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Publications in this series have not been edited; they are released as submitted by the author.

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ABSTRACT

A new inquiry into the groundwater potential of the Nanaimo Lowlands was jointly undertaken by concerned municipal, provincial and federal agencies because 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 focused 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 one step in the analysis, a 112.5 m core was obtained as part of the drilling of a Groundwater Observation Well in the Cedar area of Vancouver Island, about 10 km SE of Nanaimo City centre. The entire length of the core comprises the mid-Nanaimo Group, sandstone-dominated (potential aquifer zone) De Courcy Formation, the uppermost coarse grained formation in the study area. The De Courcy Formation present in the studied core is characterized by stacked, thick bedded medium to coarse grained arkosic sandstone separated by units of bioturbated sandy siltstone with thin finer grained sandstone. It includes two main facies: 1) thick bedded, grey medium to coarse grained sandstone interpreted as high-energy density current and turbidity flow deposits emplaced in a moderately deep marine setting on the surface of, and in channels on, a northwestward-sloping submarine fan system, with minor thin beds of bioturbated siltstone, and 2) thinly interbedded dark grey bioturbated siltstone to sandy siltstone interpreted as lower-energy, background sedimentation on the surface of the submarine fan systems, and very fine to medium grained sandstone, interpreted to represent slower, more distal, higher-energy density current turbidity flow events which occasionally punctuated that quiet background sedimentation. The thick bedded sandstone facies represents about 65% of the strata in the core, and has porosity ranging 2.0 to 10.2 %, averaging 6.8 %, and permeability ranging 2.8 to 105.0 mD, averaging 24.4 mD. In thin section, these sandstones are predominantly feldspathic litharenites and lithic arkoses with abundant plagioclase,

volcanic rock fragments, quartz and chert, in a clay matrix. Multiple, laterally-extensive units of thick, porous and permeable sandstone, up to 6 m thick, likely represent significant aquifer horizons within the De Courcy Formation. The interbedded siltstone and thin sandstone facies occupies about 35% of the core strata and has porosity ranging 4.0 to 9.7 %, averaging 7.4 %, and overall permeability ranging 1.8 to 40.0 mD, averaging 12.7 mD. However, within this facies, the thin sandstone beds have an average permeability of 15.4 mD, whereas the bioturbated siltstones have average permeability of only 5.4 mD. Multiple, laterally-extensive units of interbedded siltstone and thin sandstone, up to 6 m thick, may represent significant aquitard horizons within the De Courcy Formation. These results, although derived from the De Courcy Formation only, may display comparative analogies to the characteristics of the other (uncored) potential aquifer zones present lower in the Nanaimo Group; the Comox, Extension and Protection formations.

INTRODUCTION

Rationale

In 2010 the British Columbia Ministry 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 was 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 are included. One 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. Hamblin (2012) summarized the most relevant information from the previously published geological literature for the 8 formation-rank units that occur in the field area, in order to focus attention on the zones and areas of most likely bedrock aquifer potential. As part of this effort, it was decided to core a previously-planned groundwater monitoring well to obtain fresh subsurface rock-based data for at least one bedrock unit of the Nanaimo Group, which might be relevant to further analysis.

Study Area and Methods

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 to the north (south of Courtenay, near Denman Island) (see Figure 1in Hamblin, 2012,). Lowland areas of eastern Vancouver Island are underlain by Upper Cretaceous bedrock, which extends from the shores of the Strait of Georgia westward for several tens of kilometres. 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. Further details of the project and study area were given by Hamblin (2012).

Numerous surface outcrops occur within this area, and will be described in other reports, and one subsurface core was drilled within the Nanaimo 92G/4 map area under the auspices of the Regional District of Nanaimo. The Nanaimo Observation Well #390 core was located on the NW corner of the intersection of Holden Corso Road and Lofthouse Road (0439917E, 5439794N, 49^{o} 06’ 29.1” N/ 123^{o} 49’ 23.6” W, elevation 177 ft/54 m a.s.l.), about 3.5 km SE of the village of Cedar, and about 10 km SE of the City of Nanaimo, on Vancouver Island (see location on Fig. 1). Drilling/coring occurred from March 7 - 12, 2011 to a total depth of 388 ft (118.2 m). The well was spudded on a bedrock knob of De Courcy Formation sandstone in a location where there is essentially no Quaternary cover. Due to poor water quality at the total depth of the well, the lower 30 m were eventually sealed with concrete to the final well depth of 88.4 m, then hydraulically fractured on

March 21, 2011, and pump-tested on March 25, 2011 (Drillwell Enterprises/Levelton Consultants drilling report, April 14, 2011). The core was eventually shipped to GSC Calgary (where it is currently housed), and was described in February, 2012 (Fig. 3). The core spans the depth range 19 ft (5.8 m) to 388 ft (118.2 m) (total 112.5 m in 78 boxes) and recovery and core condition are excellent.

