GEOLOGY OF SOUTHERN VANCOUVER AND SALTSPRING ISLANDS

Field Trip Guidebook, April 4, 2011

For the 5th British Columbia Unconventional Gas Technical Forum

FIELDTRIP LEADERS

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FIELD TRIP ITINERARY

DEPARTURE at 7:45 AM from the Victoria Conference Centre
(Bus loading will begin at 7:30 – departure will be at 7:45 sharp)

Schedule	Location	Subject	References
7:45-8:30	Drive up Highway 1 to Malahat	Victoria area geology, earthquake hazard mapping, seismic improvements to the Trans Canada Highway	Levson et al. (1999) Monahan and Levson (2000) Lister et al. (1998)
STOP 1 8:30-9:15	Malahat Overlook	Geological overview	Massey et al. (2005) Levson et al. (1999)
9:15-9:45	Drive to Cowichan Bay		
STOP 2 9:45-10:30	Cowichan Bay	Cowichan Fold and Thrust Belt and Nanaimo Group Geology intro.	Massey et al. (2005) Mustard (2009)
10:30-10:45	Cowichan Bay	Coffee Break	
10:45-11:15	Drive to Crofton Ferry terminal	Depart Crofton on 11:55 Ferry (arrive 12:15)	
LUNCH 12:15-1:15	Vesuvius Bay	Lunch on the beach (weather permitting)	
STOP 3 1:15-2:30	Vesuvius Bay area – walk shoreline outcrops (low tide is 12:25)	Submarine fans, turbidites, etc. of the Cedar District Formation	Mustard (2009) Treptau (2002)
2:30-2:45	Drive to Ganges		
2:45-3:30	Coffee break at Ganges		
3:30-4:00	Drive to Ruckle Park		
STOP 4 4:00-5:30	Ruckle Park - walk shoreline outcrops	Subaerial to shallow marine shoreface deposits of the Comox Formation	Mustard (2009) Johnstone (2005) Johnstone et al. (2006)
5:30-6:00	Drive to restaurant in Fulford Harbour		
6:00-7:30	Rock Salt restaurant in Fulford Harbour	Dinner. Pre-order will be sent in.	
7:50 p.m.	Depart Fulford Harbour	Ferry ride to Swartz Bay	
8:25 p.m.	Arrive Swartz Bay Ferry Terminal	Pat Bay Highway to Victoria	
9:30 p.m.	Arrive at Fairmont Empress Hotel		

TABLE OF CONTENTS

In Pocket: Saltspring Island Geology Map (Greenwood and Mihalynuk, 2009)

Sedimentary Geology of Southern Vancouver and Saltspring Islands

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Introduction

This field trip focuses on the Late Cretaceous to Quaternary geology of the southern part of Vancouver Island and Saltspring Island. Topics to be discussed include the regional geological setting, deposition of the Late Cretaceous Nanaimo Group, Quaternary geology and earthquake hazards. Enroute to various stops, discussion will also include information on the local engineering geology. The trip begins with young sediments in the Greater Victoria area, progresses through older sequences to end with an outcrop of the basal Nanaimo Group.

A summary of the bedrock and surficial geology of Victoria is provided below along with detailed descriptions of featured topics at each stop. Much of the information in this section is compiled from previous guidebooks (Levson et al., 1997; Lister et al., 1998), published papers (Levson et al., 1998a, b; Levson and Monahan, 1998) and unpublished reports (Pilkington et al., 1995; McQuarrie and Bean, 1998). These information sources are identified at the head of the appropriate sections.

Victoria, located on the southern tip of Vancouver Island, is the capital of the Province of B.C. and was originally established by the Hudson's Bay Company in 1843 as a British fur trading post. The population of the Greater Victoria region is currently about 335,000. Besides government, the area is home to Canada's Pacific Naval Fleet and tourism is a major economic benefit to the region. High-tech companies are continually becoming a more important part of the local economy.

Trip Overview

The field trip begins with a half hour drive to a scenic viewpoint on the Malahat overlooking Saanich Inlet (Stop 1 - Figure 1) where an overview of the regional bedrock and Quaternary geology will be provided. During the drive north, we will discuss some of the geotechnical engineering aspects of the Trans Canada Highway upgrade west of Victoria. Construction problems associated with marine soft clays, deposited during late-glacial high sea level, and seismic stability issues will be discussed. Stop 2 (Figure 1) is at the fishing village of Cowichan Bay where the Cowichan fold and thrust belt will be introduced. We'll gather on the wharf where there is a good view of Saltspring Island as well as numerous sail boats, fishing boats and floating homes along the piers in Cowichan Bay. We will have a coffee break here. This will be followed by a drive and ferry ride to Vesuvius Bay on Saltspring Island where we will have lunch. There will be two main geological stops on Saltspring Island. The first (Stop 3, Figure 1) is an excellent tide-water exposure of turbidite sequences within submarine fan deposits of the Nanaimo Group Cedar District Formation.

Following this stop, we will drive across one of the narrow parts of Saltspring Island to Ganges where we'll have an afternoon coffee break before continuing south down the island to the Ruckle Park area. Our last geological stop will be to look at sandstones and conglomerates at the base of the Comox Formation interpreted to be subaerial to shallow marine shoreface deposits (Stop 4, Figure 1). A short drive takes us to Fulford Harbour where we will have dinner on the waterfront at the Rock Salt Restaurant. Be sure you are back on the bus in time to leave on the 7:50 PM ferry to Swartz Bay. (If you miss the ferry, enjoy your stay in Fulford Harbour!) The drive from the Swartz Bay ferry terminal to Victoria takes about half an hour so you should be back downtown by 9:30 PM.

Figure 1 fold-out map

Geology of the Greater Victoria Area

(to be discussed enroute to Stop 1; Main information sources: Levson et al. 1999; Monahan and Levson, 2000)

The bedrock geology of the Victoria area is dominated by rocks of the Wark and Colquitz gneiss complexes, part of the West Coast Crystalline complex. These rocks are mainly gneiss, diorite, amphibolite, marble and metasediments of Paleozoic to Triassic age that were metamorphosed during the early Jurassic. The Wark-Colquitz Complex may be metamorphosed sedimentary and igneous rocks originally belonging to the Devonian Sicker Group (Yorath and Nasmith, 2001). The Wark gneiss, often dark and massive, may be derived from granitic and volcanic rocks while the light and dark banded Colquitz gneiss may be metamorphosed sediments. These rocks are well exposed on glacially sculpted hills around Victoria such as Mt. Tolmie where dioritic gneiss of the Wark complex is exposed and Mt. Douglas underlain by the Colquitz gneiss. Outcrops of Wark gneiss will be seen along the Trans Canada Highway west of town enroute to Stop 1.

Bedrock outcrops occur throughout the Greater Victoria area and dominate the high areas west and northwest of the city. Bedrock hills generally increase in elevation from less than a hundred metres in the City of Victoria to a few hundred metres west of the city. Glacial till locally mantles the bedrock highs and is commonly thickest on the south sides and thin or absent on the north sides (e.g. Mt Tolmie). These “crag-and-tail” landforms reflect the dominant southerly flow of glaciers and subglacial waters in the region during the last glaciation. The north-facing (stoss) sides and tops of the bedrock hills are commonly strongly fluted and show abundant evidence of glacial abrasion (*e.g.* striae) and subglacial water erosion (*e.g.* sichelwannen). Fluted and striated bedrock indicating southerly flow is also commonly seen in shoreline outcrops throughout the region. Where Quaternary deposits overlie this irregular glacially-scoured bedrock surface, they can vary in thickness from zero to as much as 30 metres within the space of a city block.

One of the most dominant landform features in the Greater Victoria area is a large late-glacial glaciofluvial delta and outwash plain (Figure 2) situated in the Colwood and Langford areas west of Victoria. The first part of field trip route crosses the north western edge of the delta (see black line on Figure 2). The delta is raised as much as 90 m asl due to isostatically high sea level in the area at the end of the last glacial (Late Wisconsinan Fraser Glaciation). Low-lying areas east and northeast of the Colwood delta (much of Victoria, Esquimalt, View Royal, Oak Bay and Saanich) are blanketed in glaciomarine silts and clays (Figure 2).

The topography along Saanich Inlet and on Saltspring Island is largely bedrock-controlled although valleys filled with Quaternary sediments occur between the main hills and ridges. Saanich Peninsula, which will be traversed on the return trip from Saltspring Island, is dominated by a series of large drumlinoid ridges consisting of thick sequences of Pleistocene sediments (Figure 2). The drumlinoids are south-trending ridges comprised mainly of silts, sands and gravels with a thin mantle of till in most places.

The oldest Quaternary deposits in the Greater Victoria area include glacial and non-glacial sediments that underlie the Vashon till of the Late Wisconsinan Fraser Glaciation (Table 1). The pre-Vashon sediments occur principally in the central and eastern parts of Saanich Peninsula, where they are up to 60 metres thick. They include the Cowichan Head Formation and the Quadra Sand (Clague, 1976). The Vashon till is a discontinuous unit and is generally less than a few metres thick. In the subsequent discussion of earthquake hazards, the Vashon till and underlying Pleistocene deposits are grouped together as “older Pleistocene deposits”, because they are over consolidated and shear-wave velocities are generally high (Monahan and Levson, 1997).

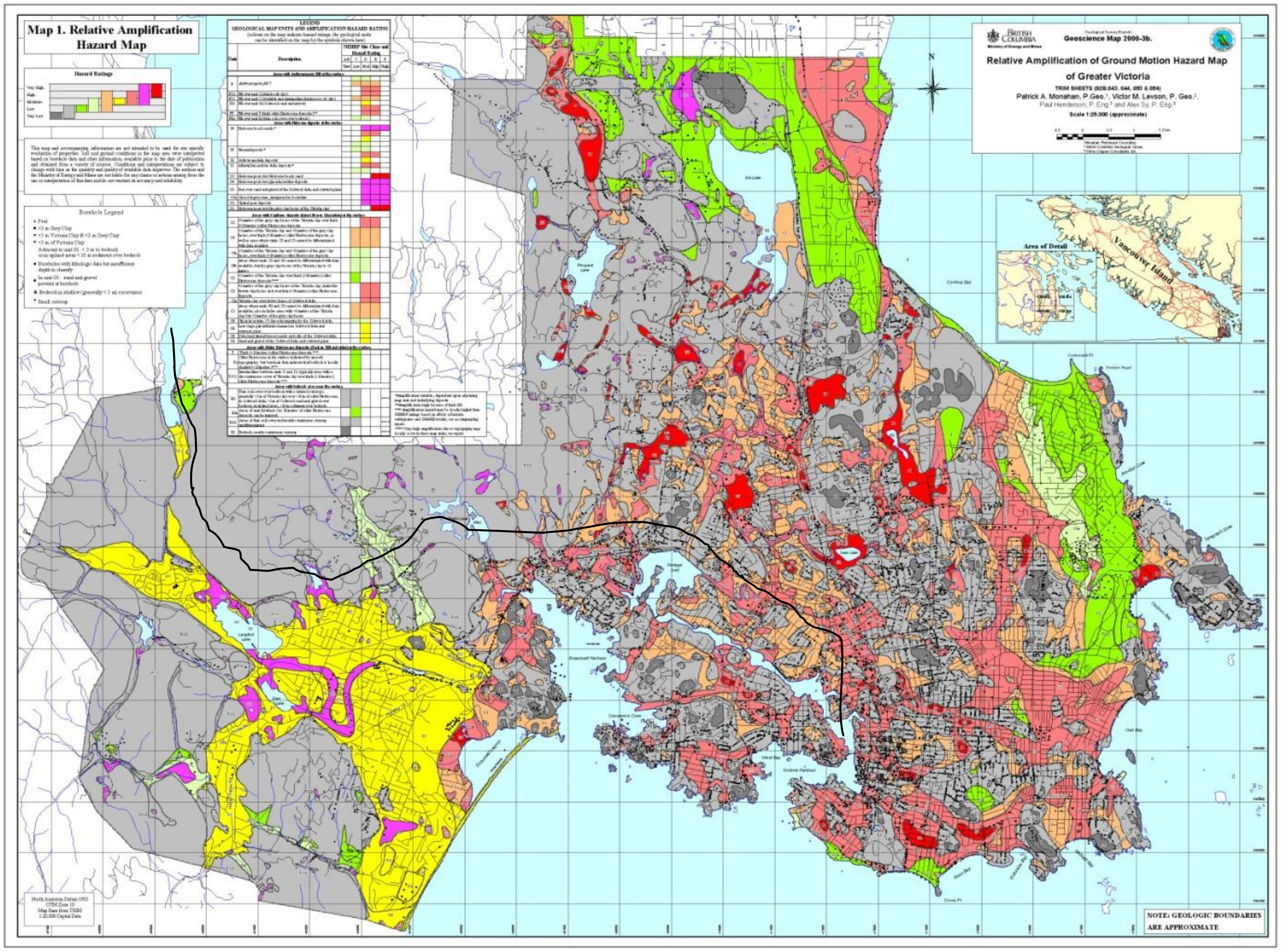

Figure 2. Quaternary Geology of the Victoria area (Monahan and Levson, 2000). Black line shows the approximate route through the greater Victoria area. Grey areas are bedrock and areas with thin soil; pinks and reds are underlain by Victoria clay; yellow is the Colwood raised delta; greens are older Pleistocene sediments.

