AN ABSTRACT OF THE THESIS OF

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Title: THE GEOLOGY AND STRATIGRAPHY OF THE LOWER NANAIMO
GROUP, NANAIMO, BRITISH COLUMBIA

Abstract approved: Redacted for Privacy
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The western part of the Late Cretaceous Nanaimo Basin is exposed on Vancouver Island at Nanaimo, British Columbia. The five lowest members of the Nanaimo Group are present and represent a complete sedimentary cycle. The two lowest formations, the Comox and Haslam, represent the marine part of the cycle. The Comox rests with angular unconformity on the underlying Triassic Karmutsen volcanics, and is composed of shallow marine deposits of sandstones, conglomerates and limestones, one of the limestones being an algal type not previously reported for the Nanaimo Basin. The Haslam represents a quiet marine environment, possibly lagoonal, which grades upward into a swampy environment represented within the lower Extension Formation.

The Extension Formation represents the first of the terrestrial part of the cycle. Above the Wellington Coal Member, deposited in a swampy environment, lie channel

conglomerates and sandstones indicative of a braided stream environment. The Newcastle Formation onlaps the Extension Formation and is composed of sandstones, siltstones, conglomerates, and the Newcastle and Douglas Coal Seams. The environments of deposition of the Newcastle Formation are postulated to be the upper floodplain of a short headed stream. Paleocurrent data and composition of the rocks indicate sources to the west.

The Protection Formation is the uppermost of the formations in the area, and is composed of thick- and thin-bedded sandstones. The sandstones indicate a barrier-beach complex, probably deposited as the paleo-shoreline migrated west during a transgression.

Subsequent faulting, and fluvial and glacial erosion produced the present topography of the area.

The Geology and Stratigraphy of the Lower Nanaimo Group, Nanaimo, British Columbia

by

William Ruddiman III

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THE GEOLOGY AND STRATIGRAPHY OF THE LOWER NANAIMO GROUP, NANAIMO, BRITISH COLUMBIA

INTRODUCTION

Location

The study area is located along the south-central part of the east coast of Vancouver Island, due west across the Strait of Georgia from the city of Vancouver, B.C. (see Figure 2). The city of Nanaimo and adjoining areas compose most of the study area, a strip of coastal land approximately seven miles long by three miles wide, plus Newcastle and Protection Island and a group of smaller islands on the north side of Departure Bay. The total land area covered by the study is approximately 25 square miles.

Geography

The topography of the area clearly shows the effects of the continental glaciation that covered the area during the last glacial epoch. The landscape slopes upward fairly steeply from sea level to about 200 feet, and then is marked by a series of low ridges that trend northwest, a combining of glacial moraines with the northwest strike of the underlying bedrock. This area of ridges and swales is called Harewood, south and west of Nanaimo city center, and Northfield, north of the Millstone River. The Millstone

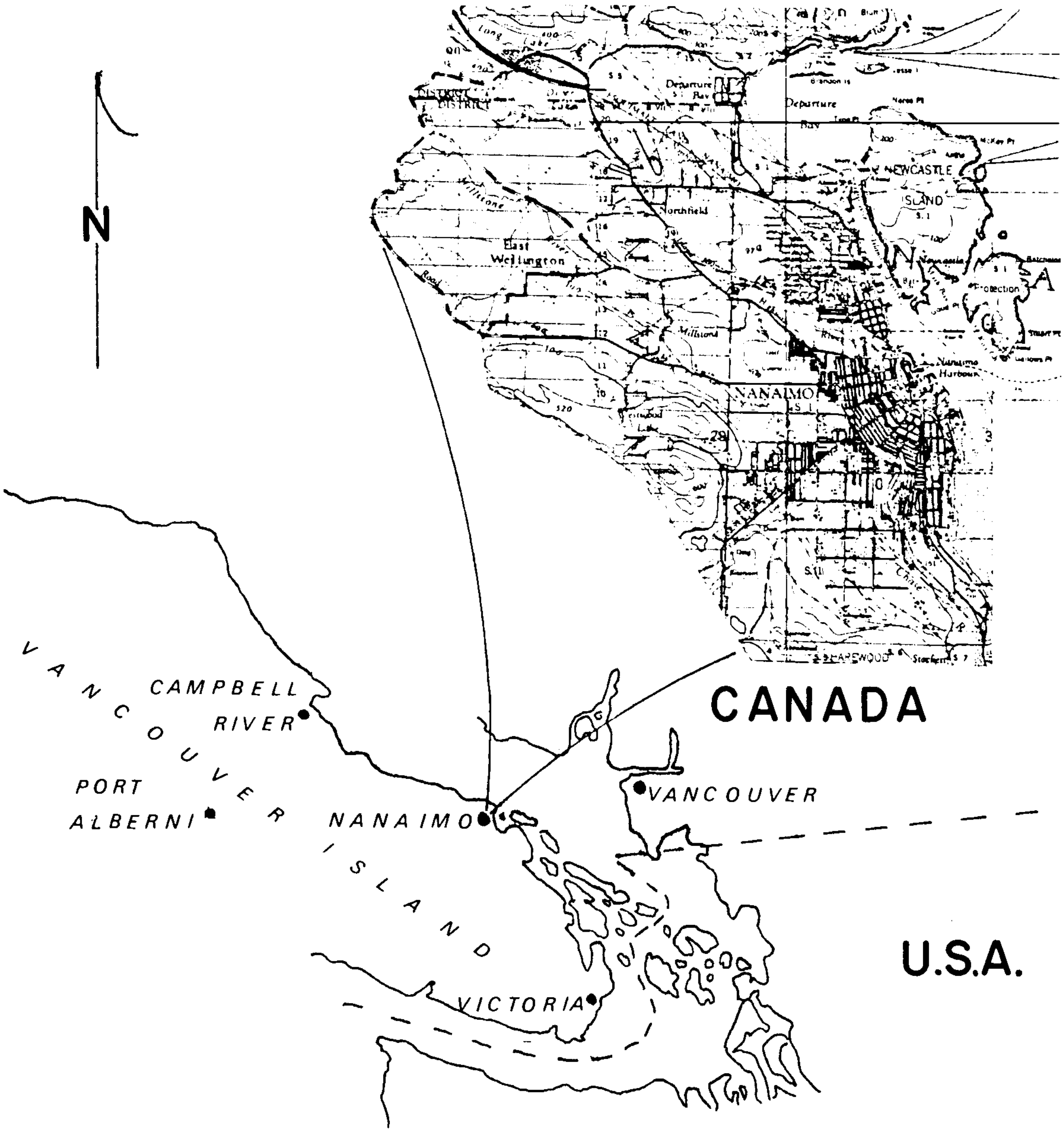


Figure 2. Index Map of the Study Area.

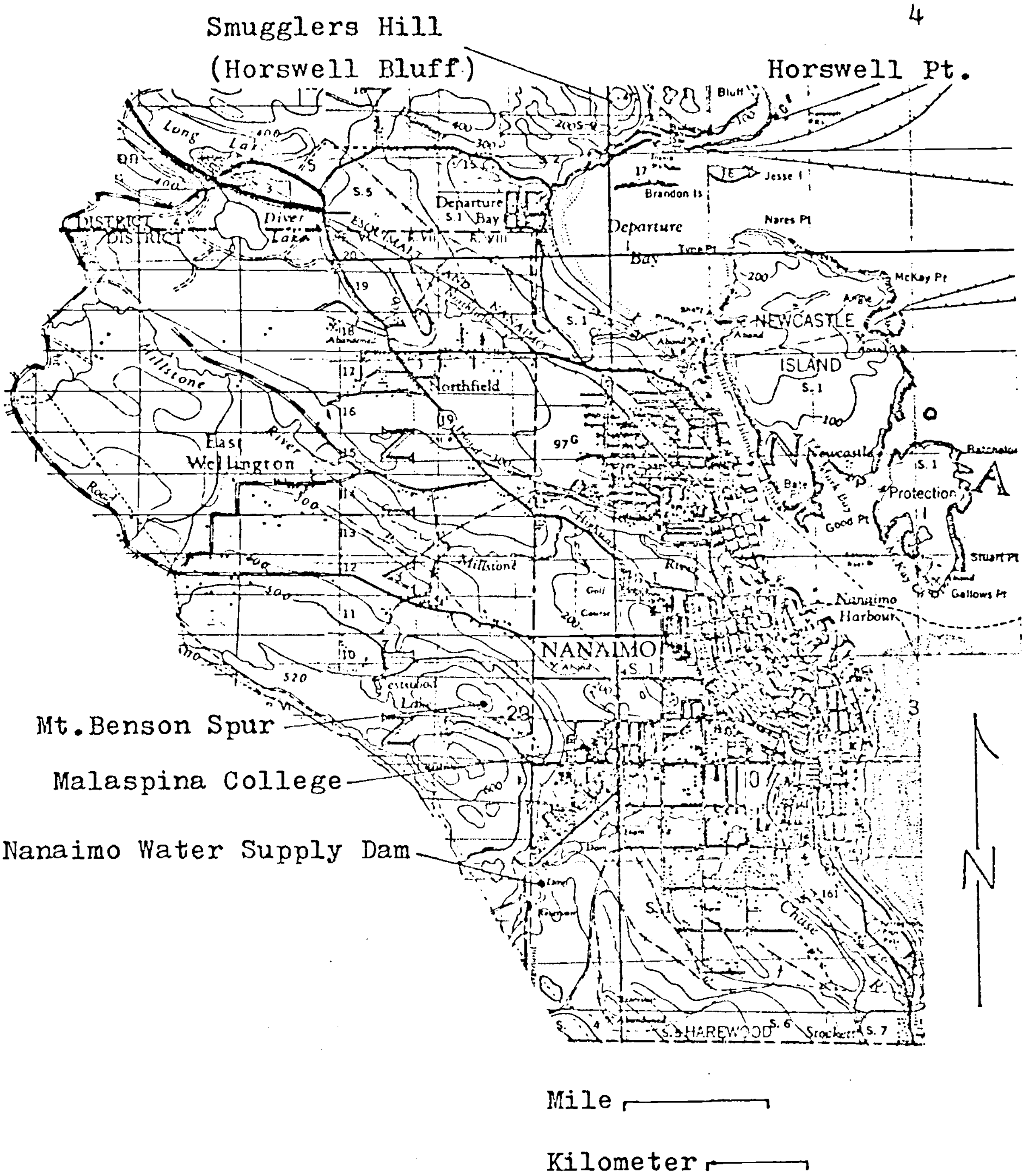


Figure 3. Topographic Map of the Study Area.

River cuts a broad valley through the central part of the area on a northwest trend, following a post-Cretaceous fault for some distance before cutting across it and flowing into Nanaimo harbor.

The northern part of the area is dominated by Smugglers Hill, an east-west-trending pre-Cretaceous high rising 400 feet above sea level. South and west of Smugglers Hill, in the west-central part of the area, is the highest point in the study area, an unnamed spur of Mt. Benson which is 800 feet in elevation. South of this spur, along the western boundary of the area, a series of small cuestas that follow the regional northwest bedrock trend form a highland about 400 feet above sea level west of the Harewood area.

Newcastle and Protection Island are parts of two south dipping cuestas located in Nanaimo harbor east of Nanaimo city center. Newcastle Island dips gently (six to eight degrees), from cliffs 200 feet high on the north end of the island to sea level at the south end. Protection Island has a topographic profile similar to Newcastle Island, except the highest point is only about 100 feet and the dip slopes are slightly more gentle.

Climate and Vegetation

The climate of the area is very mild and pleasant, as compared with much of Vancouver Island and the coastal mainland of British Columbia. The summers are warm, with high temperatures in the mid 70's to low 80's and night time low temperatures in the mid 50's. Because of close proximity to the Strait of Georgia, the humidity is high during most of the summer, but because of the warmth of the strait waters, morning fog is rare.

The mountains of western and central Vancouver Island produce a rain shadow which extends from north of Nanaimo to Victoria on the southern end of the island and covers most of the Gulf and San Juan Islands. This accounts for the yearly average precipitation of 36.60 inches (1941-1970, Nanaimo Tourist Information Bureau), which falls mostly as rain during the winter months.

The vegetation reflects the combination of moderate rainfall and high humidity. The area was originally heavily forested, but was largely cleared of timber during the late 1800's either for lumber for the coal mines or for farm land. The surviving forest areas are located on the sides of the Mt. Benson spur and on Newcastle Island, a provincial park.

The forests are made up predominantly of evergreens, with some deciduous trees in the clearing and logged off areas. The most common evergreens are Douglas fir, *Pseudotsuga menziesii*, Western Red Cedar, *Thuja plicata*, and Western Yew, *Taxus brevifolia*. In the drier areas with shallow soils and good drainage, Arbutus (called Madrone in the U.S.), *A. menziesii*, is a common evergreen. The most common deciduous trees are Broadleaf Maple, *Acer macrophyllum* and Western Flowering Dogwood, *Cornus nuttallii*, its flower being the provincial symbol of British Columbia. Oregon White Oak, *Quercus garryana*, is fairly common to the drier, rocky parts of the area, such as Smugglers Hill and the northern parts of Newcastle Island.

Access and Exposure

The access to all parts of the area is excellent. Much of the area lies within the city street system of Nanaimo, and can be reached by paved road. The outlying areas are reached by all weather highway, dirt roads and fairly good powerline access roads.

Access to Newcastle Island is provided by a harbor ferry on an hourly schedule. Protection Island does not have a regular ferry service, but the author was able to gain access by the use of a sailboat.

The exposures of bedrock are quite good, considering the urban nature of the area and the extensive glacial cover. The best exposures can be found along the shoreline, in the stream cuts of the Chase and Millstone Rivers, and in road cuts in most parts of the area.

GENERAL GEOLOGY

Previous Work

The geology of the Nanaimo area has been the subject of economic interest and intermittent geological study for more than 100 years. The earliest studies were exploratory expeditions. In 1857, J. S. Newberry made a study of the plant fossils of the coal-bearing strata and determined they were of Cretaceous age. James Hector studied the area in 1861 and reaffirmed Newberry's Cretaceous age determination and described some of the marine fossils, as well as producing a sketch map of the coal seams occurring on Newcastle Island.

From 1871 through 1876, James Richardson investigated the coalfields of Vancouver Island for the Geological Survey of Canada and in 1876 published a report correlating the Nanaimo coal beds and marine units with those of the lower Comox Basin (Richardson, 1876).

G. M. Dawson named the strata in the Nanaimo area the Nanaimo Group in 1890 and proposed a correlation between the lower members of the group and the Chico Formation of the Cretaceous Chico-Tejon Group of California (Dawson, 1890).

From 1910 to 1914, C. H. Clapp worked intermittently in the Nanaimo area and published a Geological Survey of

Canada memoir in 1914 (Clapp, 1914). He named the formations of the group, established the stratigraphy, and correlated the formations with those of the other basins of the region.

The Geological Survey of Canada commissioned another study of the Nanaimo area by A. F. Buckham in 1939. This study lasted until 1948 and resulted in two brief summaries of the work (Buckham, 1947). Much of Buckham's work was later reported in a Geological Survey of Canada memoir on the ammonite faunas of the Nanaimo Group by Usher (Usher, 1952).

The mid-1950's saw the last of the coal mines closed and the emphasis of the geological work shifted toward the use of paleobotany (Bell, 1957), palynology (Crickmay and Popcock, 1963) and micropaleontology (McGugan, 1964), for biostratigraphic studies of the Nanaimo Group.

The work of Hacquebard *et al*. (1967) on the Nanaimo coals, as part of a petrographic study of selected Canadian coals, has helped to define the environments of deposition.

The most recent work on the area has been that of Muller and Jeletzky (1967, 1970) on the biochronology and stratigraphy of the Nanaimo Group, and Muller and Atchison (1971) on the coals of Vancouver Island.

Regional Geologic Setting

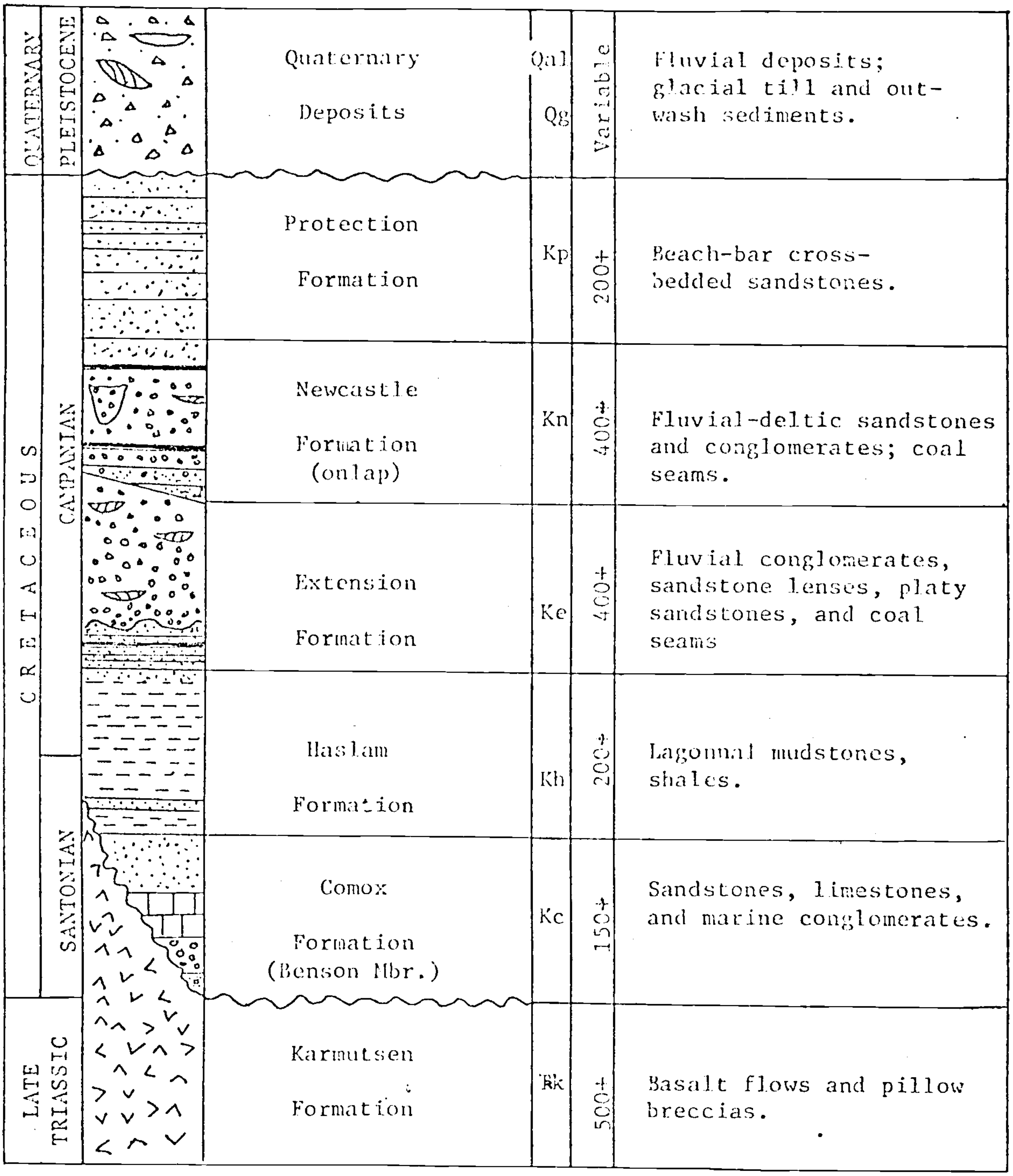
The rocks of the study area lie within the Nanaimo Basin, one of five remaining segments of an extensive Late Cretaceous depositional basin located along the east coast of Vancouver Island (Muller and Jeletzky, 1970). The original basin extended from at least Campbell River on the north to the northernmost of the San Juan Islands on the south, and as far west as Port Alberni (see Figure 1). The eastern margin of the basin may have extended as far as the Garibaldi area on the mainland (Muller and Jeletzky, 1970), but if so has been obscured by later plate tectonic movement.

