most of the unidirectional data is from asymmetrical ripple marks, the calculated mean probably only reflects the transport direction common during deposition of the finer grained units.

The modified-combined mean for the paleocurrent data for the formation is S. 7° W. with a standard deviation of 44 degrees (Figure 38). Because only 11 measurements were taken, no real conclusions can be drawn from this data; however, a shift in the current direction from the northerly direction common to the Comox Formation to the south may have occurred during deposition of the Extension-Protection Formation.

Postulated Source Areas

Source area localities and lithologies for the sediments of the Nanaimo Group clastic rocks can be interpreted from an analysis of the paleocurrent data, sandstone petrology, and conglomerate clast lithologies noted within these Upper Cretaceous formations.

Generally, the Nanaimo Group sandstones present in the study area are composed of quartz, plagioclase feldspar (An_{38} to An_{52}), volcanic rock fragments, chert, biotite, metamorphic rock fragments, siltstone fragments, alkali feldspars, muscovite, granitic rock fragments, augite, epidote, hornblende, leucoxene, and magnetite. Quartz is mainly monocrystalline and undulatory, although polycrystalline and unstrained varieties are noted in most samples. Alkali feldspars are rare, with microcline only locally common in some coarser grained Comox sandstones. Chert occurs both as recrystallized volcanic glass and as reworked nodular and vugular varieties. Volcanic rock fragments usually are of an andesite composition, whereas metamorphic rock fragments generally consist of phyllites and quartz mica schists. Biotite is a fairly abundant constituent of most of the sandstone units.

Clasts within the conglomerate units are dominated by andesite, greenstone, basalt, metamorphic, chert, granitic, dacite, and sedimentary lithologies. The metamorphic clasts consist of phyllites, quartzites, and quartz mica schists. Sandstones and silicified mudstones are the common sedimentary clast lithologies.

Possible source rocks for the clastics of the Nanaimo Group formations are noted from a study of the regional pre-Cretaceous geology. Early Paleozoic gabbro and quartz diorite basement rocks are exposed on the San Juan Islands to the east of the study area. The oldest rocks exposed on Vancouver Island are the Pennsylvanian through early Permian Sicker Group consisting of volcanic breccia, tuff, argillite, greenstone, andesite, chert, graywacke, and limestone. Exposures of the Sicker Group extend from the Chemainus River to Alberni on northern Vancouver Island, along several northwest-trending outcrop belts north of the San Juan fault system, at Buttle Lake, and on Saltspring Island (Muller and Carson, 1969). The late Paleozoic granitic Tyee Intrusions intrude Sicker Group rocks at Maple Mountain, on Saltspring Island, south of Ladysmith, and north of Cowichan River (Muller, 1975). Early Mesozoic metamorphic equivalents of the Sicker Group (Wark Diorite and Colquitz gneiss) underlie a large part of southern Vancouver Island (Muller, 1975). Unconformably overlying these Paleozoic and early Mesozoic rocks is the Late Triassic through Early Jurassic Vancouver Group.

Subdivisions of the group consist of Karmutsen Formation pillow basalts and breccias, Quatsino Formation limestones, and Bonanza Subgroup limestones, argillites, and andesitic to dacitic breccias, tuffs, and lava flows. The Middle to Late Jurassic Saanich Granodiorite intrudes Vancouver Group rocks on southern Vancouver Island. These intrusions consist of plutonic granodiorite, quartz monzonite, and quartz diorite with dacitic to dioritic dike systems. The Island Intrusions have been correlated to the Coast Intrusions of mainland British Columbia, which are of a similar composition (Fyles, 1955). Vancouver Group and Saanich Granodiorite rocks therefore occur north, south, and west of the study area, with Saanich Grandiorite equivalents located to the northeast. The Leech River Schist, bounded by the San Juan fault to the north and the Leech River fault to the south, is considered to be of a Late Jurassic to Early Cretaceous age (Muller, 1977). These metasediments consist of argillite, slate, phyllite, and garnet-biotite-quartz schist. In addition to the Jurassic Coast Intrusions, Jurassic through Early Cretaceous andesitic to basaltic volcanic and sedimentary rocks occur to the east of the Nanaimo Basin on mainland British Columbia.

Although the sandstone mineralogies and conglomerate clast lithologies of the Nanaimo Group units present in the thesis area are fairly diverse, so too are the lithologies of the probable, pre-Cretaceous source rocks. The volcanic, granitic, and metamorphic rocks south of the study area probably supplied sediments to the depositional basin during most of Comox time. Sicker Group and Tyee rocks exposed on Saltspring Island north of the study area may also have been sediment sources during late Comox and through Extension-Protection time, as well as the volcanic, granitic, and sedimentary rocks to the northeast on mainland British Columbia. Because the northern extent of the Late Cretaceous depositional basin is uncertain, the probability of sediment transport over large distances through the basin southward is only theoretical. Localized, since eroded or downfaulted topographic highs composed of basement rock may also have existed north of the study area within the depositional basin, but this is also only speculative.

Depositional Environments

Comox Formation

The Comox Formation consists of a generally fining upward sequence of clastic rocks that begins with conglomerates of the Benson Member disconformably overlying basement rock and terminates with a gradational upper contact with the overlying Haslam Formation mudstones and siltstones. An overall, upward fining vertical succession of facies probably is the result of transgressive onlap and landward migration of the shoreline and depositional environments (Visher, 1965). The conglomerates, pebbly sandstones, thinly bedded sandstones, thickly bedded sandstones, normally graded sandstone to siltstone sequences, and carbonaceous mudstones of the Comox possibly reflect deposition within a transitional, continental to nearshore marine environment.