TABLE 1. Quaternary Sediments of the Victoria Area

Holocene	Post -glacial	Salish Sediments	Peat, Organic Soil, Beach Sands
		Capilano Sediments	Colwood Sand & Gravel, Victoria Clay
	Fraser Glaciation	Vashon Drift	Glacial Till
Pleistocene		Quadra Sand	Sand and Gravel
	Olympia Non-glacial	Cowichan Head Formation	Silt, Sand and Gravel

The Vashon till is overlain by the Capilano sediments, which were deposited at the close of the Fraser Glaciation when sea level was higher than present. The principal units of the Capilano sediments in the Victoria area are the Victoria clay and the Colwood sand and gravel. The Victoria clay is a unit of glaciomarine clayey silt that forms a discontinuous blanket-like deposit below an elevation of about 75 metres. It ranges in thickness from zero on bedrock hills to 30 metres in depressions on the till or bedrock surface. The Victoria clay has three distinct facies. A lower, soft to firm, grey clay (grey clay facies) is in most places gradationally overlain by a desiccated and oxidized crust of stiff, brown clay (brown clay facies) 2 to 5 metres thick. The Victoria clay commonly coarsens slightly upward, and a sand facies locally occurs near the top.

The brown clay facies of the Victoria clay is at the surface in most of the Victoria area. However, in closed depressions and other low-lying areas, the brown clay facies is absent and the Victoria clay is gradationally overlain by up to 6 metres of organic silt and peat that represent Holocene lake and bog deposits.

The Colwood sand and gravel is a glacio-fluvial outwash and deltaic deposit that occurs at the surface over much of Colwood and Langford (Monahan and Levson, 2000; Figure 2). The maximum known thickness of the Colwood sand and gravel is 30 metres. The surface of the delta and outwash plain has been incised by late-stage glacio-fluvial channels and contains closed depressions interpreted to be kettles. Some of these are still occupied by creeks and lakes, and are in part filled with peat. Sand and gravel forset beds are known from gravel pits, but deposits of silt up to several metres thick interbedded with sands occur on the delta slope on the northeast and southeast sides of the delta and are interpreted to represent distal and lateral foreset deposits (Monahan and Levson, 1997). Similar sediments likely underlie much of the delta plain.

Holocene marine muds are locally overlain by prograding shoreline sands. Shoreline sands are in turn locally overlain by peat, and in some places, shoreline peat deposits are overlain by recent beach sands and intertidal sediments (Clague 1996; Monahan and Levson, 1997).

Earthquake Hazard Mapping in Greater Victoria

(main information sources: Levson et al. 1998a, b; Monahan et al. 2000a, b)

Victoria is located in one of the most seismically active regions of Canada. As a consequence, the British Columbia Geological Survey completed an earthquake hazard mapping program in the Victoria area, the results of which will be briefly discussed on the trip. Earthquake hazards include liquefaction, amplification, landslides, tsunamis/sieches, subsidence and ground rupture. Amplification of ground motion is an especially important hazard in the Victoria area because of the widespread presence of soft glaciomarine silts and clays susceptible to amplification.

The relative potential for ground disturbance during an earthquake can be identified from mappable geologic and geotechnical site conditions (Levson et al., 1998a). During the field trip we will we discuss some relationships between engineering geology and earthquake hazards, using results of liquefaction and amplification hazard mapping programs conducted in southwest British Columbia (Levson *et al.*, 1998b; Monahan *et al.,* 2000a). A map that shows areas susceptible to earthquake-induced slope instability (McQuarrie and Bean 2000) has also been produced for the Victoria area. The three types of hazards are combined into one map (Figure 3; Monahan *et al.,* 2000b).

Studies of ground motion amplification hazards were conducted in the Victoria area by Monahan and Levson (1997) and Monahan et al., (1998, 2000a). Geologic map units were selected to correspond with soil classes adopted by the U.S. National Earthquake Hazards Reduction Program at that time (Finn, 1996). The categories for susceptibility to amplification were defined on the basis of shear wave velocity data and the physical properties of the soils (moisture content, plasticity index and undrained shear strength). The amplification hazard for each map unit was expressed as a range that reflects observed geological variation (Monahan et al., 2000a).

The composite earthquake hazard map shown in Figure 3, is based mainly on the amplification hazard which dominates in the Victoria area. Map units are color-coded to reflect the various amplification hazard ratings. Liquefaction hazard ratings are shown with cross-hatching patterns and earthquake induced landslide hazards are depicted with stipple patterns. This map was prepared for regional landuse and emergency planning purposes. It is one of the most frequently purchased and downloaded products of the BC Geological Survey. The map receives periodic surges in interest, especially following large earthquakes. For example, after the 9.0 Magnitude earthquake near Honshu Japan on March 11, 2011, the Times Colonist ran a full page color spread of the Victoria earthquake hazard map with accompanying articles on March 20, 2011.

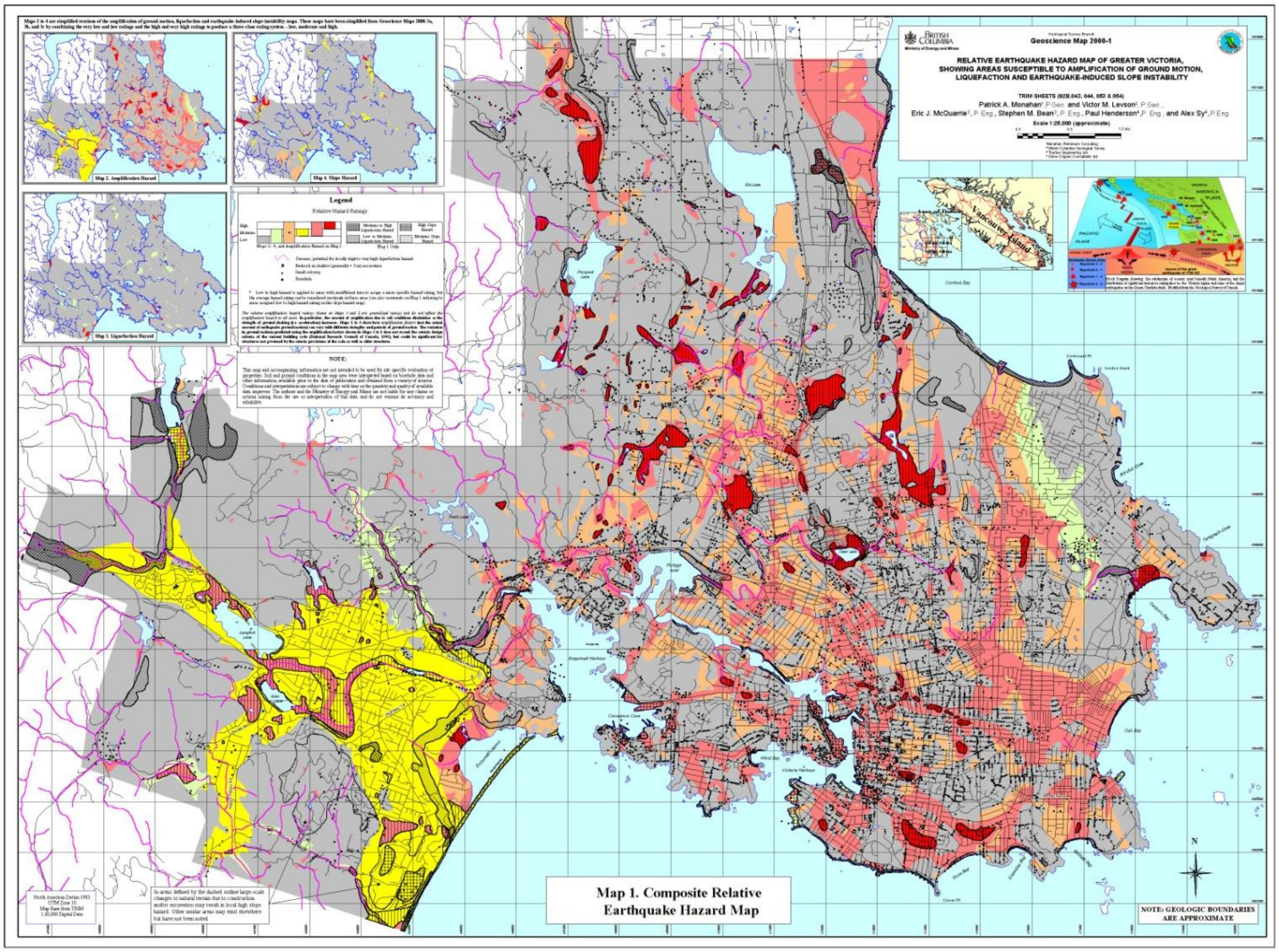

Figure 3. Composite relative earthquake hazard map of Greater Victoria (Monahan et al. 2000b)

Improvements to the Trans Canada Highway – Engineering Geology

(modified from Lister et al. 1998)

West of Victoria, the Trans Canada Highway was widened and upgraded to freeway status in 1997 as part of the Vancouver Island Highway Project. Three interchanges were constructed and portions of the Esquimalt and Nanaimo railway relocated. Limited choices of highway alignment alternatives, and the local geology of an irregular bedrock surface overlain by soft clays, meant extensive rock cuts as well as construction on soft soils (Pilkington *et al.*, 1995).

Problems associated with excessive settlement and slope stability were abundant throughout the project area. Some of the most challenging areas will be discussed along route, including ground conditions, engineering concerns and the solutions to these problems. Aspects of this work with seismic considerations are particularly emphasized here. More complete discussions of other geotechnical concerns are provided by Pilkington *et al.* (1995) and Lister *et al.* (1998).

Craigflower Creek crossings

A small fish bearing stream called Craigflower Creek meanders through the Colwood Overpass section of the Victoria West Approaches. The Creek crosses the highway and its access ramps at six locations and as a result, major extensions to pre-existing culverts and new bridges were required. The ground conditions at the creek crossings are typical of the area. There is a layer of brown, desiccated, very stiff clay from the surface to 3-5 m depth. Below the brown clay is a very soft, sensitive, highly compressible grey clay that has a moisture content close to or above the liquid limit. The depth of the grey clay varies, but at the creek crossings it is typically 15-25 m deep. Below the grey clay in some areas is a thin, very dense glacial till layer overlying bedrock. The creek channel bottom is usually at the brown/grey clay boundary.

Long term settlements of the culvert extensions and surrounding fills were estimated to be on the order of 1-1.5 m. Oversized concrete box segments with flexible connectors were used to accommodate the loss in hydraulic capacity after settlement as well as the differential settlement between the pre-existing culverts and the new sections. A thick soft grey clay layer below the brown clay was found at two of the new bridge structures. The bridges were supported on piles driven to bedrock to eliminate settlement problems but the approach fills were expected to settle 0.3-0.5 m. The solution was to use ultralightweight fill (polystyrene costing approximately \$100/m^3) for the approach fills, which eliminated settlement problems and also reduced the lateral loading on the bridge abutment walls during a seismic event.

Colwood Overpass

The Colwood Overpass, at the intersection of Highways 1 and 1A, is within a deep glaciomarine trough bounded by steeply dipping bedrock. Brown clay 2-7 m thick overlies soft, compressible sensitive grey clay up to 26 m thick. The eastern abutments are located at the deepest part of the trough and long term settlement was expected.

The bridge piers are founded on bedrock so a lightweight fill (polystyrene) was used on the northeast approach to minimize settlement. Pumice was also used immediately behind all four abutments to act as a shock absorber during an earthquake. Due to expected uneven settlements in the abutments, the bridge was designed to allow for jacking, with shims that can be removed.

Highway Widening at Thetis Lake Park

Adjacent to Thetis Lake Park, the Trans Canada Highway was widened and moved southwards from the pre-existing alignment into a large depression. The local topography consisted of a small valley running approximately north-south, with bedrock on both sides. The soil profile in the valley includes 3-5 of dessicated brown clay over 0-16 m of grey clay. A thick fill was proposed and various options were considered for improving the embankment foundations.

Mineral fill with staging would be the typical construction method but this option was rejected due to insufficient time and the high possibility of a failure occurring. Lightweight fill and retaining wall options were also rejected because an analysis of the existing highway embankment to the north indicated failure would occur in a moderate to large earthquake. Excavation of the clay by trenching and backfilling with blasted rock was considered until a test excavation highlighted the difficulties involved. A bridge was considered but the earthquake stability of the existing highway embankment required an expensive piled foundation to resist the increased lateral loads. An option to use vibro concrete columns or stone columns was also rejected.