During core description, permeability data was obtained, and samples were collected for porosity data and thin sections, all plotted against the core description (Fig. 4). Porosity data was produced from 45 selected samples (35 from thick sandstone beds, 10 from thin sandstone beds, none from siltstone beds) sent to Core Laboratories Canada in Calgary. Permeability data was produced for 166 sample points (108 from thick sandstone beds, 58 from thin sandstone beds, 23 from siltstone beds) by direct measurement on the core using a TinyPerm hand-held air permeameter. Two to three TinyPerm readings were obtained at each chosen depth position, with the “final” value being an average of the two closest values. In some cases, where all three readings were very different, multiple readings were taken until three consistent results were obtained. The shale readings required longer reading times than sandstones, but the permeameter seal was easier to maintain for fine-grained rocks, so only one reading was taken at these positions. Measurements were obtained at the base, middle, and top of each major sandstone interval throughout the core, and also in at least one of each of bioturbated, deformed (soft-sediment deformation) and fractured intervals.

In addition, 44 samples (42 sandstone, 2 siltstone) were obtained for petrographic thin section description and mineralogical analysis (including composition, texture, sorting, diagenetic components and porosity), and the details are published in a separate report (Zhai and Grasby, 2014), which also includes numerous thin section photomicrographs. Only the main results are summarized here.

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). Dawson (1890) first proposed the name “Nanaimo Group” for these economically-important strata. Early geological mapping by Clapp (1914) in the Nanaimo area, and by Clapp and Cooke (1917) in the Duncan area, 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 onlap and pinch-out. 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.

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. There has been little geological study of the aquifer potential of these rocks. Hamblin (2012) provided a more complete summary of all previous work and interpretations and also summarized the information most relevant to the concept of groundwater potential, including the geological background to the De Courcy Formation, the subject of this report, and briefly summarized below.

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NANAIMO GROUP REGIONAL TECTONIC AND DEPOSITIONAL SETTING

Cordilleran Tectonic Setting

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). The basin was likely flanked by open ocean to the west (Johnstone, et al., 2006; Ward and Stanley, 1982). On Vancouver Island, Nanaimo Group strata unconformably overlie the Wrangellia Terrane, a complex of Devonian to Jurassic metamorphosed and deformed sedimentary and igneous rocks (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 faulting and thrust compression (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 (Mustard, 1994).

Basin Infill

In the study area, basement beneath the Nanaimo Group consists of dark, metamorphosed basalts and pyroclastics of the Permian Sicker Group, and dark green basaltic 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), which influenced the presence, distribution and thickness of the unconformably-overlying lower Nanaimo Group units (Ward and Stanley, 1982; Johnstone et al., 2006).

The Nanaimo Group comprises a stratigraphic thickness of as much as 4 km, with ages ranging from Turonian (~ 90 my) to Maastrichtian (~ 70 my) (Haggart, 1994), 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 (the subject of this report), Northumberland, Geoffrey, Spray and Gabriola. Only the lower 8 are present in, and relevant to, this study area. The age range of the Nanaimo Group in this study area, based on a synthesis of macrofossil, microfossil and radiometric dating studies, is Santonian-Campanian age (~86 – 74 M.y., a duration of about 12 Ma) (Mustard, 1994; Haggart, 1994).

Provenance

Published paleocurrent data (Mustard, 1994) suggests predominantly westward, south-westward and north-westward transport of sediment into the Nanaimo Basin during Comox to Northumberland time. Mineralogical studies likewise suggest that most sediment was derived from the Coast Belt to the east and the Northern Cascades to the southeast (Ward and Stanley, 1982; Pacht, 1984; Mustard et al., 1995). Most Nanaimo sandstones are immature to submature, moderately-sorted feldspathic litharenites 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 (including the De Courcy Formation) 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. The core described here is located in the easternmost part of the study area and therefore includes only the De Courcy Formation. 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). Throughout the region, fracturing is present in many outcrops and may extend into the subsurface, affecting the hydrogeological characteristics at depth (Mackie, 2002; Allen et al., 2003).

