Hydrogeological Investigation of Quaternary and Late Cretaceous Bedrock Aquifers, Comox Coalfield, Vancouver Island, British Columbia, Canada.

Gypsy C. Fisher
B.Sc., University of Victoria, 2003

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MASTER OF SCIENCE

In the School of Earth and Ocean Sciences

Supervisory Committee

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We accept this thesis as conforming to the required standard

Dr. Vic Levson, Co-Supervisor (School of Earth and Ocean Sciences, University of Victoria; and, BC Ministry of Energy, Mines and Petroleum Resources)

Dr. Kevin Telmer, Co-Supervisor (School of Earth and Ocean Sciences, University of Victoria)

Dr. Mel Best, Departmental Member (School of Earth and Ocean Sciences, University of Victoria; and, Bemex Consulting International)

Dr. Diana Allen, Additional Member (Department of Earth Sciences, Simon Fraser University)

Abstract

Supervisory Committee

Dr. Vic Levson, School of Earth and Ocean Sciences, University of Victoria; and, BC Ministry of Energy, Mines and Petroleum Resources
Co-Supervisor

Dr. Kevin Telmer, School of Earth and Ocean Sciences, University of Victoria
Co-Supervisor

Dr. Mel Best, School of Earth and Ocean Sciences, University of Victoria; and, Bemex Consulting International
Departmental Member

Dr. Diana Allen, Department of Earth Sciences, Simon Fraser University
Additional Member

This study involved a regional hydrogeological assessment of the Comox Coalfield on Vancouver Island, British Columbia. Two site-specific geological and hydrogeological investigations were conducted. The first involved generating a 2.5 dimensional hydrostratigraphic model of part of the Quadra Sand Comox-Merville Aquifer using lithology information from 196 drilled domestic-use groundwater wells. Well logs were standardized with respect to lithologic and hydraulic characteristics. Contact surfaces were created for identifiable hydrostratigraphic units employing an iterative geostatistical interpolation process that incorporated contact points from well logs and interpreted points based on the regional hydrogeology. Modeled hydrostratigraphic surfaces were compared to logged contacts and to exposures at Willemar and Lazo bluffs at Comox. Six lithostratigraphic units were identified in the coastal exposures. Hydraulic conductivity values, estimated from grain size data using the Hazen method, for the lowermost 4 units were: 2.3 x 10^{-3} cm/s, 9.1 x 10^{-6} cm/s, 9.4 x 10^{-3} cm/s, and 4.7 x 10^{-6} cm/s, respectively. The hydrostratigraphic model was verified using statistical variance analysis, field reconnaissance data, and the identification of a separate surficial aquifer within the study area. The model identified all units mapped in the field and two units below sea level, inferred to be the Cowichan Head

Formation. The Comox Bluff model successfully predicted, within 2 m vertically, subsurface hydrostratigraphic boundaries 80% of the time.

The second component of the study included a hydrogeological investigation of stacked Quaternary and Late Cretaceous bedrock aquifers at Oyster River. This investigation incorporated drilling logs, borehole geophysics, aqueous geochemistry, pumping and recovery test data, and hydrostratigraphic interpretation of surficial exposures. The potential for hydraulic communication between the Late Cretaceous Nanaimo Group fractured sedimentary bedrock and the overlying unconsolidated Quaternary aquifers was examined. Two adjacent groundwater observation wells were drilled; one completed in bedrock (146.9 m) and one in the surficial sediments (7.3 m). The deeper well penetrated the Trent River and Comox Formations of the Nanaimo Group. A water-bearing fracture zone approximately 3 m wide was encountered at 135 metres below ground surface, coincident with the Comox Y and Y Lower coal seams. Dissolved methane gas was detected in the bedrock aquifer, with an initial concentration of 2,123 mg/L. Schoeller diagrams reveal that the gas in bedrock is coal related.

A pumping and recovery test in the deep well suggests that there is unlikely any hydraulic communication between the bedrock and surficial aquifers encountered at Oyster River. This assessment is based on infrequent water level measurements in the shallow well, which did not consistently draw down during pumping of the deeper well. However, the pumping rate was not sustainable for this test and it could not be held constant. Fracture transmissivity and hydraulic conductivity for the bedrock aquifer were estimated using the Theis Recovery method at 7.06×10^{-7} m^2/s and 2.29×10^{-7} m/s, respectively.

The hydrogeological research conducted at Comox and Oyster River highlights the effectiveness of a multidisciplinary approach for subsurface investigations. This study contributes site level data upon which regional inferences can be built for the Comox Coalfield.

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Acknowledgements

In response to the need for further hydrogeological baseline data in the Comox Coalfield, a collaborative endeavour was initiated in 2005 between the BC Ministry of Energy, Mines and Petroleum Resources and the BC Ministry of Environment to drill and test three new groundwater observation wells in the central eastern region of Vancouver Island. The innovative and cooperative attitudes of these Ministries have been a great support to this research; to all involved I am very grateful. Furthermore, without the financial and technical support of the BC Ministry of Energy, Mines and Petroleum Resources, this valuable work could not have been accomplished.

I would like to thank Dr. Vic Levson for offering me the opportunity to work together, and for always keeping an open and positive attitude. I have greatly appreciated learning from you and I will always keep close the lessons that I have learned. I would also like to thank Dr. Diana Allen and Dr. Mel Best for your never-ending patience with me; I feel honoured that you gave me so much of your time and energy.

I would like to say a special thank you to my loving husband, Jordan, without whom I surely would never have finished this degree. Your undying support, encouragement and patience means more to me than words can express. Thank you. Thanks too to my brother, Jai, who is ever my beacon of balance in this life.

Dedication

I dedicate this thesis and MSc degree to my mother, Yogesha Bennun.

You are and always will be my hero. I love you, and I thank you.

1 Thesis Introduction

1.1 Coalbed Gas Development in British Columbia, Canada

The groundwater resources of British Columbia (BC), Canada are becoming of increasing concern with respect to growing demands for domestic water supply, as well as for the industrial needs of the Province's burgeoning oil and gas sector. Coalbed gas (CBG) is natural gas found in coal seams, and is primarily composed of methane gas, but commonly associated with trace amounts of carbon dioxide and nitrogen. Once produced, coalbed gas is very similar to conventional natural gas; however, unlike conventional natural gas, CBG tends not to contain impurities such as hydrogen sulphide, and is therefore considered "sweet" or a clean energy source. Coalbed gas is generally of near-pipeline quality when produced, not requiring extensive processing and, consequently, is of increasing interest to the Province of British Columbia. Upon drilling into the coal seam, groundwater associated with the seam is pumped out, thereby reducing the pressure and consequently releasing the gas. Typically CBG is produced from 200 m to 2 km below ground surface (bgs), and is either found to be "dry" with all void spaces filled with gas, or "wet" where both gas and associated groundwater are found together in the coal seam. The quality of coalbed gas produced water varies according to geology, depth and age (i.e., mineralization time of the water).

There have been 89 test holes for CBG drilled in BC since 1984; 58 of them from 2001 to present, 14 were drilled in 1984 on Vancouver Island, and one well drilled in 2001/02 but which is now inactive (Ryan, 2002; Ryan *et al.*, 2005). The BC Oil and Gas Commission regulates the development of coalbed gas throughout the province. Companies are required to test water wells within a 1 km radius of a CBG well (samples taken before and after drilling). Surface casing is required to be set below the base of all strata known, or reasonably expected, to serve as a source of drinking water, and at least 25 m into a competent formation.

1.2 The Comox Coalfield on Vancouver Island, British Columbia

The Comox Coalfield on Vancouver Island, BC was chosen as the overall region of interest for this thesis. It offers both active community groundwater aquifers as well as sites for potential coalbed gas development. The coalfield itself extends over one thousand square kilometres, and is one of two major coalfields on Vancouver Island (the Nanaimo Coalfield is situated further south) with a total coal resource in the range of 3 billion tonnes and an *in situ* gas resource of about 0.65 trillion cubic feet (tcf) (Bickford and Kenyon, 1988; Ryan *et al.*, 2005). The major coal seams of interest are located within the lower strata of the Late Cretaceous Nanaimo Group sedimentary sequence (Mustard, 1994). Overlying the basement Karmutsen volcanics, the Dunsmuir and Cumberland members of the Comox Formation are host to the region's significant coal resources. These members range in cumulative thickness from 3 to 14 m at various intersected localities, thus there is growing confidence in potential new coal-related uses such as coalbed gas (Ryan *et al.*, 2005). The coalbed gas reserves of the Comox Coalfield lie below 450 m and may extend to depths as great as 1,500 m, well within the depth range of coalbed gas extraction techniques (Cathyl-Bickford, 1991). Gas compositions obtained from coal exploration programs within the coalfield reveal that the gas is of acceptable quality for a gas-transmission system (Refer to Section 2.2.3).

To date, few holes have been drilled for coalbed gas pilot projects within the Comox Coalfield, so there are limited data to determine the possible impacts of future CBG activities on the regional hydrogeology. In an attempt to address this question with the limited data available, this thesis focuses initially on the development of site-specific hydrogeological investigations that will contribute baseline data upon which a generalized conceptual model of the region can be created. Study sites for this research are located throughout the Comox Coalfield, and exemplify a broad array of geological and hydrogeological environments, including: the fractured sedimentary bedrock host to several coal, inland paleo ice-marginal glaciofluvial deltas, thick sequences of ice-proximal glaciomarine sand deposits, and a modern-day marine fan delta. Combined, these environments characterize much of the hydrogeological regime of the Comox Coalfield.

Of the four wells drilled during the course of this thesis research, the deep well drilled at Union Bay produced very little saline water and was subsequently abandoned. The paired wells at Oyster River, as well as the surficial well completed within the T'Sable River fan delta, continue to be monitored through the BC Ministry of Environment's groundwater observation network (BC MoE, 2001). This thesis details the hydrogeological investigations conducted at Comox and Oyster River within the Comox Coalfield, Vancouver Island, British Columbia, Canada.

1.3 Purpose of Research and Objectives

Detailed baseline studies conducted at selected sites may offer a means to better understand how stratigraphy might influence fluid flow and allow for inferences on the natural hydrogeological variance throughout the region. With the onset of new oil and gas industries such as coalbed gas development as well as increasing interest in groundwater resources within the region, the potential of user conflict arises. Consequently, research that investigates the region's hydrogeology and potential for aquifer communication can aid in management decisions and help to inform pertinent stakeholders.

The overall purpose of this research is to contribute to understanding of the hydrogeology of the Comox Coalfield region on Vancouver Island, BC. This is accomplished by mapping the hydrostratigraphy of the extensive surficial aquifers to infer lateral continuity of units, and by assessing the potential interaction between these surficial aquifers and the underlying fractured sedimentary bedrock which contains the coalbed gas. The research is driven by two main hypotheses: (1) that lithologic logs from water well records can provide sufficient information with which to map the regional hydrostratigraphy, and (2) that a multidisciplinary approach provides value to baseline hydrogeological investigations.

A common lament in the literature is that well logs are often an unreliable data source and ought to only be used as a supplemental source of information (Kenny *et al.*, 1997; Russell *et al.*, 1998). However, in practice, areas of suppressed topography may not have many exposed sections or other forms of data other than pre-existing boreholes (Levson *et al.*, 2004; Smith *et al.*, 2005). Consequently, well logs continue to be a frequently used data source for subsurface investigations. As well, data standardization can add value and confidence to subsequent hydrogeological interpretations (Ross *et al.*, 2005; Parent *et al.*, 2003; Toews and Allen, 2007).