The design eventually chosen consisted of about 1,800 H-piles with an average length of 14 m driven to refusal on a 1.6 m triangular grid pattern. The piles created a reinforced block of soil about 100 m long by 40 m wide beneath the new embankment. The piles were cut off at ground level and a 1/4" (6.35 mm) thick steel plate was placed on each pile head. A relieving platform of granular fill and geogrid was constructed over the piles to spread the load from the embankment fill.

Millstream Interchange

Sands and gravels of the Colwood delta underlying the Millstream interchange are ideal for construction purposes. However, they are locally overlain by peats that infill depressions probably formed as kettle holes. Up to 7 m of peat and 5 m of discontinuous clay were present both to the north and south of the new interchange. The peats were thickest at the approximate location of the southern abutment and the on and off ramps. With up to 8 m of fill required for the abutment, primary settlements of up to 2.5 m were calculated with about 90% occurring in the first year. Options to reduce settlement problems included surcharging the peat and the use of lightweight fills. Excavating the peat was the selected option. Pumping water was required to maintain a dry hole during excavation and, due to high levels of several metals in the water, it had to be transported to a natural storage area north of the highway where it was allowed to gradually filter back to the peat area.

STOP 1: Malahat Overlook – Regional geology of southern Vancouver Island

Our first stop is at a scenic viewpoint on the Malahat overlooking Saanich Inlet (Stop 1 - Figure 1). The regional bedrock and Quaternary geology of southern Vancouver Island will be discussed here. The outlook provides an excellent view of Saanich Inlet, northern Saanich Peninsula, southern Saltspring Island, the Gulf and San Juan islands and Mount Baker in the distance. Low lying areas on Saanich Peninsula such as the Victoria International Airport area are draped by the Victoria clay which is generally thinner on the peninsula than in the Victoria area. The isolated bedrock hill on the peninsula directly to the west (Mt. Newton) is an Early Jurassic granodiorite, part of the Island plutonic suite. Nanaimo Group rocks occur at the north end of the peninsula and Mt. Tuam occurs at the south end of Saltspring Island. Jocelyn Hill is visible to the south and Mt. Finlayson occurs at the southeast end of Saanich inlet.

Mt. Baker, visible on a clear day, is a spectacular glacier-capped Quaternary volcano, one of many that extend along the mainland coast. The top part of Mt. Baker is Late Pleistocene in age while the lower part formed in the Mid-Pleistocene between about 300,000 and 500,000 years ago. Four episodes of magmatic eruptive activity are known to have occurred since deglaciation about 14,000 years ago. However, numerous destructive lahars, debris flows and debris avalanches have occurred as a result of thermal activity, earthquakes, and heavy rains. Deposits from these events extend all the way to the coast and pose a hazard for many communities as do other volcanoes such as Mt. Rainer above Seattle and, of course, Mt. St. Helens. Historical activity on Mt. Baker includes several explosions in the mid-19th century seen from Bellingham, numerous debris avalanches in the last 50 years and increased fumarolic activity and snow melt in the Sherman Crater area near the peak that started in 1975 and continues to the present.

Saanich Inlet is a glacially carved fjord with steep bedrock walls and average water depths over 100 m. The deepest point is 236 m and a bedrock sill at the north end of the inlet restricts water circulation and anoxic waters occur in the deeper parts of the inlet (Yorath and Nasmith 2001). Two cores from an Ocean Drilling Program (ODP Leg 169S) in the inlet found glaciomarine muds overlain by organic-rich sediments deposited after 12,000 14C yr ago, under well-oxygenated conditions as reflected by bioturbation and a diverse bivalve community (Blais-Stevens et al. 2001). At about 10,500 14C yr, a spectacular event deposited a massive unit, 40–50 cm thick, with a sharp lower contact and an abundance of reworked Tertiary microfossils. The event has been interpreted as subaqueous flow resulting from massive flood events caused by the collapse of glacial dams in the Fraser Valley. Progressively greater anoxia in bottom waters began about 7000 14C yr ago as indicated by preservation of varved sediments with diatomaceous spring–summer laminae and terrigenous winter laminae. Many massive beds of coarser sediment occur within the otherwise laminated sequences in the inlet. These are interpreted to be submarine debris flow deposits and many are widespread and probably related to earthquake triggers. Two of the layers correspond to known earthquakes: the 1946 Vancouver Island (M 7.3) and the A.D. 1700 Cascadia subduction earthquake (M 9). A recent analysis (Blais-Stevens et al. 2011) found 18 units with probable seismic triggers, suggesting an average earthquake return period of about 220 yr. Nine of the units overlap in age with known great plate-boundary earthquakes. The remaining nine give an average return period of about 470 yr for strong shaking from local earthquakes (Blais-Stevens et al. 2011).

Bedrock Geology of Southern Vancouver Island

(by Nick Massey)

The Victoria area is geologically unique for Vancouver Island, in that it is located at the junction of three lithostratigraphic terranes, each with its own distinct rock types and geological history (Figure 1). Saanich Peninsula is underlain by rocks of Wrangellia terrane which constitutes most of Vancouver Island (Muller, 1983; Yorath, 1995). The rocks outcropping at Stop 1 are Paleozoic granitic rocks of Wrangellia. Small limestone units of uncertain Paleozoic or Triassic age were mined for cement across the inlet at Butchart Gardens and at a mine site below the outlook; the light color on the rock surfaces here is lime from mining dust (Yorath and Nasmith, 2001). Typically, the Wrangellian stratigraphy has been tilted to the northeast so that the structurally deepest parts of the crust occur along the southwestern margin of the terrane. The southern half of Saanich Peninsula is underlain by gneiss, diorite, amphibolite, marble and metasediments of the Wark-Colquitz Complex. These rocks were formed from Paleozoic- to Triassic-age protoliths that were metamorphosed, intruded and migmatized during the early Jurassic. They are in fault contact with Mesozoic volcanic and sedimentary rocks of the northern part of the peninsula. The latter rocks comprise flood basalts and micritic limestones of the Triassic Vancouver Group and andesitic fragmental volcanic rocks of the Lower Jurassic Bonanza Group. These rocks are intruded by the Saanich granodiorite, a pluton of early to middle Jurassic age. Deformation, uplift and erosion occurred prior to the development of the Georgia Basin to the north and deposition of clastic sediments of the Late Cretaceous Nanaimo Group on the northern tip of Saanich Peninsula, on Saltspring Island, in the Cowichan valley area and farther north along the east side of Vancouver Island.

The Leech River Complex, a fragment of the Pacific Rim terrane, occurs along the southern margin of Wrangellia, separated from it by the Survey Mountain thrust which dips about 40° to the northeast and extends deep into the crust (Clowes *et al.*, 1987). The Leech River Complex consists of quartz-biotite schist, metagrewacke, meta-arkose, metabasalt and minor ribbon chert which crop out west of the Victoria area. The fieldtrip route crosses the Leech River complex in the Goldstream Park area and along Finlayson Arm at the southern end of Saanich Inlet (Figure 1). Here the complex consists of a steeply dipping, 6 km thick succession of tightly folded and variably metamorphosed argillite, sandstone, chert and volcanic rocks that were emplaced beneath the Wark Gneiss along the San Juan – Survey Mountain Fault system (Yorath and Nasmith, 2001). Minor outcrops of the Leech River complex can also be seen in the Victoria area along the shoreline at Foul Bay and on the Trial Islands. Rocks of this terrane are believed to be related to those of San Juan Islands, east of Haro Strait.

Underlying the southern tip of Vancouver Island, from Metchosin to Sombrio Point, are basalts and gabbros of the Metchosin Igneous Complex (Massey, 1986). This ophiolite is the northernmost exposure of the Paleocene to Eocene Coast Range Basalts, which outcrop in Oregon and Washington, and also occur offshore in the Tofino Basin. The rocks formed as a series of seamounts and islands on ocean floor created in a transform marginal basin. They were thrust northward beneath the Leech River Complex along the Leech River fault. Emplacement was followed by uplift and deposition of the conglomerate and sandstone of the Oligocene Sooke Formation.

Seismic Slope Stability Mapping

(main sources: McQuarrie and Bean, 1998, 2000)

A seismic slope stability map was compiled by Thurber Engineering Ltd. for the Greater Victoria area (McQuarrie and Bean, 2000; Figure 4). The map is based on a compilation of existing subsurface data, slope stability assessments, bedrock and surficial geology maps, topographic data, airphoto interpretation and field observations. Stability analyses were conducted using either the infinite slope method or computer assisted limit equilibrium methods. Twelve different slope models were analyzed that included typical or simplified slopes found throughout the Victoria area as well as specific, complex slope models where more detailed information was available. Typical slopes included simplified sand or clay slopes (representing the two most common Quaternary deposits in the Victoria area). The stability analyses determined both the static factor of safety and the yield acceleration (the seismic acceleration that reduces the factor of safety to 1.0).

Seismic Slope Hazard Classification System

The Victoria seismic slope hazard maps use the same 5 class system (very low, low, moderate, high and very high) as the liquefaction and ground amplification hazard maps. The classification system is based primarily on the yield accelerations determined from the stability analyses, but other factors were considered at both ends of the hazard classes. For example, rock slopes in the Greater Victoria area are relatively stable and were generally given a low hazard rating. Many steep rock faces with striae surfaces have not failed since deglaciation. The potential for boulder ravelling or very small rock falls exists throughout most hilly areas, particularly during an earthquake, but overall such rock hazards are of relatively minor impact and can only be identified by site specific assessments. This low hazard rating does not imply that a structure located at the base of a steep bedrock slope within such an area is safe since the map is not intended to identify hazards on a lot by lot basis. Instead, a low hazard rating in the bedrock-controlled hilly areas is a reflection of the relative overall slope stability hazard.

The main exception to this low hazard rating on rock slopes is in the Mount Finlayson-Malahat-Goldstream River area where the terrain is steeper, the relief greater and the bedrock much weaker than elsewhere in the Greater Victoria area and the steeply eroded valley terrain poses considerably greater terrain hazards. The other area where bedrock has a direct influence on the slope stability is at the north end of the Saanich Peninsula where northward dipping beds in the Nanaimo Group sedimentary bedrock forms potential failure surfaces for sliding of the overlying colluvium during an earthquake. Both the Mount Finlayson-Malahat-Goldstream River area and the Saanich Peninsula will be seen on the field trip.

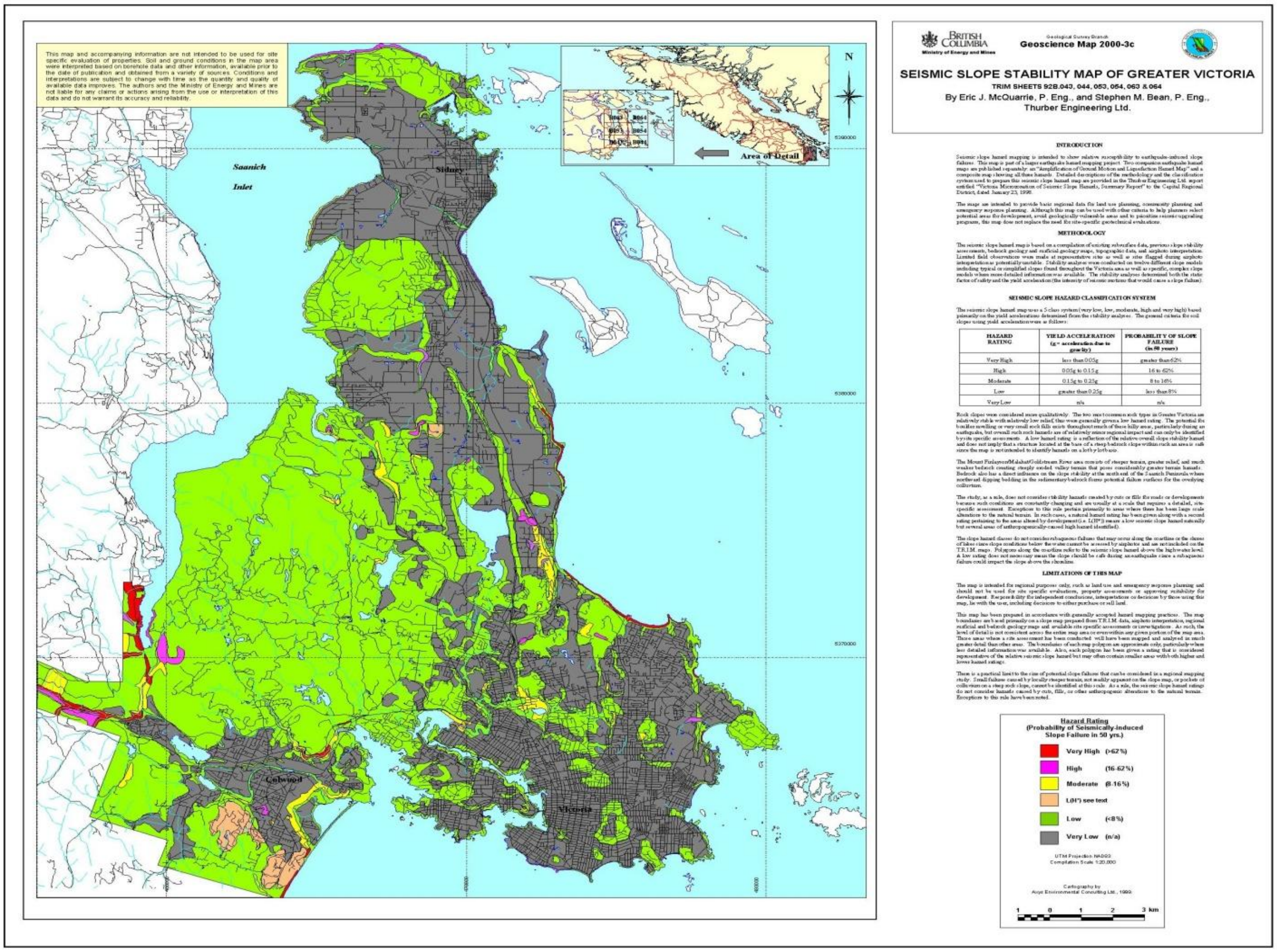

Figure 4. Seismic slope stability map of the Greater Victoria Area (McQuarrie and Bean, 2000). Note the high to very high hazard in the Mount Finlayson/Malahat/Goldstream River area that will be traversed on the first part of the field trip.