The basal Benson conglomerates, which are in erosional, nonconformable contact with the Jurassic igneous rocks, are representative of deposition in either a high-gradient fluvial environment or in a high-energy littoral environment. An intermittent, high-gradient braided stream system depositional environment can be interpreted from the large conglomerate clast sizes (pebbles to boulders), the variable angularity (subangular to rounded), and the poorly sorted, locally channelized, and interbedded nature of these conglomerates. In braided streams, erosion is rapid and discharge is sparodic and high (Selley, 1970). Rivers of this type generally are overloaded with sediment and contain channels that become clogged by coarser material during higher river flows. Interbedded sheets of sands are deposited during receding flows after flooding. A littoral depositional environment, consisting of sandy to pebbly beaches similar to those presently observed along the eastern shoreline of Vancouver Island, is another interpretation for this conglomerate unit. Erosion of headland sea cliffs by continental stream flow and marine wave action, followed by rapid deposition of the material below, can result in the accumulation of poorly sorted, sandy to pebbly beaches (Pettyjohn, 1975). Processes affecting beaches can vary seasonally (Yasso, 1971; Reineck and Singh, 1973). Storm activity during high tides can increase erosion rates and remove finer grained materials away from the cliff face into deeper, calmer water. Calmer regimes during low tides result in the redeposition of the finer grained sands over the gravel lag deposits. Such conditions are probably reflected within measured section A-B (Appendix I), characterized by thin (to one foot thick) conglomerate beds interbedded with sandstone (five to ten inches thick) and pebbly sandstone (two to four inches thick) strata. The Jurassic basement rocks therefore were probably uplifted (possibly the result of faulting?) and then inundated by a transgressing seaway, resulting in the erosion of the igneous rocks and subsequent deposition of the sediments on an erosional wave-cut surface. The general lack of pebble imbrication, rarity of channeling, and fairly well rounded nature of the conglomerate clasts are suggestive of such a littoral environment. Because conglomerate clast lithologies are fairly diverse, a combination of both fluvial and littoral depositional regimes is a probability, with high-energy streams depositing clastic material along a rugged, wave-worked coastline.

Continued transgression probably resulted in the deposition of sands and silts over these beach gravels. Shoreline relief possibly diminished as a response to erosion and weathering, as well as to the marine transgression. A decrease in topographic relief is related to a decrease in the total energy present within a system. Meandering river channels usually develop where gradients and discharge are relatively low. Humid, vegetated regions where seasonal discharge rates are fairly steady and sediment availability is low because of subdued and vegetated topography generally are characterized by high-sinuosity, meandering river systems. Sheets of laminated and ripple-marked, very fine sand, silt, and clay are deposited on the overbank areas of the river floodplain (Selley, 1970). Because Bell (1957) suggested that a warm humid to temperate climate existed at the time of deposition of these Upper Cretaceous sediments, vegetation probably was fairly abundant. The formation of peat and the preservation of vegetation along bedding surfaces is common in meandering river environments as well as in these Comox units. Episodic flooding of a meandering river can result in the sequential deposition of fining upward sequences of overbank sands to silts (Selley, 1970). The river channel deposits generally are laminated to thinly bedded, trough cross-bedded, or tabular planer cross-bedded and contain leaves and wood fragments (Selley, 1970). A large section of the Comox Formation is characterized by these features and therefore may have been deposited within a meandering river environment.

A transition from these sandstone to siltstone sequences to carbonaceous siltstones and mudstones may reflect a change in the environment from a river traversed coastal plain to a lagoonal and tidal flat complex. This facies shift may have been a response to continued transgression. Within the low-energy tidal flat and lagoonal environments, muds, silts, and fine-grained sands settled out of suspension. These lagoons and swamps may have been separated from the sea by offshore bars (Buckham, 1947) and thus subjected to higher energy regimes only during high tide and storm activity. During such occasions, semi-consolidated muds and silts became ripped up and marine sands and biotics were transported into the environment. Burrowers (such as Planolites), clams, echinoids, and a variety of plants generally inhabit the lagoonal and tidal flat environment. Nearby shoreline vegetation can supply leaves and wood to this facies where they settle out and decay, eventually transforming into peat and carbonaceous material. Laminated bedding, mud rip ups, and flame structures, as well as symmetrical, asymmetrical, and interference ripple marks are the common sedimentary structures within such an envrionment (Kukal, 1971; Reineck and Singh, 1973). The middle to upper Comox strata contain characteristics of this lagoonal-tidal flat facies.

Seaward of the tidal flat is a higher energy, barrier bar environment, apparently preserved within the Comox Formation. Thickly bedded and large-scale, tabular cross-bedded, rippled sandstones containing thick shelled, broken molluscs are common to this facies noted within Comox sandstones. The sandstones are only moderately sorted and are immature to submature, possibly indicative of rapid burial within this high-energy environment.

The deposition of fine-grained sands and silts grading to mudstones and containing marine fauna probably is the result of complete inundation by the sea. The Haslam Formation, in conformable, gradational contact with the Comox Formation, reflects this continued transgression. Therefore, the Comox strata probably reflect preserved sediments deposited within landward migrating marine facies following an episode of tectonic uplift. The combination of a marine transgression from subsidence or eustatic changes and leveling of the uplifted source area probably resulted in this transgression. The tectonics and possible causes for the marine transgression are discussed further in the Geologic Summary section.