The first objective of this research is to assess the utility of groundwater well logs for subsurface hydrogeological investigations by employing an interpretive framework. This will be accomplished by constructing a hydrostratigraphic model based on groundwater well log data, using field reconnaissance and variance analysis to verify the model. An expert-driven data standardization process is developed for the drillers' descriptions in order to clarify the hydrogeological significance of the logged observations and build confidence in the subsequent interpretations.

The second research objective is to assess hydraulic communication between stacked surficial and fractured bedrock aquifers. To achieve this, a multidisciplinary approach to site-level hydrogeological investigations is emphasized, and includes drill logs, borehole geophysics, aqueous geochemistry, pumping and recovery test data, and field reconnaissance of surficial exposures. Data collected from the paired groundwater observation wells drilled for this study contributes to the hydrogeological understanding of both Quaternary sediments and the underlying fractured Nanaimo Group sedimentary bedrock sequence.

2 Geology and Hydrogeology of the Comox Coalfield Region, Vancouver Island, British Columbia, Canada.

2.1 Physiography

The study area spans much of the length of the Comox Coalfield, situated within the central-east coast region of Vancouver Island, BC, Canada. The communities of Campbell River and Qualicum lie to the north and south, respectively, while Courtenay and Comox are situated in the middle of the area (Figure 2.1). The Comox Coalfield includes both upland areas abutting the inland Beaufort Mountain range to the west, and coastal lowland areas bordering the Strait of Georgia to the east. The Beaufort Mountains, with an elevation exceeding 1,500 m are likely a recharge area for the region's coastal lowland bedrock aquifers, which drain into the Strait of Georgia (Figure 2.2).

The physiography of the study area is primarily comprised of the coastal lowlands along the central-east coast of Vancouver Island. In many places the boundary between the mountain slope to the west and the undulating coastal lowland approximates the contact between the Nanaimo Group sedimentary bedrock and the basement rocks below (Mustard, 1994; Figure 2.3). Roughly 4 km in width, the coastal lowlands constitute the unsubmerged southwestern edge of the Georgia Depression, rising from sea level to an average elevation of 200 m. Having been completely covered by glacial ice during the Pleistocene epoch, resultant glacial and glaciomarine deposits almost entirely cover the coastal lowland area, thereby controlling the region's topography (Fyles, 1963). Prominent features of the study area include: large raised glaciofluvial deltas aligned along the mountain front; thick pro-glacial sediments exposed in coastal sea cliffs; and, steep-walled river valleys exposing thick sections of shale and sandstone, thinly blanketed by unconsolidated glacial deposits.

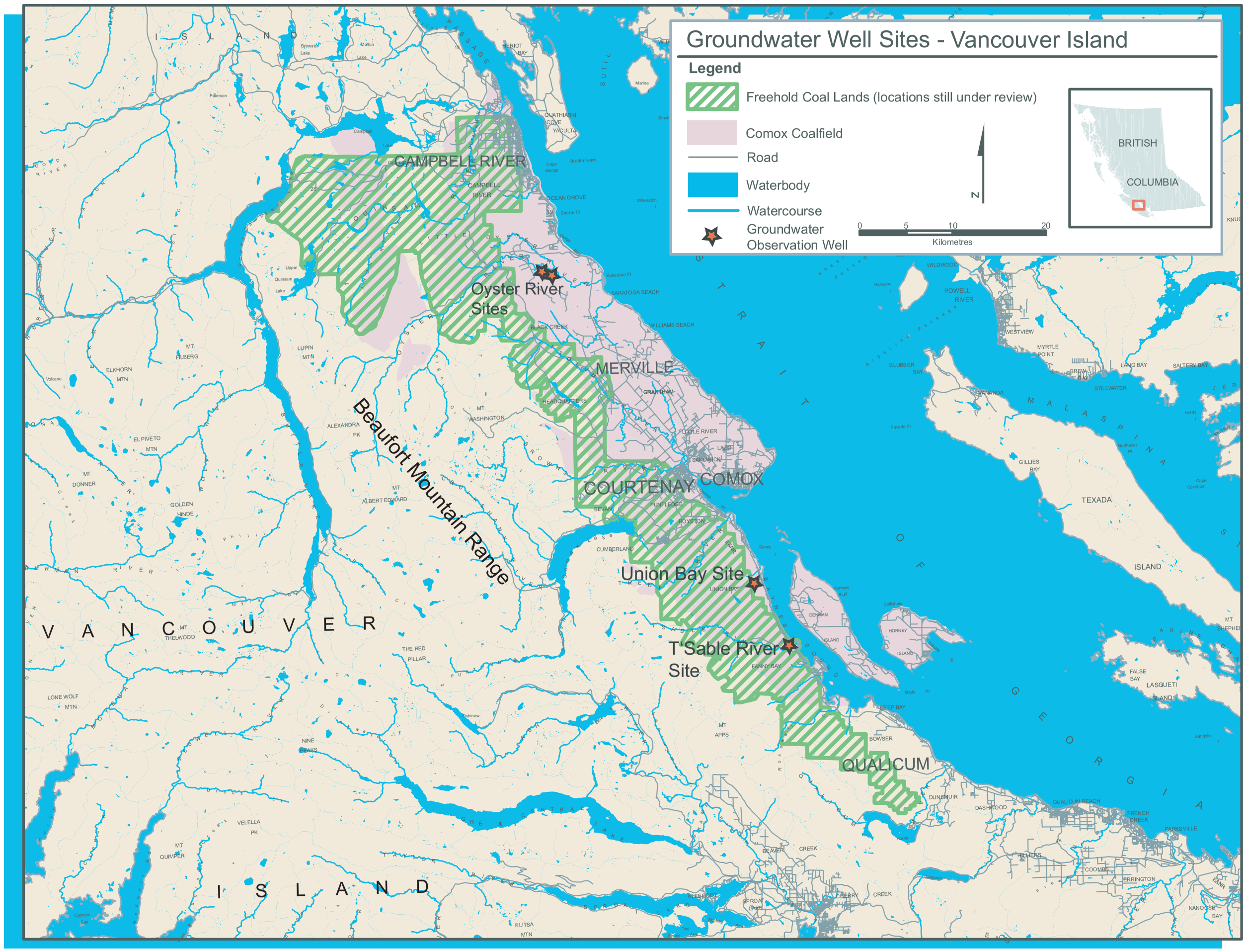


Figure 2.1. Study sites within the Comox Coalfield, Vancouver Island. Four groundwater observation wells were drilled in the course of this research. The paired wells at Oyster River and the surficial well at T'Sable River continue to be monitored as part of the BC Ministry of Environment's groundwater observation network. The bedrock well at Union Bay produced very little saline water and was subsequently closed.

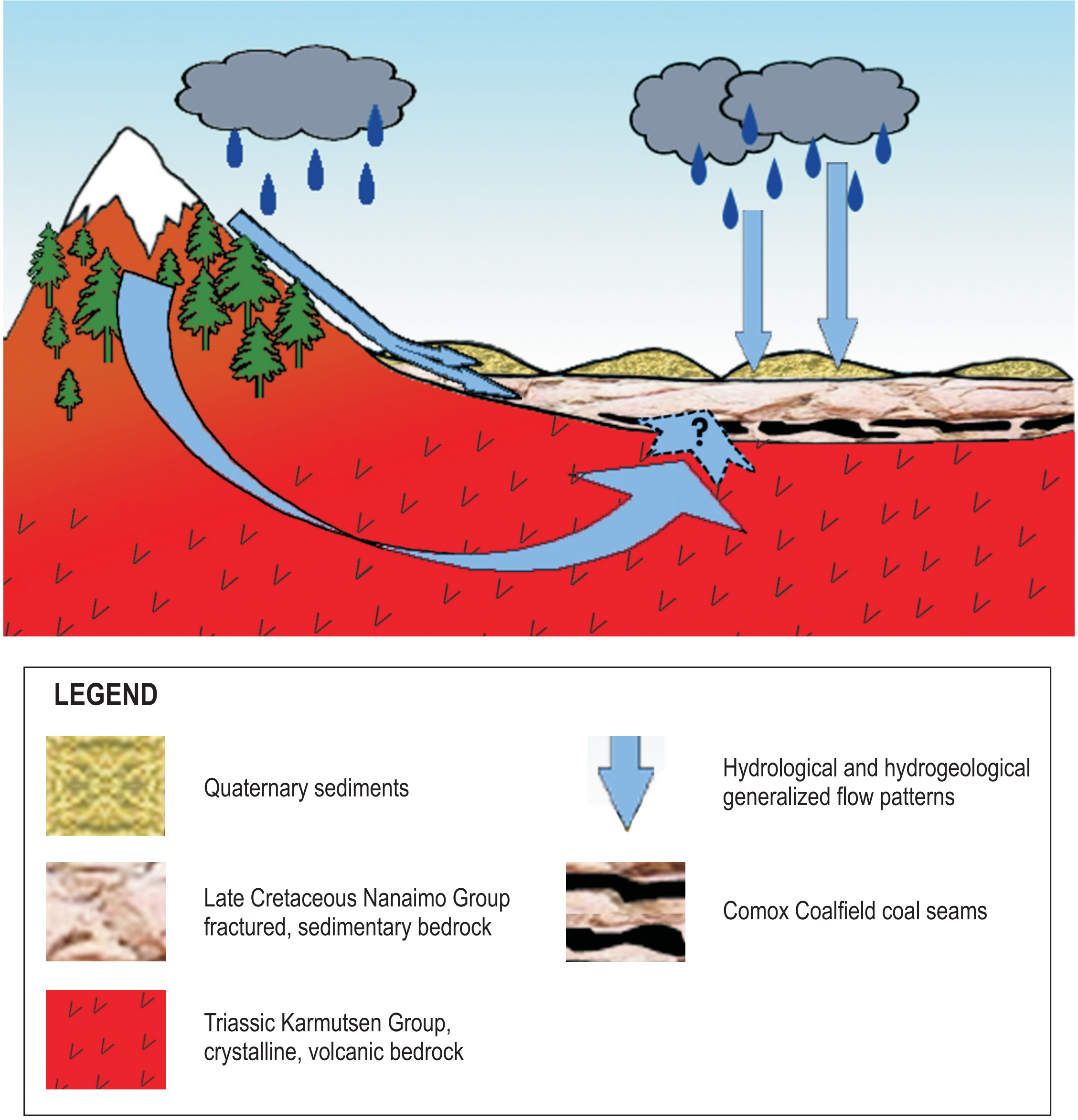


Figure 2.2. Conceptual diagram of the regional groundwater flow for the Beaufort Mountains and coastal lowlands.