STOP 2: Introduction to the Nanaimo Group

Stop 2 (Figure 1) is at the historic fishing village of Cowichan Bay where the general geology of the Nanaimo Group will be discussed. The stop is on the wharf where there is a good view of the Bay area. Since the 1860's, Cowichan Bay has been a significant salmon fishing and logging community, with tourism, boatbuilding and other interests now also important. The village lies just south of the Cowichan River delta where log booms can still be seen (Figure 5). Alluvial sediments in river valley make excellent agricultural soils as do glaciomarine and glacial deposits in the rolling hills west of Cowichan Bay. Raised glaciofluvial deltas, like the Colwood delta, also occur here and provide excellent sources of aggregate (Figure 6.)

Figure 5. Google earth image of the Cowichan Bay area. the Cowichan River delta lies just north of the village

Figure 6. A raised glaciofluvial delta with steep, seaward-dipping forset beds in a gravel pit west of Cowichan Bay.

The Paleozoic Sicker and Buttle Lake groups of Wrangellia Terrane outcrop on the peninsula on the opposite side of the bay and at Mount Sullivan on southwestern Saltspring Island farther to the east (Figure 1). They are intruded by the Triassic Mount Hall gabbro which occur on the hills on the peninsula, including Grouse Hill at the north end, and on Saltspring Island. The gabbro sills were folded with the rocks they intrude between Triassic and Cretaceous times (Greenwood 2009). This folding occurred after pre-Late Devonian deformation and before folding of the Cretaceous Nanaimo Group (see Structural Geology section below). The older rocks are separated from the Nanaimo Group sediments that underlie the Cowichan Lake valley by one of many northeast dipping thrust faults (Figure 1). The Cowichan Lake fault system extends, from just south of Cowichan Bay, to the northwest along the river valley to Shawnigan Lake where it occurs at the base of the steep slopes on the north side of the valley.

Upper Cretaceous Nanaimo Group (Source: Mustard 2009)

The following geological discussion of the Nanaimo Group and subsequent sections are from a 2009 field guide by Peter Mustard which is used here with permission. Only minor modifications and additions have been made for this guidebook. Mustard (2009) acknowledges a number of sources including: a 2004 CSPG field trip guidebook (Mustard et al., 2004), contributions from Dr. Jim Haggart of the GSC on the biostratigraphy and paleontology summaries; an M.Sc. thesis on the Cedar District Formation, and specifically the Vesuvius Bay section (Treptau, 2002), with additions by Dr. Peter Mustard and Dr. James MacEachern of SFU Earth Sciences; and an M.Sc. thesis on the Comox Formation and specifically the Ruckle Park section (Johnstone, 2005; Johnstone et al., 2006).

The Nanaimo Group is an Upper Cretaceous succession of siliciclastic rocks preserved within and on the margins of the Strait of Georgia in southwest British Columbia, Canada (Figure 1). This succession has been the subject of extensive study since coal was first mined in the Nanaimo area in 1852, from strata described subsequently by Newberry (1857). Early research is reviewed in detail in Mustard (1994) and Muller and Jeletzky (1970).

Research in the basin has been driven by economic interest (extensively mined coal deposits and more recently, interest in coalbed methane potential), by the abundance and quality of the marine fossils, and by the spectacular exposures of submarine fan facies associations, especially in coastal areas of the many islands of the southern Strait of Georgia, most of which are composed entirely of Nanaimo Group.

Regional Geological Setting

The Nanaimo Group is exposed in two major and several minor separate outcrop areas (Figure 7). Early workers interpreted deposition to have occurred in up to five separate sedimentary basins (e.g. Clapp and Cooke 1917; Mackenzie 1922). Most recent regional studies suggest, however, that strata preserved in these slightly separate geographic regions are actually erosional remnants of what were once continuous strata, and most workers consequently consider the Nanaimo Group to have been deposited in a single basin (Muller and Jeletzky 1970; Ward 1978a; Haggart 1991; Mustard 1994; Enkin et al. 2001). The single basin interpretation has resulted in the formation nomenclature used here (Figure 8). However, some researchers continue to favor the existence of at least two separate basins, and use or have proposed separate formation names for each (e.g. England and Hiscott 1992; Cathyl-Bickford and Hoffman 1998).

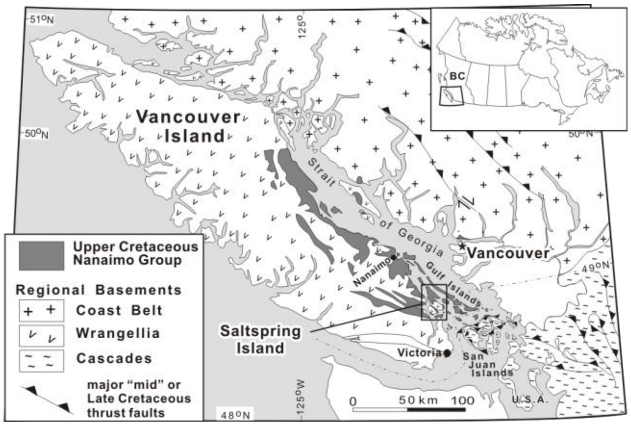

Figure 7. Regional geologic setting of the Nanaimo Group. Main figure is modified from Mustard (1994). Major "mid" to Late Cretaceous aged thrust faults are taken from Umhoefer and Miller (1996) and Berger (2002).

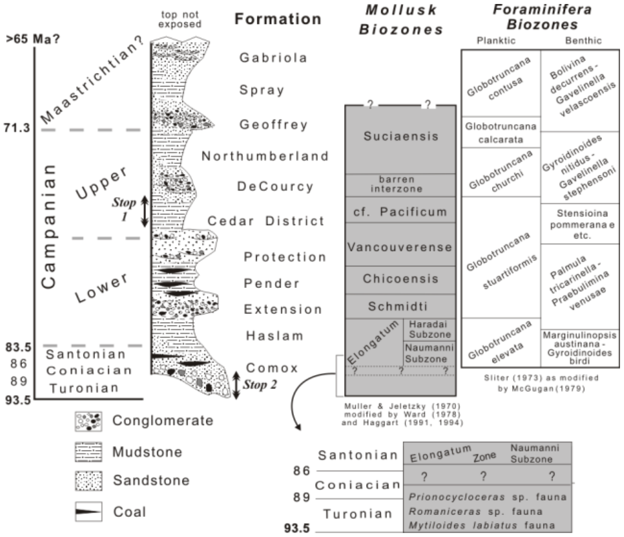

Figure 8. General stratigraphy of the Nanaimo Group, showing the most recent biostratigraphic zonations based on molluscan and foraminiferal fossils. The time scale used here and in the text is from Okulitch (1999).

The Nanaimo Group unconformably overlies Wrangellia Terrane on its west side, the Coast Belt on its east side, and it is in inferred fault contact with the San Juan thrust system to the southeast (Figure 7). The Nanaimo Basin was an elongate northwest-trending depocentre during Turonian to Maastrichtian time, although there is no constraint on its original extent to the west or north (Mustard 1994). Deposition was continuous at least from Santonian to late Maastrichtian ages, although both Turonian (Haggart 1994) and Coniacian (Haggart et al. 2003) strata occur in the basal Nanaimo Group, indicating the basin began on a topographically irregular basement with moderate relief about 90 Ma. The uppermost strata are sparsely fossiliferous and thus difficult to constrain in age. They are likely Maastrichtian, but may include Paleocene-age material (Sweet and Mustard 2003). The Nanaimo Group is unconformably overlain by late Paleocene rocks in a few places. The basin accumulated a thick succession (> 4 km), consisting of subaerial and marine siliciclastics, with the majority of the upper two-thirds of the succession represented by both vertically stacked and laterally overlapping submarine fan complexes. Figure 8 provides a schematic summary of Nanaimo Group stratigraphy and biostratigraphic constraints.

Structural Geology

Most of the Nanaimo Group has been structurally deformed by several Cenozoic tectonic events, and generally dips gently to the northeast. Broad, predominantly northwest-southeast trending folds and associated faults control the topography of the Canadian Gulf Islands within the Strait of Georgia, and are associated with the Cowichan Fold and Thrust Belt (CFTB) (England and Calon 1991). This Eocene-aged, southwest-verging thrust system is interpreted to be related to the collision and under plating of the Pacific Rim and Crescent Terranes to the west side of Wrangellia (ibid.). More recent work has identified a younger north-east verging fold and thrust system that partly cross-cuts the CFTB, suggesting a later change from compressional to transtensional tectonics in the Late Paleogene to Early Neogene. This is expressed as the Gulf Islands Thrust System (GITS) in the outer Gulf Islands (Journeay and Morrison 1999). Further Pliocene-to-modern uplift of the Coast Mountains and eastward tilting of Wrangellia, associated with continued subduction of the Juan de Fuca Plate, represents a third cycle of deformation. Figure 9 shows the general geology of the southern Gulf Islands, including major structural elements.

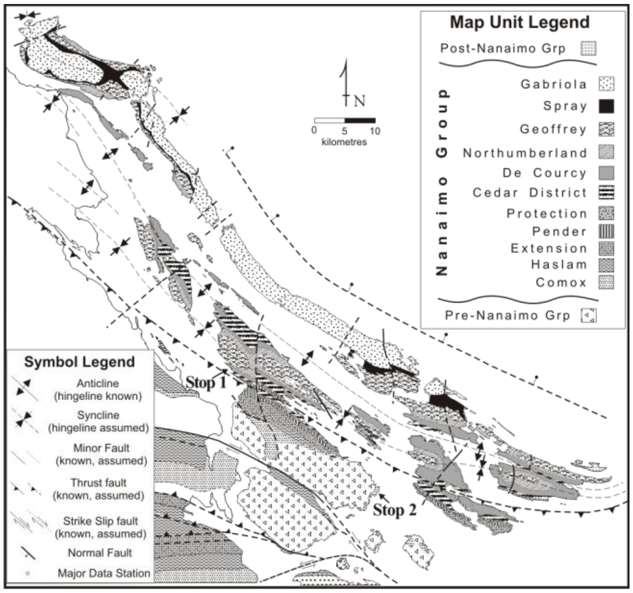

Figure 9. General geology of the southern Gulf Islands. Nanaimo Group major contacts are from England (1991) significantly modified as a result of unpublished mapping by Peter Mustard and several of his SFU graduate students. Major structural elements are from Journeay and Morrison (1999).

Basin Tectonic Setting

Currently, two models are frequently cited for the specific tectonic setting of this basin. England and Bustin (1998) suggest a broad-ridge forearc basin model for deposition. Mustard (1994) and Mustard et al. (1995) interpret deposition to have occurred within a peripheral foreland basin, in front of, and mostly derived from, a complex series of overlapping and cross-cutting thrust belts which formed in the Coast Belt and northwest Cascades about 100 to 80 million years ago (remnant thrusts are shown on Figure 7; thrust evidence is reviewed in Umhoefer and Miller 1996, with newer evidence in Rusmore et al. 2000 and Bergh 2002).

