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TABLE OF CONTENTS

ABSTRACT

A new inquiry into the groundwater potential of the Nanaimo Lowlands is being jointly undertaken by concerned municipal, provincial and federal agencies. Rapid population growth and expanding industrial development are, and will continue to, put pressure on the limited groundwater resources. The bedrock component of the project focuses on the characterization of the aquifer potential of the Upper Cretaceous Nanaimo Group, as a likely target of importance. This unit is a thick succession of 11 intertonguing sandstone-dominated and shale-dominated formations, of which only the lower 8 are present in the defined study area. As a preliminary step in the analysis, this report summarizes the most relevant information for these 8 units from the previously published geological literature, in order to focus attention on the zones and areas of most likely groundwater potential.

The sandstone- and conglomerate-dominated units of the Comox, Extension and Protection formations have significant aquifer potential due to their potential for porosity and permeability, fracturing, and extensive development at reasonable depths over wide areas (with minor potential in the De Courcy Formation, present only near the surface in a small part of the study area). Conversely, the interbedded shale-dominated units of the Haslam, Pender, Cedar District and Northumberland formations are important because they may provide significant aquitard seal units, overlying the potential aquifer zones over wide areas of the Nanaimo Lowlands.

Further study of the thickness, geographic and stratigraphic distribution, fracturing, and internal stratigraphic complexities of these 8 units of the Nanaimo Group will provide a more scientific basis for evaluation of the bedrock aquifer potential in the Nanaimo Lowlands region.

INTRODUCTION

Rationale

In 2010 the BC Dept of Environment, related local municipalities, and the Geological Survey of Canada began a joint project called “Groundwater Assessment in the Nanaimo Lowlands”. The purpose of this effort is to bring together researchers with varied and multiple expertises to produce a qualitative evaluation of the future groundwater supply and quality in the greater Nanaimo Basin of eastern Vancouver Island. Studies related to surface water, shallow Quaternary aquifers, and deep bedrock aquifers were to be included. My part of this joint project was to attempt to understand the aquifer potential of the bedrock of the Upper Cretaceous Nanaimo Group which underlies large portions of the study area. As a first step, this report provides a brief summary of the most relevant information and knowledge from previous studies, to establish a context for the current work.

Study Area

The regional study area for this project is centred on the City of Nanaimo, and lies on the eastern side of Vancouver Island, between Mill Bay to the south (south of Duncan, west of the Saanich Peninsula), and Deep Bay top the north (south of Courtenay, near Denman Island) (Fig. 1). Lowland areas underlain by Upper Cretaceous bedrock extend from the shores of the Strait of Georgia westward for several tens of kilometres onto Vancouver Island. Whereas Saanich Peninsula and the adjacent Gulf Islands in the Strait are not technically included in the study area, the pertinent lower part of the Nanaimo Group is well-exposed and easily-accessible on north Saanich, and on both Saltspring and Denman Islands, and outcrops from these locations will be studied as part of the project. The field area spans a northwest-southeast-oriented region roughly 110 km long by 50 km wide along the eastern coastal plain margin of Vancouver Island. This study area occupies portions of three 1:250,000 sheets (Victoria, 92B; Vancouver, 92G; Port Alberni, 92F) and nine 1:50,000 sheets (Sidney, 92B/11; Shawnigan Lake, 92B/12; Duncan, 92B/13; Mayne Island, 92B/14; Nanaimo Lakes, 92F/1; Horne Lake, 92F/7; Parksville, 92F/8; Comox, 92F/10; Nanaimo, 92G/4). Numerous surface outcrops and one subsurface core will be studied over the course of several years.

Previous Work

The Upper Cretaceous Nanaimo Group has been the subject of geological study since coal was first mined in the Nanaimo area in 1852 (Mustard, 1994). The earliest major geological report was by Richardson (1872) describing the "Coal Measures" and mineable coal seams of eastern Vancouver Island, including a basic map of the distribution of the Nanaimo Group and stratigraphic sections. He identified the depositional basin and described operating coal mines and several outcrops between Comox and Saanich. Dawson (1890) first proposed the name "Nanaimo Group" for these economically-important strata. Extensive, high-quality, early geological mapping by Clapp (1914) in the Nanaimo area, and by Clapp and Cooke (1917) in the Duncan area established an identifiable succession of lithological formations and faunas, many of which are still in use today. These researchers carefully described the great thickness and variety of alternating units of coarse-grained and fine-grained rocks, interpreted the presence of both marine and nonmarine facies, and noted that the Group rests on an erosional unconformity with considerable relief (up to 600 m), onto which the lower formations on onlap and pinch-out. They also provided abundant detail on the distribution and quality of the economically-important coal seams. The preliminary map of Buckham (1947) provided an updated geological map of the Nanaimo area, with marginal notes concerning the contained coal seams and the local active coal mines. Muller and Jeletzky (1970) created a unified regional geological map of the entire eastern coastal margin of Vancouver Island, compiled detailed biostratigraphic data, solidified definitions and distributions of the enclosed formations, and recognized that the Nanaimo Group represents deposition in a single large basin, despite the current distribution of the strata in several isolated preservational areas. They also suggested that the Nanaimo Group represents four major fining-upward (transgressive) cycles of deposition which became less dominated by shoreline and shallow marine deposition, and more dominated by deeper marine deposition through time (Muller and Jeletzky, 1970).

The next major effort in the region was a PhD thesis and resulting publications by England (England, 1990; Bustin and England, 1990; England and Hiscott, 1992) on the upper Nanaimo Group in the southern outer Gulf Islands. This work concluded that the upper part of the Group (Cedar District to Gabriola formations) represents deposition in a shallow to deep marine setting, with the coarse-grained units representing turbidity currents and debris flows transported westward and northwestward in major, lenticular submarine channels of a submarine fan system. England's work is most important in illustrating the extreme complexity and variety of large-scale channelized coarse grained units (potential aquifer zones) separated both vertically and laterally by fine grained units (potential aquitard zones) (England, 1990; England and Hiscott, 1991). The upper bounding unconformity of the Nanaimo Group was also described as having up to 2 km of relief (England and Hiscott, 1991).