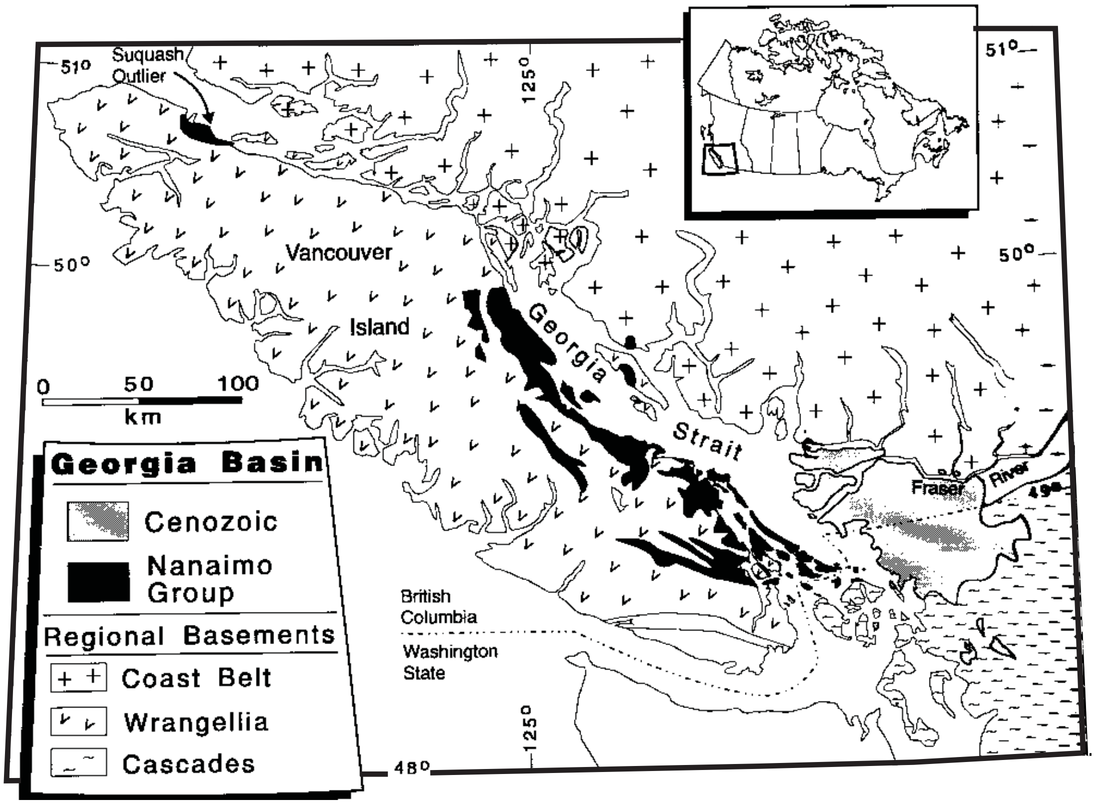


Figure 2.3. Regional setting of Georgia Basin. From Mustard (1994).

2.2 Bedrock Geology

2.2.1 Stratigraphy

The Upper Cretaceous Nanaimo Group, which hosts the coal measures of Vancouver Island, is one of the main sedimentary bedrock sequences within the Georgia Basin and unconformably overlies the Wrangellia terrane basement (Figure 2.3). With a stratigraphic thickness greater than 5 km, the Nanaimo Group spans Turonian to Maastrichtian ages, corresponding to about 91 ± 3 to 66 ± 2 million years ago (Mya) (Mustard, 1994; Ryan, 2002). Studies on the depositional environment of the Nanaimo Group have largely concluded that much of the sequence was deposited in a relatively deep marine environment roughly from sub-wavebase shelf to 2,000 m water depths (England, 1989; Mustard, 1994). Sediment gravity flows have been determined as the major depositional process and submarine fans as the main depositional system.

The Georgia Basin can be separated into two distinct sub-basins, the Nanaimo Basin in the south and the Comox Basin in the north (Figure 2.4). The former encompasses about 780 km^2, while the latter covers approximately 1,230 km^2 and hosts the Comox Coalfield (Bickford and Kenyon, 1988). Separate formation and member nomenclature for the Nanaimo and Comox Basins has been proposed by Bickford *et al.* (1990) as not all of the strata can be traced between the two sub-basins. Within the Comox Basin, the Comox Formation is the oldest of four formations contained within the Nanaimo Group. The Comox Formation is overlain by the Trent River, Protection, and Cedar District formations (Bickford *et al.*, 1990). Generalized stratigraphy is illustrated for the Comox Basin in Figure 2.5 (Harland *et al.*, 1990) and lithostratigraphic units are illustrated in Figure 2.6 (Bickford *et al.,* 1990; Cathyl-Bickford, 2001), respectively. Mostly nonmarine to shallow marine interpretations of the depositional environment are given for the coal-

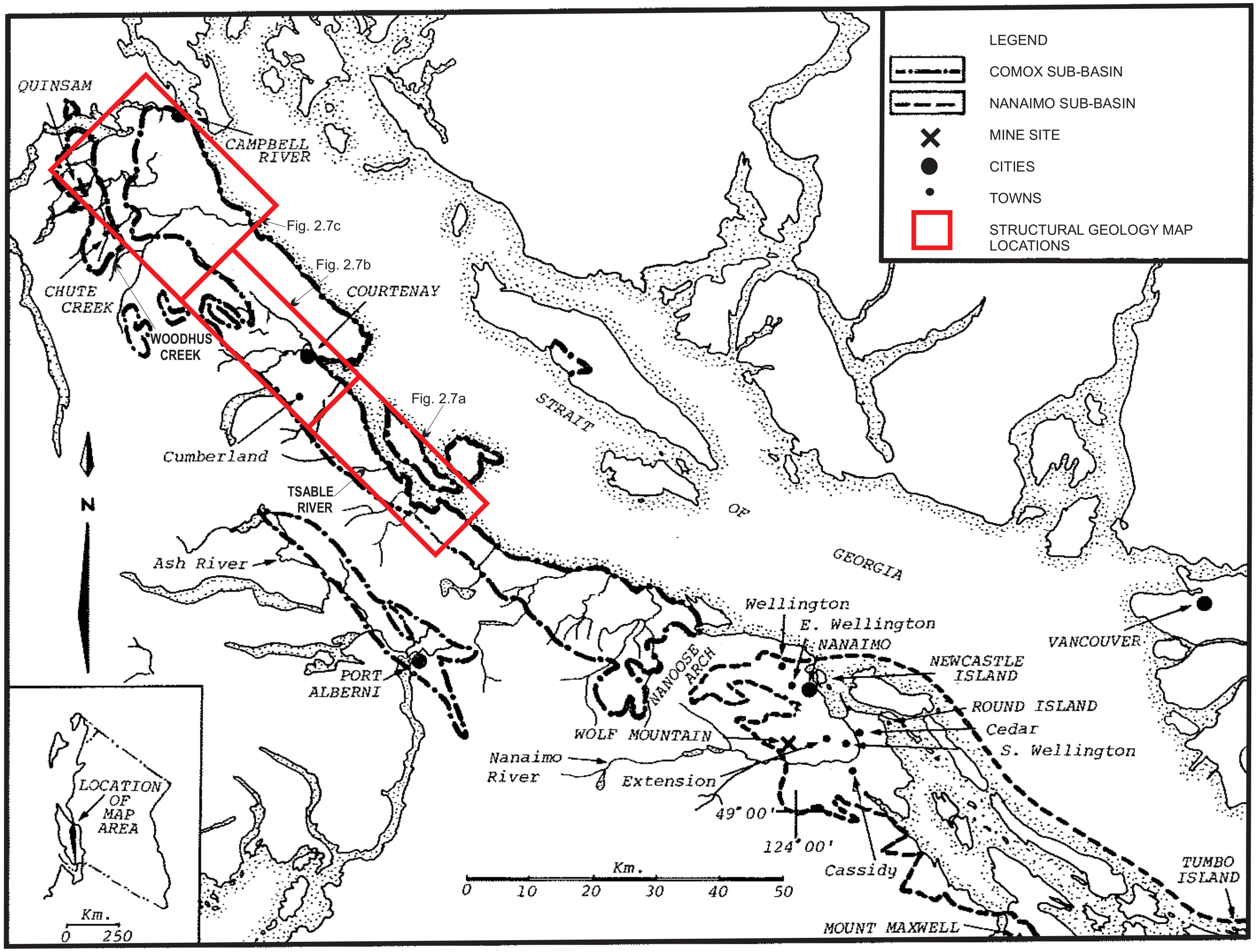


Figure 2.4. Vancouver Island Coal Basins. After Bickford and Kenyon (1988). Structural geology maps for the study area are detailed in Figures 2.8a, 2.8b and 2.8c. Regional Comox coal seams are summarized in Table 2.1, with sub-basin locations identified in Figure 2.3.

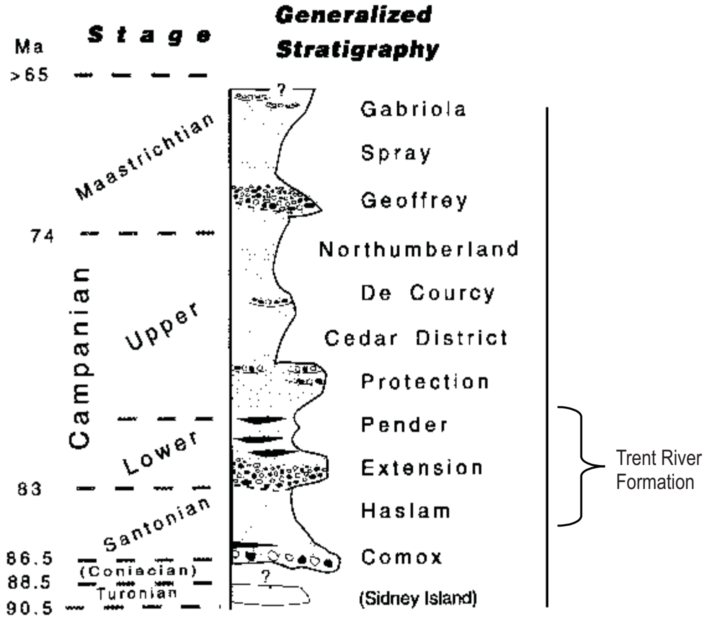


Figure 2.5. Generalized stratigraphy of the Nanaimo Group, Comox Basin. Modified from Harland *et al*. (1990).

Formation:	Member:	Lithology:
Cedar District		Mudstone and siltstone.
		Intertonguing contact
Protection		Sandstone and conglomerate.
		Erosional contact
Trent River	Willow Point	Shale.
	Baynes Sound	Sandstone.
	Oyster River	Coal measures.
	Royston	Shale.
	T'Sable	Conglomerate; minor sandstone and siltstone.
	Browns	Sandstone; minor siltstone.
	Puntledge	Shale; mudstone and siltstone.
	Cowie	Sandstone; minor siltstone, bioturbated.
	Cougarsmith	Shale; mudstone and siltstone, minor sandstone.
		Intertonguing contact
Comox	Dunsmuir	Sandstone; minor siltstone, shale, coal and conglomerate.
	Cumberland	Siltstone and sandstone; minor shale and coal.
	Benson	Conglomerate and red siltstone.
		Erosional contact
	Pre-Cretaceous volcanic, plutonic and metasedimentary basement.	

Figure 2.6. Lithostratigraphic units of the Lower Nanaimo Group, Comox Basin. Modified from Bickford *et al.* (1990) and Cathyl-Bickford (2001).

bearing Comox Formation, and member subdivisions have been proposed by Bickford and Kenyon (1988), Bickford *et al.* (1990), and Cathyl-Bickford (1992).

Encompassing three dominant depositional environments, the Comox Formation has been subdivided into three geologic members by Bickford and Kenyon (1988): the Dunsmuir, Cumberland and Benson members (Figure 2.6). The basal Benson member consists of up to 300 m of dark green and brown, basaltic, cobble to boulder conglomerate with lenses of shale, siltstone, volcanic wacke and rare, thin coals. The Benson conglomerate is overlain by the Cumberland member with 30 m to 150 m of dark grey siltstone, carbonaceous shale, sandstone and coal. The Dunsmuir member abruptly caps the Cumberland member and consists of 120 m to 150 m of thick-bedded, medium grained, quartz and feldspar-rich sandstones, with widely spaced interbeds of dark grey shale and coal (Bickford and Kenyon, 1988). Within the Comox Basin, persistent coal measures that dip slightly eastward are found in both the Cumberland and Dunsmuir members (Figure 2.7). The Benson member is absent throughout most of the basin and, consequently, the Cumberland member unconformably overlies the Karmutsen Formation in many areas. The Karmutsen Volcanics form the economic basement for coal mining within the study area (Cathyl-Bickford, 2001).