The published strike-slip basin model of Pacht (1984) is no longer considered credible (discussed in detail in Mustard 1994); it was based on the interpretation that faults within and bordering the Nanaimo Group are in general strike-slip in nature and in part synsedimentary, both interpretations now in disfavour following more recent structural studies (England and Calon 1991; Journeay and Morrison 1999; Mackie 2002). Figure 10 shows the preferred schematic model of the peripheral foreland basin setting.

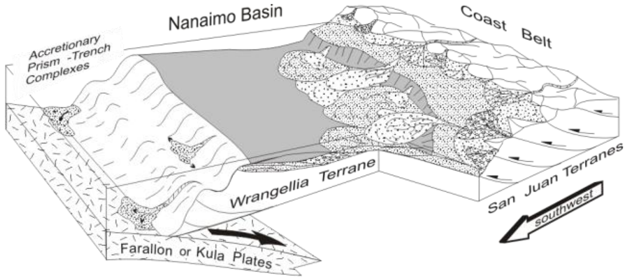

Figure 10. Schematic representation of Nanaimo Basin during marine-dominated phase of deposition (most of the preserved Nanaimo Group (modified from Mustard 1994)

Lithostratigraphy and General Depositional Settings

Eleven formations are recognized within the Nanaimo Group (Figure 8). Formation definitions are based on lithostratigraphic variations of finer units dominated by mudstone and thin-bedded sandstone with coarser units dominated by sandstone and/or conglomerate. The finer units comprise mostly turbidites and muds of dominantly deep marine origin, although significant coal and other marginal marine fine- grained deposits occur in the lower Nanaimo Group. The upper two-thirds of the group formed mostly by submarine fan deposition, but lower Nanaimo Group deposition generally reflects a complex mix of non-marine alluvial and generally shallow marine depositional environments. Figure 11 illustrates the main submarine fan depositional environments for the basin (see Mustard 1994 and England and Hiscott 1992 for detailed discussion of the sedimentology of the basin).

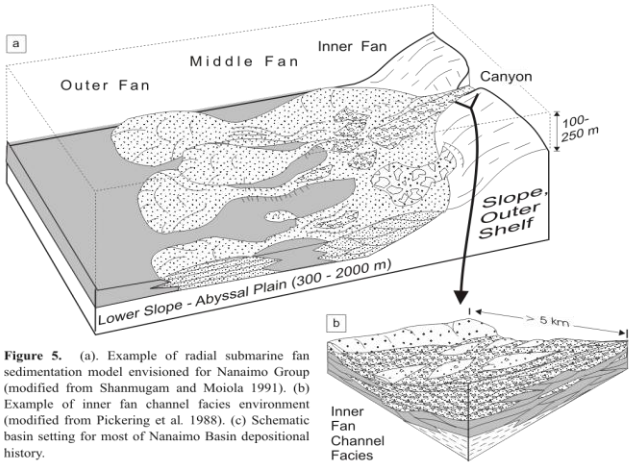

Figure 5. (a). Example of radial submarine fan sedimentation model envisioned for Nanaimo Group (modified from Shanmugam and Moiola 1991). (b) Example of inner fan channel facies environment (modified from Pickering et al. 1988). (c) Schematic basin setting for most of Nanaimo Basin depositional history.

Figure 11. Main submarine fan depositional environments for the basin

Biostratigraphy[1]

Molluscan megafossils, foraminiferal and palynological microfossils, as well as radiometric dating of Nanaimo Group strata indicate an age range of Early Turonian to Maastrichtian (about 93.5 Ma to 65 Ma on the Okulitch 1999 time scale) for the group. Formations are slightly diachronous laterally, although no significant time gaps are apparent, with the exception of variation in the age of the basal Comox Formation, locally of Turonian, Coniacian and Santonian age in different parts of the basin (e.g. Haggart 1991, 1994; Haggart et al. 2003, 2005). In general, formation boundaries are conformable and gradational, and display interfingering relationships. In some places however, locally sharp and erosive contacts have resulted in dramatic facies changes between formations, which some workers have interpreted as local unconformities (e.g. Muller and Jeletzky 1970), although no significant biostratigraphic gaps are apparent.

Molluscan biostratigraphic studies of the Nanaimo Group have principally utilized ammonites and inoceramid bivalves. Early studies are summarized in Muller and Jeletzky (1970). The current molluscan biozone scheme is shown in Figure 8, including–modifications from more recent work, most importantly the documentation by Haggart (1991, 1994, 2006) of Early Turonian strata at the base of the Nanaimo Group in the southern Gulf Islands and the work of Haggart et al. (2003) in Coniacian strata in the northern part of the basin.

Nanaimo Group microfossil studies have been restricted to foraminifera and palynomorphs. McGugan (1962) proposed the first Nanaimo Group foraminiferal biozones. This zonation was subsequently modified by Sliter (1973) and refined by McGugan (1979) to give the scheme shown in Figure 8. Other important published foraminifera studies are those of Scott (1974b) and McGugan (1981, 1982, 1990). Palynology studies have demonstrated the Late Cretaceous age of the eastern Nanaimo Group outliers on mainland British Columbia (Bradley 1973; Crickmay and Pocock 1963; Rouse et al. 1975; Mustard and Rouse 1994), and an early Tertiary age for strata previously correlated with the upper Nanaimo Group in the southeast outcrop area (Mustard and Rouse 1992).

The lower age limit of the Nanaimo Group is provided by the presence of early Turonian ammonites and bivalves in the most southerly exposures of Nanaimo Group at Sidney Island (Haggart 1991, 1994, Haggart et.al., 2005). Elsewhere in the basin, the oldest fossils found in the Nanaimo Group are generally Santonian age mega- and microfossils, although the basal part of the Comox Formation in many places lacks age diagnostic fossils and could be older (Jeletzky in Muller and Jeletzky 1970). Recently, megafossils of Early Coniacian age have been discovered from two outcrop areas of basal Comox Formation in the northern part of the basin (Haggart et al., 2003, 2005).

In contrast, the upper age limit of the Nanaimo Group is not well constrained. Late Paleocene sandstones unconformably overlie the Nanaimo Group at several places, providing an upper limit on the age of the Nanaimo Group, (Mustard and Rouse 1992). The Gabriola Formation has yielded a few poorly preserved fossils of probable Cretaceous age (Haggart 1989), but only from one locality on Galiano Island (Figure 7). A gradational contact with the underlying Spray Formation, from which Maastrichtian foraminifera have been documented in southern occurrences (McGugan 1979, 1982), suggests a Maastrichtian age for at least the lower part of the Gabriola Formation. Detrital zircons collected a few metres above the base of the Gabriola Formation at its type area on Gabriola Island are dominated by large euhedral forms which give concordant U/Pb ages of 70-73 Ma (Mustard et al. 1995, 2003), indicating that the Gabriola Formation in this area must be at least <70 Ma. Palynology data from the upper Gabriola Formation on Hornby and Gabriola islands permit a possible early Paleocene age for these strata as well (G. Rouse, pers. comm. 1993; Sweet and Mustard 2003), which would suggest a conformable Cretaceous-Tertiary boundary is present in at least these areas. However, the palynomorphs discovered so far are also permissibly Maastrichtian forms, although elsewhere in western North America they appear restricted to the Paleocene (Sweet and Mustard 2003).

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[1] This summary was originally co-authored, and the fossil plates supplied by Dr James Haggart, Geological Survey of Canada, Vancouver B.C. as part of a previous field trip guidebook (Mustard, et al., 2003).

Ichnology

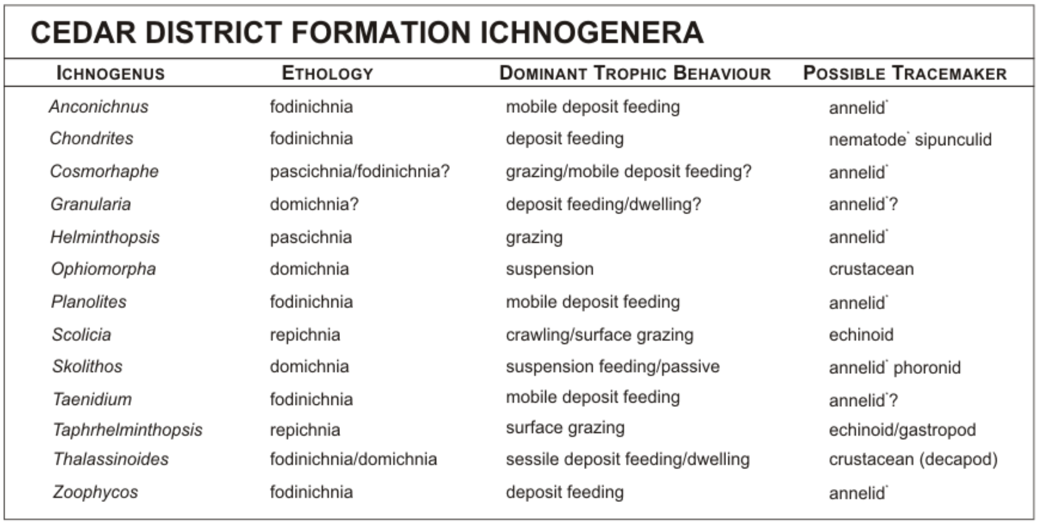
Trace fossils are unique in the rock record in that they provide both a sedimentological and biological marker in the stratigraphic record. As for physical sedimentary structures, trace fossils can reflect the influence that the prevailing environmental parameters have on the sediment and the inhabiting fauna. The behaviour of active, *in situ* organisms (benthic infauna and epifauna), and how that behaviour is modified by the constraints of the environment, is the cornerstone of ichnology (Pemberton et al. 1992b, 2002).

Ichnology refers to the description, classification, and identification of biogenic structures (that is, tangible evidence of the activity of an organism, fossil or recent, other than the production of body parts) that are preserved in the rock record (Frey 1971, 1973). Trace fossils can be used in the determination of original biological, ecological, and sedimentological conditions of the rocks in which they are preserved (Frey and Seilacher 1980). Not only is the identification of individual trace fossils (ichnogenera) important, but also, it is crucial to recognize the numerous behaviours or ethology represented by an entire trace fossil assemblage (ichnocoenose) (Pemberton et al. 1992a,b, 2002; Pemberton and MacEachern 1995). It bears stressing that a particular trace fossil largely reflects an organism's behavioural responses to a specific set of environmental conditions in the marine or non-marine realm, and can be attributed to a number of different trace-making organisms.

Trace fossils are common in the Nanaimo Group, but until recently have been largely ignored or mentioned only in passing, with no attempt at either systematic description or use as a guide to detailed interpretation of environmental parameters. Treptau (2002) conducted the first true ichnological study in the Nanaimo Group. He documented the ichnology of the Cedar District Formation through its entire lateral and vertical extent and attempted to relate the assemblages to the detailed sedimentological study he also conducted on this unit. The summary below is from this study and is directly applicable to Stop 3 (Vesuvius Bay). The Cedar District Formation comprises a succession of fine-grained, thin-bedded siliciclastic turbidites deposited as the distal parts of deep marine submarine fan complexes. It is very similar to the other mudstone-dominant formations of the Nanaimo Group (*i.e.* Haslam, Pender, Northumberland, and Spray formations), all of which in most areas appear to represent the distal portions of a series of repeated submarine fan complexes overlapping both vertically and laterally into the Nanaimo basin.

Trace fossils are relatively abundant in the Cedar District Formation (Figure 12). The ichnological assemblage is representative of an abundant, but low diversity *Zoophycos* ichnofacies, dominated by *Zoophycos, Thalassinoides, Planolites, Anconichnus (=Phycosiphon,* see Wetzel and Bromley 1994), and *Taenidium*, with lesser *Helminthopsis, Chondrites, Ophiomorpha, Granularia, Skolithos, Cosmorhaphe, Scolicia*, and *Taphrhelminthopsis*. Four recurrent post-turbidite ichnocoenoses (trace fossil assemblages) have been identified, in ascending stratigraphic order: the *Chondrites* ichnocoenose, the *Taenidium* ichnocoenose, the *Anconichnus (Phycosiphon)* ichnocoenose, and the *Scolicia* ichnocoenose. Graphoglyptids, typical of the *Nereites* ichnofacies and many pre-turbidite trace fossil suites, are notably absent.

These ichnocoenoses record an upward progression from predominantly sessile deposit feeding and mobile grazing behaviours in mudstones, to mobile deposit feeding and lesser semi-permanent dwelling behaviours of opportunistic organisms in sandstones. These ethological changes mirror the lithofacies changes and concomitant changes in substrate consistency, corresponding to the abrupt shift of one fan lobe to the next in an extensive prograding submarine fan complex.