SUBDIVISION OF THE NANAIMO GROUP

General

The Nanaimo Group displays a prominent pattern of successive formations dominated by alternating coarse grained (potential aquifer zones) and fine grained (potential aquitards zones) units (Fig. 2). Hamblin (2012) provided a more comprehensive summary of the stratigraphy and relevant literature (especially the work of Mustard, 1994), and only a brief abstract of most units is given here. The formations are described from base to top, with particular emphasis placed on the De Courcy Formation, the only unit which is penetrated by the studied core. For further detail, refer to Mustard (1994). The succession of Nanaimo rock units present in our study area 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).

Pre-De Courcy Units

The Comox Formation (of mid-Santonian to early Campanian age) comprises thick sandstone and conglomerate which forms the base of the Nanaimo Group and rests on a sharp, high-relief angular unconformity, overlying the metamorphosed, stratified, Devonian to Jurassic rocks of the Wrangellia Terrane. The formation is generally 100-200 m thick, but is quite variable due to filling topography on the underlying unconformity. 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.

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, and rests with a gradational and conformable contact on the underlying Comox, and is sharply overlain by the Extension Formation. The Haslam Formation has been interpreted to represent low-energy deposition in shallow marine shelf to relatively deep slope depositional facies. Paleocurrent data 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.

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 which sharply, but conformably overlie the Haslam finer grained strata. Conglomerates are generally moderately sorted and subrounded, and are dominated by chert and volcanic lithologies. In the local Nanaimo area, thin coal seams are present in sandstone and siltstone facies near the base. The Extension Formation has been interpreted to include high-energy deposition in shallow marine to coastal to braided fluvial depositional environments in the Nanaimo area where coal is present. Paleocurrent indicators suggest predominantly westward flow.

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. 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. A few thin coal seams are present in the finer grained strata in the Nanaimo area. The Pender Formation has been interpreted to represent low-energy deposition in shallow to marginal marine, coastal and fluvial floodplain deposits in the Nanaimo area where coal is present. Paleocurrent data is very sparse.

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. Silica cement is common at surface: these distinctive sandstones were famously quarried on Newcastle Island for building stone and grinding stones, including for international export. The Protection Formation has been interpreted to represent high-energy deposition in shallow marine shelf and coastal depositional environments in the Nanaimo area. Paleocurrent indicators suggest predominantly westward flow.

The Cedar District Formation (of late Campanian age) is characterized by thinly interbedded mudstone and siltstone with lesser fine grained sandstone. It gradationally overlies the Protection Formation. The formation generally displays coarsening- and thickening-upward trends, grading upward into the overlying De Courcy Formation, and is about 300 m thick, thickening southward to about 600 m. 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 in most areas. Paleocurrent data is sparse and suggests predominantly westward and northwestward flow.

De Courcy Formation

The De Courcy Formation (of late Campanian age), the only unit present in the studied core, is the uppermost coarse grained unit exposed within the project 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, clast-supported to matrix-supported pebble conglomerate, with minor bioturbated sandy siltstone. Sandstones have erosional bases, may appear to be massive, or may be laminated. Where conglomerates occur, they include thick, laterally discontinuous beds, although none are present in this core. Soft sediment deformation/convolute lamination, minor folding, sandstone dykes and other dewatering structures are common, as are concretions and cross beds, and the rocks are commonly silica-cemented at surface. Concretions commonly erode out, leaving round holes and honeycomb galleries. The sandstones are typically unfossiliferous, and the age constraints are uncertain. Conglomerate clasts are predominantly volcanic (Coast Belt-derived from the east) and chert/quartzite (San Juan-derived from the southeast), with minor intrusive and sedimentary content. Coarse beds are separated by darker-coloured minor fine grained silty 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.

Mustard (1994) suggested that the Cedar District – De Courcy succession represents a transgressive-regressive (T-R) sequence. In this interpretation, favoured here, the depositional sequence began with marine transgression due to a phase of significant tectonic subsidence (lower fine grained part), followed by lesser subsidence and regression (development of most of the coarsening-upward sequence). The De Courcy Formation has been interpreted to include high-energy deposition in deeper marine submarine canyon and middle to upper submarine fan facies deposited on a generally northwestward-sloping margin (Mustard, 1994). The dominant sandstone lithology represents density current grain-flow and turbidity flow deposits in broad overlapping submarine fan lobes. Conglomerate beds represent fan channel and debris flow deposits. Measurement of 800 paleocurrent indicators (by Mustard, 1994) suggest predominantly westward and northwestward flow

The De Courcy Formation is the fourth and uppermost of the coarse grained units of the Nanaimo Group present 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. However, this unit is the only part of the Nanaimo Group for which we have actual subsurface data and observations, due to the acquisition of the Nanaimo Observation Well #390 core, which penetrates part of the lower half of the formation.