In recent decades, Mustard and colleagues studied the regional stratigraphy and sedimentology, the tectonic framework and a variety of sedimentological details of parts of the Nanaimo Group (Mustard, 1994; Mustard *et al*., 1995; Mustard *et al*., 1999; Enkin et al., 2001; Katnick and Mustard, 2003; Johnstone et al., 2006). The paleomagnetic study of Enkin et al. (2001) suggested that the Nanaimo Basin and its enclosed Upper Cretaceous sediments were deposited at a southern paleolatitude comparable to Baja Mexico. However, this apparently is in conflict with the enclosed paleontological data which suggest a northern location for the depositional basin approximately in its current position (Enkin *et al*., 2001). Mustard (1994) provided a more complete synthesis of previous work and regional framework, and solidified the notion that the separate outcrop areas of the Nanaimo Group are erosional remnants of a single large depositional basin, and not representative of a variety of separate depositional basins, as some previous authors had suggested. During recent decades, some researchers have paid attention to the coal-bed methane potential of the Nanaimo coal seams (Kenyon, 1991; Ryan *et al*., 2005). There has been little geological study of the aquifer potential of these rocks.

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REGIONAL TECTONIC AND DEPOSITIONAL SETTING

Cordilleran Tectonic Setting

The Nanaimo Group is the direct result of the evolution of the Canadian Cordillera during Jurassic-Cretaceous time. The Canadian Cordillera consists of a tectonic collage of allocthonous terranes (Monger, 1989). Collisional accretion of microcontinents to the western margin of ancient North America compressed and detached the underlying Paleozoic wedge and telescoped and translated these strata as imbricate thrust sheets to form the thickened orogenic belt (Porter et al., 1982). In mid-Cretaceous time, a change from orthogonal to oblique northward convergence caused western parts of the Cordillera to be displaced to the north (Monger, 1989). Late Cretaceous (Turonian/Cenomanian-aged: immediately pre-Nanaimo Group deposition) docking of the oceanic Insular Superterrane (Alexander/Wrangellia Terranes which underlie the Nanaimo Group) led to rapidly intensifying tectonic loading (Monger, 1989; Cant and Stockmal, 1989; Stockmal *et al*., 1993), resultant deformation of the continental margin, and rapid sedimentation into the resulting depositional basin.

The Nanaimo Group resides within the Georgia Basin, the erosional remnant of a single northwest-trending structural and topographic depression which presently occupies Georgia Strait, the Gulf Islands and eastern Vancouver Island (Mustard, 1994). The current preserved extent of the Georgia Basin (now broken into several regions of occurrence of these rocks by fault-bounded basement uplifts) is about 250 x 100 km, but the original depositional extent was probably much greater (Mustard and Monger, 1991) (Fig. 1). The basin was likely flanked by open ocean to the west (Johnstone, et al., 2006; Ward and Stanley, 1982). On Vancouver Island, these strata unconformably overlie the Wrangellia Terrane, a complex of Devonian to Jurassic metamorphosed and deformed sedimentary and igneous rocks which was emplaced onto the western margin of North America during a phase of transpressional deformation in the immediately pre-Nanaimo time (Cant and Stockmal, 1989; Mustard, 1994). Nanaimo deposition may have been influenced by syn-depositional thrusting, and these strata were certainly deformed by post-depositional, Tertiary-aged strike-slip and thrust compression (Mustard, 1994).

Although previous authors have suggested both strike-slip models of basin development (Pacht, 1984) and forearc settings (Muller and Jeletsky, 1970; England, 1990), there is little supportive evidence for these tectonic interpretations. In addition, more structural information has been gathered since those studies, and there has been a realization that the original basin of deposition was much more extensive than previously envisioned (Ward and Stanley, 1982; Mustard, 1994). Mustard and Monger (1991) suggested that a foreland basin model is appropriate for the Nanaimo Group basin fill. The thick Wrangellia Terrane of Paleozoic and Jurassic volcanic and sedimentary rocks provided a semi-rigid basement which was loaded and flexurally deformed in front of the westerly-propagating thrust stacks of Coast/Cascade belts, positioned to the east of the depocentre during Late Cretaceous orogenesis (Mustard and Monger, 1991; Mustard, 1994). In this model, early thrust loading on the east side and forebulge migration westward would provide a rapidly subsiding basin of deposition, with a northwest-southeast-oriented basin axis, plus sediment sources from both east and west margins. Each subsequent phase of thrusting would cause renewed basin subsidence and develop each coarsening-upward sequence of deposition, with progressive deepening of facies through time, and predominant westward and northwestward sediment transport from sediment sources in the east and southeast (Mustard, 1994).

NANAIMO GROUP BASIN INFILL AND STRATIGRAPHIC SETTING

Basin Infill

Basement beneath the Nanaimo Group in the study area consists of dark green volcanic rocks of the Triassic Karmutsen Formation, the eroded paleosurface of which may have had topographic relief up to 220 m and rocky shorelines (Cathyl-Bickford, 1993; Johnstone *et al*., 2006). Clapp (1914) reported that most basement rocks are thoroughly fractured. This basement topography likely influenced the presence, distribution and thickness of the unconformably-overlying lower Nanaimo Group units (Ward and Stanley, 1982; Johnstone et al., 2006). Johnstone *et al*. (2006) investigated this unconformity and the sedimentation styles of the overlying Comox Formation.

The Nanaimo Group (Fig. 2) comprises a stratigraphic thickness of as much as 4 km, with ages ranging from Turonian (~ 90 my) to Maastrichtian (~ 70 my), a depositional rate of about 1 m/5,000 years. The Nanaimo Group is subdivided into 11 formations, in ascending order, Comox, Haslam, Extension, Pender, Protection, Cedar District, De Courcy, Northumberland, Geoffrey, Spray and Gabriola. Because only the lower 8 are present in, and relevant to, this study, the following discussion is confined to these units.

The maximum age range of the Nanaimo Group, based on a synthesis of macrofossil, microfossil and radiometric dating studies, is early Turonian to Maastichtian (~91 to ~66 My), although over most of the basin (including this study area), it appears that the base of the Comox Formation is Santonian (~86 My) (Mustard, 1994; Haggart, 1994), suggesting a duration of ~20 Ma for the Group in this area. The lower eight formations discussed in this report are of Santonian-Campanian age (~86 – 74 My, a duration of about 12 Ma).

It must be remembered that the present distribution of the Nanaimo Group is preservational only, and does not reflect the entire depositional basin, which likely extended further to the west, and perhaps to the east, of its present configuration. In addition, the current distribution of Nanaimo Group rocks is separated into several outcrop/subcrop regions by the later uplift of fault-bounded basement blocks (e.g. Nanoose Ridge of Muller and Jeletzky, 1970; Ward and Stanley, 1982) during post-depositional deformation. Within our study area, these outcrop/subcrop regions are, from north to south 1) Comox/Qualicum/ Parksville, 2) Nanaimo/Cedar/Saltspring, and 3) Duncan/Cowichan/Saanich regions (Fig. 1).