The Nanaimo Basin rocks unconformably overlie three different basement rock complexes. In the northern part, which includes the study area, there are the Upper Triassic basic volcanics of the Karmutsen Formation. In the southern part of the basin, the basement rocks are either Permian and older metasedimentary rocks of the Sicker Group, or the granodioritic rocks of the Middle Jurassic Island Intrusions.

The Cretaceous rocks of the Nanaimo Basin were deposited during five depositional cycles (Muller and Jeletzky, 1970), the oldest two of which are represented by rocks in the study area. The first cycle includes the Comox and Haslam Formations; the second cycle, the Extension, Newcastle, and Protection Formations.

The stratigraphic sequence of the mapped area consists of six formations, from oldest to youngest: the Karmutsen, Comox, Haslam, Extension, Newcastle and Protection Formations (see Figure 4). The Karmutsen is of Late Triassic age, the Comox and the lower part of the Haslam are of Santonian age, and the remainder of the Haslam, and the Extension, Newcastle and Protection, are of Campanian age.

The area was extensively glaciated during the Pleistocene Epoch, and a blanket of glacio- or glacio-fluvial debris as much as 200 feet thick was deposited over much of the area (see Figure 5).



QUATERNARY	PLEISTOCENE	Quaternary Deposits	Qal Qg	Variable	Fluvial deposits; glacial till and outwash sediments.
CRETACEOUS	CAMPANIAN	Protection Formation	Kp	200+	Beach-bar cross-bedded sandstones.
		Newcastle Formation (onlap)	Kn	400+	Fluvial-deltic sandstones and conglomerates; coal seams.
		Extension Formation	Ke	400+	Fluvial conglomerates, sandstone lenses, platy sandstones, and coal seams
		Haslam Formation	Kh	200+	Lagoonal mudstones, shales.
	SANTONIAN	Comox Formation (Benson Mbr.)	Kc	150+	Sandstones, limestones, and marine conglomerates.
LATE TRIASSIC		Karmutsen Formation	℞k	500+	Basalt flows and pillow breccias.

Figure 4. Formations Within the Study Area.

Figure 5. Vashon glacio-fluvial deposits, 200 meters north of Malaspina College. Hammer left center of photo for scale.

STRATIGRAPHY

Karmutsen Formation

Introduction. The Karmutsen Formation the oldest rock unit in the study area, is made up of Late Triassic volcanics. It was originally named the Vancouver Volcanics by Clapp (1914), but was renamed the Karmutsen Formation by Cunning (1932). Muller and Carson (1969) estimate a total thickness of approximately 19,000 feet: 12,000 feet of pillow lavas and 7,000 feet of basalt flows. Approximately 500 feet of section are exposed in the area, mostly basalt flows.

The Karmutsen Formation is the volcanic basement rock on which the younger sedimentary rocks were deposited, and only crops out on the margins of the basin or where it has been faulted up. In the study area, Smugglers Hill represents the margin of the basin, part of a paleo-highland named the Nanoose Ridge. The Mt. Benson spur, an upthrown fault block, is composed largely of Karmutsen volcanics (see Figure 6).

Lithology. Two types of volcanics are exposed in the area: thick, massive, basalt flows, and a pillow breccia. The flows commonly have blocky jointing which locally acts as planes of weakness for the intrusion of veins of quartz and

Figure 6. Approximate Bedrock Distribution of the Karmutsen Formation.

quartz-epidote, the epidote replacing feldspar. The flow texture is best exhibited on the Mt. Benson spur and the higher parts of Smugglers Hill (see Figure 7).

The pillow breccia is less common, cropping out only along the shoreline on the north side of Departure Bay (see Figure 8). The pillow breccia is commonly made up of subrounded fragments of pillows two to 10 inches in diameter, along with some poorly preserved pillows ranging in size from six inches to one foot in diameter. The fragments usually occur in a matrix of quartz, epidote and zeolites.

The basalts of the Karmutsen Formation have a uniform gray green (5GY 3/2) color, weathering to a lighter green (10GY 5/2). Hand specimens are aphanitic, although a porphyritic texture is commonly exhibited in thin section.

Petrography. Rocks of the Karmutsen Formation commonly exhibit a porphyritic texture in thin section, with larger phenocrysts of plagioclase in a diabasic matrix of augite and plagioclase microlites. The plagioclase ranges from An_{50} to An_{70}. Minor minerals include magnetite and pyrite.

Alteration is very common, the pillow breccias showing much more alteration than the flows. Pillow breccia samples from Horswell Point have most of the ferromagnesian minerals altered completely to chlorite and the plagioclase to sericite. Veins of quartz and epidote are common in the Horswell Point sample.

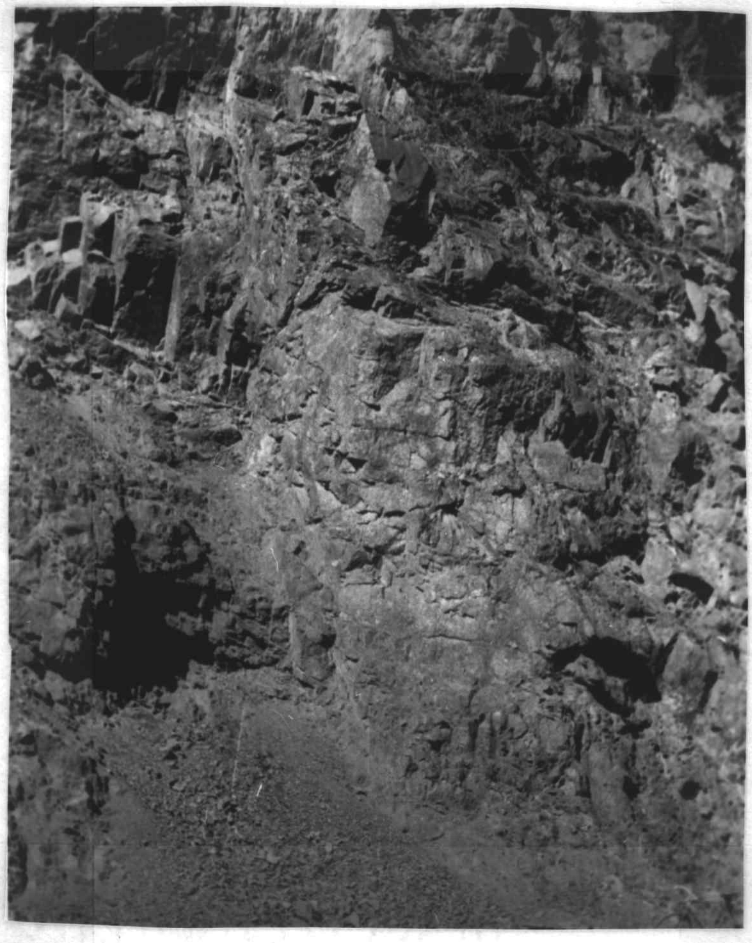


Figure 7. Karmutsen flow basalts at small quarry 200 meters north of Malaspina College. Note blocky jointing pattern. Bicycle at lower right for scale.

Figure 8. Karmutsen pillow breccias, 100 meters west of marine biological station on Departure Bay. Pack for scale.

Samples of the flow basalt taken at the quarry at the base of the Mt. Benson spur exhibit much less alteration, mainly augite altering to chlorite and minor penninite. This lesser alteration is the result of fresher rock. Recent deep quarrying for road metal makes it possible to obtain weathered samples.

Comox Formation

Introduction. The Comox Formation was named by Clapp (1912) for exposures in the Comox Basin to the north of the field area. It was later realized that the Benson Formation, the lowest member of the Nanaimo Group, and also named by Clapp, is correlative to the Comox. Muller and Jeletzky (1970) standardized the formation names within the basins, gave priority to the name Comox and downgraded Benson to a member within the Comox.

Outcrops of the Comox are limited to the edge of the Nanaimo Basin or where the unit has been exposed by post-Cretaceous faulting. Within the study area, an example of the former case may be observed at the base of Horswell Bluff along the north shore of Departure Bay, whereas an example of the latter occurs on the Mt. Benson spur east of Westwood Lake. A belt of Comox probably also occurs along the base of Smugglers Hill from Departure Bay to Long Lake (see Figure 9), but has been subsequently covered by glacial debris.

The best exposure of the Comox can be observed at Horswell Point on the north side of Departure Bay. At that location about 15 meters of the stratigraphic section are present, along with the basal contact between the Karmutsen volcanics and the Comox sedimentary rocks.

Figure 9. Approximate Bedrock Distribution of the Comox Formation.

The thickness of the Comox within the field area is highly variable, being dependent largely on the topography of the underlying Karmutsen basement. At Horswell Point and along the north shore of Departure Bay the thickness reaches greater than 20 meters. Exploration drilling for coal near Malaspina College revealed the Comox was less than four meters thick and was not present in a nearby bore hole (Muller and Atchison, 1971).

Basal Contacts. The contact between the Comox and Karmutsen Formations is the contact between the sedimentary rocks of the Nanaimo Basin and the basement. The contact is an irregular, angular unconformity, the Comox being deposited on an old erosional surface. At Horswell Point, the contact is between a pebbly sandstone, which lies below the Benson Conglomerate, and a pillow breccia of the Karmutsen Formation. West of that location, along the shore of Departure Bay, the contact is again exposed, but the sandstone is missing, and the Benson Conglomerate lies directly on the Karmutsen (see Figure 10). Farther west, at the mouth of Departure Creek, the impure limestone of the upper Comox rests directly on the Karmutsen, although the contact has been obscured by houses. At the location on Westwood Creek, below the dam at Westwood Lake, the upper impure limestone again appears to rest on the Karmutsen, although the contact is covered.

Figure 10. Benson Conglomerate, Horswell Point. Contact with Karmutsen Formation in lower right. Photo courtesy K. F. Oles.

Lithology. The Comox is composed of rocks of varied lithologies. The lowest in the sequences is a fine-grained pebbly sandstone, which locally is overlain by the Benson Conglomerate. At Horswell Point, the Benson Conglomerate is overlain by an algal limestone, which is not present at other locations. The uppermost beds within the Comox present in the study area, are impure limestones. Where the algal limestones are present, the impure limestones rest unconformably upon them. At other locations, where the algal limestones are not present, the impure limestones rest directly on the Benson Conglomerate.

Basal Pebble Sandstone. The lowermost member of the Comox Formation is a basal pebbly sandstone about seven meters thick that was developed locally on the Karmutsen at Horswell Point. The pebbles are subrounded to rounded, range from five to twenty-five centimeters in diameter, and are in matrix support in bioturbated sands rich in pelecypod shell fragments. Ten centimeters above the basal contact is a layer of *Inoceramus* shells about four centimeters thick, which is uniform in position and thickness over the entire twenty meters it is exposed.

The color of the sandstone and clasts is a greenish-gray (5GY 6/2) over the first six meters of section, but above six meters the color changes abruptly to a reddish hue (5R 4/2). The reddish zone is one meter thick, and changes abruptly upward back into a green (5GY 6/2) sandstone. The upper sandstone is in sharp, undulating contact with the overlying Benson Conglomerate.

Benson Conglomerate. The Benson Conglomerate is a locally developed unit which usually rests on the Karmutsen volcanics. The clasts are sub-angular to rounded and range in size from one centimeter to over a meter in diameter. The sorting is poor and the clasts are in matrix support. The matrix is composed of fine volcanic fragments, shell fragments and encrusting red algae. Megafossils are rare, but some poorly preserved pelecypods were found at one location 200 meters west of Horswell Point. The Benson Conglomerate is eight meters thick and is overlain at a sharp planar contact by an algal limestone.

Algal Limestone. The algal limestone is a rare unit within the Comox, and has not been previously reported at any other locations. It crops out at several locations along the north shore of Departure Bay, where it ranges in thickness from one to six meters. It also varies in concentrations of algae, becoming less concentrated to the east. The color is dependent on algal concentration, a medium grey (N5) at high concentration, more greenish as the concentration of algae lessens. The limestone is primarily composed of a red encrusting algae that resembles Archaeolithothamnium sp. (Johnson, 1961)(see Figure 11).

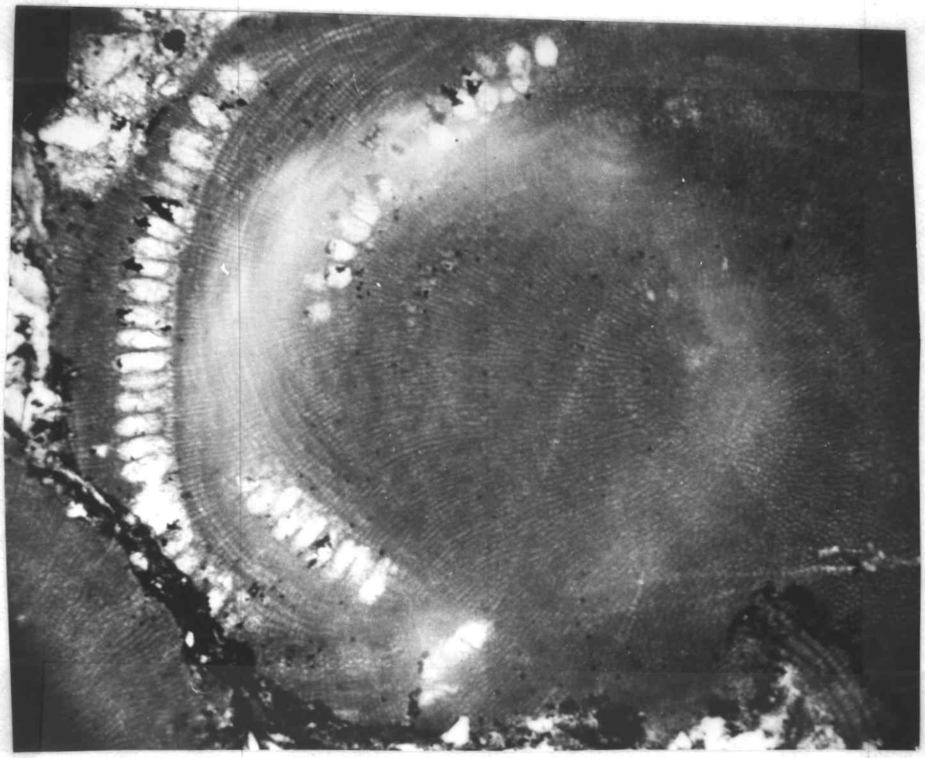


Figure 11. Archaeolithothamnium (?) algae, algal limestone, Horswell Point.

Upper Impure Limestone. The upper impure limestone is the uppermost exposed unit within the Comox Formation. It crops out at several locations on the north side of Departure Bay (see Figure 12) and at one location on Westwood Creek. The limestone is greenish grey and contains volcanic clasts similar to the basal sandstone except they are generally smaller in diameter. The impure limestone has a greater amount (56%) of calcite shell fragments than the basal sandstone, and the average framework grain is also larger. The effects of bioturbation are very obvious throughout the limestone, trace fossils and shell fragments being very widespread. Several examples of Ostrea breweri and Plicata cf hydrotheca, along with one poorly preserved mold of an ammonite, were found at Horswell Point. A well preserved colonella sp. algae (Mallory, 1980) and several poorly preserved gastropod shells were found at an excavation near Westwood Creek.

Sedimentary structures such as groove casts, ripple marks, flute casts, were not found apparently because of the complete bioturbation of the sediments at the time of deposition.

Petrography. The Comox Formation rests upon the volcanic rock of the Karmutsen Formation, and its sediments reflects this source. The clasts of the Benson Conglomerate are composed entirely of Karmutsen volcanics, and the fine-

Figure 12. Comox Formation, Horswell Point. Benson Conglomerate at left of photo, algal limestone center, and impure limestone (darker) at right. Log in background is 10 meters long.

grained matrix of most of the rest of the Comox is derived from it.

The lowest beds of the Comox, which lie below the Benson Conglomerate at Horswell Point, are lithic wackes composed of a fine-grained framework of quartz, feldspar, and augite, with local larger rounded clasts of volcanic material in matrix support (see Figure 13). The matrix is composed of silt-size quartz and clay, probably from alteration of the volcanic material. Calcite is a minor constituent, restricted to shell fragments and very minor sparry calcite cement. This mineralogy persists upwards to immediately below the Benson Conglomerate, where hemitite dominates the alteration products giving the rock a strong reddish cast.

The Benson Conglomerate clasts, in the mapped area, are completely composed of Karmutsen volcanics. However, Muller and Jeletzky (1970) report as much as 15 percent granitic and five percent metasedimentary clasts at a location near the Tsable River, north of the area. The matrix is composed of smaller fragments of volcanic material, pelecypod shell fragments, and calcareous red algae fragments.

Above the Benson Conglomerate, the general composition of the framework changes, becoming predominant skeletal fragments in matrix support. Directly above the Benson Conglomerate the beds are composed of red algae with minor

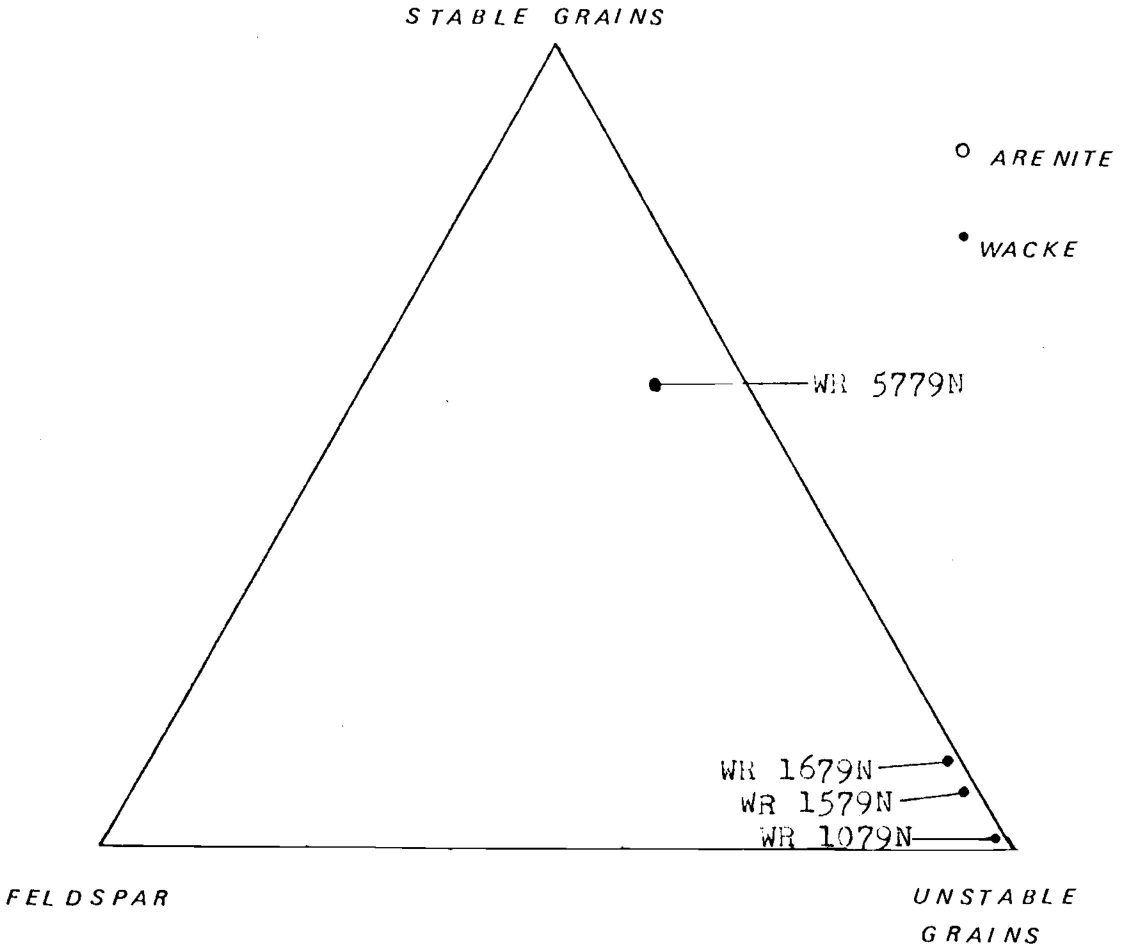


Figure 13. Classification of the Sandstones of the Comox Formation.

contributions of pelecypod test, bryozoan skeleton fragments, and other carbonate material. The matrix is a fine-grained combination of clays and recrystallized sparry calcite.