The Trent River Formation has been subdivided into nine members within the Comox Basin, which cumulatively describe alternating deposits of shale and sandstone, with the T'Sable conglomerate located in the middle of the formation (Bickford and Kenyon, 1988; Cathyl-Bickford, 1992, 2001; England 1989). Abruptly overlying the Trent is the Protection Formation (Figure 2.6), with interbedded sandstone and conglomerate deposits (Bickford *et al*., 1990). The Cedar District Formation's mudstone and siltstone is the uppermost deposit of the Lower Nanaimo Group sequence in the Comox Basin (Bickford *et al*., 1990). The Trent River, Protection, and Cedar

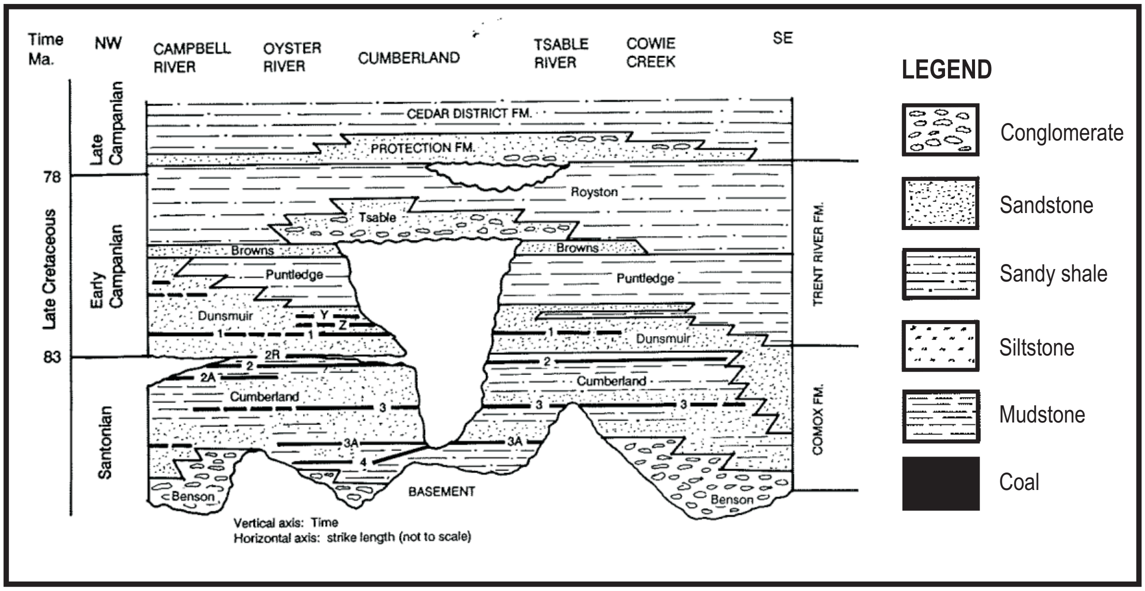


Figure 2.7. Chronostratigraphic diagram of the Lower Nanaimo Group.
After Bickford *et al*. (1990).

District Formations have been interpreted to be deposited in marginal to shallow marine facies (Mustard, 1994).

2.2.2 Structural Geology

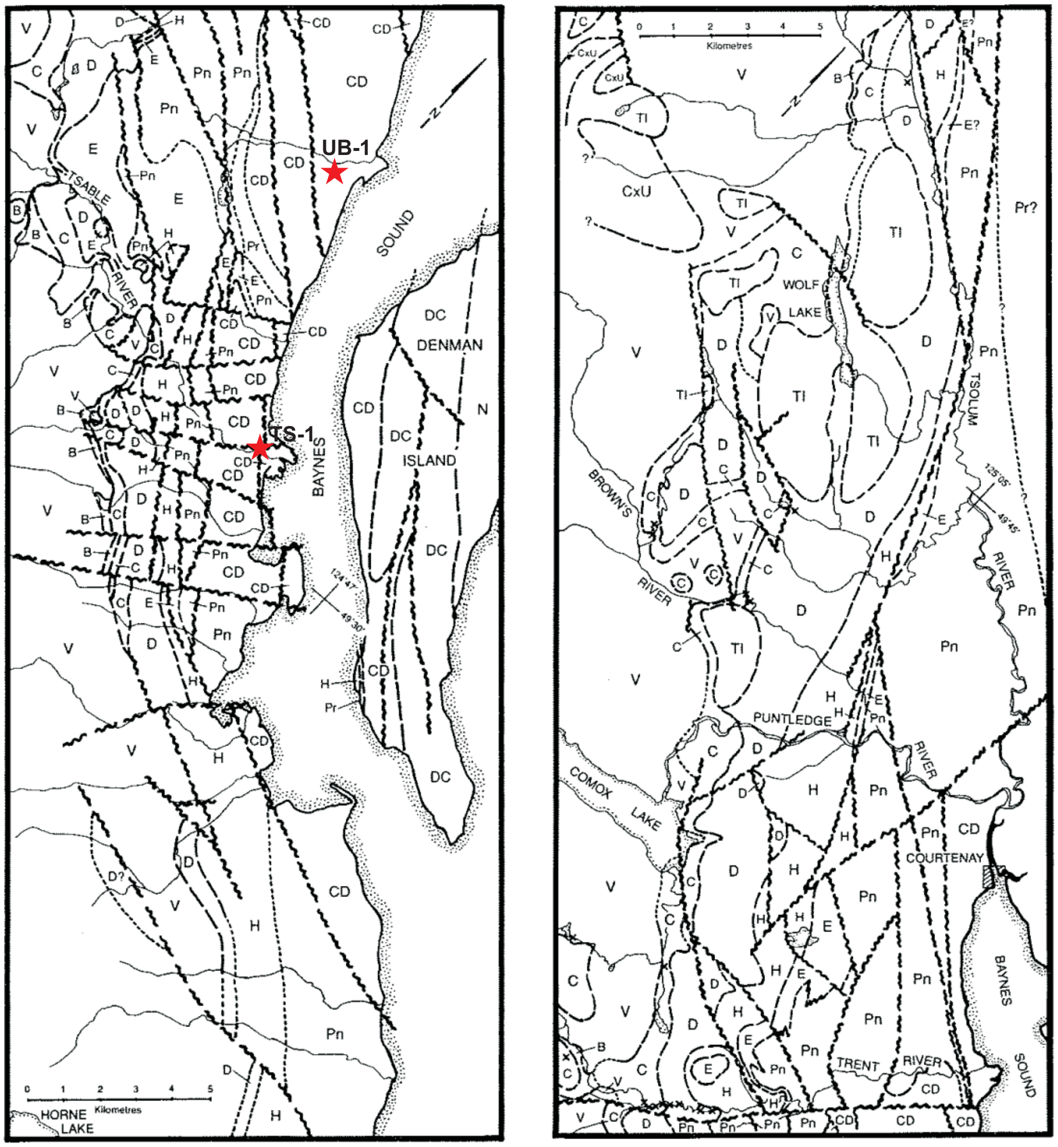
The Georgia Depression, at least 100 km wide and a minimum of 250 km long, is one in a series of elongate forearc basins initially developed in the Late Cretaceous (Mustard, 1994). The Depression was formed by the subduction-related lithospheric downwarping of the Wrangellian crust as it became trapped within the arc-trench gap during convergence on the Pacific margin of North America (ca. 88.5 – 68 Mya) (England, 1989). Contrasting the significantly more complex Cowichan Fold and Thrust System primarily affecting the Nanaimo Basin, the Comox Basin is generally considered a large homocline as it dips gently to the northeast, and which is cut by a few large high angle faults with inferred normal dip-slip and strike-slip movement (Muller and Jeletzky, 1970; England, 1989). The compressional tectonic stresses of the Late Cretaceous period (ca. 68 – 66.5 Mya), exhibited by the deformation of exposed strata, postdate basin formation and Nanaimo Group sedimentation (England and Calon, 1991; Mustard, 1994). The Comox Basin is thought to have ridden passively on a deep thrust system, staying mostly undeformed during contraction, and remaining at or near maximum burial from the end of the Cretaceous Period to at least the mid-Eocene (ca. 66.5 – 45 Mya) (England, 1989). Transpressional folding and thrusting in the southern half of the basin developed structures displaying south westward convergence, while north eastward back-thrusts occur locally in the upper Nanaimo Group (Cathyl-Bickford, 1991). Faults following bedding near the base of the Benson member, shearing the coal of the Comox Formation, are facilitated by, and in tectonic contact with, the basement paleo-surface (Bickford *et al.*, 1990).

Three sets of extensional faults have been identified to cut the southern area of the basin homocline and overly the predominant strike-slip shear zone at depth (Cathyl-Bickford, 1992). Displacements throughout the basin appear to be within the tens to hundreds of metres range (Mustard, 1994). The upper limit of contraction is constrained to late Eocene time (ca. 40 Mya) by fission-track ages and thermal history modeling (England and Calon, 1991). Uplift of the entire region during the Cenozoic resulted in deep exhumation of the western part of the Georgia Basin, with an inferred eroded section thickness of 2 km to 6 km (England, 1989). For further detail on the origin and structural history of the Georgia Basin, refer to England (1989). Geologic and structural maps of the Comox Basin are illustrated in Figures 2.8 a, 2.8 b and 2.8 c.

The locations of the groundwater observation wells drilled during this study are also highlighted on Figures 2.8 a, 2.8 b and 2.8 c: OR-1&2 are paired bedrock and surficial wells drilled proximate to the Oyster River; UB-1 is a bedrock well drilled in the community of Union Bay; and, TS-1 is a surficial well drilled within the modern fan-delta of the T'Sable River. For further information on the two wells drilled at Oyster River refer to Chapter 4. The Union Bay well was drilled to a depth of 100 m below ground surface (bgs). Very little saline water was produced at approximately 25 m bgs; however, the well was deemed effectively dry and was subsequently closed. The drilling log of the Union Bay well is included in Appendix 5.1. The drilling log and aqueous geochemical analysis of the surficial well drilled at T'Sable River is provided in Appendix 5.2.

2.2.3 Coal Geology and Coalbed Gas Content

The Comox Coalfield itself encompasses over 1000 km^2 (Figure 2.1), and is elongate in shape. The coalfield stretches across the Comox Basin reflecting the northwest-southeast alignment of Vancouver Island and the Georgia Depression. Vitrinite reflectance data show that



(a) (b)

Figures 2.8a&b. Geology of the Comox Basin. Modified from Bickford and Kenyon (1988). Refer to Figure 2.8c for legend. See Figure 2.4 for location of Figures 2.8a&b. Locations of wells drilled in this study are shown in Figure 2.8a. UB-1 is a deep well drilled in the upland area of Union Bay; however, the well produced only a very limited amount of saline water and so was subsequently abandoned. TS-1 is a shallow surficial well completed within the T'Sable River fan delta.