Provenance

Published paleocurrent data (Mustard, 1994) is abundant in several of the coarse grained formations of the Nanaimo Group, and rather sparse in the fine grained units. However, taken together, most data suggests predominantly westward, south-westward and north-westward transport of sediment into the Nanaimo Basin during Comox to Northumberland time. Mineralogical and detrital zircon studies from the 1980's and 1990's likewise suggest that most sediment was derived from the Coast Belt to the east (through major west-flowing fluvial systems) and the Northern Cascades to the southeast (Ward and Stanley, 1982; Pacht, 1984; Mustard *et al*., 1995). Locally-derived sources from the Wrangellia Terrane, exposed immediately west of the study area, are important in the basal Comox Formation (Mustard, 1994), which also displays a more complex paleocurrent pattern, resulting from deposition onto the pre-Nanaimo, high-topography unconformity surface.

Most Nanaimo sandstones are immature to submature, moderately-sorted feldspathic arenites with 10-15% matrix and calcareous cement (reducing surface porosity to less than 5% in most outcrops), with lesser chert-rich and lithic-rich sandstones (Mustard, 1994). Chert is particularly abundant in lower formations, and plagioclase is especially abundant in upper units, and volcanic rock fragments are present throughout (Ward and Stanley, 1982; Mustard, 1994). Ward and Stanley (1982) identified 3 distinct petrologic intervals in Nanaimo Group rocks, in ascending order: 1) Comox Formation sandstones of volcanic lithic arenite and arkosic sandstones, 2) Haslam Formation chert lithic arenite, 3) Extension to Gabriola formations arkosic sandstones with minor lithic sandstones. These mineralogical characteristics may influence the porosity and permeability in different units.

Structural Complications

Much of the study area of eastern Vancouver Island is characterized by gentle east- or northeast-dipping beds, forming an overall monoclinal ramp sloping into the adjacent Georgia Strait. This geometry determines that lower stratigraphic units are present in surface outcrop to the west, and higher stratigraphic units are present in surface outcrops to the east. Therefore the more complete sequence of potential aquifer units is present toward the eastern margin of the study area.

However, in numerous locales, all components of the Nanaimo Group are deformed into linear, northwesterly-trending folds (Clapp, 1914; Yorath *et al.,*1992; Mustard, 1994). In addition, a major northwest-trending set of listric northeast-dipping thrust faults are prominent throughout the region and affect both the Wrangellia basement and the overlying Nanaimo Group (Gabrielse and Yorath, 1992; Mustard, 1994). Due to these structural complications, well-exposed, continuous outcrop sections of Nanaimo Group successions are uncommon, understanding the extent and distribution of potential aquifers is difficult, and most areas suffer from significant disruptions of aquifer continuity.

Other Resources

Groundwater is the focus of this report, but the Nanaimo Group has a long history of exploitation of other resources. The Nanaimo Group was well-known for its coal production for over a century, from the 1850's to the 1970's (Richardson, 1872; Clapp, 1914; Kenyon, 1991). Production was primarily from the Extension and Pender formations in the Nanaimo area (aggregate seam thicknesses of up to 20 m), with additional mining in the Comox Formation of the Courtney-Comox area (aggregate seam thicknesses of up to 12 m) (Kenyon, 1991; Cathyl-Bickford, 1993). During the 19thC, Nanaimo Group sandstones were quarried for grindstones and building stone (Richardson, 1872, Clapp, 1914). During the past two decades, attention has turned to the hydrocarbon potential of these strata. Bustin and England (1990) sampled extensively and observed that the rocks are characterized by Type II and Type III organic matter, low total organic carbon, moderate to low hydrogen indices, moderate to low oxygen indices, and range from thermally mature to overmature. In addition, questions remain regarding the presence of sufficient porosity and permeability at depth to form good reservoirs (Mustard, 1994). Bustin and England (1990) concluded that the Nanaimo Group has little oil-generating, but possible gas-generating, potential. (Kenyon (1991) and Mustard (1994) noted that coals are high-volatile bituminous, lie within the gas window, have well-defined fracturing, and have significant coal-bed methane potential. Likewise, Ryan et al. (2005) presented data suggesting that the coal seams of the Comox Formation in the Courtney-Comox area have significant coal-bed methane potential. Currently, several industry consortiums are evaluating the possibilities of further coal mining.

SUBDIVISION OF THE NANAIMO GROUP

The following brief summary descriptions are primarily taken from the comprehensive work of Mustard (1994) with supplemental information from a variety of authors, as noted, as applied only to the aquifer potential of the currently-defined Nanaimo Basin study area. The Nanaimo Group displays a prominent pattern of successive formations dominated by alternating coarse grained (potential aquifer zones) and fine grained (potential aquitards zones) facies. This is illustrated by a simplified geological map and cross-section in the Nanaimo sub-region (Fig. 3) and the stratigraphic chart of Figure 4. The units are described from base to top, and only those present in the study area are discussed.

Comox Formation

The Comox Formation (of mid-Santonian to early Campanian age) comprises thick sandstone and conglomerate which forms the base of the Nanaimo Group in almost all areas. It is the lowest, earliest of the 11 formations which make up the Group. The unit rests on a sharp, high-relief angular unconformity, overlying the metamorphosed, stratified, Devonian to Jurassic rocks of the Wrangellia Terrane (first noted by Richardson, 1872), and displays great variability (Muller and Jeletzky, 1970). The formation is generally 100-200 m thick, but is quite variable due to filling topography on the underlying unconformity: in some places, it appears to be absent and younger units overlie the basement. Typically there are basal conglomerates (Benson Member of Cathyl-Bickford, 1993; Benson Formation of Clapp, 1914 and Clapp and Cooke, 1917) consisting of poorly- to fairly-sorted, matrix- to clast-supported, pebble to cobble conglomerate (locally-derived clasts dominated by volcanic and felsic intrusive lithologies), set in a medium to coarse grained arkosic sandstone matrix. These are typically overlain by thick bedded, medium to coarse grained arkosic sandstone with minor interbedded siltstone and mudstone of the Dunsmuir Member (Cathyl-Bickford, 1993). Coal is present in the Comox area to the north. There is generally an overall fining-upward succession, passing gradationally upward into the overlying Haslam Formation.