The impure limestone beds above the algal limestone become progressively more impure, containing more volcanic fragments, more matrix material and less algae upward in section. Small spherical concretions, approximately three centimeters in diameter and formed around small fragments of volcanic material, were found on bedding planes at several locations on Horswell Point.

At Westwood Lake the rock is best termed a calcareous lithic wacke and contains larger (one to four centimeters), more rounded clasts scattered throughout the rock than at Horswell Bluff. Several fragments of a gastropod were found, two of which exhibit a geopetal structure.

Volcanic rock fragments are diagenetically altered to chlorite and clays, and quartz is partially replaced by calcite.

Environment of Deposition and Provenance. The Comox Formation was deposited in a marine environment, as indicated by the widespread distribution of marine fossils throughout the beds. The basal sandstone was probably deposited in a nearshore environment, below wave base or in the lee of the Nanoose uplift headland, where strong currents or wave action did not have access to the sediments to winnow away the finer material. The rounded cobbles and pebbles were probably washed in by occasional storms from the Benson Conglomerate depositional environment discussed below. The red zone near the top of the basal sandstone is the product of an oxidizing environment, either at the site of deposition because of a change in current patterns, bringing oxygen-rich waters into the area, or by post-depositional diagenesis, or by an event which transported laterite debris into the basin of deposition.

The Benson Conglomerate was produced in a high energy environment, probably the surf zone, as indicated by the rounding of the cobbles and boulders, and the lack of sorting. Deposits very similar to the Benson are being produced at present on the Oregon Coast at Yaquina Head, north of Newport. At that location, boulders are being eroded off sea cliffs and are rounded by surf action at the base of cliffs. This seems to be a modern analogue to the deposits along Horswell Bluff.

After the Benson Conglomerate was deposited, a localized event took place in the vicinity of Horswell Bluff, which produced an environment favorable to the production of large amounts of red algae. The emplacement of an offshore bar, or other obstruction to wave or current action, produced a calm water environment which allowed the algae to accumulate. This also explains the lack of cobbles in the subsequently deposited sediments. That the algae accumulated in place is indicated by the lack of abrasion to the algal skeletons. The red algae are indicative of a sub-tropical to tropical shallow water environment (Johnson, 1961).

The upper Comox beds are heavily bioturbated and rich in organic debris. The grain size of the framework grains indicates a moderate energy environment, probably below wave base. The most likely environment of deposition is either a bay bottom or open lagoonal environment.

The source of the Comox appears to be completely local within the study area. No minerals or rock fragments were found that could not be attributed to erosion of the Karmutsen, to local organic activity, or to diagenesis.

Haslam Formation

Introduction. The Haslam Formation has the least exposure of any of the Cretaceous formations of the study area. The formation was named by Clapp (1912) for outcrops on Haslam Creek, about 25 kilometers south of the study area.

Outcrops of the Haslam Formation are scarce, mainly because of the abundance of mudstone and sandy siltstone which are predominantly slope-formers. The outcrop is confined to a belt running along the south side of the Millstone River and to one location along the Chase River (see Figure 14). Another belt of Haslam Formation probably lies along the northern part of the area, based on the structure and the geometry of the beds, but cannot be seen because of the thick glacial cover. The best outcrops are located on the Chase River, immediately downstream from the Nanaimo waterworks, and in Westwood Creek south of the Jingle Pot Road. Most other locations of the Haslam provide only mudchip float on the surface.

Basal Contacts. The basal contact of the Haslam Formation with the Comox Formation is not exposed in the study area. However, it is exposed in Brannen Creek northwest of the area, and was described by Muller and Jeletzky (1970) as gradational from the sandstones of the Comox into the sandy siltstones of the lower Haslam.

Figure 14. Approximate Bedrock Distribution of the Haslam Formation.

Lithology. The Haslam Formation is composed mostly of fine-grained shaly siltstones and mudstones. The best outcrops, on the Chase River, expose the upper 50 feet of the formation (see Figure 15). Here, the formation is made up of a thin-bedded (three to ten centimeters) sandy siltstone, dark grey (5Y 4/1) in color, with elliptical concretions up to one foot by three feet scattered along the bedding planes. The grain size increases and the color tends toward a tannish yellow upward in section as the Haslam grades into the East Wellington sandstone. Some small scale convoluted bedding is present, along with local bioturbation. The locality on Westwood Creek exhibits a similar lithology, except for a lack of concretions and fossils. Numerous *Cucullaea* (*Idonearca*) *truncata* (Mallory, 1980) and one poorly preserved ammonite were found.

On Holland Road, south of the Millstone River, a greenish brown (5GY 6/2) mudstone crops out in a roadside ditch. There is neither clear bedding nor regular jointing and the rock breaks with a conchoidal fracture. Farther west, along the creek that drains the west end of Westwood Lake, the same mudstone is found as float on the surface, but there are no outcrops.

Petrography. The petrographic study of the Haslam Formation was confined to the upper part, because of a lack of samples from the lower part. The rock is a calcareous

Figure 15. Haslam Formation, Chase River. Note thin beds, elliptical concretions right of waterfall.

lithic wacke (see Figure 16) containing abundant fine-grained angular well-sorted quartz clasts and primary clays which indicate the sediment was immature. The primary framework minerals are strained and unstrained quartz, biotite and some minor feldspar, chert and muscovite. The framework is in matrix support in a mixture of kaolinite and minerals of the chlorite group. Diagenesis has occurred, some of the primary minerals being replaced by calcite which, in turn, has been replaced by pyrite. The lighter colors of the upper Haslam are caused by the alteration of the biotite to hematite and limonite, which stains the kaolinite.

Environments of Deposition and Provenance. The Haslam Formation was deposited in an environment strongly influenced by the marine domain, as indicated by the presence of marine fossils. The fine-grained nature of the sedimentary rock, the presence of pyrite, and the lack of rounding and winnowing of the finer material suggests a low energy, restricted environment, away from sediment sources. Sliter (1973) suggested an outer slope environment, with depths of about 200 meters for locations of the Haslam to the south of the study area.

The Haslam within the study area is postulated to have been deposited in a more restricted, shallower water environment than that studied by Sliter. The transition of

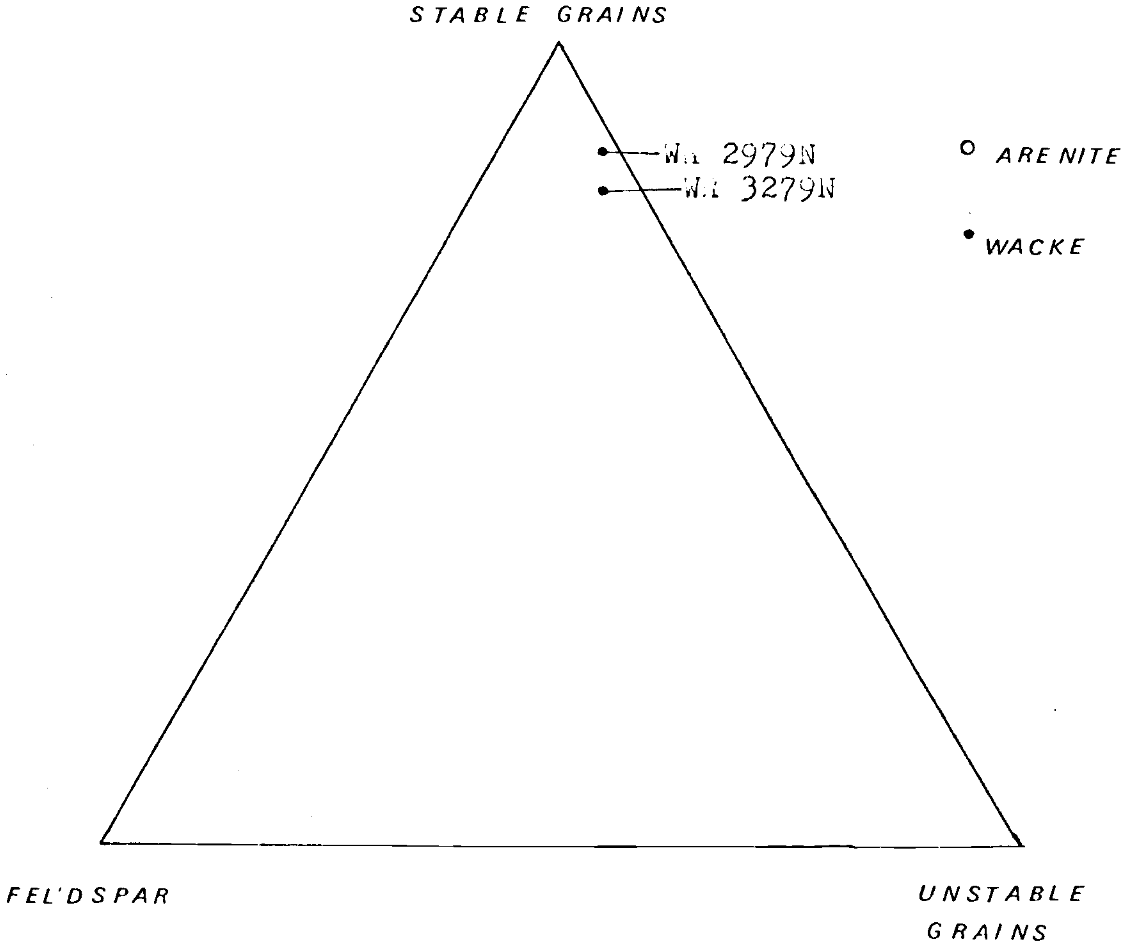


Figure 16. Classification of the Sandstones of the Haslam Formation.

the Haslam marine siltstones into the terrestrial swamp deposits of the East Wellington Member without an intervening beach deposit suggests a lagoonal environment. Some communication with the open ocean is indicated by the presence of the marine fossils.

The sources of the sediment changed in the time between the deposition of the Comox and that of the Haslam Formation. The biotite present indicates an expanding source area that began to include sediments from the Westcoast Crystalline Complex, or perhaps some of the dikes and sills of the Bonanza Subgroup of the Karmutsen Formation. The lack of hornblende in the Haslam Formation and the small amount in the Bonanza Subgroup, would tend to favor the Bonanza as a major sediment contributor. The presence of chert and muscovite indicates some contribution by the Sicker Group. All sources are postulated to have been west of the area.

Extension Formation

Introduction. The Extension Formation constitutes the largest part of the exposed outcrop of Cretaceous rock within the study area. The formation was named by Clapp (1912) for exposures in the Extension coalfield south of the area. The Extension was combined into the Extension-Protection Formation by Muller and Jeletzky (1970). This report uses Clapp's original definition because of the ease of segregation from the other formations in the Nanaimo area. The East Wellington Formation, as defined by Clapp (1914), is considered the lowest member of the Extension Formation for the purposes of this report.

Outcrops of the Extension are widespread over much of the western and northern parts of the area (see Figure 17). The best exposures crop out along the Millstone River west of Westwood Road, and on small cuestas south of Chase River.

The thickness of the Extension is estimated to be 130 meters, the majority of which is composed of conglomerates.

Basal Contacts. The lower contact between the Extension and Haslam Formations can be observed at an excellent exposure on Chase River immediately below the Nanaimo water supply dam. The underlying Haslam Formation, a sandy marine siltstone, gradually changes over a 15 meter interval into the platy, carbonaceous sandstone of the East Wellington Member.

Figure 17. Approximate Bedrock Distribution of the Extension Formation.

Lithology. The Extension Formation comprises two distinct units, the East Wellington Member and the Extension Conglomerate Member. The East Wellington Member is a thin-bedded, platy sandstone, containing abundant leaf impressions and interbedded coal seams (see Wellington Coal Seams, Economic Geology section). The sandstone is a massive sandy siltstone at the base grading upward into a platy silty sandstone. The color ranges from a brownish grey (5R 3/1) at the base of the East Wellington Member to a dark yellowish brown (10YR 4/2) near the top. The thickness of the East Wellington Member is about seven meters at the only exposure present in the study area, along the Chase River immediately east of the water supply dam. The upper contact is one of cut-and-fill, the Extension Conglomerates cutting channels three meters wide by a meter deep into the underlying East Wellington Member (see Figure 18).

The Extension Conglomerates compose the bulk of the Extension Formation, attaining a thickness of approximately 120 meters within the area. This member is composed of interfingering, anastomosing channel-shaped deposits of sandstone and conglomerate. The deposits range from two to eight meters in width, a meter to a meter and one half in thickness, and 100 meters or more in exposed length. The sandstones commonly are festoon crossbedded and fair to well sorted. The conglomerate usually exhibits a preferred pebble elongation in the direction of paleocurrent flow,

Figure 18. Extension Formation, Chase River immediately below Nanaimo waterworks. The black zone above the vine maple is the Wellington Coal Seam, overlain by the platy sandstones of the Wellington Member. The conglomerate at the top of the photo is the basal part of the Extension Conglomerate Member.

but no imbrication was found. Fossils are scarce within the member, but one piece of petrified wood was recovered from a conglomerate lens and a poorly preserved leaf impression was found in one of the sandstone channels.

The rock types of the Conglomerate Member range from clean sandstones to pebbly sandstones to conglomerates. The grain size of the sandstones ranges from medium to coarse and the rocks are commonly an olive grey (5Y 5/2), although large outcrops locally take on a bluish hue. The pebbles of the conglomerates are commonly sub- to well-rounded and range from one to four centimeters in diameter. The color is a greenish grey (5G 5/1) which varies to a dusky yellow (5Y 6/4) with the amount of weathering the outcrop has undergone. Calcareous concretions also are present in the sandstone lenses, ranging up to a meter in diameter.

Petrography. The sandstones of the East Wellington Member are very similar to those of the Upper Haslam Formation. The rock is classified as a lithic wacke and has much of the same composition as the Haslam beds, except the larger framework grains of quartz, chert, biotite, muscovite and feldspar are more abundant and iron oxide staining is more prevalent. No calcareous shell fragments were found in the East Wellington Member, probably because the beds were terrestrial deposits, as indicated by the thin bands and lenses of carbonaceous material. The petrography of Wellington coal seams is covered in detail in the Economic Geology section.

The Extension Conglomerate Member is quite different in texture and composition from the East Wellington Member. The sandstone channel filling ranges from lithic wackes to lithic arenites (see Figure 19), and usually is composed of medium- to coarse-grained subangular framework grains in framework support. The framework grains are quartz, feldspar, biotite, igneous and metamorphic rock and chert fragments, with minor amounts of magnetite and hornblende (see Appendix A). The matrix is chiefly composed of silt-size quartz grains, chlorite, and iron oxides.

The conglomerate is composed of subrounded to rounded clasts of chert, quartzite, granitic material and aphanitic extrusive volcanics (probably derived from the Karmutsen Formation). The matrix is sandstone similar to the sandstone channel fillings described above.

Diagenesis is common within the formation. The East Wellington Member commonly exhibits minor alteration, quartz being replaced by calcite, and magnetite and hornblende oxidized to iron oxides. The Extension Conglomerate Member exhibits similar alteration, and also contains clumps of smectite clays, produced by alteration of the matrix material.

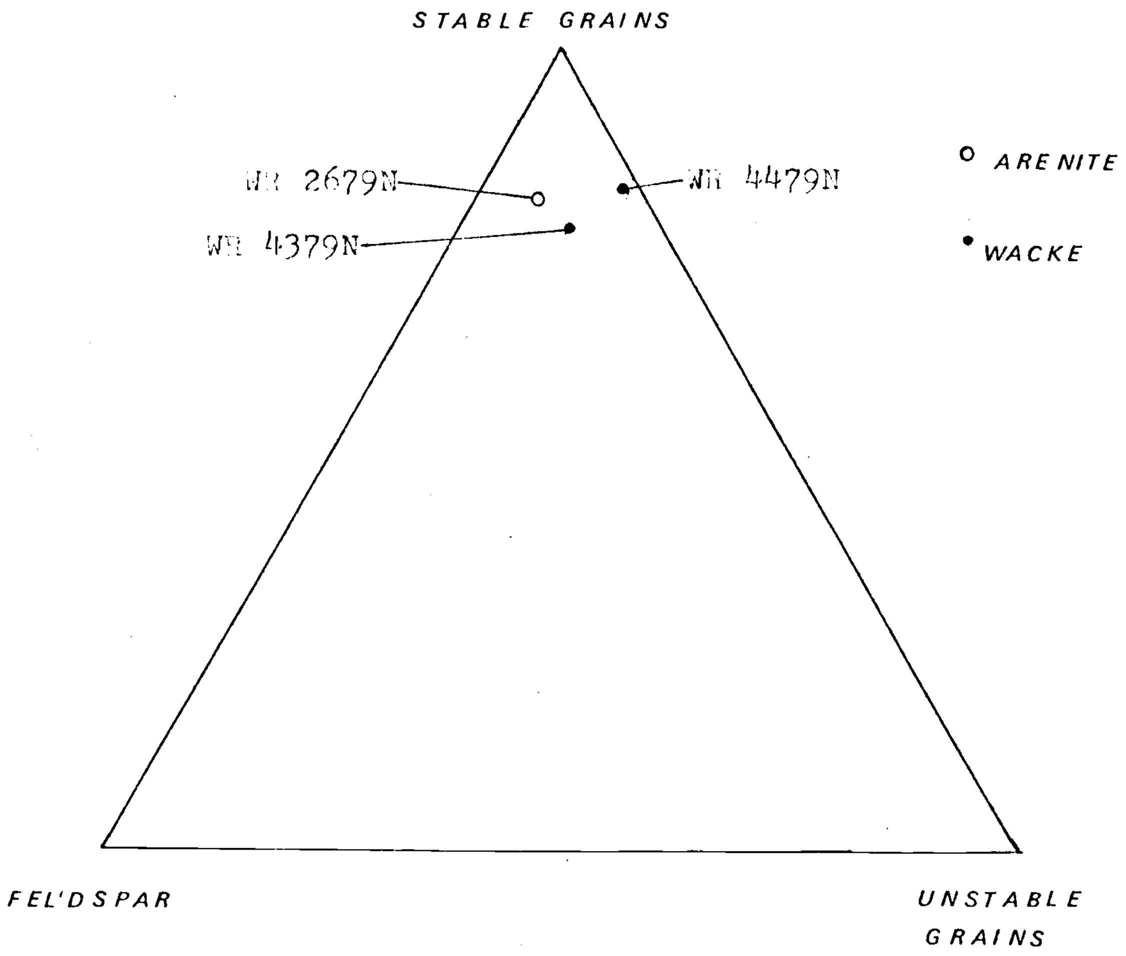


Figure 19. Classification of the Sandstones of the Extension Formation.