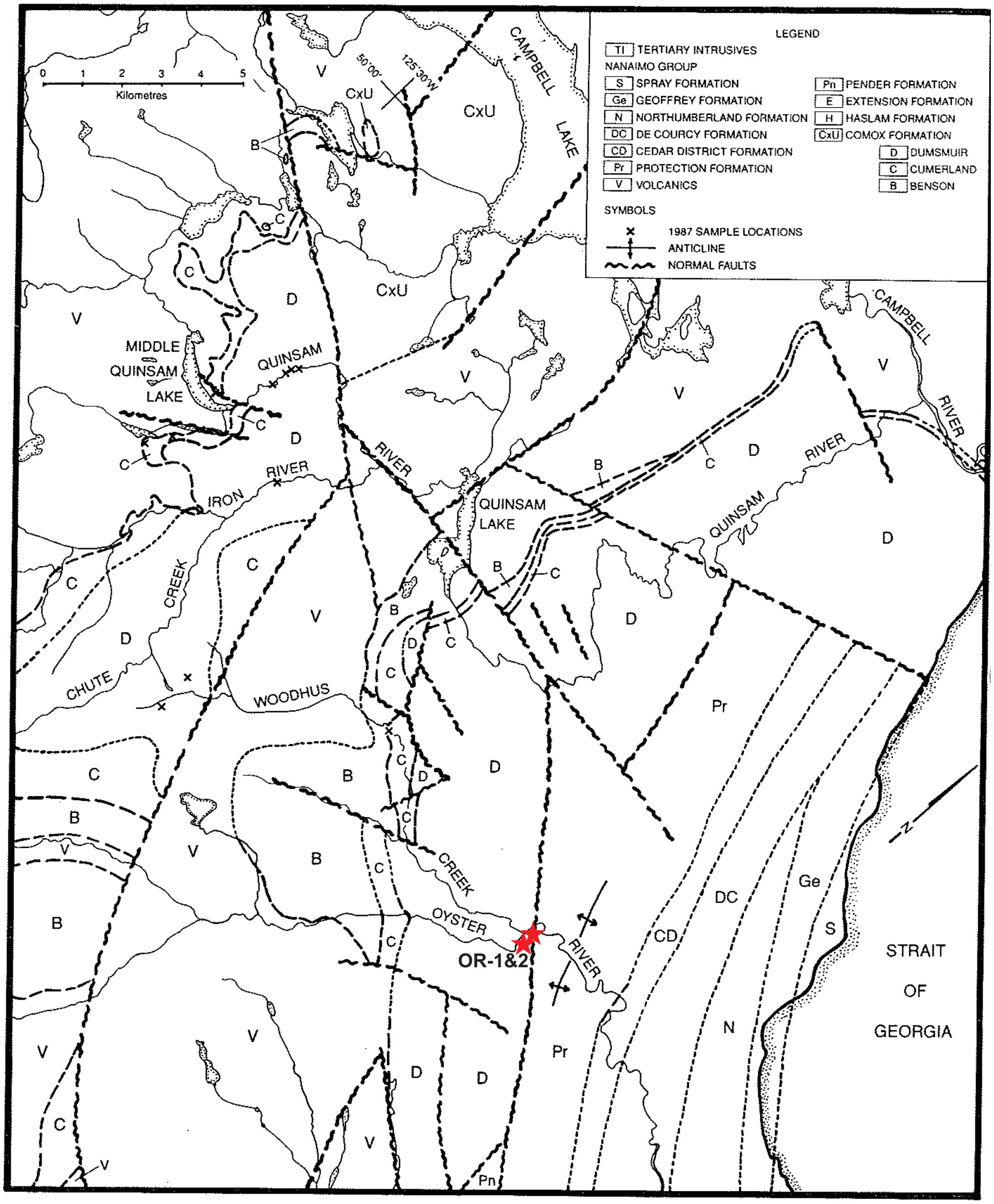


Figure 2.8c. Geology of the Comox Basin. Modified from Bickford and Kenyon (1988). See Figure 2.4 for location map. OR-1&2 show the locations of the Oyster River wells drilled for this study.

much of the Nanaimo Group is mature for oil and gas generation (England, 1989). Coincident with the overarching regional thrust system are elevated vitrinite reflectance levels in the Comox Formation and consequent increased levels of coal maturation (England, 1989).

With approximately four major coal seams within the Dunsmuir and Cumberland members of the Comox Formation, ranging in cumulative thickness from 3 m to 14 m at various intersected localities, there is interest in the coalbed gas potential of the formation (Ryan *et al.*, 2005). Much of the readily accessible (shallow) coal of the Comox Coalfield has already been mined out through conventional methods. The coalbed gas reserves lie below 450 m and may extend to depths as great as 1,500 m, well within the depth range of coalbed gas extraction techniques (Cathyl-Bickford, 1991). Table 2.1 presents a correlated chart of Comox coal encountered at various sub-coalfields throughout the basin, based on lithologic and geophysical data.

Within the Dunsmuir member, coal beds that have been identified are labelled, from top down, the W, X, Y, Z, and No. 1 seams. The W, X, Y, and Z seams are relatively equally spaced within the top two-thirds of the member and are typically about 30 cm thick. Approximately 25 m above the base of the Dunsmuir, the No. 1 coal seam (the major coal seam in the member) ranges between 0.75 m and 2.1 m in thickness. It has a massive sandstone roof and dark shale floor. The Dunsmuir member itself thickens towards the north and becomes finer grained with increasing siltstone and shale interbeds, while the coal beds increase to mineable thickness (conventional coal mining) in the northwest region of the Comox Coalfield (Quinsam). (Cathyl-Bickford, 1988)

Underlying the Dunsmuir member, the Cumberland member hosts major coal seams 2, 3a, and 4, as well as minor beds 2a and 3. The No. 2 bed is the most persistent Cumberland member coal, averaging 1.5 m in the Quinsam Coalfield (northwest part of the Comox Coalfield), ranging between 0.75 m to 1.5 m in the Cumberland Coalfield (central west), and 1.8 m to 4.2 m in the T'Sable River Coalfield (southeast). This bed has also been correlated with 1.6 m of the Woodhus

Table 2.1. Correlation of Comox coals, Comox Basin. From Bickford and Kenyon (1988). Sub-basin locations are included in Figure 2.4.

MEMBER	**DEPOSIT**				
	Quinsam	**Chute Creek**	**Woodhus Creek**	**Cumberland**	**T'Sable River**
Dunsmuir member				W	
				X	
				Y	
	4	**A,B**		Z	
	3	C,D		**1 (Upper)**	30
Cumberland member	**2**		**Upper**	**2 (Farm)**	**20 (2)**
	1 Rider		Lower	2a	15
	1			3	10 (3)
				3a	
				4 (Lower)	

Creek upper seam; Woodhus Creek is a western tributary of the Oyster River in the northwest part of the Comox Coalfield. The coal is associated with thin bands of carbonaceous shale. The No. 2a bed consists of 0.3 m to 0.6 m of coal, thickening northward in the basin. This bed has been correlated with 3.6 m of the Woodhus Creek lower seam and 2.9 m of the Quinsam No. 4 bed. The No. 3 bed is comprised of 0.9 m to 1.5 m of coal and shale, thickening up to 4.2 m in the T'Sable River Coalfield to the southeast. The No. 3a bed comprises 1.3 m to 1.6 m of coal, dirty coal, and sandstone. The No. 4 bed, the deepest coal of the Cumberland member, varies from 1.2 to 2.4 m of coal, interrupted by basement paleo-highs, and is thickest at the Cumberland Coalfield. The Benson member, the lower most member of the Comox Formation, is a basal conglomerate devoid of thick coal beds (Cathyl-Bickford, 1988).

Comox coals have been found to be stronger and have better defined cleat systems than the coals located in the Nanaimo Basin to the south, which tend to be sheared and friable (Cathyl-Bickford, 1991). A vitrinite reflectance study conducted by Kenyon and Bickford (1989) throughout the Comox Basin revealed a trend of increasing coal rank from north to south, contrasting a lack of variation in the Nanaimo Basin. Isotherm data, collected by Ryan *et al*. (2005) west of the present Quinsam mine, support the conclusion of increasing coal rank from north to south in the Comox Basin. Although high-volatile bituminous A and B coals are present in both sub-basins, anthracitic rank values were also detected for the Comox Basin. It has been inferred that a horizontal isorank line, such as that of the Nanaimo Basin, is indicative of fold-thrust deformation of the coal-measures before final coalification (Kenyon and Bickford, 1989). The trend of increasing seam rank from north to south in the Comox Basin demonstrates a higher geothermal gradient in the southern part of the basin (Kenyon and Bickford, 1989). The pre-tectonic coalification pattern causing the constant rank values corresponds to the regional formation overprinted by thermal aureoles associated with plutonism (England, 1989; Kenyon and Bickford, 1989). This is further evidenced by a Tertiary intrusion mapped in the Browns River area, which increased the rank of the coal (Rmax%) from 0.79% to 1.69% mean maximum reflectance of vitrinite (Bickford and Kenyon, 1988; Ryan, 2002).

A number of “good drilling shows” of coalbed gas and coal-source “conventional” gas have been identified in the Comox Coalfield. Gas contents obtained from a four-hole coal exploration program, west of the Quinsam mine, ranged from 0.2 to 1.3 cubic centimetres per gram (cc/g) on an air-dried basis, and from 1.1 to 2.1 cc/g on a dry mineral-matter free basis (Ryan *et al*., 2005). Gas content data from Priority Ventures wells drilled in the Courtenay area on an “as-received” basis ranged from 2.1 to 7.4 cc/g and from 3.6 to 12 cc/g on a dry ash-free basis (Ryan, 2002). Nearby in the Royston area, an exceptionally heavy outpouring of gas occurred while drilling at approximately 420 m depth (Cathyl-Bickford, 1991). Further south in the T’Sable River area of the basin, Ryan collected coalbed gas samples in 1996 with contents ranging from 2.4 to 6.5 cc/g on a dry-ash free basis (Ryan, 1997, 2002). At this same location, the Alvensleben T’Sable River ATR-1 coal exploration borehole encountered gassy coal at a depth of 550 m; the well was later abandoned due to excessive gas pressure (Cathyl-Bickford, 1991). Gas from the Douglas coal seam encountered in the Nanaimo Coalfield was found to contain 95% methane, 4.5% heavier hydrocarbons, and 0.5% carbon dioxide (Kenyon and Murray, 1990; Cathyl-Bickford, 1991). The chemical composition of gas samples desorbed from coal seams 2, 1 Rider, 1, and 1 Lower west of the present Quinsam Mine site in the northwest region of the Comox Coalfield were analyzed to be on average 97% methane, less than 0.2% heavier hydrocarbons, and 2% carbon dioxide (Ryan *et al*., 2005). The gas compositions from both coalfields are acceptable quality for a gas-transmission system.

For further detail on the coal geology for the Comox Coalfield refer to Bickford and Kenyon (1988), Bickford *et al.* (1989), Bickford *et al.* (1990), Matheson (1990), Cathyl-Bickford (1991), Ryan (2002), and Ryan *et al.* (2005).

2.3 Quaternary Geology

The unconsolidated deposits overlying the fractured Nanaimo Group bedrock were deposited throughout the Pleistocene and Holocene epochs, roughly 2.6 Mya to 10 thousand years ago (kya) and 10 kya to present, respectively (Clague, 1994). The surficial geology of the coastal lowland area encompasses six distinct glacial and interglacial periods, with the last nonglacial continuing to present (Fyles, 1963; Clague, 1994). Although time periods of nonglacial deposition and erosion are much greater than those of glacial deposition, nonglacial sedimentation often results in considerably thinner formations than glacial units. Figure 2.9 depicts the Quaternary stratigraphic sequences in southwestern British Columbia (Clague, 1994), while Figure 2.10 illustrates a generalized diagrammatic section of sediments typically found in the eastern coastal lowland area (Halstead and Treichel, 1966).