The Comox Formation has been interpreted to include high-energy deposition in alluvial fan to braided fluvial and coastal floodplain to shoreline facies, with an overall transgressive or deepening-upward trend. Paleocurrent indicators display scattered directions, but generally suggest flow toward the western hemisphere. Deposition may have been influenced by high-relief topography on the underlying unconformity surface (Ward and Stanley, 1982; Johnstone *et al*., 2006). Johnstone *et al*. (2006) described 3 distinct facies typical of deposition on rocky shorelines with cliffed headlands and protected coves: 1) locally-derived conglomerates representing gravel-dominated fans built out from coastal cliffs and gullies, 2) well-sorted sandstone facies reflecting deposition on storm-dominated shorelines, and 3) fine grained units reflecting protected embayment settings.

The Comox Formation is the lowest coarse grained unit of the Nanaimo Group, present in outcrop on the western margins of the basin and present in the subsurface at depth beneath most of the basin, and is considered here to present significant regional aquifer potential. Due to its wide distribution, great thickness, general coarse grain size and extensive regional seal, these strata may represent the most important bedrock aquifer zone. However, the possibility of local thinning/thickening and pinchouts of Comox sandstones against significant underlying basement topography may result in a less predictable/less continuous distribution at depth than expected. Whereas fluvial facies distributions in the lower Comox may imply rapid lateral facies changes (and consequently less-continuous aquifers with variable characteristics), the upward transition to shoreline and shallow marine facies may suggest more laterally-continuous aquifers with more predictable characteristics.

Haslam Formation

The Haslam Formation (of late Santonian to early Campanian age) is dominated by grey to dark grey siltstone and mudstone with thin interbeds of fine to coarse grained sandstone. The unit is generally about 100-200 m thick (thickening southward; Clapp and Cooke, 1917), and rests with a gradational and conformable contact on the underlying Comox, and is sharply overlain by the Extension Formation. However, in the Duncan/Cowichan area, there are places where the Comox Formation is not present (due to relief on the underlying unconformity), and the Haslam rests directly on underlying basement rocks (Clapp and Cooke, 1917). Fine grained facies may be dark grey, organic-rich and laminated, are typically calcareous, with calcareous concretions (Clapp, 1914), but are more typically bioturbated. Shelly fossils are present, in distinct calcarenite beds in some locations (Clapp, 1914), but not usually abundant. Thin, interbedded sandstones are generally sharp-based, laminated and rippled, display partial (B-D) Bouma turbidite sequences, and are typically arranged into coarsening and thickening upward sequences several to tens of metres thick. In addition, overall there is a general coarsening-upward trend over the entire thickness (Ward and Stanley, 1982). To the southeast, sandstone and conglomerate facies are more prominent (Ward and Stanley, 1982).

The Haslam Formation has been interpreted to represent low-energy deposition in marine shelf to relatively deep slope depositional facies. Muller and Jeletzky (1970) suggested a relatively nearshore shelf setting. Paleocurrent data is sparse but suggests westerly depositional flows, similar to the rest of the overlying Nanaimo Group, suggesting that the significant local topography which influenced Comox deposition had largely been “smoothed-out” during Haslam time (Ward and Stanley, 1982).

As the lowest unit of the Nanaimo Group dominated by fine grained facies, and its general large thickness and blanket-like distribution, the Haslam Formation is considered to represent an important potential regional aquitard (-aquiclude?) zone, which could provide a regional-scale seal to the potential aquifers of the underlying Comox Formation.

Extension Formation

The Extension Formation (of early Campanian age) includes 100-200 m of thick bedded, clast-supported pebble to cobble conglomerate and medium to coarse grained arkosic sandstone. These rocks sharply, but conformably overlie the Haslam finer grained strata. Conglomerates are generally moderately sorted and subrounded, and are dominated by chert and volcanic lithologies. Although there is an intimate interbedding of sandstones and conglomerates throughout, there is a general upward decrease in conglomerate and increase in sandstone, depicting an overall fining-upward trend, and gradational upper contact with the finer grained Pender Formation. In the local Nanaimo area, thin coal seams are present in sandstone and siltstone facies near the base. Cathyl-Bickford and Kenyon (1988) and Mustard (1994) recognized a basal Northfield member of interbedded siltstone, fine sandstone and minor coal (the “East Wellington Sandstone” of Clapp, 1914), and an upper Millstream member of clast-supported, subangular to subrounded quartz conglomerate with minor sandstone. At surface, many Extension sandstones and conglomerates are tightly cemented by quartz and calcite (Cathyl-Bickford, 1993), but little is known of the porosity and permeability at depth. A few thin beds of shaley sandstone to sandy siltstone, with minor coaly lenses, are present (Clapp, 1914). Coals are of high volatile, bituminous A rank (Muller and Jeletzky, 1970).

The Extension Formation has been interpreted to include high-energy deposition in deeper marine submarine canyon and fan facies in northern areas, and shallow marine to coastal to braided fluvial depositional environments in the Nanaimo area where coal is present. Paleocurrent indicators suggest predominantly westward flow, with considerable scatter, possibly influenced in some areas by topographic relief on the sub-Nanaimo regional unconformity.

The Extension Formation is the second, and overall the coarsest, of the coarse grained units of the Nanaimo Group, present in outcrop in the central parts of the basin and in the subsurface at depth beneath central and eastern parts of the basin. It is considered here to present considerable aquifer potential. Due to its wide distribution, significant thickness, general coarse grain size, geographic consistency, potential for significant porosity and permeability, and potential regional seal over large areas of the basin (by the overlying Pender Formation), these strata may represent the second-most important bedrock aquifer zone, after the Comox Formation.

Pender Formation

The Pender Formation (of early Campanian age) represents a succession 100-200 m thick of siltstone and mudstone with common interbeds of fine grained sandstone (equivalent to the Cranberry and Newcastle formations of Clapp, 1914, and the Ganges Formation of Clapp and Cooke, 1917). The lower contact is generally gradational and conformable from the underlying Extension Formation, and the upper contact is likewise gradational and conformable into the overlying Protection Formation. Fine grained facies may be dark grey, organic-rich and laminated, but are more typically bioturbated. Thin, interbedded sandstones are generally sharp-based, laminated and rippled and display partial

Bouma turbidite sequences. On a formation scale, there is a thinning- and fining-upward trend from the underlying Extension, followed by a general thickening- and coarsening-upward trend into the overlying Protection Formation. A few thin coal seams are present in the finer grained strata in the Nanaimo area. Cathyl-Bickford (1993) and Mustard (1994) described a basal Cranberry member (Cranberry Formation of Clapp, 1914) of 50-200 m of fine to coarse sandstone with minor siltstone and coal, and an upper Newcastle Member (Newcastle Formation of Clapp, 1914) of about 100 m of dark grey, carbonaceous mudstone with thin sandstones and thick coal seams of high volatile, bituminous A rank (Muller and Jeletzky, 1970).