Post-De Courcy Units

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 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. It is not present at the location of the Observation Well #390, and does not occur in the upper part of the recovered core.

The Geoffrey Formation (of late Campanian to early Maastrichtian age) comprises 400-500 m of thick bedded coarse grained sandstone to boulder conglomerate, but is not present in the study area.

The Spray Formation (of early Maastrichtian age) includes 250 – 300 m of recessive grey siltstone and mudstone, with thin interbeds of fine grained sandstone, but is not present in the study area.

The Gabriola Formation (of poorly constrained Maastrichtian age) comprises about 350 m of medium to coarse grained arkosic arenite with some conglomerate, but is not present in the study area.

FACIES PRESENT IN CORE

Introduction

Only the De Courcy Formation is represented in the core. The core was described at the GSC (Calgary) core facility using standard methodology, and this description is presented in graphical form in Figure 3. Porosity and permeability data collected are presented in Figure 4, matched against the core graphic log. Below are simplified descriptions and interpretations of the two main facies displayed in the core, with minor additional petrographic information gleaned from Zhai and Grasby (2014).

Facies 1. Thick Bedded, Grey Fine to Coarse Grained Sandstone

Description Well-sorted, medium grained sandstone to granulestone occurs in erosively-based fining-upward beds from 50 to 300 cm thick, commonly with basal lags of granules and shale rip-ups (Fig. 5). Internal stratification includes abundant horizontal and low-angle lamination, trough cross bedding, convolute lamination in middle to upper parts of beds, and current ripple cross lamination at bed tops. Horizontal to sub-vertical burrowing is common, especially in upper halves of beds, and carbonized wood fragments are present in some beds. Uncommon thin, bioturbated sandy siltstone beds up to about 20 cm thick occur between some beds. Stacks of these sandstone beds commonly reach thicknesses of 4 m without interruption by any finer grained units, and can reach up to 6 m or more in thickness, which may have significant lateral continuity. Beds of this facies represent about 65 % of the De Courcy Formation present in this core, presumably representative of the Formation in general over the area if its occurrence. In addition, the characteristics demonstrated by the rocks of this core are likely applicable to other Nanaimo Group formations dominated by coarse grained facies such as the Comox, Extension and Protection formations.

Interpretation These beds are interpreted to represent high-energy density current grain-flow and turbidity flow deposits emplaced in a moderately deep marine setting on a De Courcy northwestward-sloping submarine fan system. Some of the thicker beds with deeply eroded bases may represent flows within minor channels on the fan surfaces, but there is no specific evidence of channelization present in this core. In addition, no conglomerates are present in the core, which have been previously interpreted as major channel facies in other locations, although these facies may exist in the area. Beds of this nature should have significant three-dimensional lateral extent and retain their relatively uniform internal characteristics over major lateral distances, suggesting significant aquifer potential for the De Courcy Formation.

Thin Section Observations (summarized from Zhai and Grasby, 2014) Sandstone beds are comprised of poorly- to moderately- to well-sorted and angular to subangular grains with minor visible interstitial pore space. Grains consist of abundant rock fragments (13-50%) (dominantly volcanic), feldspars (10-32%) (dominantly plagioclase, but with some orthoclase), quartz (25-50%), chert, and lesser mafics (biotite and amphibole) and metamorphic/sedimentary rock fragments. Most sandstone samples are feldspathic litharenites (57% of samples) and lithic arkoses (32% of samples), with relatively immature compositions and textures. Much original interstitial pore space was largely infilled with 10-15% clay matrix, plus authigenic chlorite, quartz overgrowths, feldspar overgrowths and calcite cement.

Porosity and Permeability Both porosity and permeability vary greatly within and between these beds, due to internal variations in grain size, bioturbation, authigenic dissolution and cementation. Most current porosity is secondary after feldspar and unstable rock fragment dissolution. Microporosity and micro-fractures are present, and may enhance porosity and permeability. Porosity ranges 2.0 to 10.2%, averaging 6.8 % (based on 35 sandstone samples: no porosity measurements were obtained from the thin silty interbeds). Part of this porosity is microporosity within diagenetically-altered feldspars, rock fragments and clays. Overall permeability ranges over two orders of magnitude, from 2.8 to 105.0 mD, averaging 23.7 mD, based on 108 samples. However, when measurements from the few thin silty interbeds (5 samples averaging 8.9 MD) are removed, the thick sandstones average a respectable 24.4 mD permeability.