2.3.1 Westlyn Drift

The oldest identified Quaternary deposit in southwestern BC is the Early to Mid Pleistocene Westlyn Drift, dated as older than 128 kya (Clague, 1994). This deposit is comprised of till, glaciomarine diamicton, glacial-fluvial sand and gravel, and rhythmically bedded glaciolacustrine clay and silt.

2.3.2 Muir Point Formation

The last interglacial period, known as the Sangamonian Stage or oxygen isotope stage 5e, resulted in deposition of the Highbury Sediments of the Fraser Lowland and the Muir Point

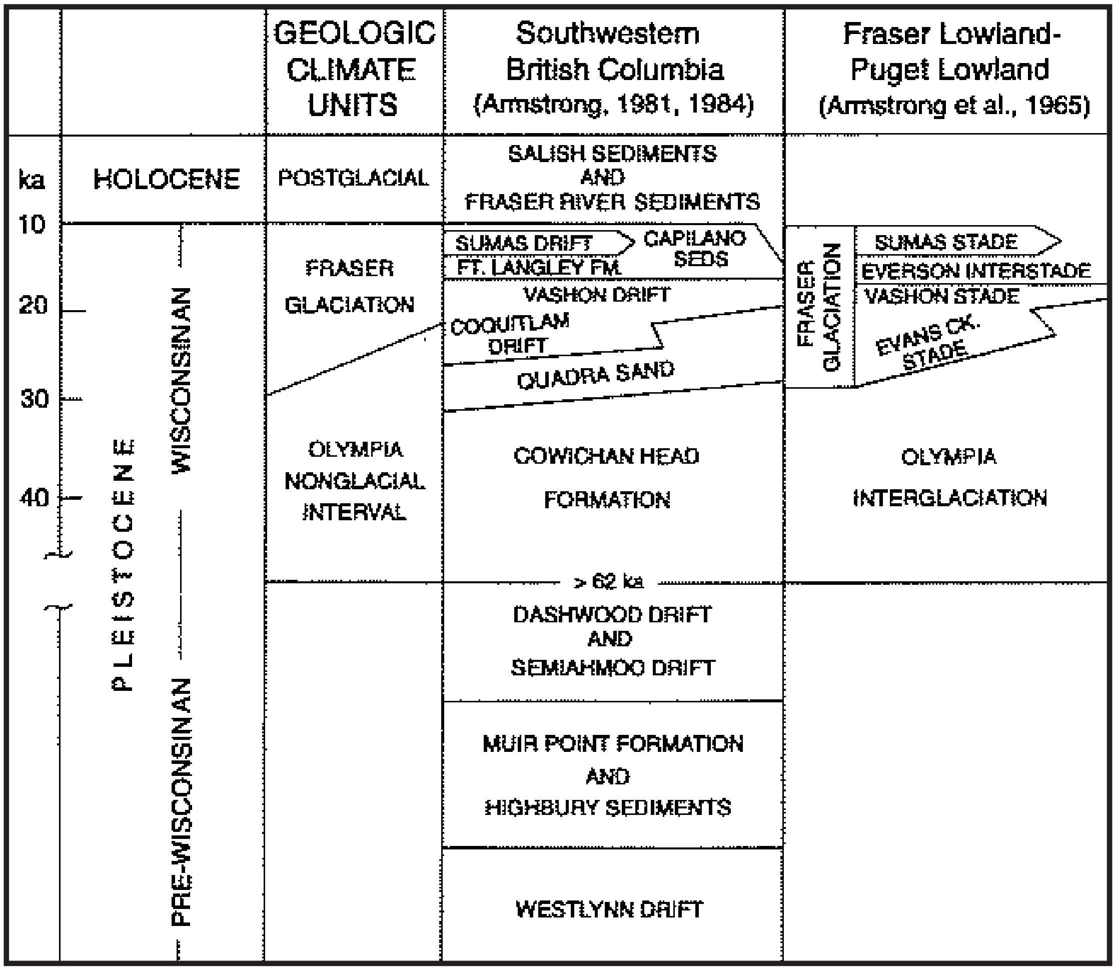


Figure 2.9. Quaternary stratigraphic sequences in southwestern British Columbia. From Clague (1994).

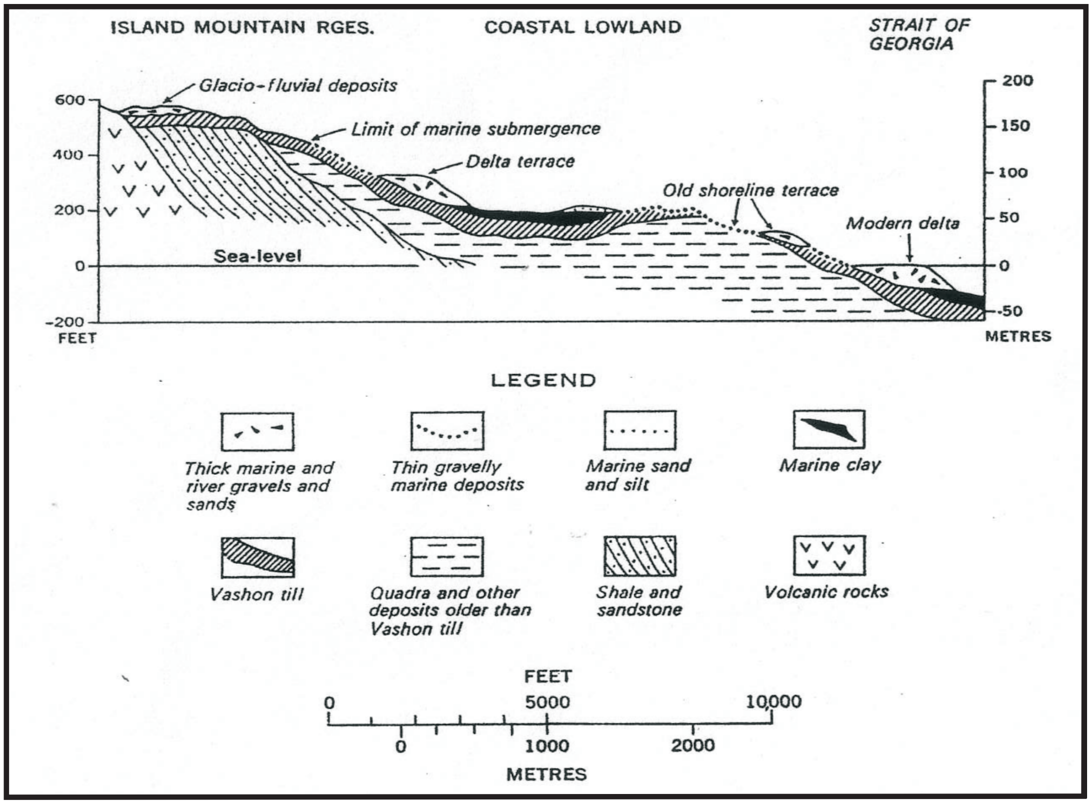


Figure 2.10. Diagrammatic section looking northwest showing material beneath the eastern coastal lowland, Vancouver Island. After Halstead and Treichel (1966).

Formation on southern Vancouver Island (Clague *et al*., 1992; Clague, 1994). The Muir Point Formation includes silt, sand, gravel and diamicton deposits, as well as alluvium and colluvium covering the coastal floodplains. Fossil pollen assemblages showing abundant Douglas fir, alder, and western red cedar indicate that the climate during the Sangamonian interglacial was warmer and dryer than that of today (Clague, 1994).

2.3.3 Mapleguard Sediments

The transition to the Penultimate Glaciation, known as the Dashwood Glaciation on Vancouver Island and the Semiahmoo Glaciation in the Fraser Lowland, is thought to be marked by the Mapleguard Sediments. Bedded silt, sand, and minor gravel from fluvial, deltaic, or marine origin describe these sediments. Younger than the Muir Point Formation, the Mapleguard Sediments are either strictly non-glacial or outwash sediments deposited during the early stages of the Penultimate Glaciation (Clague, 1994).

2.3.4 Dashwood Drift

Confined between early Wisconsinan (oxygen isotope stage 4, ca. 65-80 kya) and the Sangamonian aged Muir Point Formation, the Dashwood Drift was deposited along the south coast of British Columbia. This sedimentary unit consists of till and an overlying unit of glaciomarine silt and silty sand (Fyles, 1963; Clague, 1994).

2.3.5 Cowichan Head Formation

The warmer climate of the mid-Wisconsinan brought about the onset of the Olympia nonglacial interval. Thick sequences of the Cowichan Head Formation were deposited during this time, accumulating gravel, sand, silt and peat sediments in fluvial, estuarine, and marine environments (Fyles, 1963; Clague, 1976; 1994). Radiocarbon ages (^{14}C years) for this unit range from 23.8 kya to 58.8 kya (Clague, 1980; 1986). Plant microfossils and oxygen-isotope fractionation indicate that the climate during the Olympia nonglacial interval was cooler and moister than present. Furthermore, pollen spectra, abundant in spruce, western hemlock, mountain hemlock, and pine, and low in Douglas-fir, show markedly different assemblages than that of the Muir Point Formation; the previous interglacial stade denotes a climate warmer and dryer than that of today, as opposed to the comparatively cooler, moist environment of the Olympia nonglacial interval (Clague, 1994).

2.3.6 Quadra Sand

The Late Pleistocene Quadra Sand is widely distributed throughout the Georgia Depression and Puget Lowland (Figure 2.11), and it is the oldest Quaternary deposit exposed within the study area. This lithostratigraphic unit consists of thick sequences of horizontally- and cross- stratified, well-sorted sand with minor silt and gravel, locally exceeding 75 m thickness in the coastal lowlands (Fyles, 1963; Halstead and Treichel, 1966; Clague, 1976; 1977; 1994). Provenance and paleocurrent studies (Clague, 1977) determined that the Quadra Sand was sourced from the Coast Mountains to the northeast of Vancouver Island and deposited in front of ice advancing south down the Georgia Depression. The unit is time-transgressive and has been dated as older than 29,000 ^{14}C years in the northern Georgia Strait and younger than 15,000 ^{14}C years in the southern Puget Sound (Clague, 1977, 1986; Mathewes, 1979). The Quadra Sand is thought to have formed subaerially in a braided glaciofluvial environment (Fyles, 1963; Clague, 1976; 1977). Sediment transport occurred in stages over time. First, the glacially derived sediment was transported and deposited in the numerous local coastal fjords and as deltas at river mouths. The sediments were then re-entrained and redistributed down the Strait, likely further eroded with time into their present formations and localized deposits (Clague, 1976). Critical