The Pender Formation has been interpreted to represent low-energy deposition in relatively deep marine shelf and slope environments of deposition in most areas, but shallow to marginal marine, coastal and fluvial floodplain deposits occur in the Nanaimo area where coal is present. Paleocurrent data is very sparse.

As the second lowest unit of the Nanaimo Group dominated by fine grained facies, and its significant thickness and wide distribution, the Pender Formation is considered to represent a potential regional aquitard zone, which could provide a regional-scale seal to the potential aquifers of the underlying Extension and Comox formations. In addition, the sandstone-dominated portions of the basal Cranberry Member may provide further potential aquifers.

Protection Formation

The Protection Formation (of early to late Campanian age) is a succession of characteristically pale grey, thick bedded, arkosic sandstone with minor bioturbated carbonaceous mudstone interbeds, which is about 200 m thick, and thickens to the southeast. Cathyl-Bickford (1993) and Mustard (1994) identified 3 members: a lower Cassidy member, 80-105 m of thick-bedded, fine to coarse grained arkosic sandstone, a middle Reserve member of 40-60 m of sandy siltstone with coal and fine to medium grained lithic sandstone, and an upper McMillan member of 90 m of thick-bedded, medium to coarse grained arkosic sandstone. Beds typically fine upward from erosional bases, and include trough cross bedding, ripple cross lamination and convolute lamination. Conglomeratic or granulestone lags are common. Silica cement is common at surface (Clapp and Cooke, 1917): these distinctive sandstones were famously quarried on Newcastle Island for building stone and grinding stones, including for international export to San Francisco, in the past (Richardson, 1872). Thinning and fining upward sequences on the scale of 10's of metres are common, and the lower contact of the formation is usually sharp, whereas the upper contact is gradational.

The Protection Formation has been interpreted to represent high-energy deposition in relatively deep marine shelf to submarine fan facies in most areas, but shallow marine shelf and coastal depositional environments occur in the Nanaimo area. Paleocurrent indicators suggest predominantly westward flow.

The Protection Formation is the third of the of the coarse grained units of the Nanaimo Group, present in outcrop in the central to eastern parts of the basin and in the subsurface only beneath eastern parts of the basin (not present in western parts of the study area). It is considered here to present significant aquifer potential due to its wide distribution over central and eastern parts of the basin, and the potential regional seal provided by the overlying Cedar District Formation in the eastern part of the basin.

Cedar District Formation

The Cedar District Formation (of late Campanian age) is characterized by thinly interbedded mudstone and siltstone (about 73% of the formation, Rahmani, 1968) with lesser fine grained sandstone. It gradationally overlies the Protection Formation. Mudstones are generally dark grey, bioturbated, silty, calcareous, may be laminated and organic-rich, and commonly have conspicuous sideritc concretions along bedding planes (Clapp, 1914), which formed in early diagenesis (Rahmani, 1968). Sandstones have sharp bases, are graded, have convolute lamination and ripple cross lamination, and display partial (primarily C-E; Rahmani, 1968; Muller and Jeletzky, 1970) Bouma turbidite sequences. Sandstone dykes are present in some locations (Cathyl-Bickford, 1993). Sandstones are 40% quartz, 14% feldspar, 5% biotite and 4% rock fragments, with 17% calcite cement and 12% clay matrix (Rahmani, 1968). The formation generally displays coarsening- and thickening-upward trends, grading upward into the overlying De Courcy Formation (Muller and Jeletzky, 1970), and is about 300 m thick, thickening southward to about 600 m (Cathyl-Bickford, 1993).

The Cedar District Formation has been interpreted to represent low-energy deposition below wave base in relatively deep marine shelf/slope and submarine fan environments of deposition in most areas (Rahmani, 1968). Paleocurrent data is sparse and suggests predominantly westward and northwestward flow.

As a middle unit of the Nanaimo Group dominated by fine grained facies, the Cedar District Formation is considered to represent a potential regional aquitard (-aquiclude?) zone, which could provide a regional-scale seal to the potential aquifers of the underlying Protection, Extension and Comox formations.

De Courcy Formation

The De Courcy Formation (of late Campanian age) is the uppermost coarse grained unit within the study area and is about 300 m thick. It is typically represented by stacked/amalgamated, thick bedded, uniform, greenish grey, medium to coarse grained arkosic sandstone and lesser, matrix-supported pebble conglomerate. Sandstones have erosional bases, may appear to be massive, or may be laminated. Soft sediment deformation/convolute lamination and sandstone dykes are common, as are concretions and cross beds, and the rocks are commonly silica-cemented at surface (Clapp, 1914; Clapp and Cooke, 1917). Concretions commonly erode out, leaving round holes and honeycomb galleries (Clapp and Cooke, 1917). The sandstones are typically unfossiliferous, and the age constraints are uncertain (Muller and Jeletzky, 1970). Coarse beds are separated by darker-coloured minor fine grained sandstone to siltstone beds. The formation is about 300 m thick, thickening southward. There is generally a coarsening- and thickening-upward trend from the underlying Cedar District, and a thinning- and fining-upward trend into the overlying Northumberland Formation.

The De Courcy Formation has been interpreted to include high-energy deposition in deeper marine submarine canyon and fan facies deposited on a generally northwestward-sloping margin. Paleocurrent indicators suggest predominantly westward and northwestward flow.

The De Courcy Formation is the fourth and uppermost of the coarse grained units of the Nanaimo Group within the study area. It is present in outcrop only in the easternmost part of the basin (Cedar/Ladysmith area, southeast of Nanaimo) and in the shallow subsurface only beneath this same eastern part of the basin. It is considered here to present modest aquifer potential, only in this local area. Due to its localized distribution at or near the surface, and lack of a potential regional seal over large areas of the basin (only in the Kulleet Bay area, southeast of Nanaimo), these strata represent a localized, potential bedrock aquifer of secondary importance.