Facies 2. Thinly Interbedded Dark Grey Bioturbated Siltstone to Sandy Siltstone and Very Fine to Medium Grained Sandstone

Description Stacks of thick sandstone beds are separated by units of interbedded, generally finer grained lithologies throughout the core. These units are up to 6 m thick (typically 1-2 m), commonly fine upward, are composed of thinly interbedded siltstone and sandstone (with uncommon mudstone), and are dominated by siltstone (sandstone : siltstone ratios range from 1 : 1 to 1 : 5) (Fig. 6). Within the units, beds range from 5 to 50 cm thick and thin upward. Siltstones are typically grey to dark grey, commonly sandy, are generally bioturbated with horizontal to sub-vertical burrows, and have a massive uniform appearance, and generally fine upward through the unit. Sandstone beds display a wide range of grain sizes from very fine to medium grained, are generally well sorted, have sharp erosive bases with shale rip-up clasts, and may fine upward. Sedimentary structures include horizontal lamination, convolute lamination and ripple cross lamination. These finer grained units, which separate units of the coarser grained facies, may have considerable lateral continuity. Occurrences of this facies represent about 35 % of the De Courcy Formation present in this core. In addition, the characteristics demonstrated by the rocks of this core are likely applicable to other Nanaimo Group formations dominated by fine grained facies such as the Haslam, Pender, Cedar District and Northumberland formations.

Interpretation These bioturbated siltstone beds are interpreted to represent slower, lower-energy, background sedimentation on the surface of the relatively deeper submarine fan systems. The thin sandstone beds are interpreted as distal, minor, higher-energy density current turbidity flow events which occasionally punctuated the quiet background sedimentation. Units of this facies may have significant three-dimensional lateral extent, possibly forming effective aquitard or aquiclude barriers to vertical hydrogeological migration within the De Courcy Formation potential aquifer system.

Thin Section Observations (summarized from Zhai and Grasby, 2014) Siltstone facies are thinly laminated (alternating quartz-rich and clay-rich laminae), and are characterized by moderately- to well-sorted subangular to subrounded grains. As in the sandstone facies, grains are characterized by a diverse mix of quartz (48-63%), rock fragments (dominantly volcanic) (15-22%), feldspars (10-15%), mafics (biotite and amphibole) and metamorphic/sedimentary rock fragments in an abundant fine clay matrix (27-30%).

Porosity and Permeability Just as the lithologies within this facies vary considerably, the porosity and permeability also vary greatly within units of this facies. Porosity ranges 4.0 to 9.7 %, averaging 7.4 % (but based on only 10 samples, and only from the sandstone beds within this facies: no measurements were obtained from siltstone beds), similar to readings from the thick sandstone facies. Microporosity is abundant. Overall permeability ranges 1.8 to 40.0 mD, averaging 12.7 mD, based on 58 samples, significantly less than measured permeabilities from the thick sandstone facies. However, it is instructive to further separate data from the thin sandstone beds of this facies from those of the thin siltstone beds. Within this facies, permeabilities from the thin sandstones (39 samples) average 15.4 mD (significantly less than the thick sandstone facies, but still important), whereas those from the bioturbated siltstones (18 samples) average only 7.0 mD. In fact, removing two samples of siltstone with abundant sandstone-filled burrows and one sample of heavily- fractured siltstone, reduces this standard siltstone permeability even further to a more reliably realistic average of 5.4 mD.

DISCUSSION OF AQUIFER POTENTIAL AND REGIONAL IMPLICATIONS

Within the De Courcy Formation, thick coarser grained sandstones of Facies 1, both individually and in thicker uninterrupted stackings of coarse grained beds, which are probably present and laterally-continuous over a significant area, may represent significant potential aquifer zones with good porosity and permeability. Similar sandstones occur, and are equally-dominant (or more dominant) in other Nanaimo Group formations (Comox, Extension, Protection) throughout the field area, perhaps with similar characteristics. These other formations, however, are far more regionally-extensive in distribution, are overlain (sealed) by regionally-extensive aquitard zones and therefore provide more attractive groundwater targets. Unfortunately, we have no subsurface cores for these units.

It is likely that units of interbedded siltstone and sandstone of Facies 2 represent significant potential aquitard zones within the De Courcy, especially if dominated by impermeable bioturbated siltstone. Thin sandstone beds within this facies do present some aquifer potential, especially if connected by fracturing. Similar facies occur, to some degree, in all other sandstone-dominated formations of the Nanaimo Group throughout the field area. In addition, on a more regional scale, other formations of the Nanaimo Group (Haslam, Pender, Cedar District, Northumberland) are much more dominated by similar fine grained facies, suggesting that those formations probably also represent major aquitard units within the entire Nanaimo Group bedrock aquifer system.