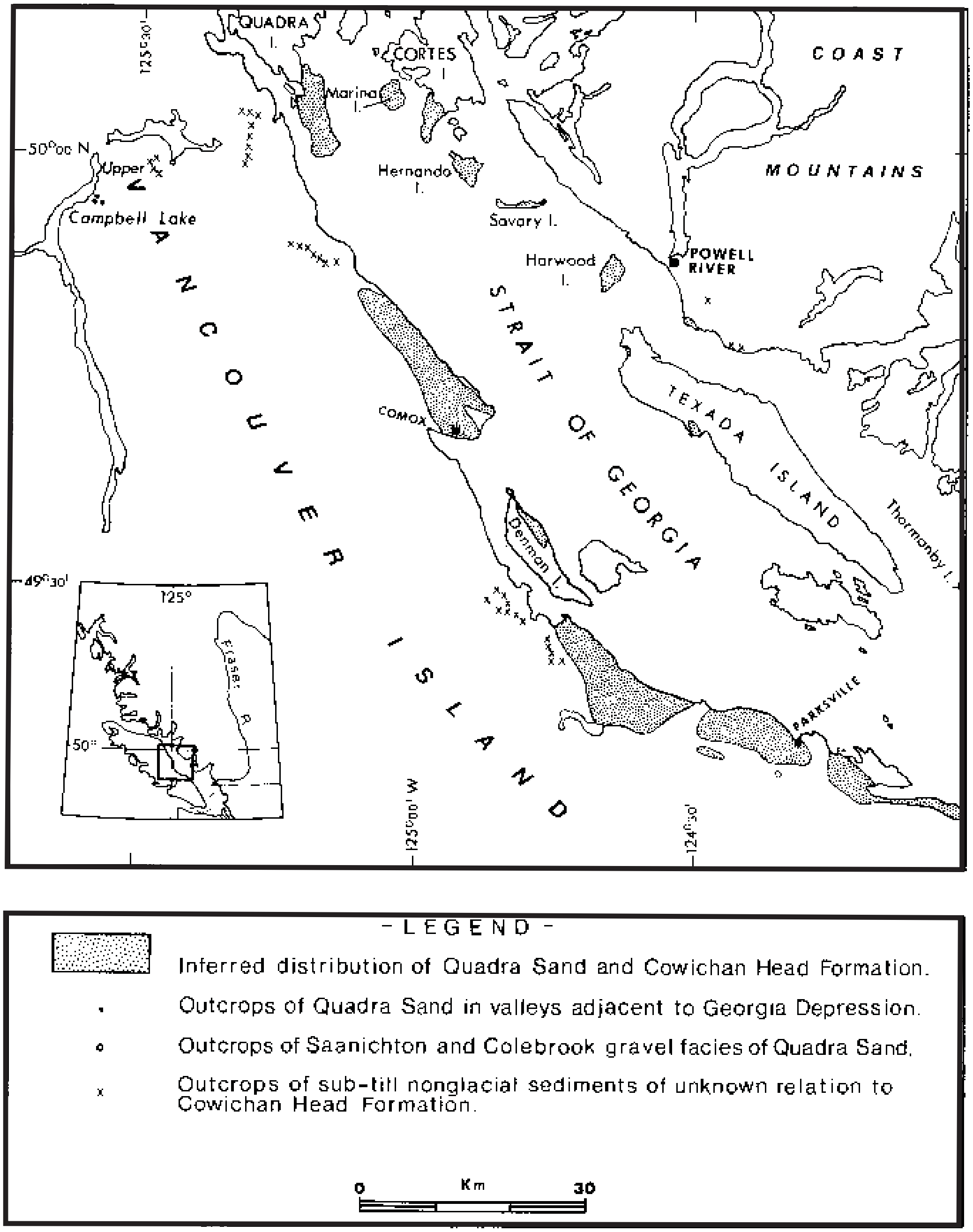


Figure 2.11. Distribution of the Quadra Sand and Cowichan Head Formations in the Georgia Depression. After Clague (1977).

aspects for interpreting the depositional environment of the Quadra Sand include the unit's significant vertical and lateral expanse, well sorted and horizontally stratified bedding, quartz grain surface textures that are associated with glacial transport, and its widespread distribution throughout the Strait as separate sediment bodies. Fyles (1963) and Clague (1977) both interpreted these details as evidence supporting the accumulation of the Quadra Sand as outwash fans along successive margins of glaciers advancing into and south along the Georgia Depression.

Microfossil investigations on samples of peat and organic-rich silt from the exposed Quadra Sand bluffs on Denman Island – located within the Strait of Georgia east of the T'Sable River (Figure 2.11) – found few, poorly preserved, pollen grains and spores in many of the samples collected (Fyles, 1963; Clague, 1977). Arboreal pollen is largely *Pinus* (primarily *P. contorta*) and *Picea*, with *Abies* and *Alnus* also in abundance and *Tsuga mertensiana* present in most samples. Non-arboreal pollen and spores include *Artemisia*, *Caryophyllaceae, Chenopodiaceae, Compositae, Cyperaceae, Ericaceae, Gramineae*, *Nuphar*, *Onagraceae*, *Ranunculaceae*, *Shepherdia*, *Umbelliferae, Equisetum, Lycopodium, Polypodiaceae, and Selaginella*. Fyles (1963) concluded that although most of this assemblage presently grows on Vancouver Island, the absence of Douglas fir and abundance of spruce indicates that the environment in which the Quadra Sand was deposited is more similar to that of the lowland coastal forests bordering the Gulf of Alaska, a somewhat cooler climate than that of present-day Vancouver Island. Although the lower contact of the Quadra Sand is gradational, the evidence of glacial association that these and other studies have found has led them to group the unit with drift of the overlying Fraser Glaciation as opposed to the Olympia nonglacial interval of the underlying sediments (Blaise, 1989).

2.3.7 Vashon Drift

During the climax of the Fraser Glaciation, a sheet of Vashon Drift was deposited throughout the region by southeast-flowing glaciers. The drift extensively blankets the Georgia Depression, southern Vancouver Island, and Puget Sound areas (Mathews *et al.*, 1970; Hicock and Armstrong, 1984). Wisconsinan-aged till deposits, comprising the Vashon Drift, follow a period of pre-Vashon glacial and fluvial erosion. The drift unconformably overlies either sands and gravels of the Quadra Sand, older Quaternary units, sandstone and shale of the Nanaimo Group sedimentary bedrock, or older basement volcanics. Sandy till is considered to be the “type” Vashon Drift for this region; however, glaciofluvial, glaciolacustrine, and glaciomarine deposits also included in this unit, can be found throughout the coastal lowland area (Fyles, 1963; Alley and Chatwin, 1979; Blaise, 1989). The sandy till has a dense silty and sandy matrix. Clasts are comprised of 20% to 40% gravel and up to boulder sized. Averaging 1 m to 10 m thick, this irregularly distributed deposit can reach thicknesses of 50 m to 60 m, locally depending on the extent of later erosion (Fyles, 1963; Hicock and Armstrong, 1984).

2.3.8 Capilano Sediments

As the Fraser Glaciation receded from its maximum extent, relative sea level was considerably higher than present and consequently glaciomarine deposits rest atop the Vashon Drift. These deposits are generally considered to be part of the Capilano Sediments, which also include glaciofluvial sequences. Marine or glaciomarine deposits range from a metre to tens of metres thick, and can be found up to 150 m above present day sea level within the study area (Fyles, 1963; Clague, 1994). Throughout the coastal lowland the texture and thickness of the glaciomarine sediments varies with slope and the type of underlying till. The texture of these sediments is considerably coarser and more varied in areas where the underlying till is sandy

(Fyles, 1963). Typically, thicker sequences are found in the valleys and lowlands where slopes are low. These finer-grained sediments derived from the receding glaciers were deposited with sediments thought to be from offshore, nearshore, and intertidal environments, to form locally organic rich, stony and stone-free clays, stratified silts and sands, stratified and poorly sorted cobble to pebble gravels, and sand and gravel deltaic formations (Fyles, 1963). The Capilano Sediments record a period of time commencing immediately upon glacial recession approximately 14,000 years ago at the latest, and continuing until relative sea level lowered more than 150 m to at least 10 m below its present elevation around 10,000 years before present (Fyles, 1963; Clague, 1991; 1994).

2.3.9 Salish Sediments

Over the last several thousand years of continued sea level rise, “modern” seashore, lakeshore, fluvial, and related deposits have accumulated, and are termed the Salish Sediments (Fyles, 1963). These materials consist largely of sand and gravel, partially surfaced by a thin layer of finer sediments or peat. Deltas along the seashore are generally over a kilometre across and tens of metres thick. Shoreline erosion cutting elongated platforms along the coastal lowlands have resulted in sea-cliffs such as those found at Comox. Modern sand and gravel deltas also formed during this time, as seen by the Trent River and T’Sable River fan-deltas.

2.4 Hydrogeology

2.4.1 Groundwater Sustainability

The sustainability of groundwater resources largely depends upon the amount of annual recharge that the aquifers receive (the portion of precipitation that infiltrates the subsurface), the degree of geologic and topographic complexity, and the water use patterns of local community and industrial needs. Estimates from studies on the Gulf Islands adjacent to the current study area suggest recharge values of 20% of the total precipitation for the area (Allen *et al.*, 2001); however, the exact amount remains uncertain (Allen, 2009). Given an approximate annual precipitation across the coastal lowlands of the Comox Coalfield of 1,445 mm, averaged from 1971 to 2000 climate normals for the areas of Campbell River, Comox, and Mud Bay (Environment Canada, 2004), the annual recharge for aquifers in this region can be roughly (based on the 20% infiltration fraction not including recharge from precipitation over the Beaufort Mountain Range) approximated to be 290 mm (20% of 1445 mm).

If no groundwater is extracted, the hydrogeologic system is in a general state of overall dynamic equilibrium given the long time period since any major climatic change. When groundwater is extracted, and the same amount of recharge is applied, then it can be reasoned that either there will be a reduction in the amount of groundwater held in storage, reduction in the baseflow to streams, or reduction in the amount of groundwater discharged to the ocean (Allen *et al.*, 2001). Such reductions can potentially lead to the lowering of the water table, drying of streambeds, or saltwater intrusion into subsurface aquifers. Long-term sustainable management of groundwater resources is therefore of critical importance in order to safeguard against aquifer mining and contamination.

2.4.2 Bedrock Hydrogeology

Fracturing resulting from a complex tectonic history, combined with dynamic depositional processes such as sediment flows, complicates the hydrogeology of sedimentary formations such as the Nanaimo Group. In such cases both the primary porosity and permeability of the formations may be significantly lower than the secondary porosity and permeability provided by fracture openings. The Nanaimo Group sandstone units are considered relatively impermeable, with a primary porosity of less 5% (England, 1989) and less than 1% in some thin section analyses (Abbey and Allen, 2000). This significantly reduced capacity to transmit water is related to extensive cementation and diagenic infilling by zeolites (England, 1990). Consequently, groundwater flow is thought to be primarily through the fractures or along bedding contacts, which dominate the interbedded mudstone and sandstone units (Surrette and Allen, 2008). Wells drilled in such highly fractured areas tend to produce higher yields (Allen *et al.*, 2001; Surrette and Allen, 2008).

Groundwater flow through fractured bedrock follows discrete flow paths defined by the aperture, orientation, and interconnectedness of the individual fractures. Geological investigations and modeling of the Nanaimo Group Formation have revealed that the distribution of the brittle strain creating the fracture zones was neither regionally homogeneous, nor dependent on either lithology or structure alone, but a combination of both (Mackie *et al.*, 2001; Surrette and Allen, 2008; Surrette *et al.*, 2008). Allen *et al.* (2003) further demonstrated that fracturing is pervasive in the mudstone interbeds either within the sandstone-dominant formations or at formation contacts. This intra-formation heterogeneity, fine-grained higher permeability interbeds within coarse-grained formations, establishes intra-formation aquifers as the predominant groundwater reservoirs and pathways for the Nanaimo Group sedimentary bedrock sequence (Allen *et al.*, 2001; Allen *et al.*, 2003; Surrette and Allen, 2008).