Haslam Formation

The Haslam Formation is composed of a massively bedded mudstone unit as well as an interbedded sandstone-siltstone-mudstone unit. Both units contain a marine fauna consisting of thick-shelled *Inoceramus*, gastropods, and ammonites, indicative of a shallow-marine, open shelf environment. Carbonized wood particles sampled from concretions probably reflect transport of terrigenous material from a near-shore environment into the deeper water. Pyrite disseminated within concretions noted within the formation usually forms under reducing conditions (Weeks, 1953).

Weak bottom currents or contourites may have resulted in the deposition of the interbedded siltstones and sandstone strata of the formation. Mudstone rip ups and groove marks at the base of these units reflect changes in the current energy from fairly low during deposition of the muds to a higher state during deposition of the coarser grained units. Internal climbing ripples and cross-laminations are also indicative of current activity. Concretions such as those common to the Haslam can form under the reducing conditions created during the post-depositional decay of organic matter (Weeks, 1953). A combination of weak current activity, the presence of fossilized marine biotics, and evidence of organic decay are indicative of deposition in a well-circulated, habitable, low-energy marine environment.

Large-scale soft sediment deformation of the upper Haslam mudstone to sandstone sequences is probably the result of downslope creep of the semi-coherent units prior to lithification. Either the depositional slope was at a fairly high angle to cause this slumping, or uplift and fault block tilting prior to deposition of the overlying, coarser grained Extension-Protection Formation caused the downslope movement of these Haslam sequences.

The combined Comox-Haslam Formation record of a marine transgression originating with a transitional fluvial-high energy marine environment and terminating with a deeper marine environment is in general agreement with Muller and Jeletzky's (1970) depositional cycle theory of a fining upward sequence for the two formations.

Extension-Protection Formation

The Extension-Protection Formation was probably deposited under conditions similar to those of the Comox Formation. However, more conglomerate units and channels occur within the Extension-Protection than in the Comox and the rhythmic, normally graded sandstone to siltstone sequences noted within the Comox are less common within the Extension-Protection Formation.

Environments in which abundant gravels are deposited include braided rivers, alluvial and deep-sea fans, shorelines, and glacial terranes (Walker, 1975). Because the Late Cretaceous paleoclimate has been interpreted as tropical to warm temperate (Bell, 1957), a glacial origin for the conglomerates is unlikely. The presence of coal, plant fragments, and marine fossils within the formation are indicative of a transitional continental to nearshore marine depositional environment; therefore, a deep sea fan origin for these deposits is improbable. Most of the Extension-Protection conglomerate units were probably deposited within a high-energy fluvial environment.

A braided river environmental interpretation for the coarser grained strata of the Extension-Protection is based upon stratigraphic and petrologic evidence as well as on sedimentary structures present within these clastic rocks. Thickly bedded, tightly packed, imbricated, well rounded pebbles and cobbles noted within the conglomerates are indicative of deposition within a high-energy fluvial environment (Allen, 1965). Numerous scour-and-fill structures and conglomerate and sandstone channels are also noted within the formation. Sediment influx in braided river systems is high, overloading and infilling distributary channels (Selley, 1970). Such channel blocking can cause a swing in the channel direction which in turn can result in additional channel cutting and infilling. Occurrences such as these are common within the Late Cretaceous Gable Creek fluvial to deltaic conglomerate units of central Oregon (Wilkinson and Oles, 1968). After flooding of a braided river system with coarse clastics, finer grained sands and silts settle out of suspension and are deposited on top of the gravels and coarse sands, resulting in a fining upward sequence of channel filling (Williams and Rust, 1969). A series of such fining upward sequences are noted within the Extension-Protection conglomerate units.

At least once cycle of delta progradation may have occurred during deposition of the formation. As noted within measured section I-J (Appendix I-a), conglomerates grade upward to sandstones and interbedded sandstone to mudstone sequences, which then grade upward to sandstones and conglomerates. Upward coarsening sequences are common in prograding delta environments (Fisk and others, 1954; Visher, 1965; Coleman and Wright, 1975). The interbedded sandstone to mudstone sequences noted within this upward coarsening cycle may represent sediments deposited within the prodelta facies of the deltaic environment (McBride and others, 1975).

A massive influx of clastics into the braided river system may have resulted in the progradation of a delta complex seaward. In the presence of relatively weak marine forces, a powerful stream could have pushed the shoreline forward rapidly and extend the delta, much of it subaerially, into a shallow-marine basin (Wilkinson and Oles, 1968).

Marine transgression over the fluvial to deltaic lower to middle Extension-Protection Formation units probably resulted in the deposition of the medium- to fine-grained, rippled and cross-bedded sandstones common to the upper units of the formation. Low to moderate current activity is interpreted from the presence of thick-shelled molluscs and scour-and-fill structures within the formation. Minor pebbly sandstone beds and thin conglomerate strata may also represent deposition along a wave-worked shoreline during this time.

Laterally discontinuous sandstone channels may have been deposited within intertidal creeks common to shallow-marine environments (Reineck and Singh, 1973). Continued marine transgression probably resulted in the eventual deposition of the overlying, finer grained Cedar District Formation.

Cedar District Formation

Exposures of the Cedar District Formation are somewhat limited within the thesis area and therefore conclusions as to the environments of deposition are also limited. Generally, the formation consists of a series of interbedded sandstones, mudstones, and siltstones; individual units of the strata range from two to six inches thick, whereas complete sequences are four to 18 inches thick. These graded sequences have sharp bottom contacts with basal groove and load casts at some locations, are normally graded, and contain internal parallel laminations, ripple laminations, and cross-laminations that are probably representative of B, C, and D subdivisions of incomplete Bouma sequences (Bouma, 1962).