Northumberland Formation

The Northumberland Formation (of late Campanian to early Maastrichtian age) represents the highest/youngest unit in the study area, present only in a small area around Kulleet Bay at the eastern shoreline margin of the area, southeast of Nanaimo. It includes up to about 200 m of recessive, dark grey bioturbated mudstone and siltstone with thin interbeds of sharp-based, very fine to fine grained sandstone. The formation fines upward from the underlying De Courcy Formation. Syn-sedimentary slump structures and sandstone dykes are present (Clapp and Cooke, 1917), and there is a slight coarsening-upward trend through the upper part of the formation as it grades upward into the overlying Geoffrey Formation, which is not exposed in the study area. Fossils are uncommon (Muller and Jeletzky, 1970).

The Northumberland Formation has been interpreted to represent low-energy deposition in relatively deep marine slope and submarine fan environments, with deposition on a northwestward-sloping margin. Paleocurrent data is very sparse.

As a middle unit of the Nanaimo Group dominated by fine grained facies, the Northumberland Formation is considered to represent a potential regional aquitard (-aquiclude?) zone, but within the study area, only provides a local-scale seal to the potential aquifers of the underlying De Courcy Formation in one limited area. This limited distribution renders it less important within the project study area.

Geoffrey Formation

The Geoffrey Formation (of late Campanian to early Maastrichtian age) comprises 400-500 m of thick bedded coarse grained sandstone to boulder conglomerate, which may harbour aquifer potential on some of the Gulf Islands. However, it is not present in the study area.

Spray Formation

The Spray Formation (of early Maastrichtian age) includes 250 – 300 m of recessive grey siltstone and mudstone, with thin interbeds of fine grained sandstone, which may represent a regional aquitard on some of the Gulf Islands. However, it is not present in the study area.

Gabriola Formation

The Gabriola Formation (of poorly constrained Maastrichtian age) comprises about 350 m of medium to coarse grained arkosic arenite with some conglomerate, which may harbour aquifer potential on some of the Gulf Islands. However, it is not present in the study area.

Depositional Cycles

Muller and Jeletsky (1970) proposed the idea that the Nanaimo Group comprises 4 complete (Comox-Haslam, Extension/Protection-Cedar District, De Courcy-Northumberland, Geoffrey-Spray), and one partial (Gabriola-?) unconformity-bound sequences (Fig. 4). These were interpreted as successive, stacked regressive-transgressive sequences, each consisting of a basal nonmarine to marginal marine coarse grained unit transgressively overlain by shallow to deeper marine fine grained deposits.

However, according to Mustard (1994) numerous studies since have failed to identify the key unconformities, and indeed, have documented coarsening-upward transgressive-regressive sequences on several scales. In this interpretation, each depositional sequence began with marine transgression due to a phase of significant tectonic subsidence (lower part of each fine grained unit), followed by lesser subsidence and regression (development of most of the coarsening-upward sequence). Thus, the identifiable T-R sequences are I) Comox-Haslam-Extension, II) Pender-Protection, III) Cedar District-De Courcy, IV) Northumberland-Geoffrey, V) Spray-Gabriola, the first three being most important to this study (Fig. 4).

In addition, most biostratigraphic and lithostratigraphic studies to date have concluded that all of the units dominated by fine grained facies, and most of the units dominated by coarse grained facies were deposited in shelf to slope to bathyal depths (Mustard, 1994). The exceptions to this are the Comox Formation everywhere, and the other, lower, coarser grained units (Extension, Protection formations) in the Nanaimo area where coal is present. Thus, the succession present in our study area, and the subject of this report, represents a sequence from a regionally extensive high-topography erosional surface (sub-Nanaimo unconformity), through a wide variety of nonmarine and coastal/marginal marine facies intertonguing with lesser, deeper marine deposits (Comox to Protection), to predominantly deeper marine coarse grained and fine grained facies (Cedar District to Northumberland), an overall deepening-upward succession (Fig. 2).

CONCLUSION

The basic geology of the Upper Cretaceous Nanaimo Group suggests that the coarser grained formations in the Nanaimo Basin may present significant zones of aquifer potential for new groundwater resources, whereas the intertonguing finer grained formations could provide zones of potential aquitard seals, a situation which might provide good prospects for multiple groundwater targets, provided porosity and permeability are present (Fig. 4). The Comox, Extension, Protection and De Courcy formations may harbour significant groundwater potential. However, the detailed internal stratigraphy, sedimentology, aquifer characteristics and presence of internal permeability barriers of these units must be studied and will determine their ultimate characters. The intervening finer-grained units, the Haslam, Pender, Cedar District and Northumberland formations may be important as sealing horizons, and therefore also warrant further study. In addition, fracturing, both local and regional, may influence or alter the rock characteristics and potential of both aquifer and aquitard horizons, and must also be studied in detail.

FIGURE CAPTIONS

1. Nanaimo Basin Aquifer Study field area (geology simplified from Muller and Jeletsky, 1970, GSC Paper 69-25).
2. Simplified geology of the Nanaimo Group of Vancouver Island.
3. Simplified geology of the Nanaimo sub-area (geology simplified from Buckham, 1947, GSC Paper 47-22; Clapp, 1914, GSC Memoir 51; Muller and Jeletsky, 1970, GSC Paper 69-25).
4. Nanaimo Group potential aquifer and aquitard zones.

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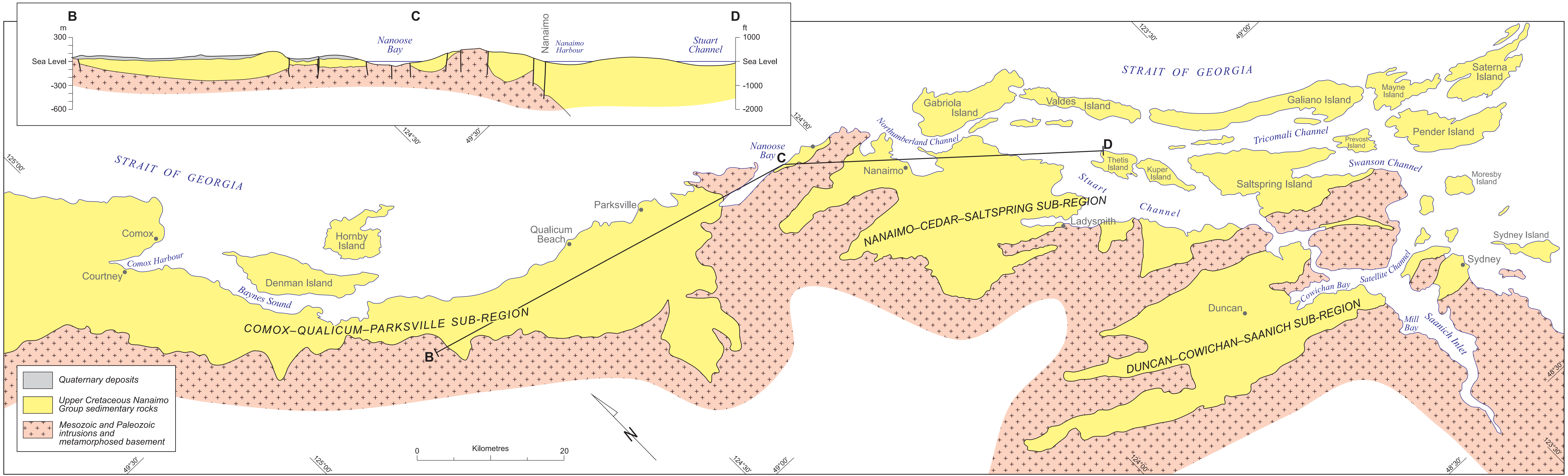