CEDAR DISTRICT FORMATION ICHNOGENERA

Ichnogenus	Ethology	Dominant Trophic Behaviour	Possible Tracemaker
Anconichnus	fodinichnia	mobile deposit feeding	annelid*
Chondrites	fodinichnia	deposit feeding	nematode* sipunculid
Cosmorhaphe	pascichnia/fodinichnia?	grazing/mobile deposit feeding?	annelid*
Granularia	domichnia?	deposit feeding/dwelling?	annelid*?
Helminthopsis	pascichnia	grazing	annelid*
Ophiomorpha	domichnia	suspension	crustacean
Planolites	fodinichnia	mobile deposit feeding	annelid*
Scolicia	repichnia	crawling/surface grazing	echinoid
Skolithos	domichnia	suspension feeding/passive	annelid* phoronid
Taenidium	fodinichnia	mobile deposit feeding	annelid*?
Taphrhelminthopsis	repichnia	surface grazing	echinoid/gastropod
Thalassinoides	fodinichnia/domichnia	sessile deposit feeding/dwelling	crustacean (decapod)
Zoophycos	fodinichnia	deposit feeding	annelid*

Figure 12. Ichnogenera identified in the Cedar District Formation, including ethological classification, trophic group, and possible tracemaker (may include other worm-like phyla). From Treptau (2002) and modified from a similar figure in Pemberton et al. (1992a)

All of the sedimentological, ichnological, and biological evidence examined for the Cedar District Formation indicate that the paleoenvironmental setting was one of high-frequency turbidite emplacement along the outer margins of a submarine fan depositional lobe complex. During Cedar District time, relatively deep marine processes dominated deposition within the basin, although the trace fossil assemblage preserved is uncharacteristic of typical distal (*Nereites* ichnofacies) turbidite assemblages. This departure from the Seilachernian ichnofacies progression is consistent with basin deposition strongly influenced by high frequency turbidite emplacement, and has been recognized in other submarine fan successions (e.g. Seilacher 1962; Crimes 1973, 1977; Crimes et al. 1981; Crimes and Crossley 1991).

Submarine Fan Deposition related to Sea Level Change and Sequence Stratigraphic Concepts

Discussions concerning the deposition of submarine fan systems are generally closely linked to eustatic fluctuations (e.g. Mutti 1985; Shanmugam et al. 1985; Kolla and Macurda 1988; Posamentier et al. 1991). It is generally suggested that global changes in sea level control both siliciclastic and carbonate deposition in the deep sea *via* turbidity currents (Shanmugam et al. 1985).

In many studies, lowstands of sea level have been cited as the dominant time for deep-sea siliciclastic deposition along the continental slope and basin (e.g. Mutti 1985; Weimer 1990). The ideal deposits of the lowstand systems tract consist of a basin-floor fan, a slope fan, and a lowstand wedge (Van Wagoner et al. 1990). Basin-floor fans are typically found at the mouths of submarine canyons, consisting of sand-rich deposits of T_{AB} and T_{AC} cycles (see Figure 13 for a review of the Bouma turbidite A-E internal sedimentary units). The slope fan comprises turbidite-leveed submarine channel and over bank deposits overlying the basin-floor fan (*ibid*). The lowstand wedge consists of incised valley deposits (and associated lowstand shoreline deposits) proximally, and thick, shale-prone wedge-shaped units downlapping on the slope fan distally. This, of course, assumes that eustatic sea level changes are the determining (and thus dominant) factor in controlling deep sea fan deposition.

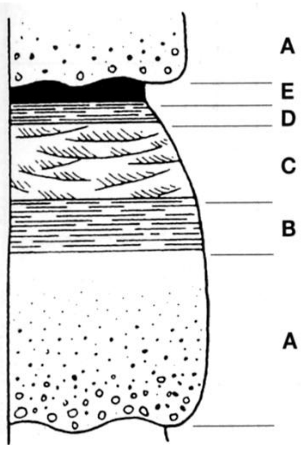


Figure 13. Ideal turbidite succession sediment layers as defined by Bouma (1962).

The concept that deep sea fan deposition and internal architecture of major successions may also depend on the nature of the sediment, tectonic setting, and basinal dynamics (e.g. size, slope, geometry) has also been recognized by many researchers (e.g. Kolla and Macurda 1988; Posamentier and Allen 1993). Several recent studies suggest that sea level transgressions and highstands can be important (if not dominant) periods of deep-sea sedimentation (e.g. Kuehl et al. 1989; Droz et al. 1996; Weber et al. 1997), especially in depositional settings where other intra- and extra-basinal factors (besides base level) may affect, and even direct, sedimentation. Nonetheless, while it appears fan development can occur at any relative stage of sea level, it is unlikely that times of highstand or transgression will have the same amount of potential volume of clastic input available as is typical of times of lowstand (Emery and Myers 1996).

Applying these allocyclic concepts to basinal interpretations of Nanaimo Group stratigraphy is difficult, and a true sequence stratigraphic interpretation on a basin-wide scale has yet to be attempted in any detail. Treptau (2002) provides a possible model of Cedar District Formation deposition in terms of relative changes in sea level as a major control on depositional processes. Nonetheless, he admits this is speculative and perhaps less useful to explain the internal architecture of the succession he studied versus his better constrained autocyclic interpretations.

Problems with regional interpretations reflect both the nature of preservation and exposure of the Nanaimo Group and the lack of availability of the preferred data sources for basin-wide interpretations. It is clear that this basin occurred as part of a very tectonically active margin (Engebretson et al. 1992). It was probably initiated by, and then strongly influenced from, active thrusting of adjacent source areas in mid and Late Cretaceous time (thrust evidence and timing is reviewed in Umhoefer and Miller 1996). We suspect that this was the main control on major sedimentation patterns and local sea-level changes, probably to a much greater extent than eustatic changes. However, the non-marine and shallow marine parts of the Nanaimo Group directly related to the thrust belts are now either submerged beneath the Strait of Georgia or (more likely) completely eroded during the extensive (>10km) late Tertiary uplift of the Coast Mountains (the latter event summarized in Monger and Journeay 1994). The lack of these critically important parts of major systems tracts frustrates any attempt to relate specific times of uplift in the source areas to times of major clastic input into the deep marine fans which comprise the only remaining record of deposition of much of the Nanaimo Group. In addition, researchers are constrained to outcrop studies, with few laterally continuous exposures of any large extent, and large distances between major outcrop areas, largely manifest by water-filled parts of the Strait of Georgia, lacking preserved Nanaimo Group even at depth. As well, there has been very little hydrocarbon exploration in this basin, reflecting both the poor permeability and porosity of the potential reservoir rocks, and the position of the basin on the margin of a relatively densely populated and ecologically sensitive part of the province. Thus there are almost no well logs or high quality seismic data permitting basin scale correlations and easy (if perhaps still suspect) identification of sequence stratigraphic systems tracts in the regional stratigraphy.

The Nanaimo Group on Salt Spring Island

Salt Spring is both the largest and most densely populated island of the Gulf Islands in the Strait of Georgia. As with all the major Gulf islands, it is underlain by strata of the Nanaimo Group. However, significant parts of the southern third of the island consist of older Wrangellia Terrane units, and there are several well-exposed examples of the unconformity between Paleozoic (mostly Devonian) Wrangellia Terrane metavolcanics or granitoids and the overlying Upper Cretaceous Comox Formation of the Nanaimo Group (e.g. Stop 4 at Ruckle Park).

All formations of the Nanaimo Group with the exception of the uppermost Spray and Gabriola formations are well-exposed on Salt Spring Island. Near continuous exposures of the lower formations are preserved as coastal exposures. However, there are several major thrust faults and a few minor normal faults which crosscut and repeat strata, hindering true thickness sections. It is estimated that the total thickness of the Nanaimo Group on the island exceeds 3 km.

STOP 3: Vesuvius Bay: Cedar District Formation

The Cedar District Formation is well exposed in the tidal zone and adjacent shoreline at Vesuvius Bay, which is on the western side of Salt Spring Island (Figure 14). The bay includes the BC Ferries dock for the Vesuvius to Crofton (Vancouver Island) ferry. The Cedar District strata are best examined from the base up. The basal contact with the underlying Protection Fm is exposed at the south end of Vesuvius Bay.

Exposed Stratigraphy

The Cedar District Formation has been most recently examined in detail as an MSc research project by Treptau (2002), supervised jointly by Dr. Peter Mustard and Dr. James MacEachern of SFU. His study focused on detailed sedimentology and ichnology of the formation throughout the Nanaimo Group. It is in all places dominated by submarine fan depositional facies, mostly turbidites and variations on other types of sediment gravity flows (see Figure 13 for a review of the ideal Bouma turbidite sedimentary units, Figure 15 for an example). The Vesuvius Bay succession is probably the best exposed nearly continuous example of this formation anywhere in the Nanaimo Group.

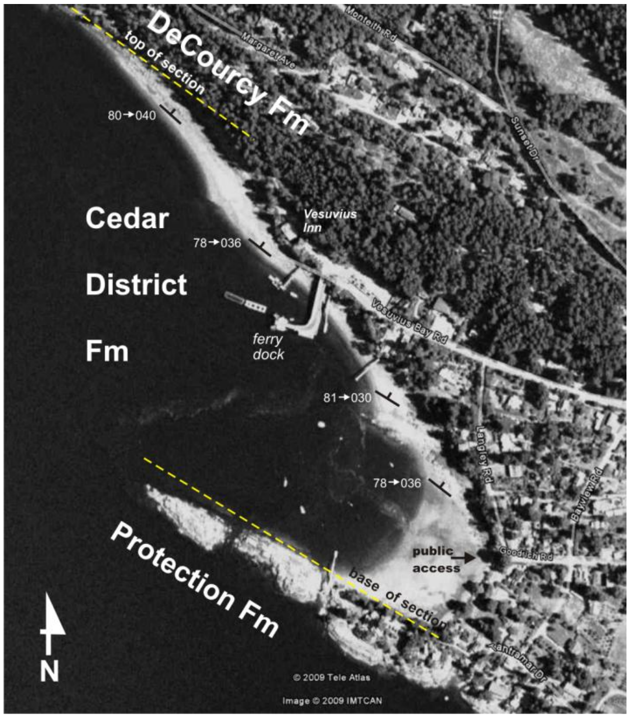


Figure 14. Location map for Stop 1 – Cedar District formation at Vesuvius Bay, Salt Spring Island (modified from Google Earth image). Bedding orientations are shown as dip towards dip direction.

Figure 15. Sandstone turbidites in the Vesuvius Bay section – displaying well-developed C layers with cross laminated ripples and convolution deformation.

The Vesuvius Bay section is reproduced in simplified form in Figure 16. It displays a typical thin (about 10 m) but gradational fining-upward lower contact from the underlying sandstone dominated Protection Fm. Above this the section coarsens and thickens upward, but with many scales of internal cycles, both fining and coarsening depending on where you pick boundaries. Most importantly, significant thick sandstone beds become dominant in the middle of the section, above about the 250 m mark. Several previous workers put the top contact of the Cedar District Formation at this point, based on the convention that the Nanaimo Group formations are identified as "mud-rich" or sand/gravel" rich as their main basis for recognition. However, there is a significantly thick (>100 m) succession of typical Cedar District formation mud and "fine" turbidites above the thick sand interval and regional mapping suggests that the top of the Cedar District Formation is really as shown on the section, several hundred metres north of the ferry docks, where significant cliffs dominated by thick sandstone represent the base of the overlying De Courcy Formation. This illustrates a problem in traditional Nanaimo Group stratigraphy, which assumes a "layer cake" stratigraphic model. In reality the upper 2/3 of the Nanaimo Group is dominated by repeated overlapping submarine fan complexes, which complexly intertongue laterally as well as gradationally changing vertically. Thus the succession of thick sandstone beds in the middle of this section is better interpreted as an "intertongue" of De Courcy Fm within the Cedar District Fm, representing a mid fan sand-rich lobe migrating into and then out of the lower fan depositional environment typical of most of the Cedar District Formation.