Because of the graded nature, marine faunal content (especially *Inoceramus*), and external and internal sedimentary structures common to these Cedar District sequences, a marine turbidity current origin is suggested for most of the formation. Graded beds containing internal Bouma sequence sedimentary structures usually are deposited as a result of gravity-induced, subaqueous, downslope movements of sediment-charged density (turbidity) currents (Bouma, 1962; Middleton and Hampton, 1973). Basal load and groove casts are also usually associated with turbidity flows (Selley, 1970). A shallow- to intermediate-marine environment is interpreted from the presence of thick-shelled Inoceramus tests and carbonized wood fragments.

Because the upper contact is reported to be gradational from the generally fine-grained turbidites of the Cedar District to the coarser grained sandstones of the overlying DeCourcy Formation at other localities within the Nanaimo Basin (Stickney, 1976; Hanson, 1976), and because sandstone beds of the turbidite sequences thicken and dominate over the mudstones and siltstones upsection within the Cedar District on Pym Island, the Cedar District Formation strata may represent the initial deposits of a coarsening upward, prograding delta. Allen (1960), Shepard (1960), and Walker (1969) have recognized turbidite sandstones within delta front and prodelta deposits. Muddy flood water can be sufficiently dense at the river mouth to form turbidity currents that continue to flow downslope to the prodelta environment (McBride and others, 1975). If these turbidites are indeed prodelta deposits, a prograding delta could have deposited the coarser grained marine sands common to the delta platform and delta front (McBride and others, 1975) characterized by the upper Cedar District and lower DeCourcy sandstones.

Geologic Summary

The four oldest Nanaimo Group formations present in the study area were deposited within a subsiding marine basin located to the east of southern Vancouver Island during Late Cretaceous time. Uplift of pre-Late Cretaceous basement rocks on Vancouver Island to the west and on mainland British Columbia to the east created rugged, high-relief source areas that were chemically weathered in a warm tropical climate (Bell, 1957) and mechanically eroded by high-energy braided stream systems. The depositional basin (Nanaimo Basin) probably formed in response to these uplifts to the east and the west; coupling of vertical movements on either side and the resulting stresses possibly caused depression of the central basin (Nelson, 1977). Monger and others (1972) describe the Nanaimo Basin as a successor basin that formed as a result of a collision between an oceanic and a continental plate, whereas Muller (1977) states that the Nanaimo Basin represents a fore-arc basin and that the successor basins are located to the east on mainland British Columbia. Gradual subsidence of the basin continued from the Jurassic through the Late Cretaceous, at which time it became the center of deposition for the Nanaimo Group clastics (Jeletzky, 1965).

Following uplift of the pre-Late Cretaceous basement rocks, Comox and Haslam sediments were deposited in response to a continual transgression of a Late Cretaceous marine seaway over the rugged terrain. Rapid erosion of these highlands and deposition of the clastic material, reflected by the compositional and textural immaturity of the Comox sediments, probably occurred during this time. Braided stream systems trending north-northwest into the basin deposited Benson Member gravels and sands onto a high-energy, cliffed shoreline. Continued erosion of the highlands and transgression of the marine seaway resulted in subdued topographic relief and the deposition of sediments by low-energy meandering streams within a river traversed coastal plain environment. This was followed by silt and clay deposition in protected tidal flat and lagoonal environments and finally by sand deposition in a higher energy barrier bar environment. The succeeding marine transgression resulted in the deposition of the massive marine mudstones and sandstone-siltstone-mudstone sequences of the Haslam Formation. Either basin defaulting or downwarping or eustatic sea level changes can account for this record of marine transgression throughout the deposition of the Comox and Haslam Formations.

Localized uplift within the basin elevated these units prior to complete lithification and possibly resulted in the subsequent soft sediment deformation of the upper Haslam Formation strata. An eroded surface developed on the top of the Haslam Formation on which the basal conglomerates of the Extension-Protection Formation were deposited. The Extension-Protection units are representative of a cycle of basin deepening (marine transgression), delta progradation and apparent marine regression, and a continuation of marine transgression. Tectonic uplift is suggested from the textural immaturity of the coarse clastics of the formation as well as from the high influx of clastic material within braided river systems that apparently extended south-southeast into the marine environment as a prograding delta. Lower energy regimes and subdued topography are reflected by the finer grained sediments deposited during late Extension-Protection through early Cedar District time.

Sahllow- to intermediate-marine silts and muds deposited during early Cedar District time may be representative of the distal turbidite flows of a prodelta environment. Although no paleocurrent directions for the Cedar District have been interpreted in the thesis area, generally east to southeast directions have been noted for the formation within the basin to the north (Hudson, 1974; Hanson, 1976). As the delta prograded seaward (southeastward?), these distal turbidites were overlain by proximal turbidites in which sand layers thickened at the expense of muds and silts that were transported to deeper water basinward. Delta progradation probably continued through early DeCourcy time.

Following lithification of the Nanaimo Group clastics, faulting resulted in the northwest-trending structural fabrics common to the area as well as in the secondary folding and tilting of the Nanaimo Group strata. Uplift probably occurred in conjunction with the folding and faulting. Tertiary imbricate and reverse faulting along the San Juan and Orcas fault systems (Muller, 1977) complicated the structure in the area by offsetting and terminating preexisting faults and by drag folding and overturning Nanaimo Group strata along curved fault planes. The regional stress system is presently of a north to south compressional type (Crossan, 1972).