Paleocurrent Data. Directional measurements were obtained for the Extension Formation over much of the eastern and central parts of the study area. Bidirectional indicators such as channel axis and pebble elongations are the most common types found, although some unidirectional cross-bedding was also found. The grand mean is S. 02° E., indicating the sea was to the east of the area at the time of deposition (see Figure 20).

Environment of Deposition and Provenance. The East Wellington Member is the product of a low energy environment, as can be deduced by the excellent preservation of the leaf impressions present. The interbedded coal seams indicate the area was a swampy, forested area closely associated with the lagoonal environment (see Environments of Deposition, Economic Geology section).

The Extension Conglomerates were deposited in a much higher energy environment than that of the East Wellington Member. The presence of clean, well-washed, winnowed sandstones (see Appendix A), rounded to subrounded clasts, interfingering multiple scour-and-fill channels, and the lack of any marine fossils suggest fluvial terrestrial deposition by strong tractive currents. The depositional environment is postulated to be a braided stream facies, perhaps at the upper end of a paleodelta.

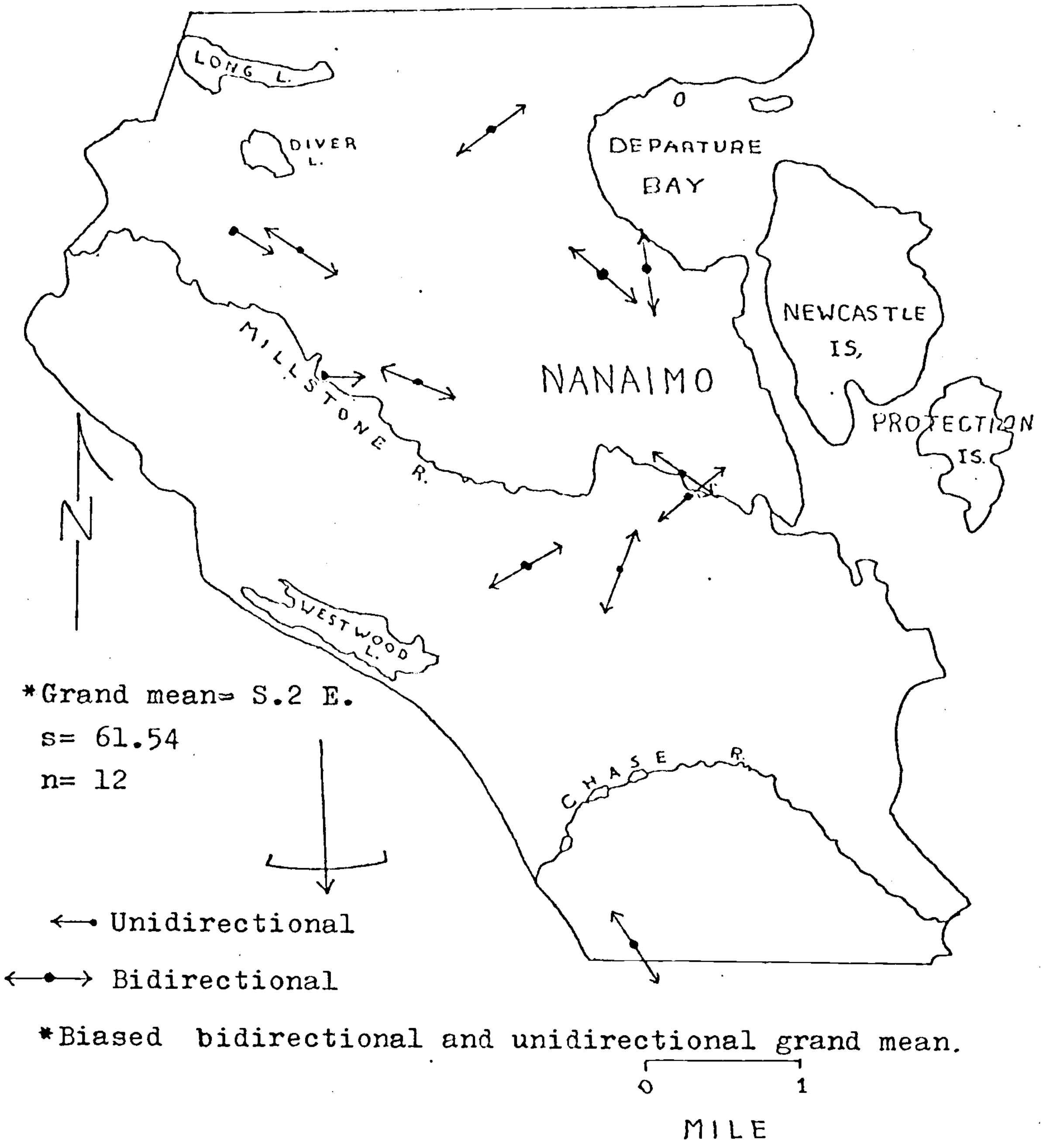


Figure 20. Paleocurrent Directions of the Extension Formation.

The sediment sources for the East Wellington Member, can be considered the same as those for the Haslam Formation because of the similarity in mineralogies. The Extension Conglomerate Member sources differ from those of the Haslam Formation and the East Wellington Member. The abundance of chert and quartzite suggests a strong contribution from the Sicker Group. The granitic clasts indicate contributions from one of the igneous intrusive bodies to the west, either the Westcoast Crystalline Complex, the Bonanza Subgroup, or one of the Island Intrusions. The aphanitic volcanic material indicates a continued source in the Karmutsen Formation.

Newcastle Formation

Introduction. Because of the great variety of lithofacies present in a small area, the most interesting of all the formations of the study area is the Newcastle Formation. Clapp (1912) named this unit for the strata on Newcastle Island which lie between the Newcastle Coal Seam and the lower beds of the Protection Formation. The Newcastle was later combined with the Extension, Cranberry and Protection Formations by Muller and Jeletzky (1970). This report uses Clapp's original definition because of the ease of differentiation between the Newcastle and most of the other units in the area. The Cranberry is included in the lower part of the formation because of the lack of outcrop of the Newcastle Coal Seam used to separate the two elsewhere.

The Newcastle Formation crops out in a wide belt over much of the central and southeastern part of the area, and along the north end of Newcastle Island. The best exposures are located on the north end of Newcastle Island, in downtown Nanaimo, along the Chase River from the mouth to the Douglas Avenue bridge (see Figure 21), and along the Millstone River from the mouth to the west end of Bowen Park. Downtown Nanaimo is the most interesting place to observe the Newcastle because of the wide variety of lithologies, including the Douglas Coal Seam, present within a small area (see Figure 22).

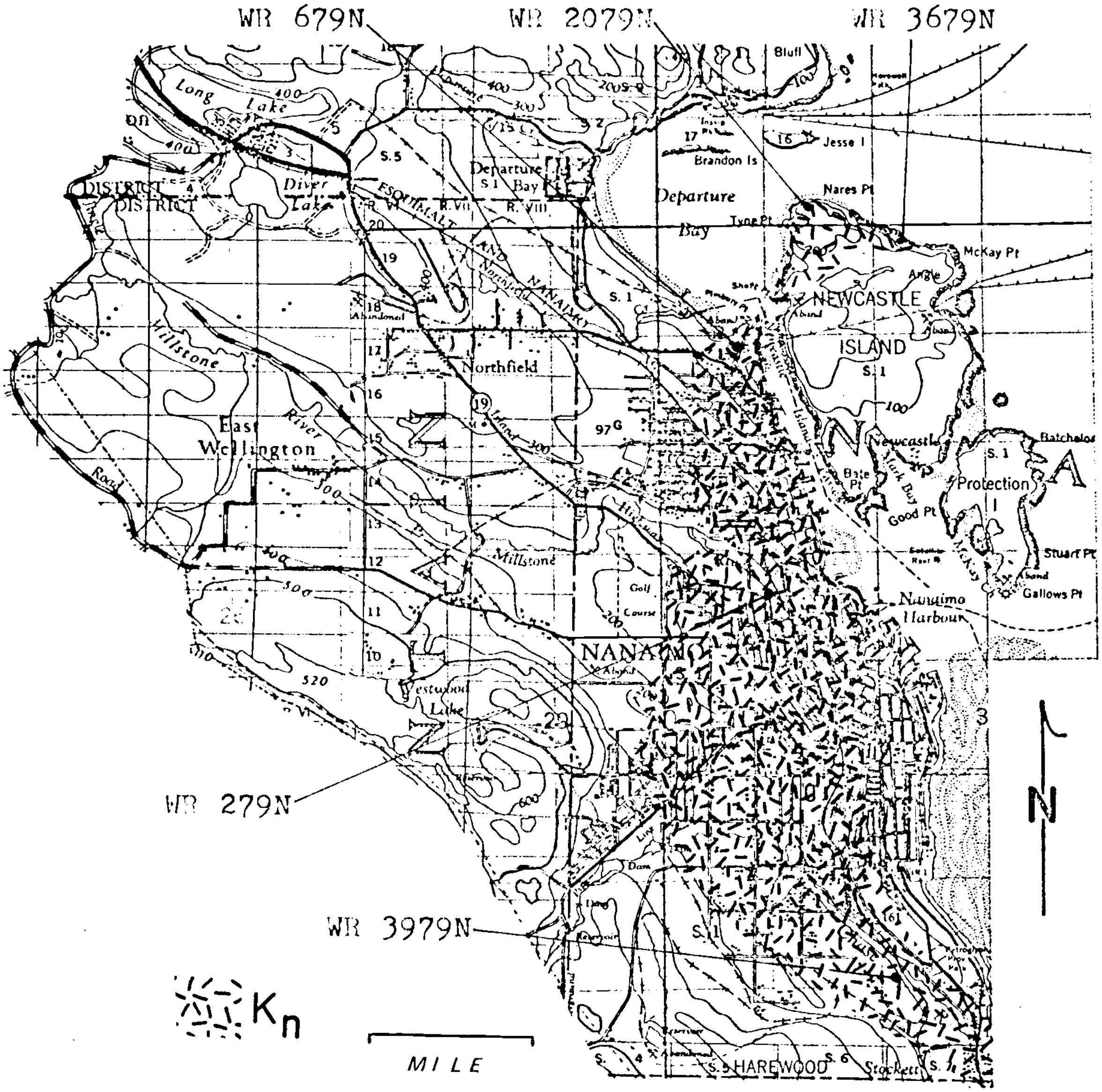


Figure 21. Approximate Bedrock Dristribution of the Newcastle Formation.

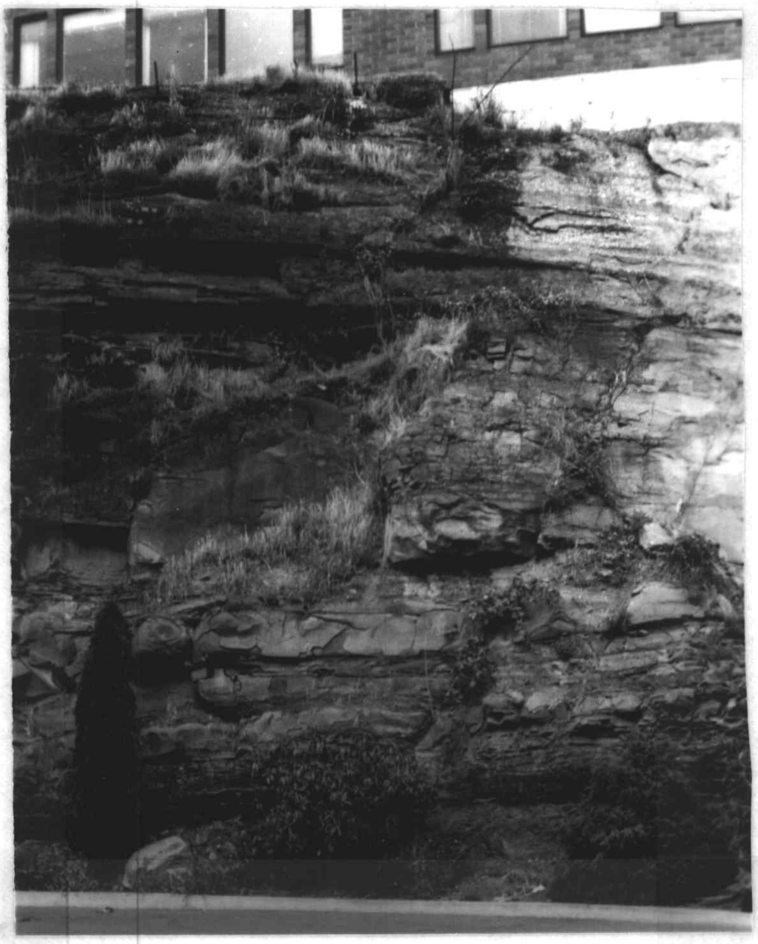


Figure 22. Various lithologies of the Newcastle Formation, behind Chevron station, Terminal Avenue, downtown Nanaimo. Douglas Coal Seam exposed at base of outcrop.

The thickness of the Newcastle Formation is estimated by cross section construction (see plate 2) to reach 130 meters within the study area.

Basal Contacts. The basal contact of the Newcastle is well exposed along the Millstone River, from 100 meters east of the Canadian Pacific railroad bridge to the west end of Bowen Park. The contact is one of onlap, the sandy siltstones, mudstones and pebbly sandstones of the lower Newcastle lying on conglomerates of the Extension Formation. The surface of contact is cut-and-fill, the lens shaped channels averaging one to five meters in width and one to two meters in depth. The angle of onlap between the Newcastle and the Extension Formations is approximately five degrees.

Lithology. The Newcastle is the most varied in lithology of any of the formations of the study area. The stratigraphic sequence is sandy siltstones, mudstones and pebbly sandstones, followed by the Newcastle Coal Seam. Above the Newcastle Seam are two types of conglomerate, the Douglas Coal Seam, more sandstones and conglomerate, and finally the thin-bedded sandstones and mudstones of the uppermost beds. The sequence is conjectural because of poor exposure and the lack of continuity between outcrops.

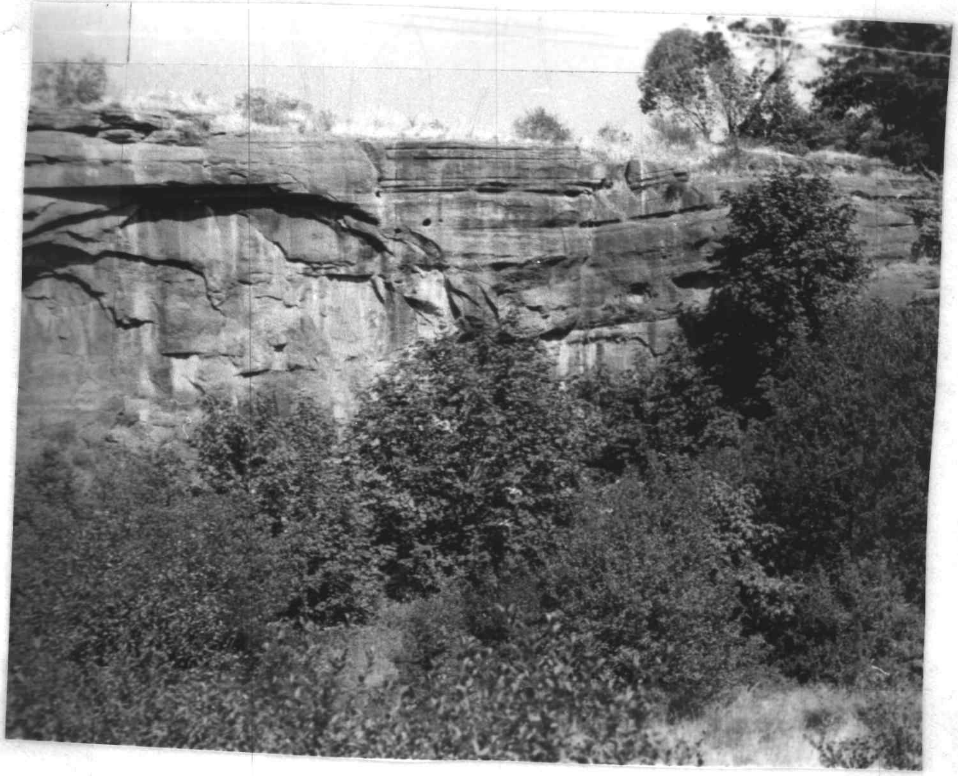


Figure 23. Large exposure of Newcastle conglomerates and sandstones, Chase River. Note cross-bedding indicating northward transport direction.

Lowermost Sandstones. The lowest beds are grayish yellow (5Y 6/4) sandy siltstones, up to two meters thick, which are interbedded at sharp planar contacts with greenish grey (5GY 4/1) mudstones less than one meter thick. The siltstones near the base of the section, contain abundant poorly preserved leaf impressions and small lenses of coal, two to three centimeters thick and 25 to 50 centimeters wide, becoming less abundant upward. At the top of the Millstone River section lies a brownish grey (5YR 5/1) pebbly sandstone, three to four meters thick, in sharp planar contact with the underlying beds of sandy siltstone. The pebbles range in size from one to four centimeters in diameter and are sub-rounded to rounded. The sandstone contains abundant planar forest cross-bedding exhibiting a northwestern to western direction of transport. The cross-bedding is emphasized by the accumulation of pebbles on the forest bedding planes.

Newcastle Coal and Immediately Overlying Beds. Above the sandstones lies the Newcastle Coal Seam (see Newcastle Coal Seam, Economic Geology section). The beds above the Newcastle Coal Seam vary from place to place and were responses to differing environments of deposition. At the north end of Newcastle Island, the Newcastle Seam is overlain by a very large, v-shaped yellowish gray (5Y 7/2) channel deposit of conglomerate, approximately 70 meters thick at the thickest point and 500 meters wide. The pebbles are in framework support, two to ten centimeters in diameter and sub- to well-rounded. Several yellowish grey (5Y 8/2) sandstone lenses are present within the conglomerate deposit, ranging in size from one to two meters thick and six to fifteen meters wide.

To the southwest, at Tyne Point on Newcastle Island, a light olive gray (5Y 6/2) conglomerate with completely different characteristics crops out. This conglomerate is composed of a rhythmically bedded sequence of beds, each of which averages about 50 centimeters in thickness. Each bed is composed of fine pebbles, fining upward into a coarse sand. A similar conglomerate is found underlying the Douglas Coal Seam in the downtown Nanaimo area (see Figure 37, p. 92). A similar unit was found at the B. C. Ferry terminal on Pimbury Point, except that each of the beds has a definite plano-convex shape, -30 to 50 centimeters thick and 20 to 30 meters long. These lenses are distributed at vertical intervals of 50 to 150 centimeters in a tannish yellow (5Y 8/2), medium-grained, concretion-bearing sandstone. Several lenses with similar internal characteristics were also found at this location, but have different shape, averaging two meters thick and eight meters wide.