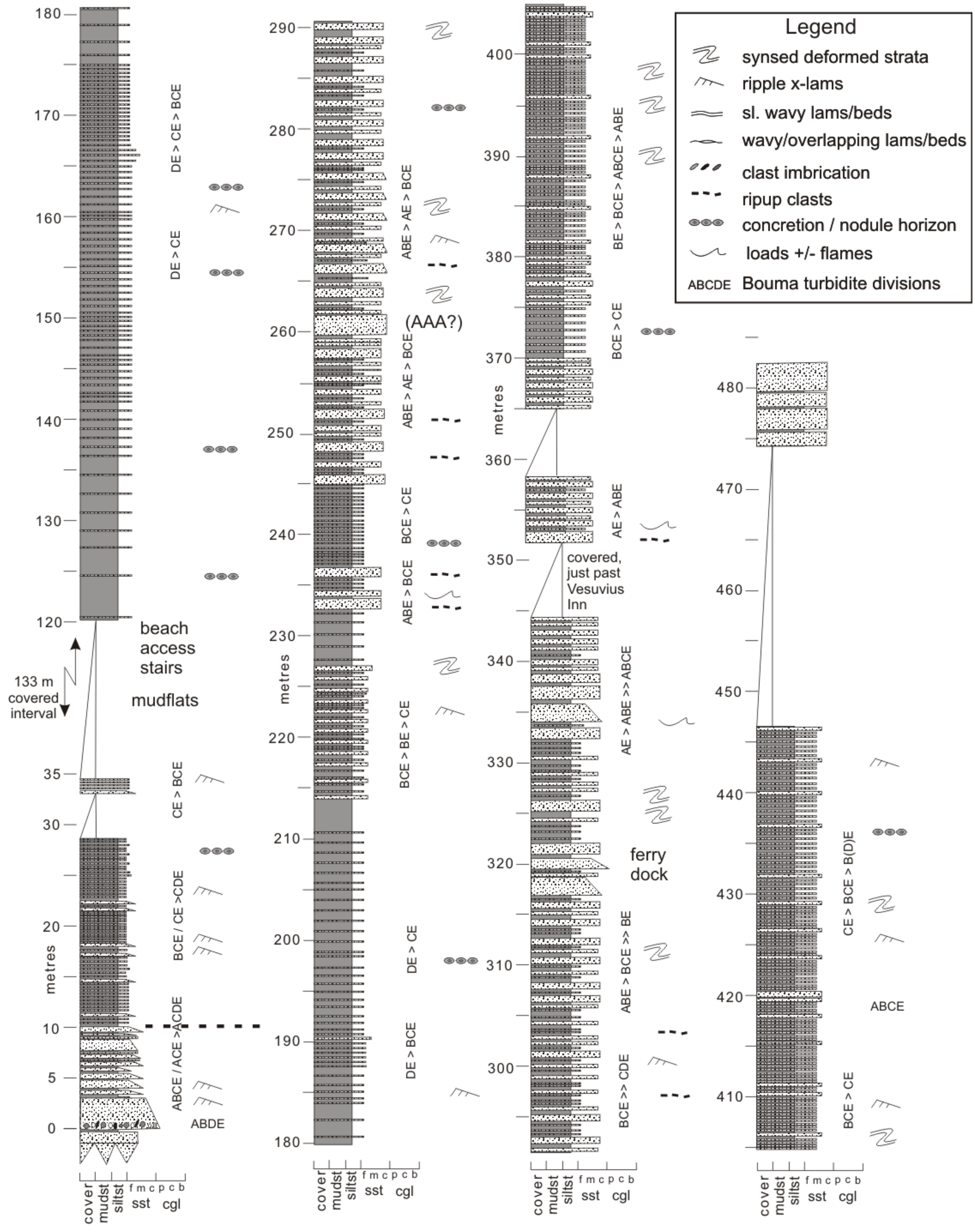


Figure 16. Simplified measured stratigraphic section through the Cedar District Formation at Vesuvius Bay, Salt Spring Island.

The Vesuvius Bay section displays classic turbidite and other sediment gravity features (e.g. Figures 15, 17). In addition, spectacular slump folds and synsedimentary deformation structures are preserved in several places (e.g. Figures 18 and 19). Traces fossils are abundant (e.g. Figure 20). Macrofossils are also common, with abundant Inoceramid shell fragments preserved on many bedding planes (Figure 21). In cross section, their shells are composed of prismatic calcite crystals as can be seen in Figure 22.


Figure 17. Small rip-up clasts with weak imbrications at the base of a turbidite at Vesuvius Bay on Saltspring Island.

Inoceramids from the Late Cretaceous are up to 3 m long and they may be the largest clams that ever lived (Figure 23). The bivalves found at Vesuvius Bay grew relatively wide and thin (Figure 21) possibly to spread their weight over a larger area and “float” on the soft ocean bottom sediments, an adaptation termed the "snowshoe effect". Occasionally, fossils of small fish that found shelter inside the living clams or even pearls may be pressed into the shell (Kauffman et al. 2007; Everhart 2010). Inoceramids may have looked like those depicted in Figure 24.

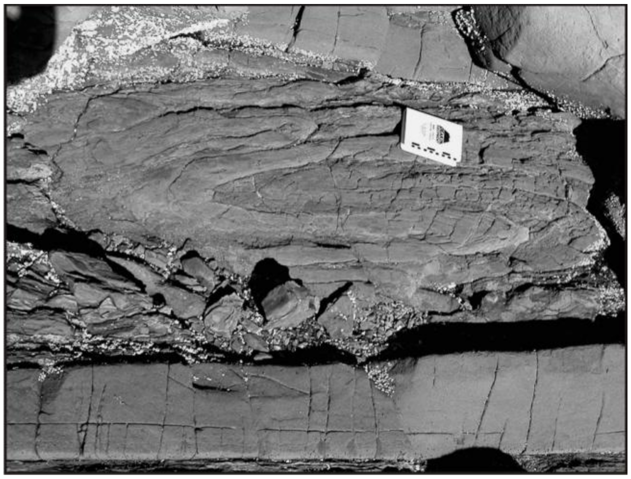


Figure 18. Slump fold within turbidites of Cedar District Formation. Left of photo is roughly west and fold vergence in general suggests westerly directed slump motion. Book is about 20 cm on longer edge.


Figure 19. Intense soft-sediment deformation in a sandy turbidite at Vesuvius Bay on Saltspring Island.

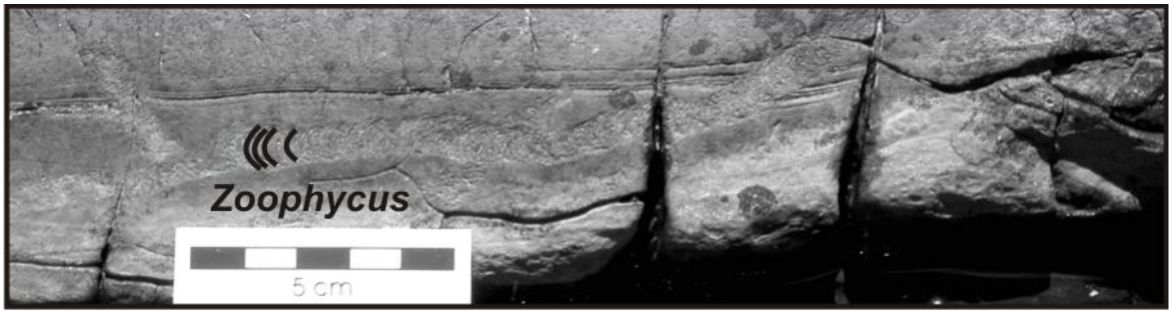


Figure 20. Extensive *Zoophycus* trace fossil in Cedar District Fm turbidites of the Vesuvius Bay section. View is a side view through typical *Zoophycus lateral* “arm” structure, with a few internal “spreiten” outlined for reference.

Figure 21. Photo of thin, flat bivalve fragments at Vesuvius Bay on Saltspring Island.

Figure 22. Close-up view of bivalve fragments at Vesuvius Bay on Saltspring Island; note the prismatic calcite crystals.

Figure 23. Specimen of Platyceramus platinus from the Smoky Hill Chalk on display at the Sternberg Museum, Kansas. This shell is about 1 m wide (scale = 10 cm). Source: Everhart (2010)

Figure 24. Artistic conception of Inoceramids on the ocean floor (Source: Everhart, 2010)

Sandstone samples collected for detrital zircons have been taken from both the top of the Protection Fm and from the base of the De Courcy Fm of this section. The youngest detrital zircons in both samples are about 75 Ma (+/- 3), thus compatible with the "late" Campanian age for Cedar District Fm. More interesting, in both samples >50% of the 60 zircons/sample are Proterozoic to Archean in age (mostly 1.3 to 2.6 Ga). Sources for such Precambrian zircons are absent in the local source areas, suggesting an influx of material from well east of the Coast Belt via a "big river" system (e.g. Mahoney et al. 1999).

Transect of Saltspring Island

After leaving Stop 3 we proceed to Ganges for a coffee break and then continue on to the southeast tip of the island to look at the Comox Formation and the basal unconformity of the Nanaimo Group. Along the route we will traverse a number of formations within the Nanaimo Group which can occasionally be seen in road cuts. Please refer to the Saltspring Island geology map (Greenwood and Mihalynuk, 2009) provided in pocket for the details of the different formations along the way.

Northeast trending faults cut all the map units. The Ganges thrust, along the Ganges-Booth Bay valley, and the Fulford thrust fault along the northeast side of the Fulford valley, both dip to the northeast. The latter fault places the Saltspring Intrusion over the younger Haslam Formation shale.

On the south side of Fulford valley, the Gulf Islands Fault separates Haslam shale from older volcanic rocks and dips to the southwest, probably as a high angle thrust fault (Greenwood 2009).

STOP 4: Ruckle Park: Comox Formation

Note:
All the outcrops at this stop are in a BC Park. No sampling is allowed.

The Comox Formation at Ruckle Park

The Comox Formation is the basal unit of the Nanaimo Group and is dominated by sandstone and conglomerate in most places, although significant coal deposits occur in the unit in northern areas (Cumberland, Comox areas). A geologic map and locations of measured sections in the Ruckle Park area are shown on Figure 25. Composite stratigraphic sections are provided in Figure 26.

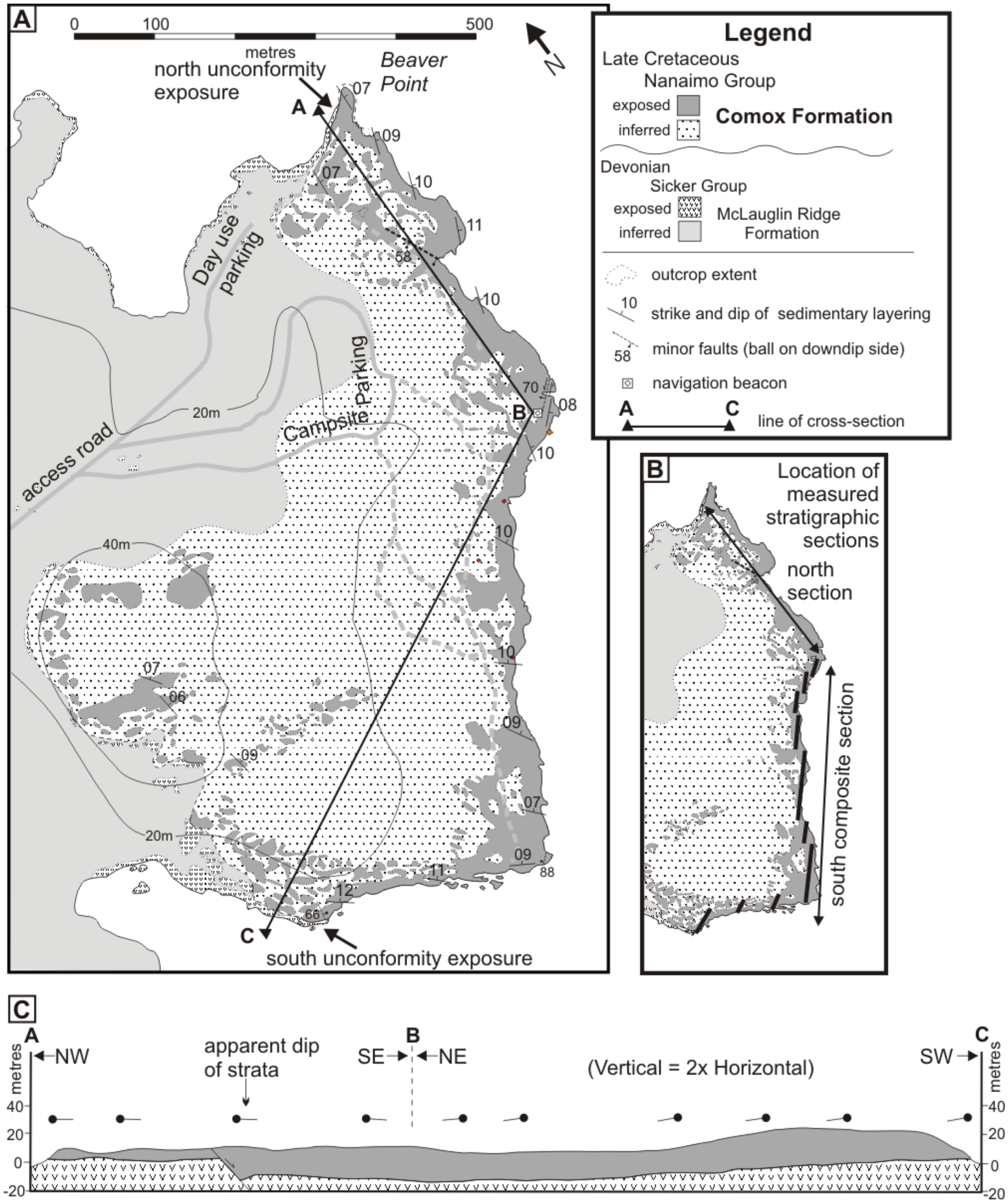


Figure 25. **A.** Geologic map of Beaver Point area of Ruckle Park. **B.** Location and general offsets for measured stratigraphic sections of Figure 13. **C.** Structural cross-section through area (see A for location of line of section.)