CONCLUSIONS

1. The basic geology of the Upper Cretaceous Nanaimo Group suggests that the laterally-extensive coarser grained formations in the Nanaimo Basin may present significant mappable zones of aquifer potential for new groundwater resources, whereas the intertonguing, laterally-extensive finer grained formations could provide mappable zones of potential aquitard seals. These units can be mapped at surface, and may be traced in the subsurface with appropriate data, such as drilled wells and cores, or seismic.

2. Similarly, within each formational-rank coarser grained, potential aquifer zone, the stratigraphic alternation of individual laterally-extensive coarse grained and fine grained facies (as illustrated by this core) may divide each formational-rank aquifer zone into individual aquifer horizons separated by aquitard horizons. This situation might provide good prospects for vertically-stacked, multiple groundwater targets (both on local and regional scales), provided that adequate porosity and permeability are present.

3. The De Courcy Formation, the uppermost coarse grained unit in our study area and the subject of this report, may harbour significant groundwater potential. The studied core includes the following facies: 1) Thick Bedded Fine to Coarse Grained Sandstone, and 2) Thinly Interbedded Bioturbated Siltstone and Very Fine to Medium Grained Sandstone.

4. The Thick Bedded Fine to Coarse Grained Sandstone facies occurs in fining-upward beds up to 3 m thick, and may be stacked into units up to 6 m thick, and represent about 65 % of the De Courcy strata in the core. They are interpreted to represent high-energy, laterally-extensive, density current and turbidity flow deposits periodically emplaced on the surface of a submarine fan system. In thin section these rocks contain abundant plagioclase and volcanic rock fragments, and are classified as feldspathic litharenites and lithic arkoses. Porosity ranges 2.0 to 10.2 %, averaging 6.8% (based on 35 samples), and is primarily secondary, after dissolution of feldspars and rock fragments. Permeability ranges 2.8 to 105.0 mD, averaging 24.4 mD.

5. The Thinly Interbedded Bioturbated Siltstone and Very Fine to Medium Grained Sandstone facies occurs in beds up to 50 cm thick and may be stacked into units up to 6 m thick, and represent about 35% of the De Courcy strata in the core. They are interpreted to represent lower-energy, laterally-extensive, units of background sedimentation interrupted by periodic distal turbidity flow deposits. In thin section these rocks are thinly laminated, contain abundant quartz, volcanic rock fragments and feldspars and are classified as litharenites. Porosity in the included sandstone beds ranges 4.0 to 9.7 %, averaging 7.4% (only 10 samples), and is primarily microporosity. No measurements were taken from siltstone beds. Overall permeability ranges 1.8 to 40.0 mD, averaging 12.7 mD, but thin sandstone beds from this facies average 15.4 mD whereas bioturbated siltstones average only 5.4 mD.

6. These data suggest that the De Courcy Formation (up to 300 m thick) may be a significant aquifer zone worthy of further investigation. Within this core, the formation displays consistent

vertical stratigraphic alternation of laterally-extensive, potential aquifer horizons (65% of strata) and laterally-extensive, potential aquitard horizons (35% of strata), each several metres thick.

7. However, an even more important conclusion is that the information derived from this core (the only long subsurface core available in the Nanaimo Basin) may serve as a regionally-valid analogy for other, higher-potential aquifer zones encompassed in the underlying (and more widely distributed) coarse grained formations of the Nanaimo Group: the Comox, Extension, and Protection formations, for which we currently have no subsurface data.

8. Given the information presented by this core, the detailed internal stratigraphy, sedimentology, aquifer characteristics and presence of internal permeability barriers (both horizontal and vertical) of the De Courcy Formation, and other potential aquifer units, must be studied in more detail to determine their ultimate characters. Additional subsurface cores of other formations within the Nanaimo Group would be crucially important in these further evaluations.

9. In addition, bedrock fracturing (both local and regional), which is displayed in this core and in many outcrops, may influence or alter the rock characteristics and the potential of both aquifer and aquitard horizons, and must also be studied in detail.

FIGURE CAPTIONS

1. Geology of the Nanaimo sub-area, with location of studied core (geology simplified from Buckham, 1947, GSC Paper 47-22; Clapp, 1914, GSC Memoir 51; Muller and Jeletsky, 1970, GSC Paper 69-25).
2. Simplified geology of the Nanaimo Group of Vancouver Island, with approximate position of studied core.
3. Measured section and description of Nanaimo Observation Well #390 core.
4. Porosity and permeability data plotted against core description.
5. Sharp base and lower portion of thick bedded, well-sorted, massive, fining-upward, permeable coarse-grained sandstone bed, ~ 91 m depth, stratigraphic top to right.
6. Thinly interbedded and burrow-homogenized dark grey siltstone and fine-grained sandstone, with abundant soft-sediment deformation, ~ 67 m depth, stratigraphic top to right.