Pleistocene glaciation differentially scoured the nonresistant fractured fault zones and mudstone units, creating the noticeable aerial photo lineations and the cuestas of resistant strata that are common to the area. Glacial cobble- to boulder-sized erratics and gravels, sands, and clays have infilled topographic lows as well as marine embayments.

Stream erosion, chemical and mechanical weathering, and surficial slumping and landslides are occurring at the present time. Wave activity has created the numerous localized marine embayments of the areas, as well as the honeycomb weathering and the gallery structures common to the Nanaimo Group sandstone units. Ground-water percolation through fractures within the sandstones has resulted in the precipitation of calcium carbonate along the fracture surfaces, elevating them from sandstone exposures.

ECONOMIC GROLOGY

Construction Materials

Because of the extent and thickness (over 100 feet thick) of the glacial deposits within the study area, excavation of sand and gravel for road and home construction purposes is economically feasible. Numerous gravel pits are in operation on both private and provincial property in the Cobble Hill area.

The conglomerate units present in the thesis area, because of their limited extent and firmly indurated nature, are not quarried for gravel. Sandstones weather to thin plates that break away from fresher surfaces and thus are not used for major building purposes; however, the sandstones are used locally for drywall and patio construction.

Although bricks have been manufactured from the clays within Nanaimo Group mudstones north of the study area (Hudson, 1974; Stickney, 1976), the Haslam and Cedar District mudstones in the North Saanich-Cobble Hill area are firmly indurated and of a limited extent and thus are not utilized for this purpose. Clays removed from the Pleistocene glacial deposits may be better suited for brick and pottery production; however, the extent of this usage is not known.

Coal

The Hudson's Bay company began mining coal from the Late Cretaceous rocks in the Nanaimo area in 1854 (Hector, 1861). Coal mining continued until about 1960, when economic pressures resulting from low coal prices and high costs of removal forced its discontinuance. Until that time, an approximated 70 million tons of coal were removed from these coal fields (Muller and Atchinson, 1971). A well penetrating almost 800 feet of Comox strata was drilled in 1913 west of Cloake Hill in North Saanich in search of additional coal measures.

Numerous exposures of thin (to three inches thick) coal seams occur within the middle Comox Formation units in the study area. Such seams are noted immediately south of Hatch Point in the Cobble Hill area as well as in the North Saanich area 0.25 miles south of Coal Point, 0.4 miles east of Kingfisher Point, at Nymph Point, and inland along Highway 17 0.6 miles southwest of Swartz Bay. Because of their limited nature and the environmental implications resulting from mining within the area, removal of these coal deposits is impractical. The coal generally is low rank and brittle, further decreasing its economic significance.

Petroleum Potential

After only a cursory review of the stratigraphy and structure of the study area, favorable conditions for the presence of economically important petroleum deposits may appear to exist within the Nanaimo Group clastic rocks. Upon closer examination of the necessary requirements for the presence of petroleum within these sedimentary rocks, this potential becomes minimal. These requirements include: (1) the presence of biotics during sediment deposition; (2) preservation of organic protein matter; (3) chemical transformation of the proteinaceous material into "live" hydrocarbons; (4) migration and accumulation of these hydrocarbons; (5) the presence of porous and permeable reservoir rocks; and (6) the presence of a trap or cap rock to prevent further migration of the hydrocarbons. According to Fiske (1977), the required "live" hydrocarbons may be present within the Nanaimo Group mudstone source rocks. Because of the rhythmically bedded nature of the Nanaimo Group strata, numerous stratigraphic traps may exist within the study area. However, the coarser sedimentary rocks of the group contain little or no porosity (less than one percent) or permeability and thus cannot be considered as reservoir rocks. Diagenetic alteration of mafic minerals to clays, calcite and silica precipitation, and prehnite formation have reduced porosity within these sandstones to this minimum. These causes for porosity reduction have been discussed in the Porosity and Diagenesis section. As previously stated, water wells drilled through Comox strata and penetrating the underlying Saanich Granodiorite tap water from the granodiorite at many locations in the North

Saanich area; this is additional evidence for the lack of porosity within the Nanaimo Group sandstones.

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APPENDICES

APPENDIX I

Representative Measured Sections

Representative sections of the Comox and Extension-Protection Formations were measured utilizing a five-foot Jacobs staff mounted with an Abney level, and a Brunton compass. Lithologic descriptions were made with the aid of a 10X hand lens, dilute hydrochloric acid, a GSA Rock-Color Chart (Goddard and others, 1970), a sand gauge chart, and Power's (1953) Roundness Chart.

Measured Section A-B of the Comox Formation is located between Armstrong and Thumb Points in North Saanich. The location was chosen because of the exposure of the basal, nonconformable contact between the formation and the underlying Bonanza Volcanics as well as exposure of Benson Member conglomerate and lower Comox sandstone and siltstone.

The terminal point (B, Plate 1) is located at the sandy embayment 0.25 miles northwest of Armstrong Point and 500 feet southeast of Thumb Point. Curteis Point lies in a direction N 25°E. of B.

Interval (Feet)	Description

Unit Description: Conglomerate: resistant cliff-former; grayish olive (10Y 4/2) general overall weathered color; thickly bedded; fine pebbles to small boulders, medium to coarse pebbles predominant; subangular to well rounded; grain supported; andesite, greenstone, basalt, granodiorite, quartzite, sandstone, phyllite, mudstone; matrix is sandstone, fine- to very coarse-grained, subangular to subrounded; poorly sorted; well indurated; quartz, feldspar, black minerals, chert; locally display pebble elongation, generally parallel to strike.