Age constraints on Comox Formation deposition (discussed with references in the introductory section) demonstrate that initial deposition was diachronous across the basin. The basin surface was irregular with significant (100's of m) of relief present. Initial deposition probably occurred in low areas or subaerial environments as early as Turonian time. By Santonian time (about 86 Ma) deposition was consistently occurring across the basin, suggesting lows had been infilled and the basin was subsiding significantly. Rare macrofossils from the Ruckle Park area suggest deposition here was probably occurring during Santonian time.

Although no detrital zircon samples have been collected from the Ruckle Park outcrops, a sample was collected in 2006 from about 200 metres north of the park, from sandstone about 10 metres above the basal unconformity. Of the 60 detrital zircons dated from this sample the youngest is 99 (+/- 2) Ma., compatible with the Comox Formation deposition occurring in Turonian to Santonian time (about 93.5 to 83.5 Ma). Of the remaining detrital zircons, more than 2/3 are Paleozoic in age, almost all Devonian with a few Carboniferous zircons. This is compatible with local Wrangellia Terrane sources, which have common Paleozoic volcanics and intrusives (including the local Devonian aged Saltspring Island intrusions). The remaining zircons are mostly Early Cretaceous, Jurassic or Triassic age, compatible with either Wrangellia or western Coast Belt sources. No Precambrian or other difficult to explain ages of detrital zircons are present.

Early deposition was subaerial in many places, but in most there is evidence of early shallow marine shoreface or shoreline deposition. Johnstone (2006) and Johnstone et al. (2006) demonstrated that in the southern Gulf Islands and Saanich Peninsula area of Vancouver Island, initial deposition occurred along a complex rocky shoreline.

Figure 27 is a cross-section of a model shoreface environment, displaying partitions defined by differing wave energy conditions, with facies shown for typically sandy and gravelly shorelines as well as typical ichnofacies. A block model of the southern Nanaimo Basin during early Comox Formation deposition is provided in Figure 28. Within the study area, the Comox Formation was deposited upon a partly emergent Wrangellia Terrane, with the majority of the terrane submerged. This means the shoreline was exposed to the full force of the proto-Pacific ocean storms. A rocky shoreline with high local relief results in varied energy conditions and distinct facies (Johnstone et al., 2006).

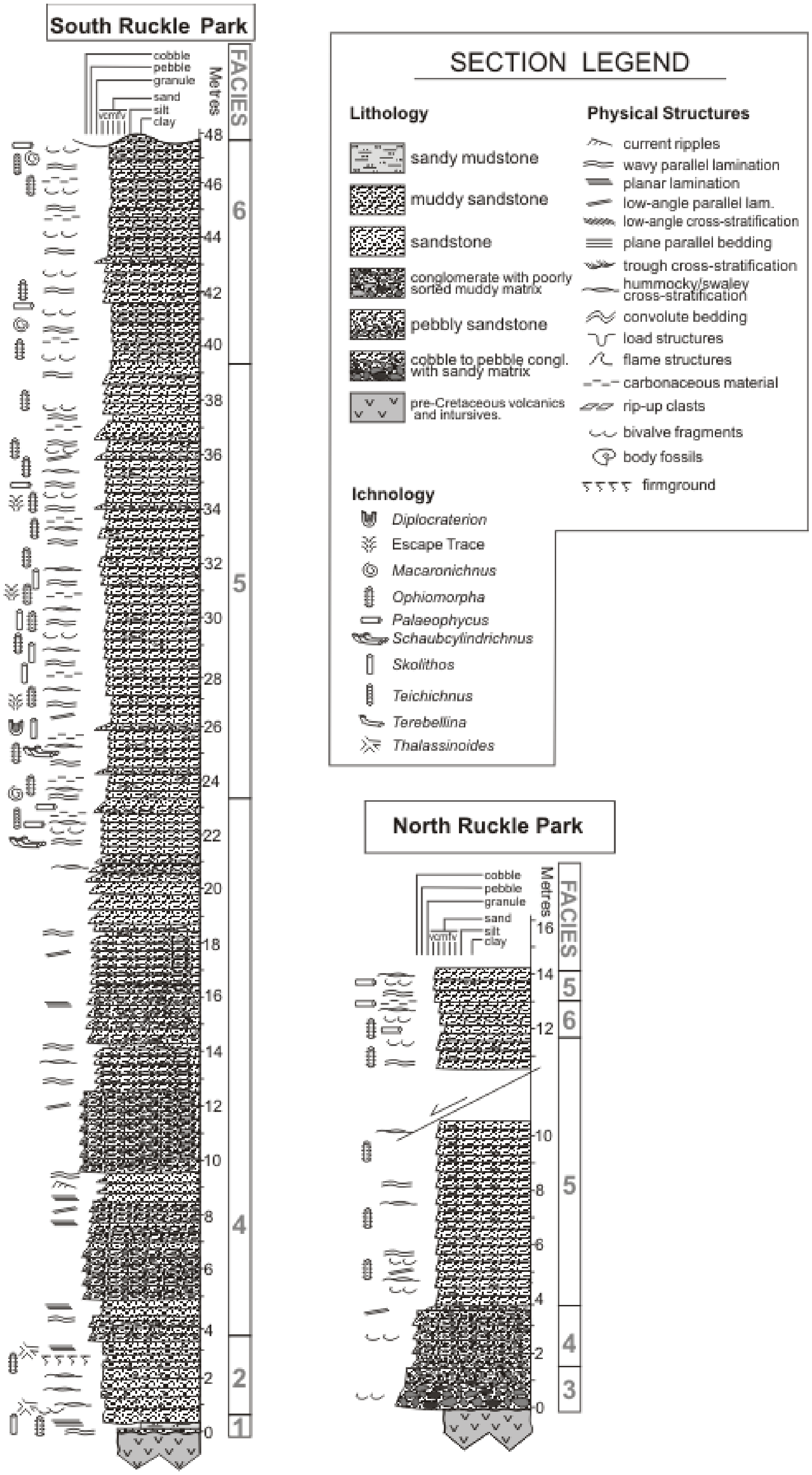


Figure 26. Measured stratigraphic sections from Beaver Point area of Ruckle Park. See Figure 25 for section locations (modified from Johnstone, et al., 2006).

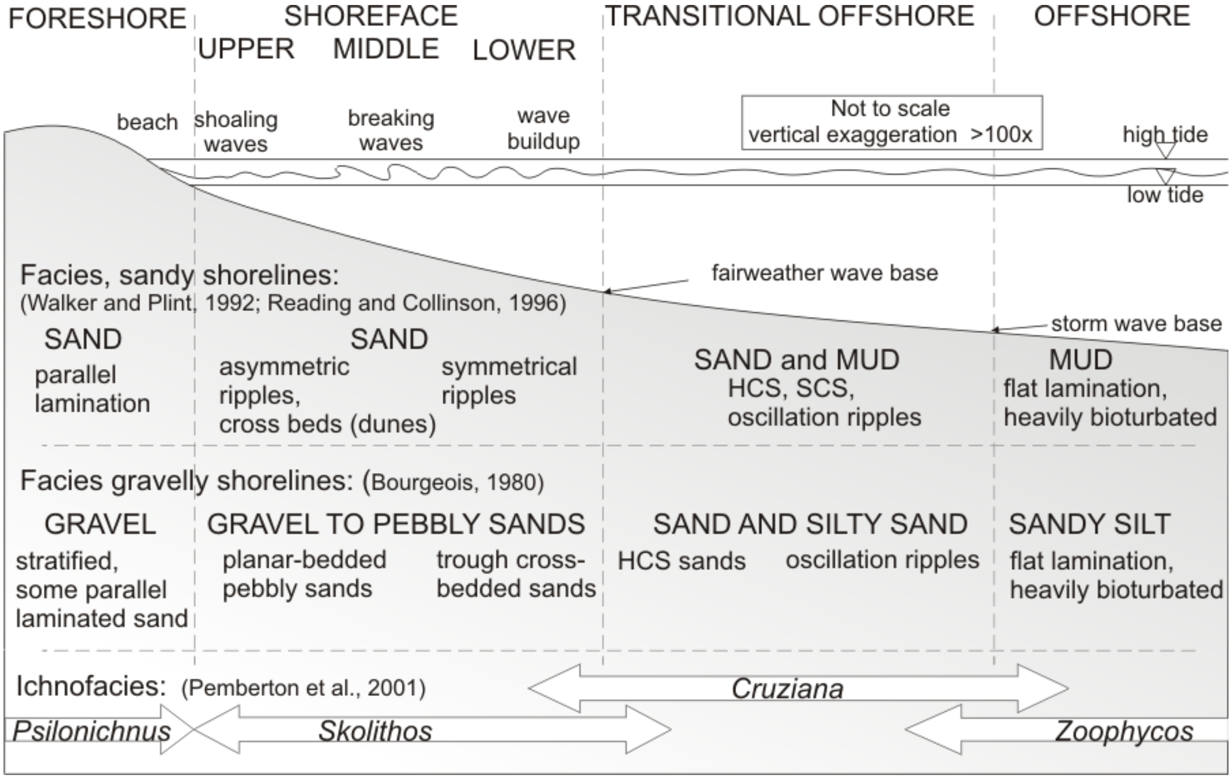


Figure 27. Cross-section of a model shoreface environment, displaying partitions defined by differing wave energy conditions, with facies shown for typically sandy (top) and gravelly shorelines (middle), plus typical ichnofacies (of a non-gravelly substrate). Figure 27 of Johnstone (2006), based on models by Bourgeois (1980), Walker and Plint (1992), Reading and Collinson (1996), with ichnofacies after Pemberton et al. (2001).

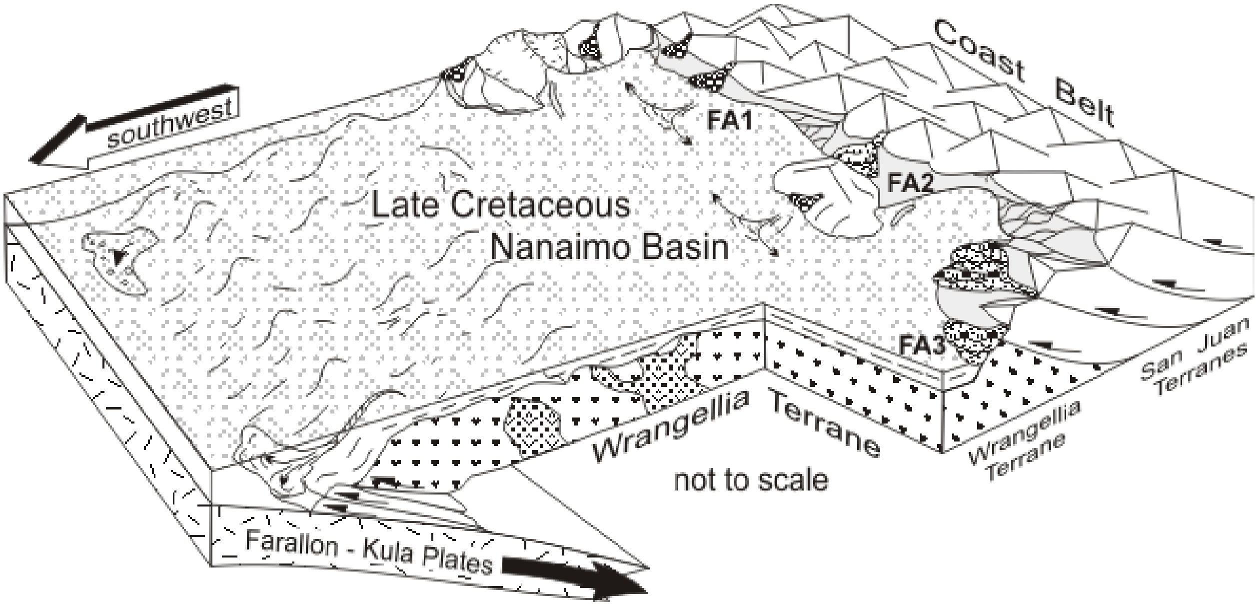


Figure 28. Block model of the southern Nanaimo Basin during early Comox Formation deposition. Within the study area, the Comox Formation was deposited upon a partly emergent Wrangellia Terrane, with the majority of the terrane submerged. This means the shoreline was exposed to the full force of the proto-Pacific ocean storms. A rocky shoreline with high local relief results in varied energy conditions and three distinct facies associated: FA1, storm-dominated rocky shoreline; FA2, low-energy rocky shoreline; and FA3, drowned fan delta. Modified from Figure 11 of Johnstone et al., (2006).

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