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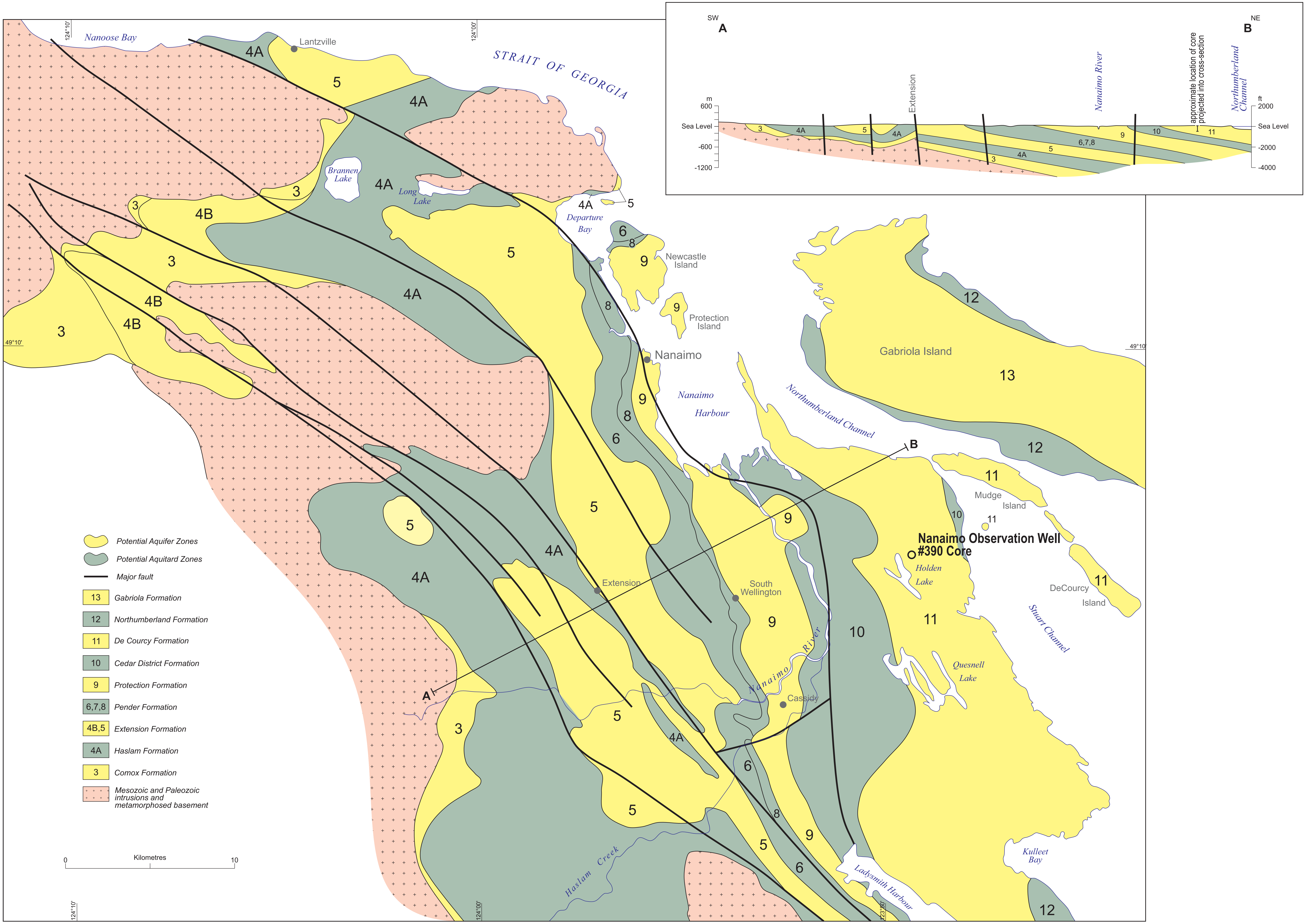

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Figure 1. Geology of the Nanaimo sub-area, with location of studied core (geology simplified from Buckham, 1947, GSC Paper 47-22; Clapp, 1914, GSC Memoir 51; and Muller and Jeletsky, 1970, GSC Paper 69-25).