Sandstone: resistant cliff-former; grayish olive (10Y 4/2) weathered; thinly to medium bedded; medium- to coarse-grained; poorly to moderately sorted; subangular to subrounded; well indurated; quartz, chert, micas, black minerals, clay matrix, feldspar; locally cemented with calcium carbonate, contains mud rip ups, or carbonized wood and leaf fragments; normally graded to siltstone; generally heavily weathered, locally to honeycomb structures; locally exfoliated or concretionary, concretions calcareous and elongate 1 to 3 inches by 2 to 5 inches; blocky fractured.

113.5-118.5	Covered by sand and gravel beach; presumably non-resistant mudstone.
103-113.5	Sandstone as unit description; thickly laminated to thinly bedded. Lower contact sharp and gently undulatory. Offset N. 65° W. approximately 50 feet to equivalent stratigraphic position to avoid water.
97.5-103	Silty sandstone; olive gray (5Y 4/1) weathered; thickly laminated; abundant carbonized plant fragments. Lower contact gradational over 2 inches by upper decrease in grain size.
97-97.5	Sandstone: light olive gray (5Y 5/2) to dark yellowish brown weathered; thickly laminated; fine- to medium-grained; moderately to poorly sorted; angular to subrounded; quartz, chert, micas, black minerals,

Appendix I (Continued)

Interval (Feet)	Description
	clay matrix; concretionary, calcareous, greenish gray (5GY 6/1); oval 2 to 8 inches in diameter. Lower contact sharp and gently undulatory.
93.5-97	Siltstone: greenish gray (5GY 6/1); thinly laminated; clays, micas, quartz. Lower contact gradational over 4 inches by upward decrease in grain size.
87.5-93.5	Sandstone as at 97.5.
	Offset N. 70° W. approximately 65 feet to equivalent stratigraphic position to avoid water.
	Attitude N. 67° W., 49° N.E. Proceed N. 23° E. up-section.
39-87.5	Sandstone to siltstone interbeds; normally graded. Sandstone as unit description. Siltstone as at 97.

Sequence: (in.)

44. sandstone 5.0
43. siltstone 24.0
42. sandstone 48.0
41. siltstone 12.0
40. sandstone. 41.0
39. siltstone 12.0
38. sandstone 2.0
37. siltstone 31.0
36. sandstone 24.0
35. siltstone 2.0
34. sandstone. 6.0
33. siltstone 2.0
32. sandstone 18.0
31. siltstone 3.0
30. sandstone 2.0
29. siltstone 3.0
28. sandstone 8.0
27. siltstone 5.0
26. sandstone 3.0
25. siltstone 2.0
24. sandstone 3.0
23. siltstone 1.0
22. sandstone 53.0
21. siltstone 1.0
20. sandstone 2.0
19. siltstone 3.0

Appendix I (Continued)

Interval (Feet)	Description
	18. sandstone 6.0
	17. siltstone 36.0
	16. sandstone 3.5
	15. siltstone 1.5
	14. sandstone 48.0
	13. siltstone 1.5
	12. sandstone 48.0
	11. siltstone. 3.0
	10. sandstone 41.0
	9. siltstone 7.0
	8. sandstone 8.0
	7. siltstone 2.0
	6. sandstone 12.0
	5. siltstone 2.0
	4. sandstone 2.0
	3. siltstone 2.0
	2. sandstone 1.5
	1. siltstone 36.0
	Lower contact gradational over 6 inches by upward decrease in grain size.
35-39	Sandstone as unit description. Lower contact sharp and gently undulatory.
33.5-35	Siltstone: medium gray (N5) to light olive gray (5Y 6/1) weathered; thinly to thickly laminated; concretionary, calacreous concretions are elongate 0.5 to 2 inches by 2 to 4 inches; clays, micas, quartz. Lower contact gradational over 3 inches by upward decrease in grain size.
32.5-33.5	Sandstone as unit description. Lower contact sharp and gently undulatory.
32.0-32.5	Siltstone as at 35.
31.5-32	Sandstone as at 33.5.
27.5-31.5	Sandstones as unit description; channelized, discontinuous channels terminate over distances of less than 10 feet laterally; weathers to small (less than 1 inch diameter) chips; carbonaceous stringers: exfoliated. Lower contact sharp and planar.
14.5-27.5	Sandstone as unit description: locally (at 17, 20, 22, and 27 feet) contains bands of fine to medium, subrounded to rounded pebbles of chert, greenstone, quartzite, basalt, quartz. Sandstone contains

Appendix I (Continued)

Interval (Feet)	Description
	mudstone rip ups at base generally aligned parallel to strike. Lower contact sharp and planar.
9-5-14.5	Conglomerate as unit description. Lower contact gradational over 6 inches by increase in proportion of pebbles.
8-9.5	Sandstone as unit description. Lower contact sharp and planar.
0-8	Conglomerate as unit description.
	Contact at A: Comox Formation and Bonanza Volcanics; nonconformable, erosional with up to 18 inches relief; basal conglomerate contains angular to subangular clasts of greenish black (5G 2/1) volcanics, presumably from underlying Bonanza Volcanics. The attitude is N. 65° W., 54° N.E. The section is measured stratigraphically up heading N. 25° E.

Initial point (A, Plate 1) located at southeasternmost part of Armstrong Point, North Saanich. Roberts Point bears S. 40° E. from A.