Figure 1. Nanaimo Basin Aquifer Study field area (geology simplified from Muller and Jeletsky, 1970, GSC Paper 69-25).

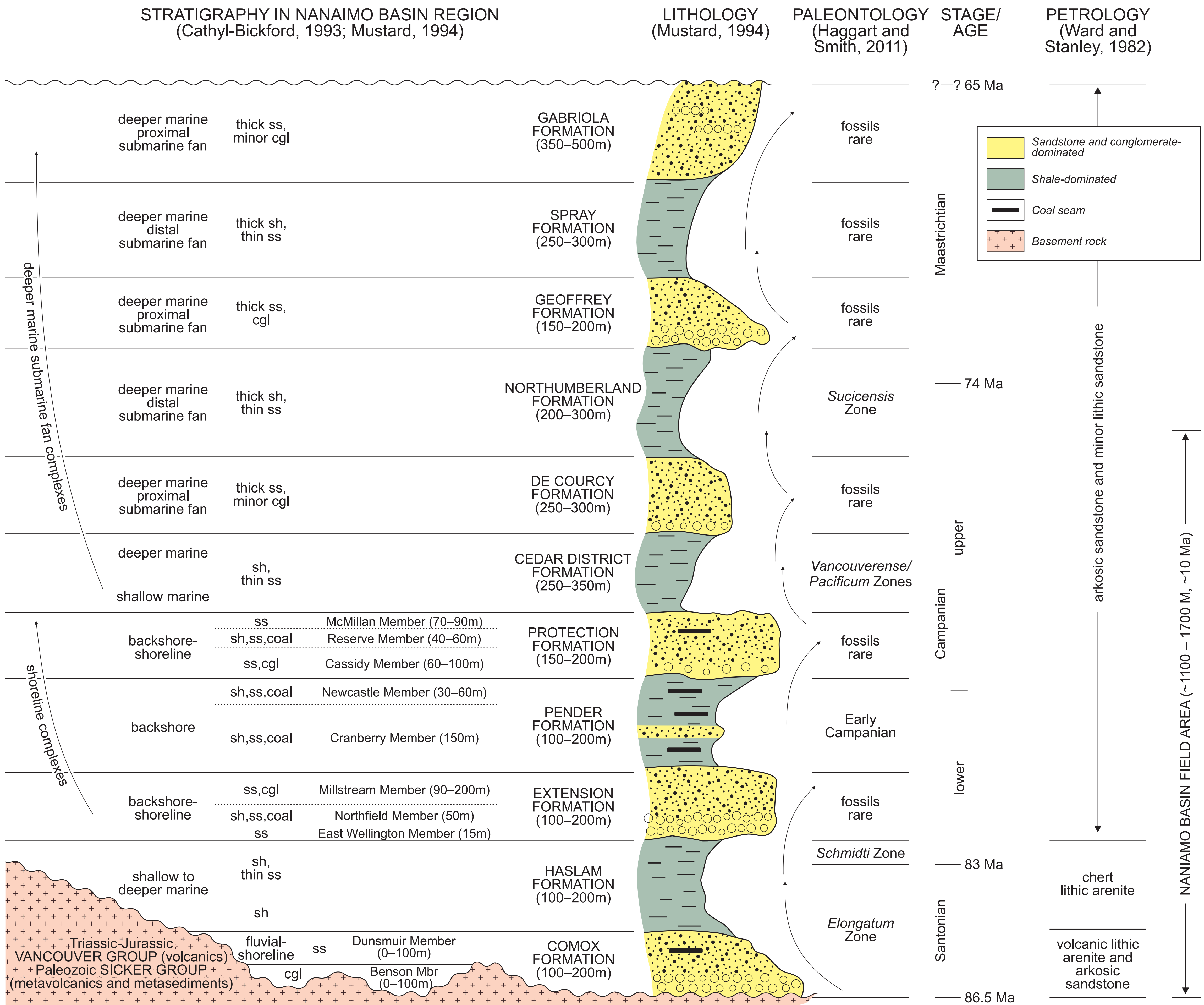

Figure 2. Simplified geology of Nanaimo Group of Vancouver Island.