Douglas Coal Seam and Immediately Overlying Beds. Resting above the conglomerate is the Douglas Coal Seam, which can be observed at several locations in the downtown Nanaimo area (see Douglas Seam, Economic Geology section). The Douglas Seam is overlain by one or the other of two rock types that occur in close lateral proximity. The first is a medium- to fine-grained, yellowish brown (10YR 6/4) sandstone unit about six meters thick. The sandstone is composed of beds up to a meter thick, is locally finely laminated and contains a few scattered specimens of *Tancrdia* cf. *Kurupana* (Mallory, 1980). The other rock type is a medium gray (N5) fine pebble conglomerate composed of overlapping multiple channels five meters thick and 15 meters wide. The pebbles are one to two centimeters in diameter and are sub-rounded to well rounded (see Figure 37, p. 92).

Uppermost Sandstones. The uppermost beds of the formation are exposed at two locations on Newcastle Island: at McKay Point on the east side and at Shaft Point on the west. The McKay Point beds are a series of finely cross-laminated, greenish grey (5GY 6/1) sandstones interbedded with olive gray (5GY 4/2) mudstones. The sandstone and mudstone beds range from 10 to 50 centimeters thick, the mudstones becoming thinner and less abundant upwards. The sandstones lie in sharp planar contact with the mudstones, and contain cross-laminations that change direction from north to south in the vertical space of 10 centimeters. One well preserved specimen of Cyprimeria moorei was found in one of the uppermost sandstone beds.

On Shaft Point, the uppermost beds are a light yellowish brown (5Y 6/1), are festoon cross-bedded, indicating transport direction north, have been slightly bioturbated, and are about 12 meters thick. One piece of petrified wood, 15 centimeters in diameter and 25 centimeters long was found which contains numerous worm borings. Numerous yellowish brown (10YR 5/2) calcareous concretions averaging 70 centimeters in diameter also were found, forming around nuclei of wood fragments.

Petrography. The Newcastle Formation is more variable in composition than any other formation within the study area. The sandstones range from quartz- to lithic- to feldspathic wackes (see Appendix A). The lower sandstones are classified as lithic wackes (see Figure 24). The framework clasts are fine-grained, angular to sub-angular, and in framework support. The major contituents are quartz, chert, feldspar, igneous and metamorphic rock fragments, and magnetite. Subordinate minerals include biotite, muscovite, and augite. The matrix is composed of silt-sized quartz and clays with subordinate iron oxides and calcite cement (see Appendix A).

The sandstones of the upper part of the formation generally have 10 to 30 percent less matrix material and

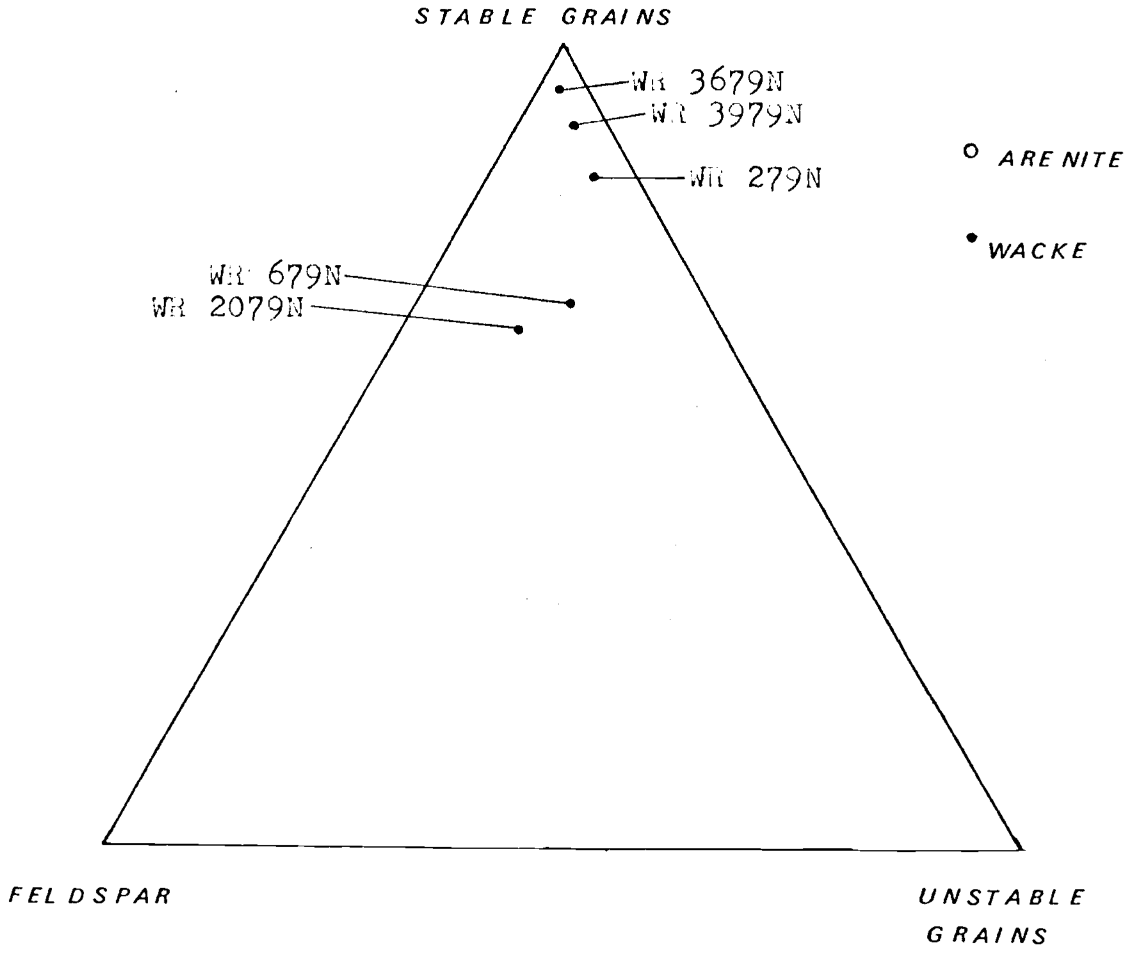


Figure 24. Classification of the Sandstones of the Newcastle Formation.

vary more in composition than the lower sandstones. The trend upward is toward more abundant chert and quartz, and less matrix. The uppermost beds contain almost 70 percent chert and quartz and are almost arenites (see Appendix A, WR3879N). The matrix materials are the same as those of the lower beds.

The conglomerates are similar to those of the Extension Formation, containing chert, quartzite, and granitic clasts with the addition of diktytaxitic basalt and sandstone clasts (see Appendix B).

The petrography of the Newcastle and Douglas Coal Seams is discussed in the Economic Geology section.

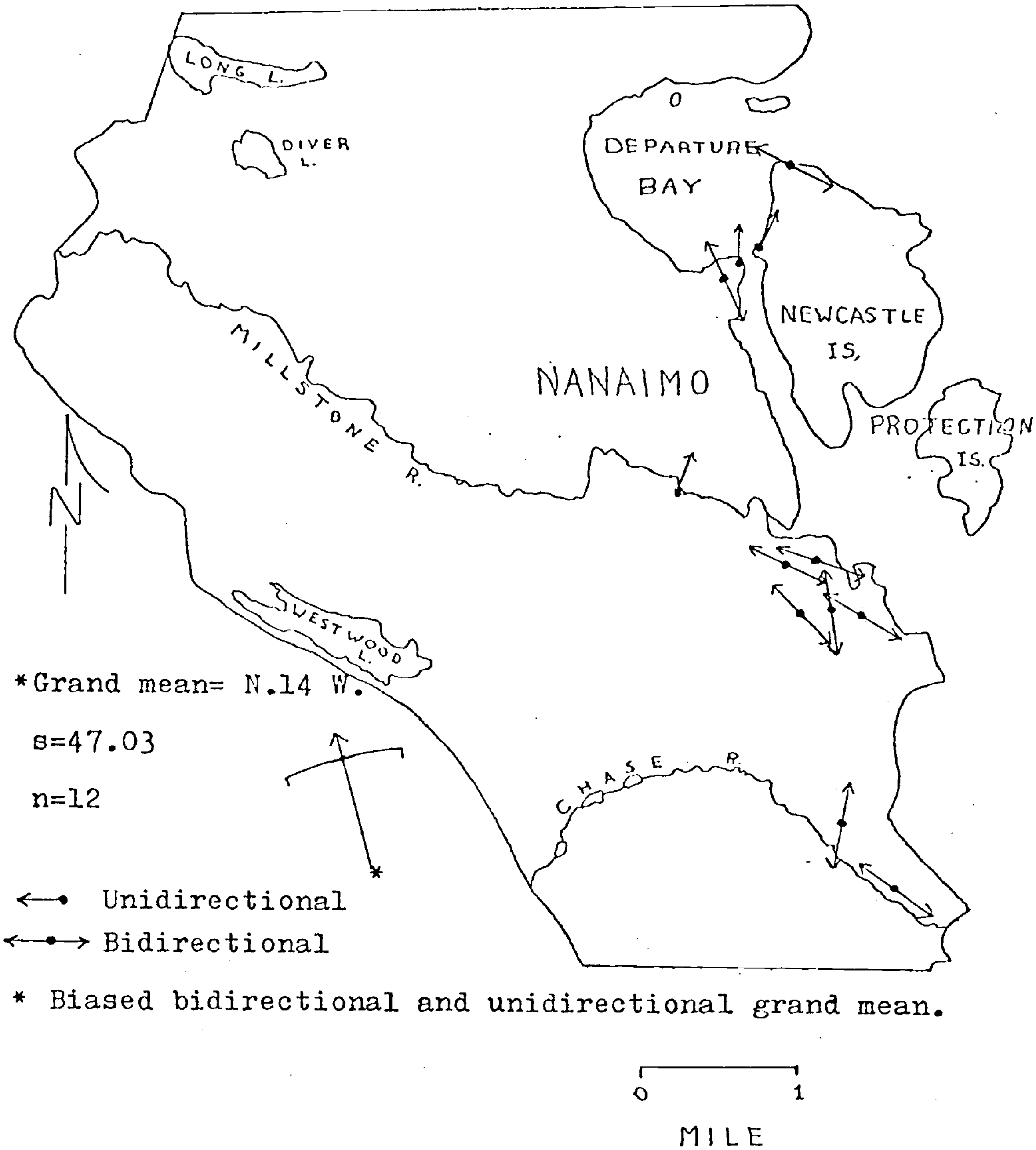
Diagenetic alteration within the Newcastle Formation, appears slight, confined to iron oxides formed by alteration of magnetite and biotite altering to iron oxides, and some alteration of feldspar to clay.

Paleocurrent Data. Directional measures were collected at locations on Newcastle Island and at numerous locations throughout eastern Nanaimo. Bidirectional current indicators are the most common types found, consisting of measurements of channel axes and the long axes of pebbles and woody fragments. Unidirectional current indicators are far less common at most places primarily consisting of cross-bedding and -laminations and flame structures.

The paleocurrent directions of the Newcastle Formation are markedly different from those of the Extension Formation (see Figure 25), having a grand mean of N. 14 W., as compared with S. 2 E. calculated for the Extension.

Environments of Deposition and Provenance. The Newcastle Formation is a response to processes within the fluvial realm. The lowermost sandy siltstones contain abundant plant debris and coal and lack sedimentary structures, such as cross-bedding and flute marks. These factors suggest a low energy swampy environment similar to those described by Flores (1975) and Allen (1965). Above the siltstones, the cross-bedded pebbly sandstones indicate a higher energy tractive current at work.

The thick channel conglomerate found at the north end of Newcastle is postulated to be the main channel of a paleo-Nanaimo River system. This hypothesis is supported by the shape and size of the deposit, and the size of the clasts, which suggest a highly competent current. The thin beds of conglomerate that are found near this main channel on Newcastle Island, and below the Douglas Coal Seam, are postulated to be distributary channels, providing water circulation to the swampy areas of the floodplain. The fining upward sequence indicates repeated flooding episodes that filled the system with coarse material, each event



*Grand mean= N.14 W.

s=47.03

n=12

←• Unidirectional

←•→ Bidirectional

* Biased bidirectional and unidirectional grand mean.

Figure 25. Paleodispersal Directions of the Newcastle Formation.

marked by finer upward deposits as flooding abated and current competence decreased.

Above the conglomerate rest the Newcastle and Douglas seams, deposited in a swamp environment (see Economic Geology section). Above the Douglas Seam, in the downtown Nanaimo area, rests the six meter thick sandstone unit described in the lithology section. This sandstone is interesting in that it is bioturbated and is overlain by conglomerates, but contains no cross-bedding. This sandstone is postulated to have been deposited within a channel in the upper flow regime (Harms and Fahnestock, 1965).

The upper sandstones and mudstones exhibit features indicative of the barrier beach complex of the Protection Formation transgressing into the fluvial environment of the Newcastle Formation. The thin, cross-laminated sandstones resemble those described by Reinson (1979) as belonging to washovers from the barrier beach into the lagoonal environment. The interbedded mudstones represent fluvial deposition between washovers. The variation in current direction in the sandstones is probably because the washovers originated from different locations along the barrier beach system.

The overall environment of the Newcastle closely resembles that of the delta plain facies described by Flores (1975) for short headed stream deltas. The short headed stream delta model is favored over other fluvial models because of the significant amount of conglomerate present. This indicates a highly competent stream was present at the time of deposition, probably originating in the area to the west of Nanaimo and flowing a few tens of miles before entering the paleo-seaway.

The sediment sources of the Newcastle are much the same as those for the Extension Formation, except for the addition of the diktytaxitic volcanic rocks, probably derived from the Bonanza Subgroup. The sediments that formed the uppermost beds of the Newcastle Formation are very rich in chert, indicating a major contribution by the Sicker Group at that time. Some zoned feldspar and microcline are also present in the uppermost beds, indicating that the Nanaimo Batholith had begun to contribute sediments at that time.

Protection Formation

Introduction. The Protection Formation is the youngest of the Cretaceous units exposed within the study area. It was named by Clapp (1912) for exposures on Protection Island and was later consolidated into the Extension-Protection Formation by Muller and Jeletzky (1970). Because the exposures of the Protection are readily differentiated from the other formations, this report will use Clapp's original definition.

Outcrops of the Protection are confined to the eastern part of the area: the southern part of Newcastle Island, Protection Island, and a belt extending from the Tourist Information Bureau in downtown Nanaimo to beyond the southern boundary of the area at Chase River (see Figure 26). The best outcrops can be found on the shorelines of Newcastle and Protection Islands and scattered throughout southern Nanaimo. Road cuts along Highway 1 from the city limits of Nanaimo south to the southern boundary of the area also provide excellent exposures (see Figure 27).

Basal Contacts. The contact between the Protection Formation and the underlying Newcastle is obscured throughout much of the area by houses, roads and other man-made objects or by water. The only location where it can be seen clearly is on the east side of Newcastle Island. At that location the contact between the Protection and the

Figure 26. Approximate Bedrock Distribution of the Protection Formation.

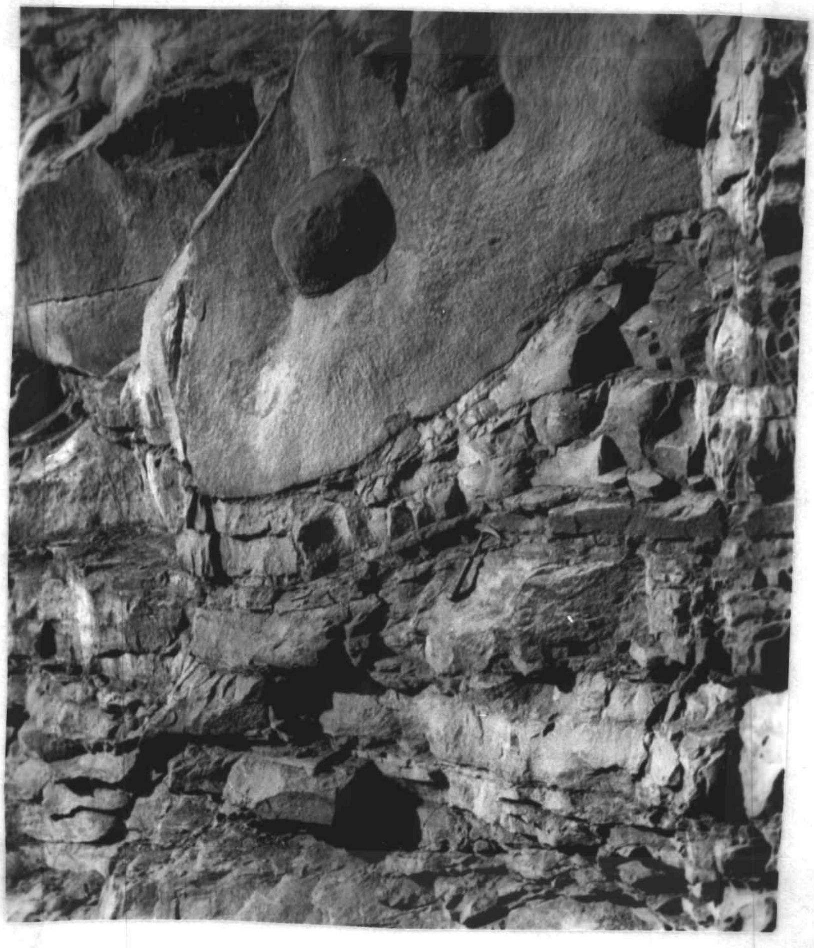


Figure 27. Channel and beds in the Protection Formation, Highway One, south of Nanaimo. Note spherical concretions. Hammer for scale.

Newcastle is planar, with a three meter-thick sandstone bed exhibiting convolutions and flame structures overlying a series of thin- to thick-bedded sandstones of the Newcastle Formation. The most striking difference between the Protection and Newcastle Formations is the change in color from the greyish (5Y 5/1) brown of the Newcastle to the tannish white (5Y 7/2) of the Protection Formation. This is caused by a change in composition of the sediments, to be discussed later.

Lithology. The lithology of the Protection Formation is somewhat varied. Sandstone is dominant and the beds range in size from thinly bedded, two to ten centimeters thick, to beds four meters thick. The thinner beds are commonly cross-bedded, the cross-beds ranging from planar to forest, and from less than a meter to 10 meters in length. The thicker beds usually are massive but exhibit a tendency towards fining upwards. These beds were quarried for building stone during the later nineteenth century.

Spherical calcareous concretions are common in the thicker beds, ranging up to almost two meters in diameter, but commonly averaging less than a meter thick. Bioturbation is present to a limited extent, mainly on one exposed horizontal surface on the shore of Newcastle Island at the east entrance to the channel between Newcastle and Protection Islands. The burrows resemble structures constructed by Zoophycos (Seilacher, 1964). One coal seam was found within the formation, lying about 20 centimeters above the bioturbated zone (see Figure 28). The coal ranges up to 20 centimeters in thickness and is exposed only along the southeast side of Newcastle Island and along the north shore of Protection Island. The areal extent of the coal does not seem to be much larger than what is exposed on outcrop, as it lenses out in all directions. The sandstones range in color from a whitish brown (10YR 7/2) to a grayish white (N7). The lighter colors make the Protection easy to distinguish from the other formations within the area.