Appendix I-a

Representative Measured Section I-J, Extension-Protection Formation

Measured Section I-J of the Extension-Protection Formation is located along the southeastern shoreline of Piers Island between 500 feet north of the southeasternmost point and 0.25 miles south of the northeasternmost point of the island. Included in the section is the basal disconformable contact with the underlying Haslam Formation as well as the thickly bedded conglomerates and channel sandstones of the formation.

The terminal point (J, Plate 1) is located 0.25 miles south of the northeasternmost, unnamed point of Piers Island. Triangulation location was not possible because of a lack of suitable landforms.

Interval (Feet)	Description

Unit Description: Sandstone: resistant cliff-former; light olive gray (5Y 6/1) to olive gray (5Y 4/1) weathered; medium to thickly bedded; medium- to coarse-grained; poorly to moderately sorted; subangular to subrounded; quartz, chert, black minerals, micas; locally cemented with calcium carbonate; normally graded to siltstone; locally contains carbonized wood fragments and broken bivalve tests; generally deeply weathered, locally to honeycomb structures.

Conglomerate: resistant cliff-former; moderate brown (5YR 4/4) to dark yellowish brown (10YR 4/2) weathered; thickly bedded; fine pebbles to medium cobbles, medium to coarse pebbles predominant; subangular to well rounded; grain supported; basalt, andesite, chert, greenstone, sandstone, diorite, silicified mudstone; matrix is sandstone, coarse- to very coarse-grained, angular to subrounded, quartz, chert, feldspar, muscovite, black minerals. Locally display pebble elongation; scour-and-fill channels common in cross-section.

585-590	Covered by sand and gravel beach; presumably non-resistant mudstone.
523-535	Sandstone as unit description. Lower contact gradational over 10 inches by upward decrease in proportion of concretions.
510-523	Sandstone as unit description. Contains calcareous concretions that are elongate 3 to 5 inches by 6 to 15 inches; medium gray (N5) weathered. Lower contact gradational over 2 feet by upward decrease in proportion of pebbles.
503.5-510	Conglomerate as unit description. Lower contact gradational over 4 inches by upward increase in proportion of pebbles.
442.5-503.5	Sandstone as unit description. Conglomerate channels common; 7 feet wide by 4 feet deep; as unit description.
430-442.5	Conglomerate as unit description. Lower contact sharp and gently undulatory.

Appendix I-a (Continued)

Interval (Feet)	Description
423-430	Sandstone as unit description; very thin to thinly bedded. Lower contact sharp and planar.
406.5-423	Conglomerate as unit description. Lower contact sharp and gently undulatory.
397-406.5	Sandstone as unit description. Locally contains bands of fine to medium pebbles: subangular to rounded, chert, basalt, greenstone, quartzite. Lower contact gradational over 2 feet by upward decrease in proportion of pebbles.
384-397	Conglomerate as unit description. Lower contact sharp and gently undulatory.
	Offset N. 60° W. approximately 25 feet to equivalent stratigraphic position to avoid water.
382 5-384	Sandstone as unit description; very thin bedded. Lower contact gradational over 5 inches by upward decrease in proportion of pebbles.
	Attitude N. 64° W., 50° N.E. Proceed N. 26° E. up-section.
373.5-382.5	Conglomerate as unit description. Lower contact gradational over 6 inches by upward increase in pebbles.
371.5-373.5	Sandstone as at 384.
349.5-371.5	Conglomerate as unit description. Locally contains sandstone channels as unit description that have sharp, planar to gently undulatory contacts. Lowr contact sharp and gently undulatory.
	Offset N. 65° W. approximately 20 feet to equivalent stratigraphic position to avoid water.
347-349.5	Sandstone as unit description. Lower contact sharp and planar.
	Attitude N. 54° W., 52° N.E. Proceed N. 36° E. up-section.
319.5-347	Conglomerate as unit description. Contains 0.5 to 2 feet thick interbedded sandstones as unit description. Lower contact sharp and gently undulatory.
319-319.5	Pebbly sandstone: contains bands of fine to medium, subangular to rounded pebbles of chert, basalt, greenstone; sandstone as unit description. Lower contact sharp and planar.

Appendix I-a (Continued)

Interval (Feet)	Description
311.5-319	Conglomerate as unit description. Lower contact sharp and gently undulatory.
311-311.5	Pebbly sandstone as at 319.5
281-311	Conglomerate as unit description. Lower contact sharp and gently undulatory.
280.5-281	Pebbly sandstone as at 319.5.
266-280.5	Conglomerate as unit description. Lower contact sharp and shows scour-and-fill with underlying siltstone.
	Offset N. 52° W. approximately 25 feet to equivalent stratigraphic position to avoid water.
234.5-266	Interbedded sandstone and siltstone; normally graded. Sandstone: greenish gray (5GY 6/1) weathered; very thinly bedded; carbonaceous. Siltstone: medium gray (N5) weathered; thickly laminated; contains calcareous concretions that are elongate 0.5 to 2.5 inches by 4 to 8 inches.

typical sequence:	(in.)
j. siltstone	0.5
i. sandstone	0.25
h. siltstone	0.25
g. sandstone	3.0
f. siltstone	0.5
e. sandstone	0.75
d. siltstone	0.25
c. sandstone	2.5
b. siltstone	1.5
a. sandstone	3.0

Lower contact gradational over 6 inches.