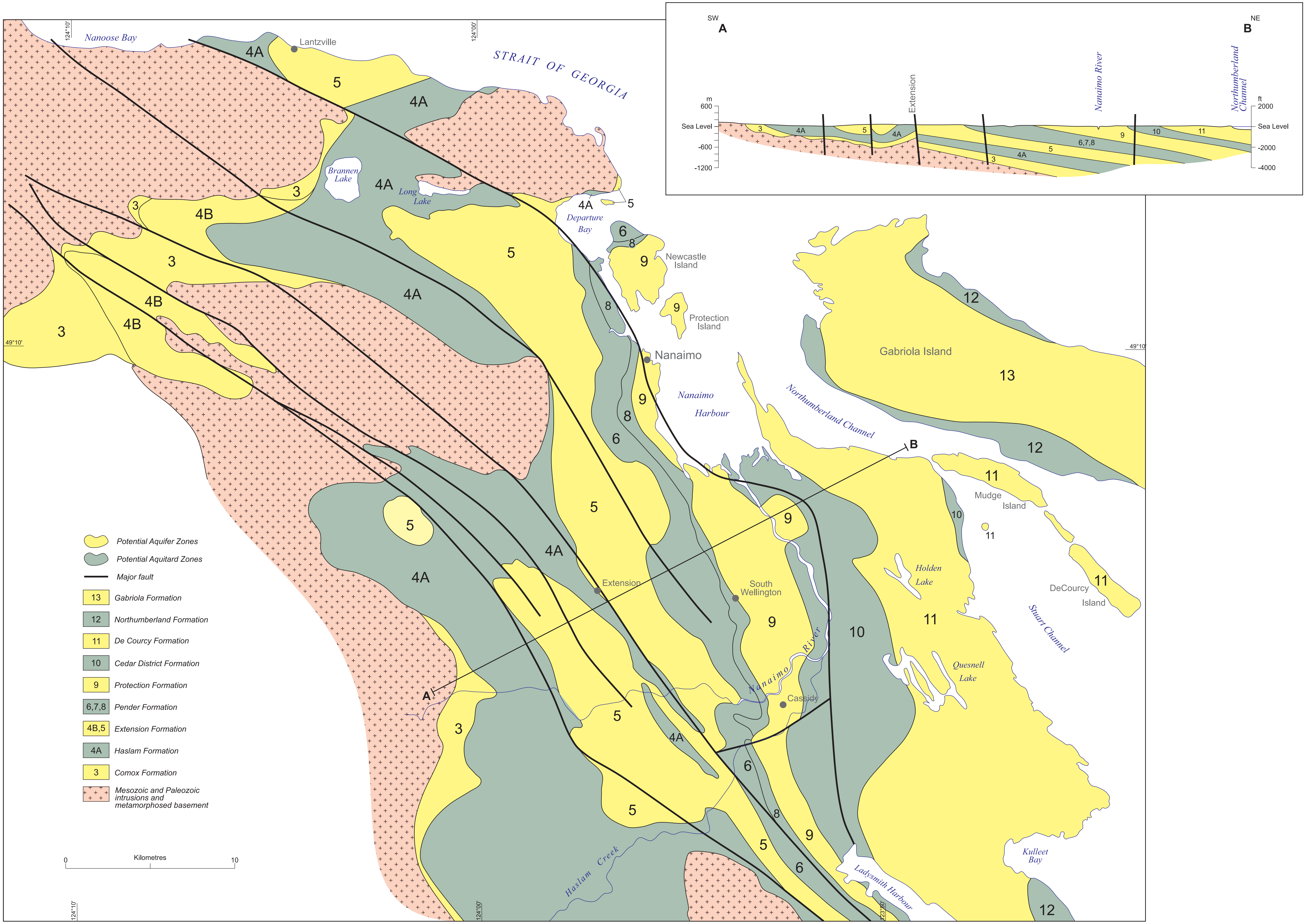

Figure 3. Geology of Nanaimo Sub-region (geology simplified from Buckham, 1947, GSC Paper 47-22; Clapp, 1914, GSC Memoir 51; and Muller and Jeletsky, 1970, GSC Paper 69-25).

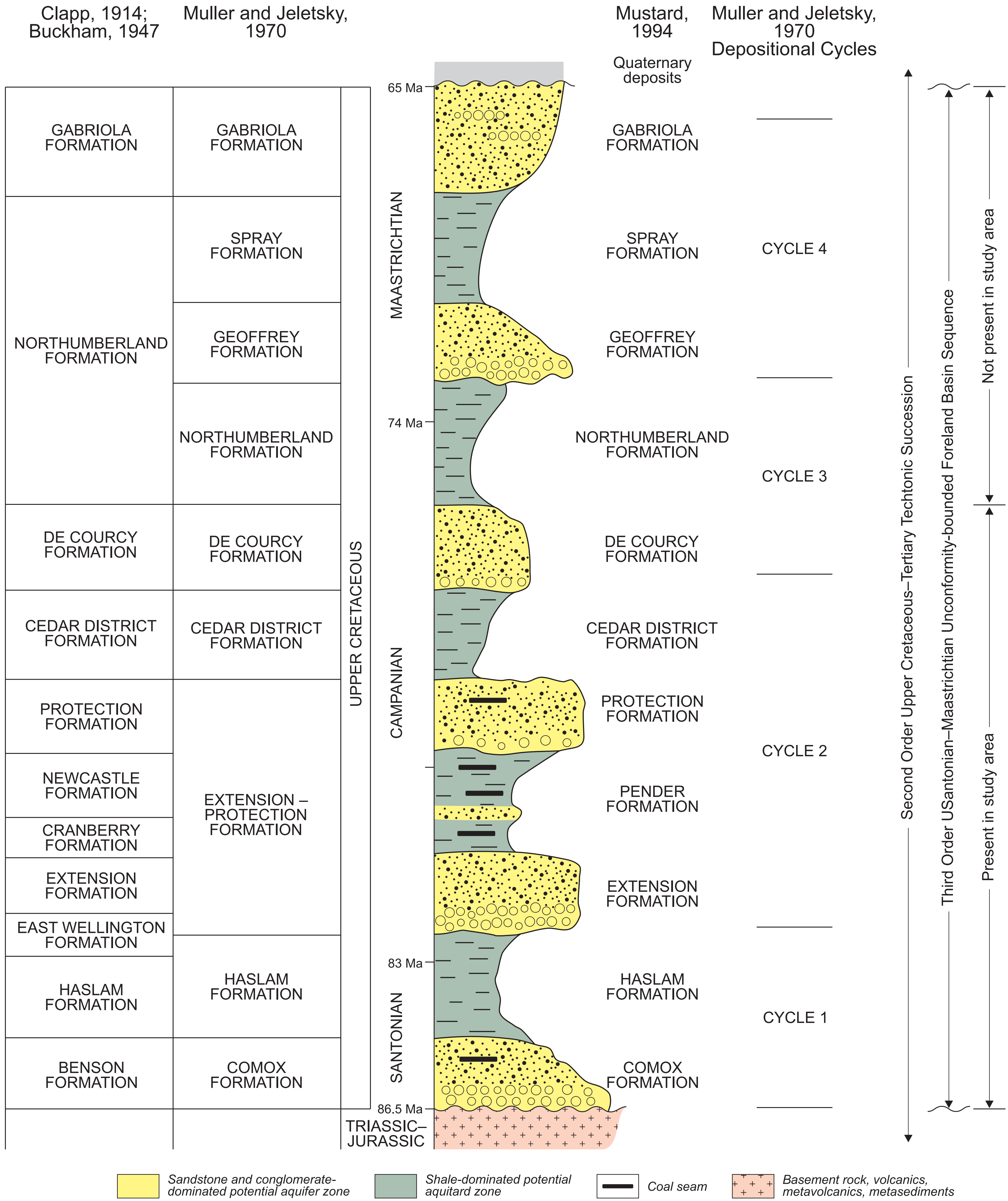

Figure 4. Nanaimo Group potential aquifer and aquitard zones.