Petrography. The Protection Formation is the most uniform in composition and appearance of any of the formations within the field area. It is composed of coarse-grained arkosic wackes, and feldspathic wackes and arenites (see Figure 29). The grains are subangular to subrounded in shape, and in framework support. The framework minerals are mostly quartz, orthoclase, labradorite, microcline, chert and biotite. Minor framework constituents include magnetite, sphene, and volcanic and metamorphic rock fragments. The matrix is fine quartz and clay, but in places is completely replaced by calcite cement.

The quartz is mostly unstrained, the chert minor. Some examples of myremekite were found in two of the slides.

Figure 28. Coal seam within Protection Formation, Protection Island. Hammer for scale.

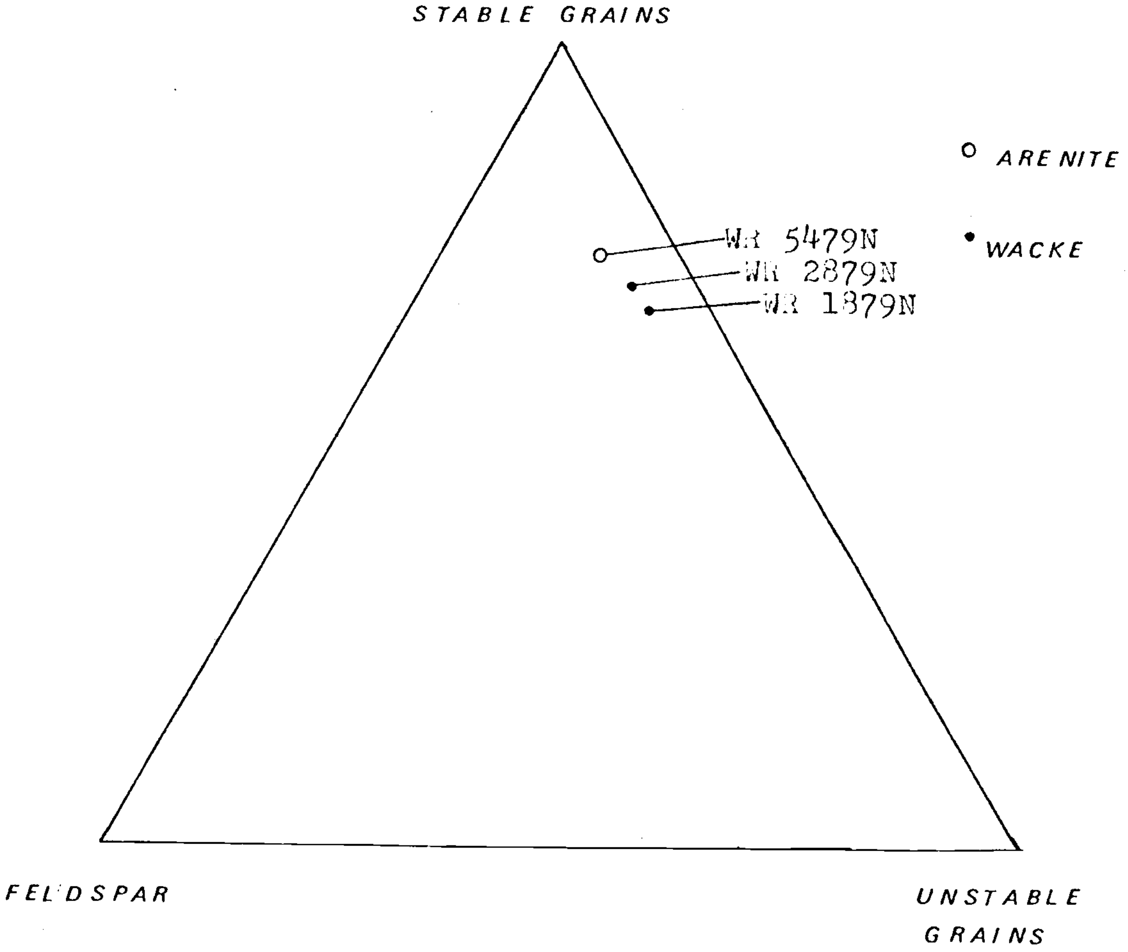


Figure 29. Classification of the Sandstones of the Protection Formation.

The feldspars consist mainly of plagioclase An_{50-70}, some of which exhibit a zoned texture.

Diagenesis is not as prevalent in the Protection Formation as in the other formations. The biotite exhibits some alteration to clay and replacement by calcite. The matrix of the volcanic rock fragments is completely altered to clay.

Environment of Deposition and Provenance. The lithology of the Protection suggests a high energy environment, cross-bedding and laminations being common. The sandstones have little matrix (see Appendix A) and some of the grains are subrounded, suggesting at least some reworking.

These factors, along with the thick, massive beds in the lower part of the formation, resemble those described by Masters (1968) as indications of a barrier-beach to off-shore environment.

The large amount of feldspar, unstrained quartz and the presence of a substantial amount of microcline suggest an intrusive source. The best candidate is the Nanaimo Batholith, which may have been unroofed at the time of deposition of the Protection Formation. This terrain dominated as the source of sediments; however, some chert is still present, indicating some minor Sicker Group contributions along with some volcanic material, probably derived from the Karmutsen Formation.

STRUCTURE

Post-Cretaceous faulting and folding are usually found in close proximity and occur throughout the study area. Clapp (1914) emphasized folding compared to faulting, but later authors (Buckham, 1947; Muller and Jeletzky, 1970; Muller and Atchison, 1971) have reversed the emphasis and now suggest faulting at depth as the cause of much of the folding in the area.

The close association between faulting and folding of the sedimentary rocks can best be observed on the Nanaimo Harbor Fault established by Muller and Atchison (1971) from coal mining information (see Figure 30). It enters the area at the end of Horswell Point, and though no actual break in the strata is visible, the area is tightly folded. Proceeding south along the fault to the northwest end of Newcastle Island, tight folding can be seen in the cliff exposures, again with no break in the strata. The fault can be traced farther south (see Muller and Atchison, 1971, Figure 12) until it is terminated against an east-west-trending fault that lies in the downtown Nanaimo area.

Also associated with the Nanaimo Harbor Fault is the Terminal Avenue Fault, lying roughly parallel and 300 meters to the west (see Figure 31). This pair is an example of multiple faults developing in the sedimentary rock from one underlying fault in the volcanic basement rock (Muller and

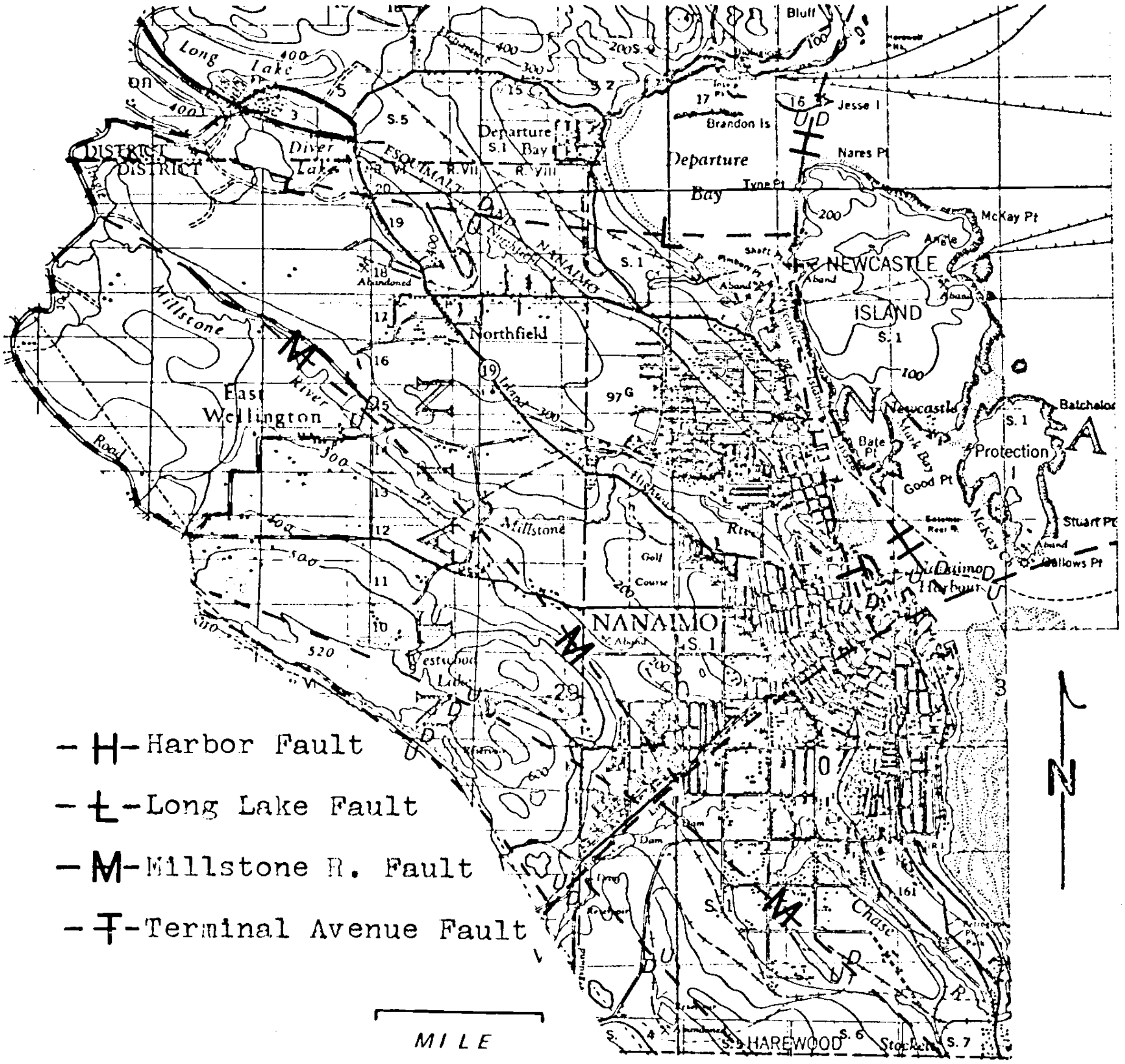


Figure 30. Structure Map of the Study Area.

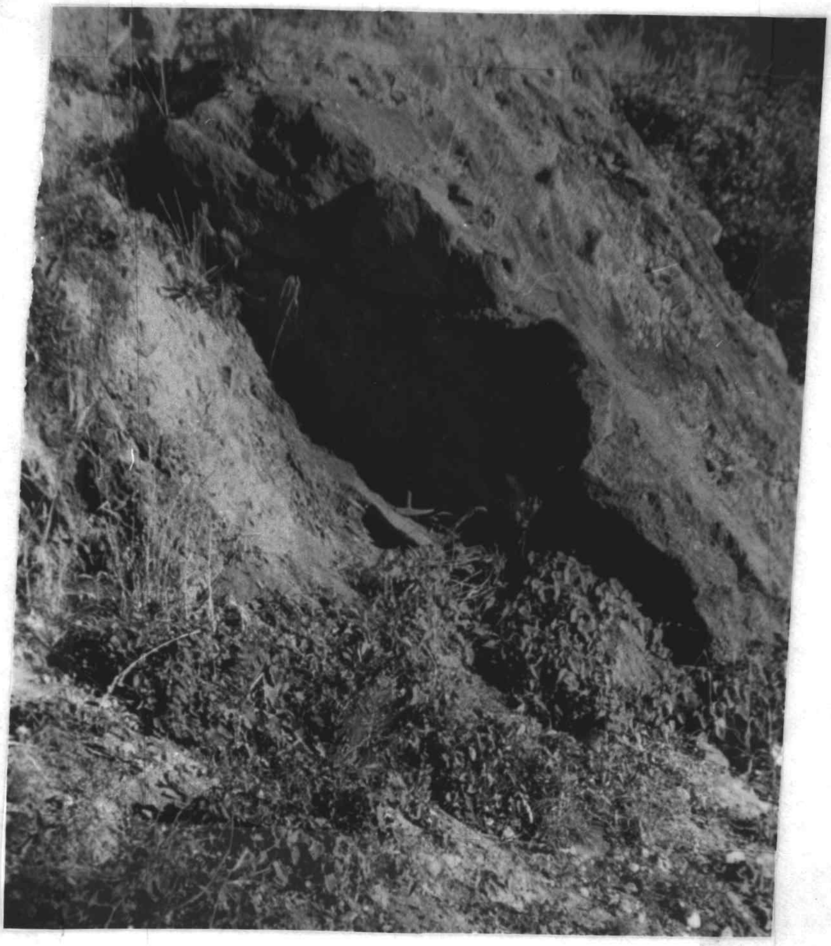


Figure 31. Tilted beds of the Newcastle Formation associated with the Terminal Avenue Fault, immediately behind the Big Eagle service station, Terminal Avenue, downtown Nanaimo. Hammer in photo center is vertical.

Atchison, 1971, p. 15). The area between the two faults has been tightly folded, producing a small anticline-syncline pair. The axis of the anticline can be seen on the north shore of the marina in downtown Nanaimo.

Buckham (1947) emphasized the importance of what he called thrust faults to the structure of the general area, and cited the Millstone River Fault as an example (see Figure 32). Muller and Atchison (1971) later reclassified Buckham's thrust faults as high angle reverse faults, a conclusion supported by the linear traces of the faults.

The east-west-trending faults are not as evident on the surface. The Divers Lake Fault, which lies in the Northfield area and westward to Divers Lake, is only encountered in the subsurface (Muller and Atchison, 1971, Figure 12), although a small vertical fault on the east side of Newcastle Island may be a continuation. In the south central part of the study area, an east-west-trending scissor fault was observed. In the downtown Nanaimo area, the south side is up, as can be observed by the offset in the Douglas Seam. Farther west, the sense of movement is reversed, the south downdropping the Extension Formation into contact with Karmutsen volcanics (see Plate 1).

Minor faulting also occurred in the volcanic basement in the Westwood Lake area, producing a small graben. Other minor faulting south of the Chase River produced several small east-dipping cuestas in the Extension Formation.

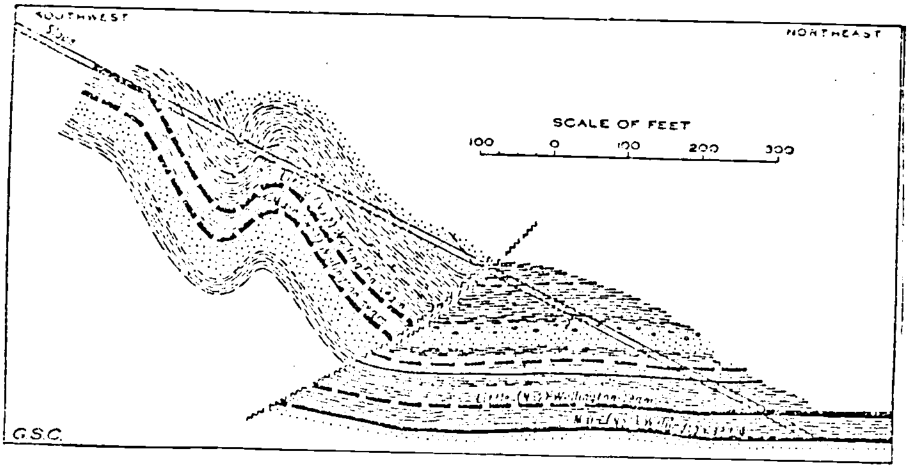


Figure 32 . Attitude of the fault plane of the Millstone River Fault. (After A. F. Buckham, 1947)

Some folding, apparently not associated with faulting, is also present in the area on the northeast side of Newcastle Island. At that location the shoreline cuts across the axis of a small anticline in the Newcastle Formation.

ECONOMIC GEOLOGY

History of Coal Mining

Coal mining was one of the earliest industries in British Columbia, the earliest discoveries being in the Suquash area of Vancouver Island in 1835. The Nanaimo area was discovered in 1851 when Joseph McKay, a clerk at the Hudson's Bay fort in Victoria, learned of the coal from Indians that traded at the fort. The next year McKay received orders from Governor Douglas to take possession of the coal seams and begin mining operations, using miners from the Suquash field, which was now depleted.

The Hudson's Bay Company, through the Nanaimo Coal Company, opened the Douglas Mine in 1852 and had produced 55,408 long tons of coal by the time it was sold to the Vancouver Coal Company in 1861. The coal industry greatly expanded when the Wellington coal field was discovered by Robert Dunsmuir in 1869. In 1871, Dunsmuir and three officers of the Royal Navy formed Dunsmuir, Diggle & Company and began mining operations at Wellington.

From that time on, there were two major coal interests in the Nanaimo area, each with numerous corporate titles caused by reorganizations over the years. The Vancouver Coal Company, which held all of the original Hudson's Bay properties, became the New Vancouver Coal Mining and Land

Company in 1889. In 1908 it became the Western Fuel Company, the Canadian Western Fuel Company, Limited in 1918, and the Western Fuel Corporation of Canada, Limited in 1921, before being bought out by Dunsmuir interests in 1928. Western Fuel continued to operate independently until it was closed in 1939.

The other major coal company on Vancouver Island was initiated by Robert Dunsmuir and later controlled by his heirs. In 1883, Dunsmuir bought out his partners in Dunsmuir, Diggle & Company and renamed it R. Dunsmuir & Sons, Limited. In 1899, the company was reorganized into Wellington Colliery Company, Limited and again in 1910 into Canadian Collieries (Dunsmuir), Limited, which is remained until it became part of Weldwood of Canada, Limited in 1960.