229-234.5	Sandstone as unit description. Locally contains sandstone channels that pinch out laterally over distances of up to 6 feet. Lower contact sharp and gently undulatroy.
147-229	Sandstone to mudstone sequences; units 0.5 to 5 inches thick; normally graded. Sandstone: greenish gray (5GY 6/1) weathered; thickly laminated. Mudstones: dark gray (N 3) weathered; massive. Lower contact covered.
89.5-147	Covered by sand beach; presumably non-resistant mudstone.

Appendix I-a (Continued)

Interval (Feet)	Description
52-5-89. 5	Conglomerate as unit description. Lower contact sharp and gently undulatory.
	Offset N. 30° W. approximately 30 feet to equivalent stratigraphic position to avoid water.
51. 5-52. 5	Siltstone: greenish gray (5GY 6/1) weathered; very thinly laminated. Lower contact sharp and planar.
	Attitude N. 22° W., 52° N.E. Proceed N. 68° E. up-section.
26. 5-51. 5	Conglomerate as unit description. Lower contact gradational over 5 inches by increase in proportion of pebbles.
25-26. 5	Pebbly sandstone as at 319. 5.
17. 5-25	Conglomerate as unit description. Lower contact gradational over 5 inches by increase in proportion of pebbles.
17-17. 5	Pebbly sandstone as at 319. 5.
4.5-17	Conglomerate as unit description. Lower contact sharp and gently undulatory.
3-4. 5	Sandstone as unit description. Lower contact gradational over 6 inches by decrease in proportion of pebbles.
0-3	Conglomerate as unit description.
	Contact at I: Extension-Protection Formation and Haslam Formation; sharp and gently undulatory; basal conglomerate contains rare clasts of mudstone presumably from underlying Haslam Formation. The attitude is N. 29° W., 64° N. E. The section is measured stratigraphically up heading N. 61° E.

Initial point (I, Plate 1) located 500 feet north of northeasternmost, unnamed point of Piers Island (extreme northern point of adjacent Olive Island bears S. 70° E., southwesternmost point of same island bears S. 55° E.).

Appendix II

Modal Analyses

Modal Analyses of Saanich Granodiorite

Sample	K-109	K-102
Quartz	6.9	24.4
Plagioclase	50.4	53.8
K-spar	26.2	3.1
Hornblende	9.3	11.3
Epidote	2.5	1.3
Augite	1.0	0.3
Magnetite	0.7	1.3
Chlorite	2.7	4.5
Others	T	T

Appendix II-a. Modal Analyses of Sandstone Samples

Sample: Formation	Comox				Haslam	Extension-Protection			Cedar District	
Number	K-11	K-39	K-119	K-155	K-15	K-76	K-134	K-162	K-150	K-151
FRAMEWORK TOTAL	90.8	79.6	93.5	75.3	68.2	94.4	89.7	88.7	77.8	77.3
Quartz total	36.3	27.7	29.6	27.3	29.6	24.6	35.6	32.3	37.8	24.2
UQ	26.1	19.5	20.6	19.6	18.2	16.7	27.8	25.3	25.0	16.4
NQ	1.8	2.3	0.6	1.7	10.3	1.1	T	T	9.3	1.5
PQ	8.4	5.8	8.4	5.9	1.2	6.8	7.2	6.3	3.5	6.3
Chert	9.3	8.7	11.8	11.8	10.7	11.9	14.4	16.4	7.6	11.6
Feldspar total	15.0	14.9	16.9	7.1	10.3	15.0	13.1	11.8	8.5	15.4
Plagioclase	12.6	13.7	15.0	6.4	10.0	14.4	12.6	11.3	8.5	14.5
K-spar	2.4	1.2	1.9	0.7	T	0.6	T	T	-	0.9
Rock frag total	14.4	17.5	26.2	15.5	2.3	29.7	16.3	17.6	2.6	37.1
Volcanic	7.3	14.6	19.7	8.6	1.1	24.9	10.7	14.1	2.4	26.1
Metamorphic	6.5	2.3	5.3	6.6	1.1	3.7	5.3	3.2	T	4.4
Granitic	T	0.6	0.9	T	T	0.8	T	T	-	5.3
Sedimentary	0.6	-	T	T	-	T	-	-	-	1.3
Micas total	7.8	5.8	5.3	5.1	5.5	2.8	5.1	6.0	8.7	7.2
Biotite	5.1	2.6	3.1	4.2	3.5	0.8	3.5	5.2	6.3	4.4
Muscovite	1.5	1.2	0.7	-	1.0	T	T	-	T	-
Chlorite	1.2	2.0	1.5	0.9	1.0	1.8	1.5	0.8	1.7	2.8
Mafics total	2.1	1.5	1.2	2.2	0.8	0.8	T	0.9	T	T
Augite	1.0	1.3	0.9	1.7	-	T	T	-	-	T
Epidote	1.1	T	T	T	T	T	T	T	-	-
Hornblende	-	T	-	T	T	-	-	T	T	-
Opaques	3.9	3.2	2.5	7.1	9.2	8.8	4.5	3.7	10.9	3.1
Others	T	T	-	T	T	T	-	-	T	T
MATRIX TOTAL	5.4	5.3	2.2	3.9	26.9	1.7	5.6	4.3	10.1	1.9
CEMENT TOTAL	3.6	14.3	4.1	20.8	4.9	3.7	4.5	5.1	12.1	0.8
Calcite	T	12.2	T	19.5	4.7	3.5	4.0	4.6	12.1	-
Clay-silica	3.6	1.4	2.5	1.3	T	T	T	T	-	0.8
Prehnite	-	0.7	1.6	-	-	T	-	-	-	-
POROSITY	T	0.8	T	-	-	T	T	T	-	-