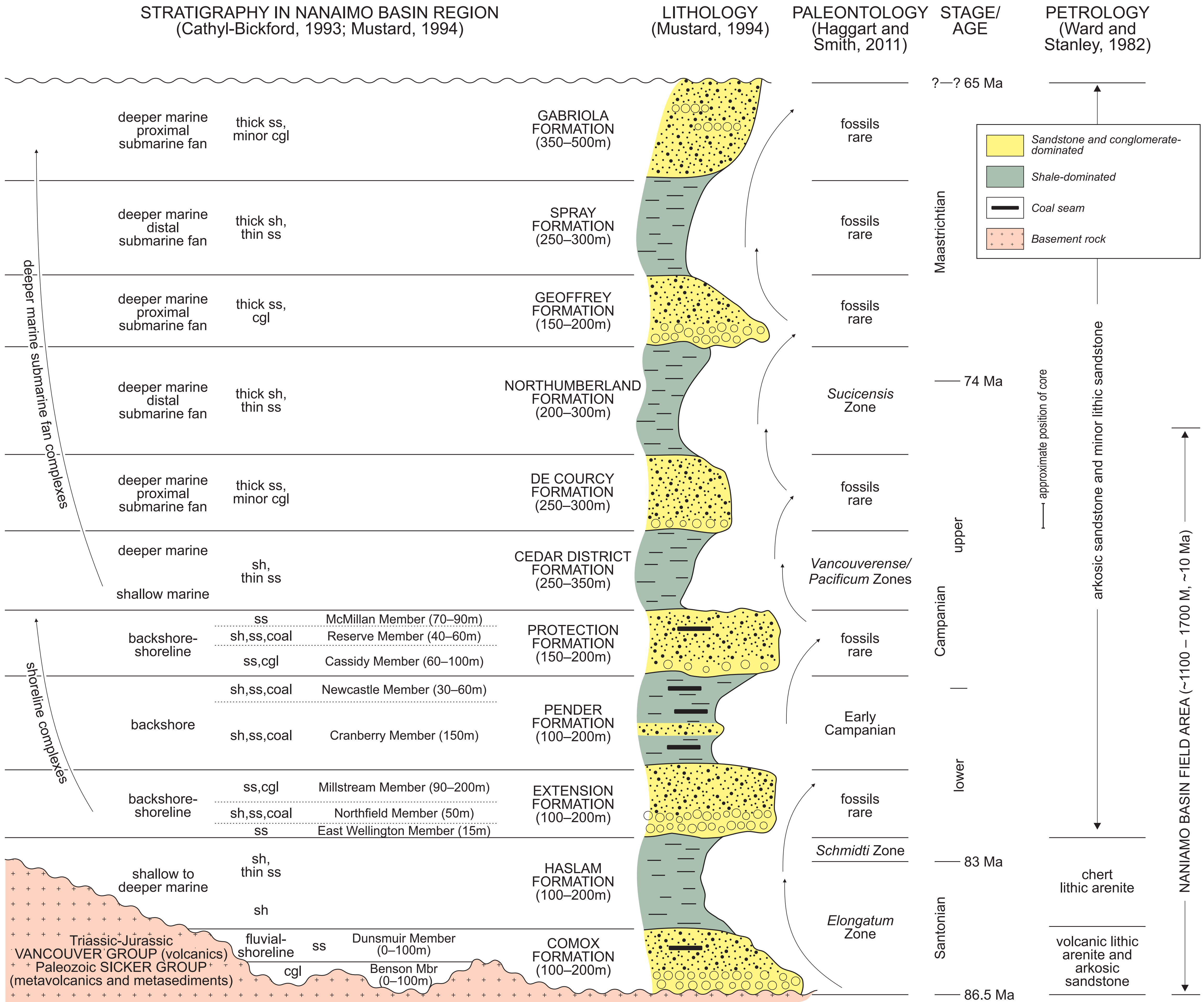

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Figure 2. Simplified geology of the Nanaimo Group of Vancouver Island, with approximate position of studied core.

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Nanaimo Observation Well #390 (OW-11-01)
corner of Holden Corso and Lofthouse roads, Cedar
De Courcy Formation, 112.5 m
NTS Map 92G/14 (Nanaimo)
49° 06' 29.1"N, 123° 49' 23.6"W; UTM Zone 10: 0438917E, 5439794N

Figure 3. Measured section and description of Nanaimo Observation Well #390 core.

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Figure 4. Porosity and permeability data plotted against core description.

Open File 7628

Figure 5. Sharp base and lower portion of thick bedded, well-sorted, massive, fining-upward, permeable coarse-grained sandstone bed, ~ 91 m depth, stratigraphic top to right.

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Figure 6. Thinly interbedded and burrow-homogenized dark grey siltstone and fine-grained sandstone, with abundant soft-sediment deformation, ~ 67 m depth, stratigraphic top to right.