The mines operated by the Western Fuel Corporation and its predecessor companies were principally confined to the Newcastle and Douglas seams in the Nanaimo area. The oldest of these mines was the Old Douglas Mine (1852-1886), that followed the Douglas seam under much of what is now southern Nanaimo (see Figure 33, #14, 15). The other mines exploiting the Douglas seam were the Fitzwilliam Mine (1876-1881) on Newcastle Island (18), the New Douglas or Chase River Mine (1874-1912) near Chase River (16), and the Number One Mines (1883-1938) on Protection Island (17). The Number One Mines were the most famous of the Nanaimo mines,

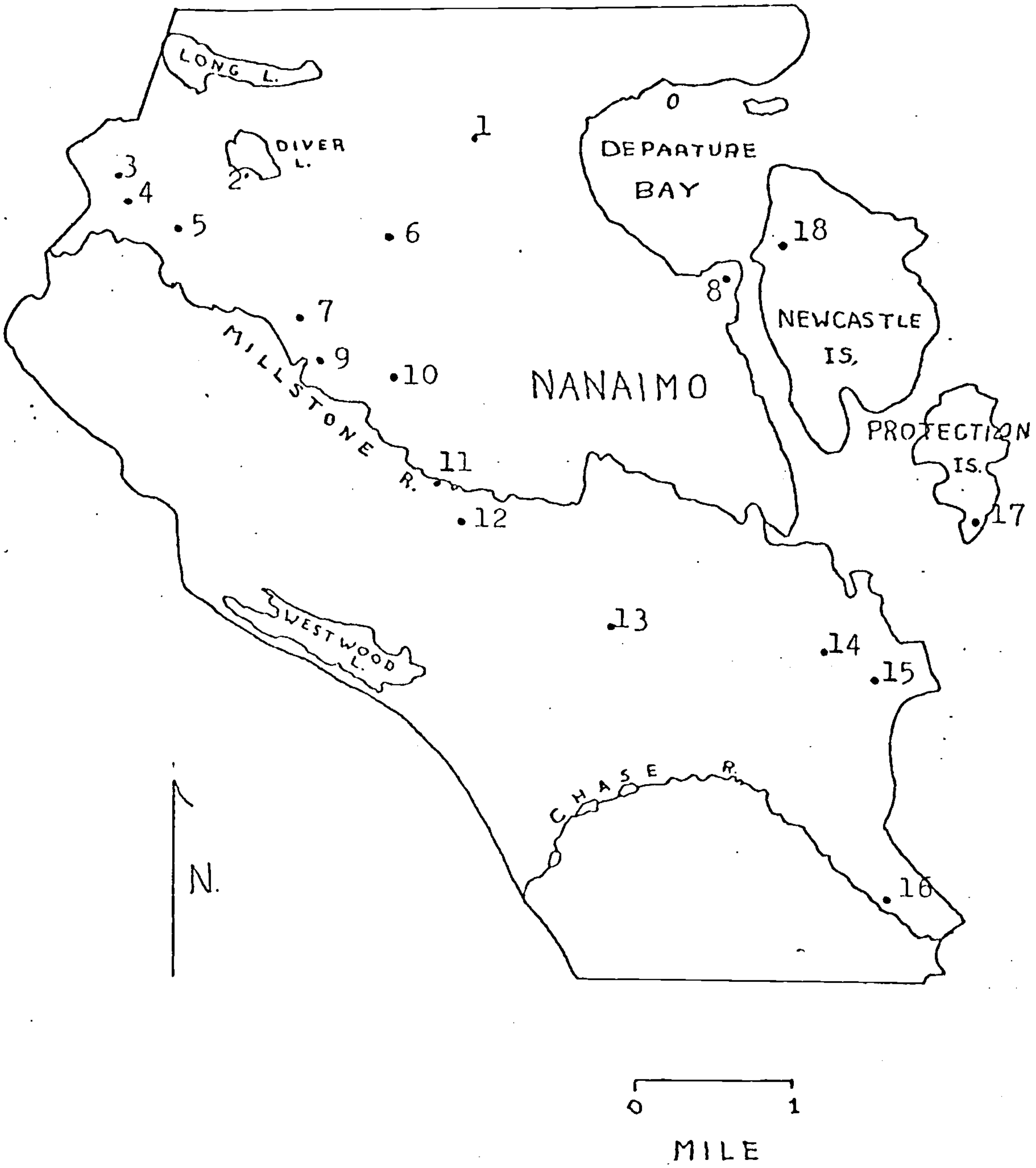


Figure 33. Location of Coal Mines in the Study Area.

producing a total of 18,000,000 tons of coal from workings that extended to a depth of 1,700 feet beneath Nanaimo Harbor. The only mine on the Newcastle seam was the Brechin or Northfield No. 4 Mine (1904-1917), its workings under Newcastle Island operated through a shaft on Pimbury Point (8). The Wakesiah Mine (1918-1930)(13) and the Northfield Mine (1889-1914)(6), were the only Western Fuel mines to operate on the Wellington seams. The Northfield Mine was reopened in 1936 by Canadian Collieries and operated until it was abandoned in 1941.

The Dunsmuir mines were confined to the Wellington seams within the study area. The Wellington Colliery (1871-1910) was the largest in the Wellington field, operating a main slope and six shafts in the vicinity of Diver Lake (1-7). The South Wellington Mine, also called the Chandler Mine (1878-1952), intermittently mined the Wellington field south of the Wellington Colliery (9-10) and was the last working mine in the thesis area. The Wellington field was largely depleted by 1900 and the bulk of the Dunsmuir activities was shifted to the Extension field south of the study area.

Several smaller operators also had workings in the Nanaimo area. The only one within the study area was the Vancouver and Nanaimo Coal Company, Limited, which owned the Jingle Pot Mine (1907-1937) on the Wellington seams west of Nanaimo (11, 12). The Jingle Pot was renamed the

Lewis Mine in 1937 and continued operating until it was abandoned in 1945.

Mining in the Nanaimo coal fields was both difficult and dangerous. During the early years, mine explosions were fairly common, the worst of which occurred in the Number One Mines on May 3, 1887 killing 150 miners. Another hazard in the later years was flooding of the workings beneath Nanaimo Harbor.

Labor problems also were common in the Nanaimo mines, and strikes periodically occurred, the longest of which lasted over a year (1913-1914). During the strike, California oil started to become more widely used because of the shortage of coal, which eventually, along with the more difficult working conditions at greater depth and lack of labor during the latter years led to the permanent closure of the last mines in 1952.

Future Coal Mining Prospects

Future coal mining in the Nanaimo area seems very unlikely, according to Muller and Atchison (1971). Based on seams greater than two-thirds of a meter thick and less than 610 meters beneath the surface, only two of the mines within the study area contain possible minable reserves. They are the Wellington Colliery no. 1 with 123,000 tons and the New Douglas Mine with a possible 310,000 tons recoverable. However, Muller and Atchison feel that recovery of this coal is not likely because of the danger of sudden emissions of gas and the breakup of the working face (called outbursts, U.S.=rockbursts) at depths greater than 300 meters.

Nanaimo Coal Seams

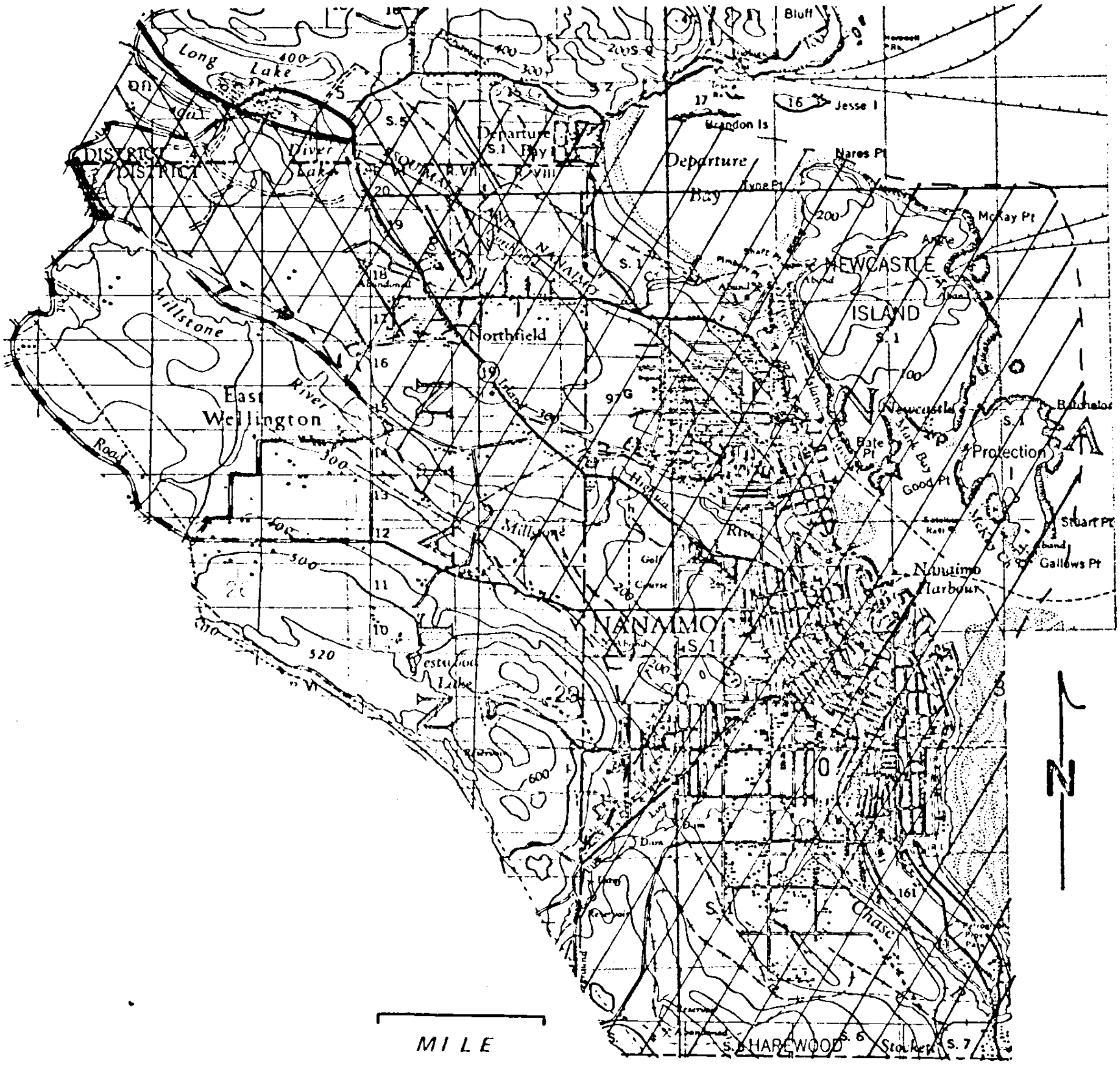
Introduction. The exposures of the coal seams in the Nanaimo area are very limited. The Wellington seams were found at only one location on the Chase River, the Douglas at two locations in downtown Nanaimo, and the Newcastle at one poor outcrop on Newcastle Island (see Figures 34 and 35). Most of the coal samples were collected from mine dumps and only a general idea of where they came from can be obtained. Access to the working faces of the mines is no longer possible, as all the mines are now sealed or flooded. Much of the information for these sections comes from the work of Clapp (1914), Buckham (1947), Hacquebard *et al*. (1967), and Muller and Atchison (1971).

Wellington Seams. The Wellington seams are stratigraphically the lowest in the Nanaimo Group, lying within the East Wellington member of the Extension Formation. The Wellington seams consist of four members: the lowest and main producing seam, the Wellington No. 1; the Little Wellington or Wellington No. 2; the Wellington No. 3; and the Wellington No. 4. The No. 1 seam is separated from the upper three seams by barren intervals of 10 meters, 30 meters, and 55 meters respectively. The No. 1 varies in thickness from zero to three meters, averaging two meters, while the other three seams average less than one meter.

Clapp (1914) believed that the Wellington seams underlay much of the study area (see Figure 34), however subsequent mining indicated a much smaller actual area. Buckham (1947) stated that the coal was workable in a zone one and one half kilometer wide parallel to the present coast. The western boundary is the surface outcrop of the seams, whereas the eastern boundary is controlled by a facies change, the seams gradually becoming dirtier to the east until they disappear.

The Wellington seams are floored by the flaggy sandstone of the East Wellington member, with lentils of siltstone between the floors and the seams in places. The roofs of the seams are more variable. Commonly they are sandy siltstones, as seen at the Nanaimo city waterworks on the Chase River, or overlain by sandstones of the East Wellington member. South of the area, the Extension conglomerates form the roof (Clapp, 1914).

The most conspicuous feature of the Wellington seams is the variation in thickness, apparently caused by postdepositional intraformational deformation. The floors of the seams always remain unaffected by deformation, but the roofs exhibit great deformation, producing pinches and



⧄ Estimated Reserves (After Clapp, 1914)

⊠ Approximate Mined Areas (After Muller and Atchison, 1971)

Figure 34. Areal Extent of the Wellington Seams.

swells in the individual seam. The coal within the swells is almost entirely clean, with only small lenses of sheared dirty coal or "rash". The pinch structures are made up almost entirely of rash.

The character of the Wellington coal is finely striated humic with a semi-bright luster. The coal is classed as a dull clarain, with rare vitrain bands and small lenses of fusain. The uniformity of the coal causes it to be fairly hard and strong and break with a hackly fracture into large lumps (Hacquebard *et al.*, 1976). Coal from the Wellington No. 1 seam is ranked as high volatile bituminous, and was considered the best of the three main seams for coking purposes (Clapp, 1914).

Newcastle Seam. The Newcastle seam is the least extensive of the seams in the Nanaimo area, only being mined under Newcastle Island an estimated 185 to 290 meters stratigraphically above the Wellington seam and 18 meters below the Douglas seam. Clapp (1914) estimated the seam's extent to be fairly large, but later mining indicated a much smaller area, some five by two and one half kilometers under Newcastle and Protection Islands (see Figure 35). The western margin is controlled by erosion, the eastern by a facies change similar to the Wellington.

The Newcastle seam is thinner than the Wellington or Douglas seams, averaging about one meter and ranging from

╱ Estimated Reserves (After Clapp, 1914)

⊠ Approximate Mined Areas (After Muller and Atchison, 1971)

Figure 35. Areal Extent of the Newcastle Seam.

one third to two and one half meters in the vicinity of faults and rolls. The seam is considered much more regular than the other two seams (Clapp, 1914). The floor of the seam is a thin-bedded, flaggy sandstone the roof is variously a sandy siltstone to a fine conglomerate.

Newcastle coal is ranked as high volatile bituminous, and is lower in fixed and actual carbon and higher in oxygen and ash than Wellington or Douglas coal (see Appendix C).

Douglas Seam. The Douglas seam is the uppermost of the producing seams of the Nanaimo (see Figures 36, 37). The seam lies within the Formation, approximately 180 to 305 meters stratigraphically above the Wellington seams. Clapp (1914) estimated a large area was underlain by the Douglas seam, which has been matched much more closely by subsequent mining than his other estimates (see Figure 38). The seam was mined in a strip running parallel to the coast about two kilometers wide and extending from under Nanaimo Harbor southward out of the area. The western margin of the seam was again controlled by erosion; the eastern extent is unknown because mining did not proceed deeper than 305 meters because of the danger of outbursts, although it is thought that it is again controlled by a facies change (Buckham, 1947).

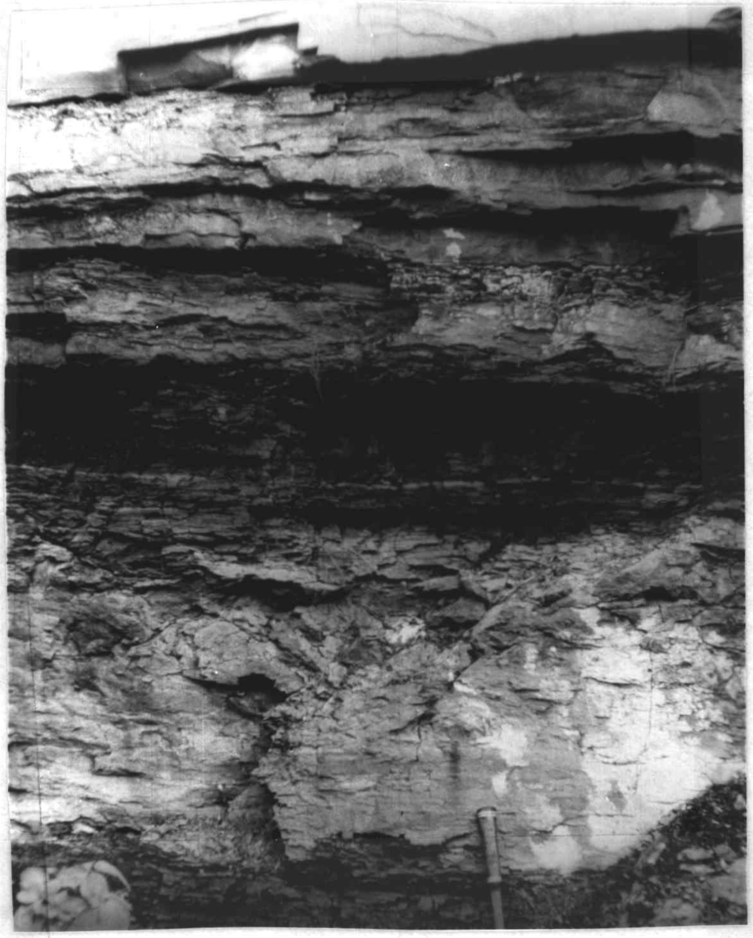


Figure 36. Douglas Coal Seam, downtown Nanaimo. Note underclay layer and underlying subsidiary seam. Hammer in lower center for scale.

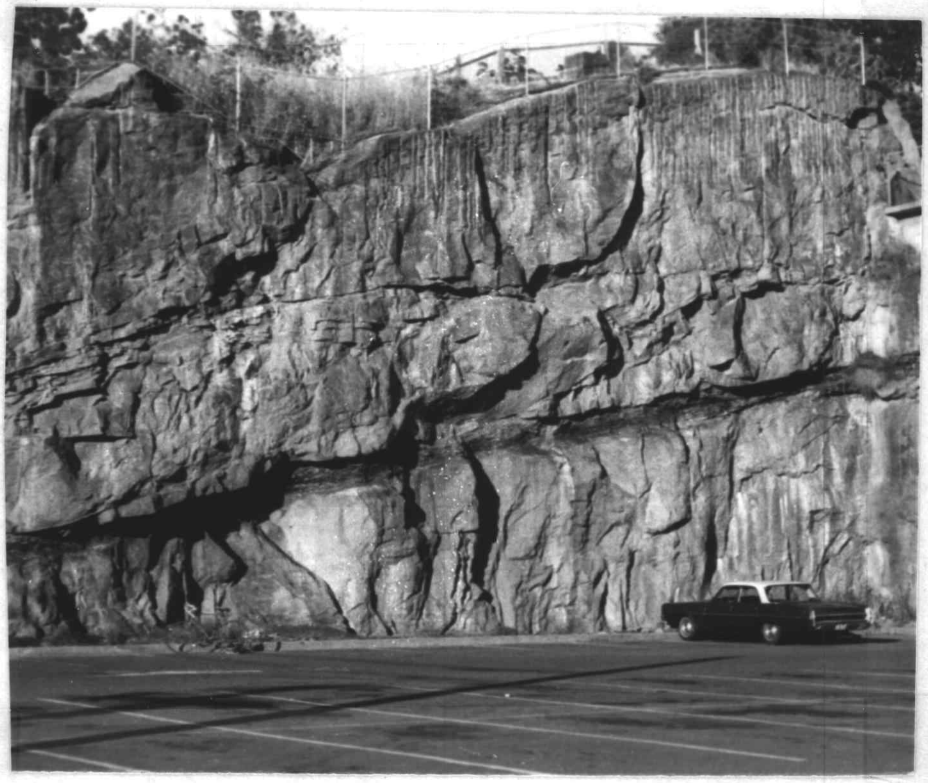
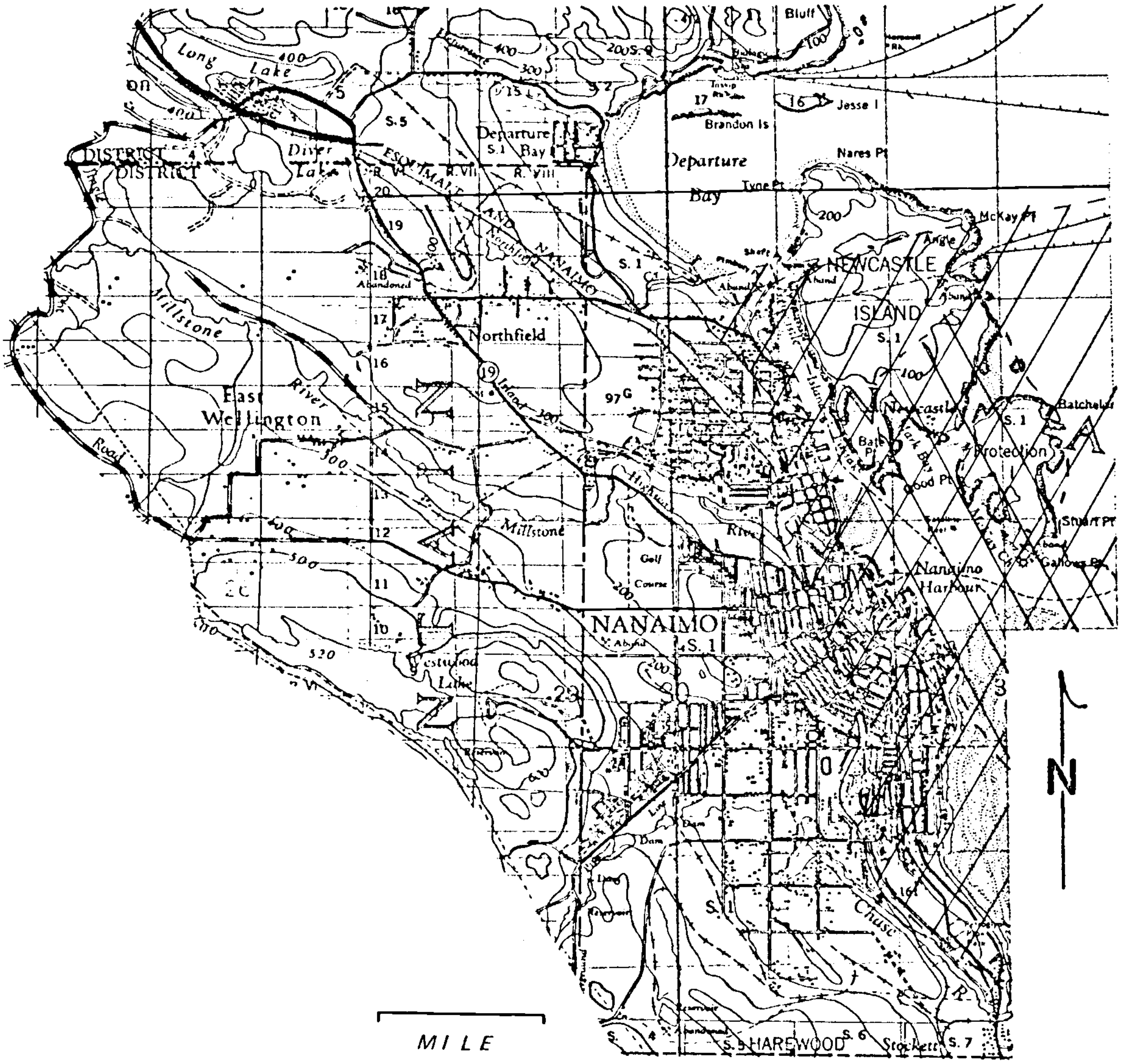


Figure 37. Douglas Coal Seam, downtown Nanaimo. Large man-made exposure; note lenses of overlying conglomerate and faint bands (above automobile) of underlying graded conglomerate.



▨ Estimated Reserves (After Clapp, 1914)

⊠ Approximate Mined Areas (After Muller and Atchison, 1971)

Figure 38. Areal Extent of the Douglas Seam.

The thickness ranges from zero to 10 meters, averaging about one and one half meters. The variation in the thickness is caused by intraformational slumping similar to the Wellington seam, except reversed, a smooth roof of fine conglomerates to sandy siltstones and a floor of predominantly deformed siltstones.

According to Clapp (1914), Douglas coal is black with a sub-brilliant to brilliant luster where not contorted. In places where it has been sheared, the coal develops highly polished, slickensided surfaces, between which the coal is a dull to sub-brilliant luster. Where the coal is contorted, it contains large amounts of ash.

Douglas coal is high volatile bituminous, similar to Wellington coal (see Appendix C).

Depositional Environments. The depositional environments of the Nanaimo coal seams have been studied by several of the workers of the Nanaimo Group. Clapp (1914) was the first to suggest an environment of deposition, postulating that the organic material was deposited in peat bogs formed in lagoons protected by barrier bars. He cited the lack of underclay, roots, and stumps to support his conclusions. Buckham (1947) supported Clapp's conclusions, but felt that, based on the field evidence, the origin of the organic material, either growing in place or transported into lagoons, could not be determined.

Hacquebard _et_ _al_. (1967) made a detailed study of the Wellington seams compiled from samples obtained from locations where the coal seams were still accessible. These studies suggested three facies occurred repeatedly over several intervals: telmatic forest moor facies, mixed open moor facies, and a reed moor facies. The telmatic forest moor suggests a shallow water swampy area with much arboraceous vegetation; the reed moor facies, a reedy marsh area; and the open moor, a boggy marsh area. The combination of these facies suggests repeated fluctuation of the water table over time.

During the field work on this project, a stump was found in the Douglas seam (see Figure 39) along with some underclay. This tends to support the idea that at least some of the organic material was formed in place in a coastal swamp, contrary to Clapp's conclusion.

Construction Materials

Building stone has been a minor industry within the Nanaimo area. In the thesis area, two quarries, both in the Protection Formation sandstones, have supplied building material although neither is now in operation. The larger of the two is located on the west side of Newcastle Island opposite Pimbury Point, and the smaller is located in the vicinity of the site of the present Tourist Bureau in downtown Nanaimo.

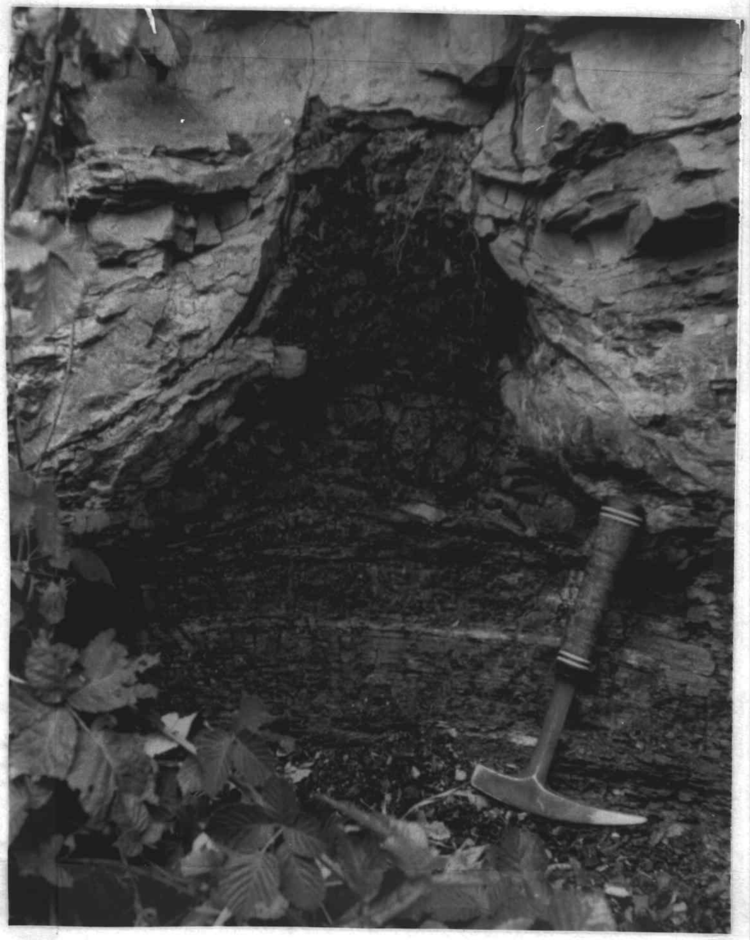


Figure 39. Stump in Douglas Seam, behind Chevron station on Terminal Avenue, downtown Nanaimo. Hammer for scale.

Road metal is also occasionally mined in the area from two quarries in the Karmutsen Formation. The larger of the two quarries is located at the base of the Mt. Benson Spur north of Malaspina College, and the smaller and presently more active one is located on the northern boundary of the area north of Long Lake.

Petroleum Potential

The possibility of economic quantities of hydrocarbons (other than coal) being found in the Nanaimo area is small. While several structural traps probably exist within the area, and the rocks of the Comox and Haslam Formations probably contain enough organic material and adequate burial depth for the generation of hydrocarbons, adequate reservoir rock does not seem to be present. This results from the closing of the original porosity of the sandstones by diagenesis. Hanson (1976) reported that one of the inhabitants of Saltspring Island had seen some oil staining associated with one of the salt springs, but did not consider it significant.

GEOLOGICAL HISTORY

The study area lies within the Insular Belt, one of five north-south-trending belts that compose the Canadian Cordillera. Each was accreted onto the continental block during Paleozoic or Mesozoic time. Belt movement, by plate tectonics, was generally northward, the Insular Belt as much as 50 degrees north during Triassic and Jurassic time with respect to the interior of North America (Muller, 1977). Rifting associated with this movement is thought to have produced the Karmutsen Volcanics.

During Cretaceous time a forearc basin developed on the east side of the Insular Belt, including the study area. The basin received sediment from a rising median ridge along the western part of the Insular Belt, but none from the Coast Plutonic Belt to the east.

Prior to the deposition of the Nanaimo Group in Late Cretaceous time, faulting of the Karmutsen Volcanics occurred, producing the Nanoose ridge and separating the Nanaimo Basin from the Comox Basin. The Karmutsen Formation also underwent much erosion, as is evident at the contacts with Nanaimo Group rocks and the irregular topography of the basement seen in the subsurface using borehole data (see Comox Formation, Stratigraphy section).

At the time of deposition of the Comox, during the Santonian Epoch, the area underwent a rapid change of environments, from the high energy environment of the Benson Conglomerate Member to the much lower energy environments of the upper Comox and lower Haslam. This trend from higher to lower energy was the result of a shift from a wave dominated environment to one dominated by quiet water. The cause of this shift may have been a sand spit or some other obstruction produced by a shift in longshore currents or some other unknown factor. This postulated barrier complex is not presently exposed in the area, but may be present to the east beneath the Strait of Georgia.

The Haslam Formation represents a continuation of the quiet water environment, probably a lagoonal facies. Circulation to open marine water was restricted, but not completely cut off, as indicated by the presence of marine fossils (see Haslam Formation, Stratigraphy section). Toward the end of the deposition of the Haslam Formation, a eustatic drop in sea level occurred, causing shallowing of the postulated lagoon to form a swampy area; this probably resulted in the deposition of the East Wellington Member of the Extension Formation in an environment conducive to the preservation of carbonaceous material which eventually became the Wellington coal seams (see Depositional Environments, Economic Geology section). The total thickness of the lagoon filling is unknown, because of subsequent erosion by the stream channels that produced the Extension Conglomerate deposits.

The Extension Conglomerate represents a shift of environments to a high energy fluvial facies. The paleoshoreline was some distance to the east at the time of deposition, as the conglomerates exhibit no tendency towards the finer-grained deposits with abundant carbonaceous debris which is indicative of an estuarine environment. The paleocurrent indicators exhibit a strong easterly trend.

The end of deposition of the Extension Formation was marked by the end of the regressive phase and the beginning of a transgressive phase, perhaps caused by a eustatic sea level rise, a subsidence of the area, or a combination of both. The Newcastle Formation onlaps the Extension Formation with a series of beds that bears a resemblance to those described by Flores (1975) as a delta plain facies of a short headed stream. The paleocurrent indicators exhibit a marked change from those of the underlying Extension Formation, now displaying a northerly tendency. This may have been the result of the production of offshore bars or sand spits, such as those present today along the Oregon Coast, thus causing the paleo-Nanaimo River to flow parallel to the coast. The river system probably flowed northward until it reached the Nanoose Uplift and then turned east and flowed into the sea.

The floodplain produced by the river was fairly extensive. Buckham (1947) estimated the original size of the coal swamps at approximately five kilometers in width, and at least 15 kilometers long, lying parallel to the paleoshoreline.

The last Cretaceous unit to be deposited, that is still preserved in the area, is the Protection Formation. This formation resulted from a continuation of the transgression which commenced during Newcastle time, and represents the shifting westward of the barrier-beach complex onto the floodplain. Many of the higher Cretaceous formations were probably deposited in the area, but are now missing because of subsequent uplift and erosion.

After the deposition of the Cretaceous rocks, faulting occurred which produced Mt. Benson and tilted and folded the sedimentary rocks. Post-faulting erosion stripped much of the sedimentary rocks. Post-faulting erosion stripped much of the sedimentary rock from Mt. Benson and the surrounding area. The most powerful erosive agent to affect the area was Pleistocene glaciation. This glaciation stripped much of the remaining sedimentary rock off the area, and was responsible for cutting Newcastle Passage and forming most of the rest of the Gulf Islands. Pleistocene glaciation occurred in two stages, Admiralty and Vashon. The Admiralty was the more intense of the glacial events, involving continental glaciers, while the Vashon involved only small, individual glaciers. Most of the drift, which reaches 60 meters in thickness, is the product of Vashon glaciation, with some pockets of Admiralty till. One outcrop of Puyallup interglacial marine deposits was found in the downtown Nanaimo area.

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APPENDICES

Appendix A

Modal Analysis of Selected Sandstone Samples

	Kc				Kh
Mineralogy	WR1679N	WR1579N	WR5779N	WR1079	WR2979N
Framework T	58.5	42	27	57	17
Quartz T	4.5	1	16	1	15
Normal Qtz.	1	1	8	0.5	7
Polyxxln. Qtz.	---	---	3	T	3
Undulat. Qtz.	3.5	---	4	0.5	4
Chert	---	---	1	---	1
Feldspar T	2	5	4	T	T
Plagioclase	---	---	---	---	T
Orthoclase	---	---	---	---	---
Microcline	---	---	---	---	---
Undef.	2	5	4	T	T
Rock Fragments T	27	28	3	2	2
Volcanic	27	27	3	2	2
Metamorphic	---	1	T	---	---
Sedimentary	---	---	---	---	---
Intrusive	---	---	---	---	---
Micas T	---	---	---	---	T
Biotite	---	---	---	---	---
Muscovite	---	---	---	---	T
Chlorite	---	---	---	---	---
Fe-bearing T	1	5	3	1	---
Epidote	---	4	T	T	---
Pyrite	---	---	---	T	---
Augite	1	1	3	1	---
Others	---	T	---	T	T
Others T	24	3	1	53	T
Matrix T	40	58	69	43	80
Calcite	31	51	5	10	36
Chlorite	4	4	8	3	2
Quartz	6	1	46	14	40
Laumontite	1	---	1	5	2
Iron oxides	---	---	T	T	T
Others	---	1	9	1	T

Appendix A (continued)

	Formation and Sample			
	Kh	Fe		
Mineralogy	WR3279N	WR4379N	WR2679N	WR4479N
Framework T	28	40	92	24
Quartz T	24	31	75	21
Normal Qtz.	15	20	20	10
Polyxxln. Qtz.	3	5	10	3
Undulat. Qtz.	6	6	2	1
Chert	---	T	43	9
Feldspar T	---	5	6	3
Plagioclase	---	2	2	1
Orthoclase	---	1	2	---
Microcline	---	T	T	---
Undef.	---	1	2	2
Rock Fragments T	T	2	7	---
Volcanic	T	1	3	---
Metamorphic	---	1	2	---
Sedimentary	---	T	2	---
Intrusive	---	---	---	---
Micas T	4	2	4	1
Biotite	3	2	4	1
Muscovite	1	T	---	---
Chlorite	T	---	T	T
Fe-bearing T	T	---	---	T
Epidote	---	---	---	---
Pyrite	T	---	---	---
Augite	---	---	---	T
Others	T	T	---	T
Others T	T	---	T	---
Matrix T	71	57	6	73
Calcite	4	---	T	T
Chlorite	1	3	T	2
Quartz	65	49	5	66
Laumontite	1	2	T	T
Iron oxides	T	3	1	2
Others	T	T	---	3

Appendix A (continued)

	Formation and Sample			
	Kn			
Mineralogy	WR679N	WR2079N	WR3679N	WR2979N
Framework T	38	16	50	89
Quartz T	27	11	48	82
Normal Qtz.	12	4	40	5
Polyxxln. Qtz.	2	2	7	15
Undulat. Qtz.	1	1	1	T
Chert	12	5	T	62
Feldspar T	5	2	1	2
Plagioclase	2	1	T	T
Orthoclase	---	---	---	---
Microcline	---	---	T	T
Undef.	3	1	1	2
Rock Fragments T	6	3	T	3
Volcanic	2	2	T	3
Metamorphic	4	1	---	---
Sedimentary	---	---	---	---
Intrusive	---	---	---	---
Micas T	T	---	1	T
Biotite	---	---	1	T
Muscovite	---	---	T	---
Chlorite	T	---	---	---
Fe-bearing T	T	T	---	1
Epidote	---	---	---	---
Pyrite	---	---	---	1
Augite	---	---	---	T
Others	T	T	T	---
Others T	---	---	---	---
Matrix T	62	83	43	11
Calcite	3	---	9	1
Chlorite	3	3	3	T
Quartz	54	70	34	10
Laumontite	T	T	T	T
Iron oxides	2	3	T	T
Others	T	7	---	T

Appendix A (continued)

	Formation and Sample			
	Kn	Kp		
Mineralogy	WR279N	WR1879N	WR2879N	WR5479N
Framework T	45	77	87	62
Quartz T	38	49	62	47
Normal Qtz.	5	10	20	30
Polyxlln. Qtz.	4	15	10	10
Undulat. Qtz.	2	12	20	5
Chert	27	12	12	3
Feldspar T	3	19	21	10
Plagioclase	1	10	10	6
Orthoclase	---	6	15	---
Microcline	T	T	T	2
Undef.	2	3	6	2
Rock Fragments T	2	2	1	2
Volcanic	1	1	1	1
Metamorphic	1	1	T	1
Sedimentary	---	---	---	---
Intrusive	T	T	T	T
Micas T	T	4	3	2
Biotite	1	4	3	2
Muscovite	T	---	---	---
Chlorite	---	---	---	T
Fe-bearing T	2	3	1	1
Epidote	---	---	---	---
Pyrite	---	---	---	---
Augite	T	---	T	---
Others	2	3	1	1
Others T	---	---	---	---
Matrix T	55	23	11	38
Calcite	---	1	T	36
Chlorite	2	T	T	---
Quartz	35	21	9	1
Laumontite	2	T	T	T
Iron oxides	9	1	1	1
Others	7	---	1	---

Appendix B

Pebble Count Lithologies

	Formation and Sample	
	——Ke——	—— Kn——
Lithology	WR6179N	WR5079N
Aphanitic volcanics	8	5
Chert	61	47
Diktytaxitc basalt	--	2
Granitics	14	18
Quartzite	17	25
Sandstone	--	3
	n=200	n=200

Appendix C

Proximate Analysis of Coals from the Study Area.*

	Moisture	Volatile combustible	Fixed carbon	Ash	Sulphur	Fuel ratio	Calorific value B.T.U.
Wellington coal							
Wellington Mine	2.75	38.03	52.64	6.58	----	1.38	12567
Wellington Mine	8.57	25.30	56.40	9.52	0.21	2.22	---
Wellington Mine	4.14	36.85	46.16	12.85	0.56	1.25	---
Newcastle coal							
Nanaimo Colliery No. 1 shaft	2.86	35.84	54.79	5.50	1.01	1.53	12951
Douglas coal							
Newcastle Island	1.57	38.14	50.84	8.63	0.82	1.33	---
Nanaimo Colliery No. 1 shaft	1.88	33.27	54.67	9.40	0.70	1.64	12672

*Taken from Clapp (1914).