2.4.3 Hydrogeology of Quaternary Sediments

Groundwater aquifers within the unconsolidated Quaternary sediments of the central-east coast of Vancouver Island include confined, semi-confined and unconfined reservoirs. Respectively, these show a generally increasing risk of surface contamination. The Quadra Sand deposit is a highly productive, confined to semi-confined, aquifer that underlies the less permeable

Vashon Drift (Clague, 1977). Discreet perched aquifers can also be found pooling atop the Vashon Drift and above finer-grained units within the Quadra Sand (Fyles, 1963; EBA Engineering Consultants Ltd., 2004). Such fine grained or cemented units can be considered aquitards depending on the degree of cementation; however, due to the variable thickness and intermittent nature of unconsolidated deposits, leakage through or connectivity around these units creates a complex hydrogeologic network. Coarse-grained sand and gravel deposits of the Capilano Sediments, such as the numerous raised deltas that occur within the study area, form semi-confined to unconfined inland aquifers. Similarly, the modern deltas along the seashore that are comprised of coarse-grained Salish Sediments, such as the T'Sable River fan-delta, produce significant volumes of potable groundwater, and numerous active domestic groundwater wells are situated within these landforms. Adequate annual recharge to these coastal aquifers is of paramount importance in order to avoid saltwater intrusion. Infiltration of the subsurface in this region is accomplished largely through direct precipitation as well as indirectly from infiltration, runoff and snowmelt sourced from the Beaufort Mountain Range and underlying bedrock formations of the coastal plateau.

3 2.5-D Reconstruction and Hydrostratigraphic Analysis of the Comox-Merville Aquifer, Vancouver Island, British Columbia, Canada.

3.1 Introduction

This study provides an assessment of the geology and hydrostratigraphy of the Comox-Merville Aquifer (BC Ministry of Environment (BC MoE) Aquifer #408), located on the central-east coast of Vancouver Island, British Columbia (Figure 3.1). As part of this study, 196 pre-existing domestic-use groundwater wells completed within the southeastern region of the Comox-Merville Aquifer were investigated for stratigraphic and hydrogeological information. Well logs were standardized with respect to lithological and hydraulic characteristics. Contact surfaces were created for identifiable hydrostratigraphic units employing an iterative geostatistical interpolation process that incorporated contact points from the logged dataset and additional interpreted points based on knowledge of the regional hydrogeology. Modeled hydrostratigraphic surfaces were compared to logged contacts at depth and to field investigations at costal exposures at Willemar and Lazo bluffs at Comox (Figure 3.2). Through this comparison, the degree to which the groundwater drillers' logs represent the subsurface hydrostratigraphy was determined.

3.2 Study Area

The Comox-Merville Aquifer occurs within the central-eastern coastal lowlands of Vancouver Island, between the Beaufort Mountain Range to the west and the Strait of Georgia to the east. Aligned northwest-southeast, the aquifer spans approximately 150 square kilometres and is located near the urban centres of Courtenay and Campbell River to the west and north, respectively. Classified as moderately developed and having a low level of vulnerability to surface

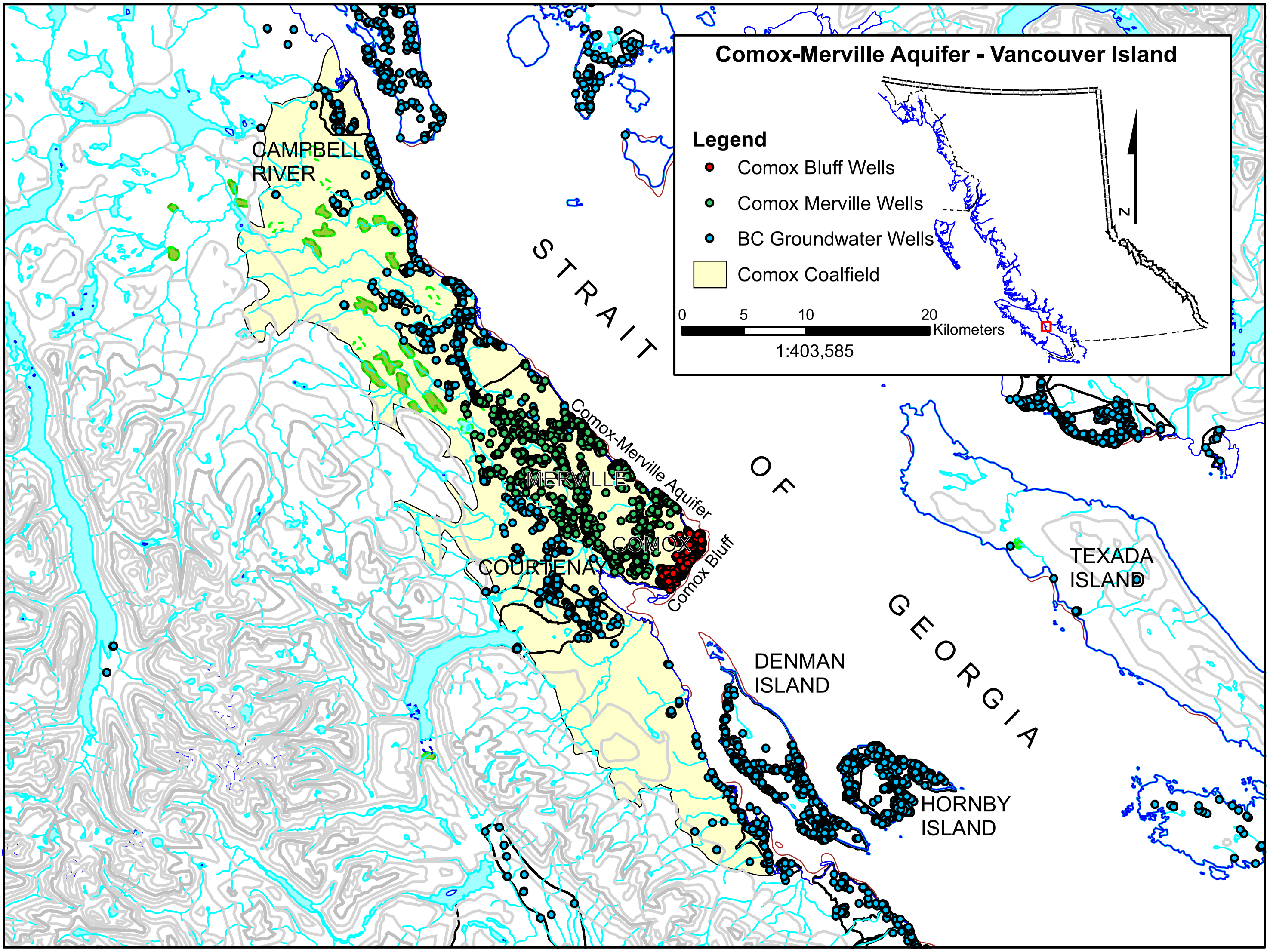


Figure 3.1. Comox-Merville Aquifer and water well location map.

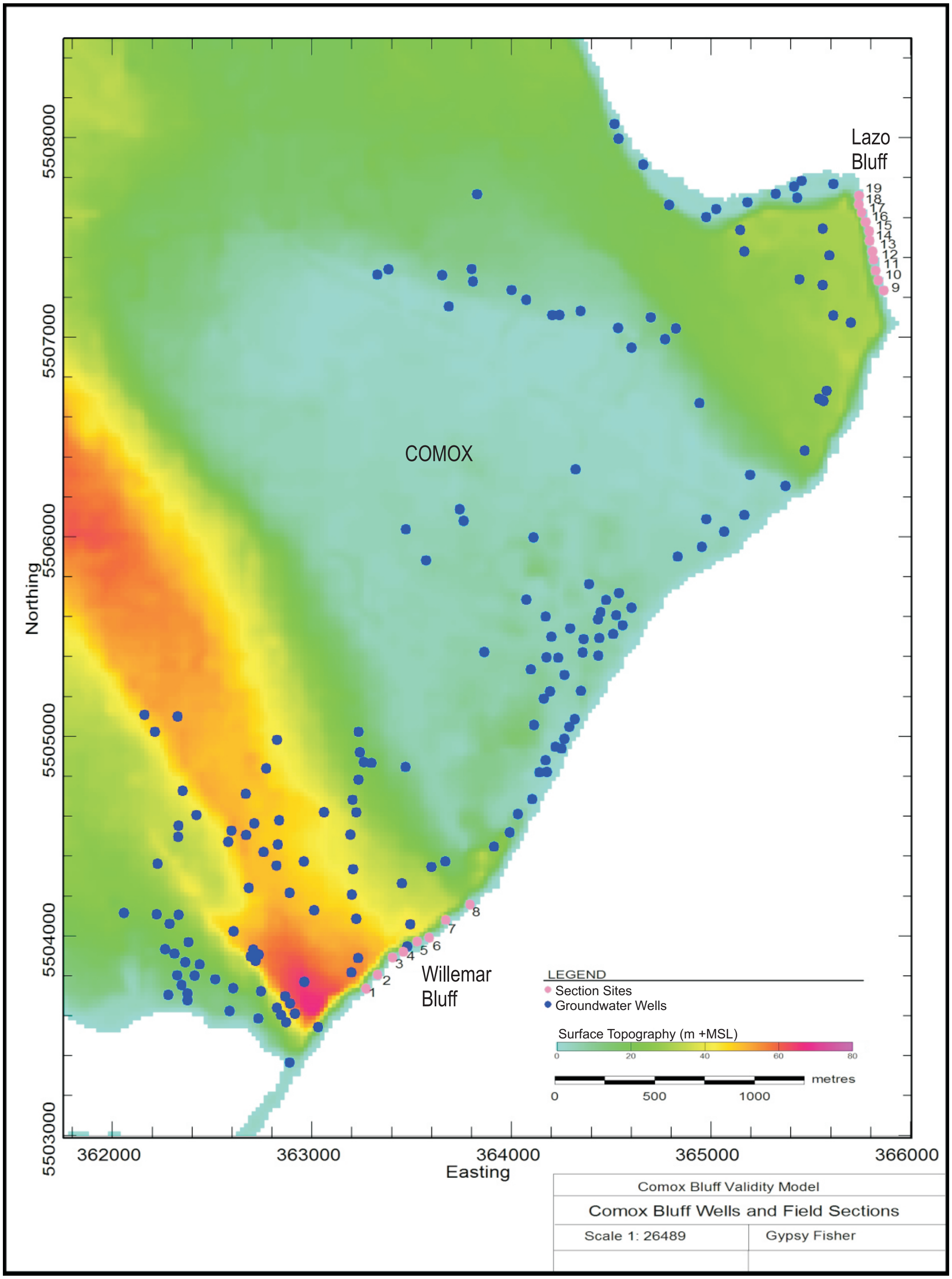


Figure 3.2. Comox Bluff Location Map

contamination (BC MoE, 2001), the aquifer is in high demand as a primary water supply for the communities of Comox and Merville.

3.3 Previous Work

No stratigraphic investigations have been conducted along the southern coastal bluffs of the Comox-Merville Aquifer since the early work of Fyles (1963) and Clague (1977). These bluffs are referred to as either the Comox Bluff for the general area, or as Willemar Bluff referring to the southern exposure, and Lazo Bluff for the northern exposure (Figure 3.2). The bluffs are primarily comprised of Late Pleistocene Quadra Sand, a prevalent advance outwash deposit of the Fraser Glaciation; it consists of a glaciofluvial sequence of horizontally- and cross- stratified, well-sorted sand with minor silt and gravel (Fyles, 1963; Halstead and Treichel, 1966; Clague, 1976, 1977, 1994). Section 2.4.6 provides a summary of previous descriptions of the Quadra Sand lithostratigraphic unit. Radiocarbon dates acquired from pieces of wood found in finer grained beds along the southeastern coast of Willemar Bluff date the Quadra Sand, the main component of the Comox-Merville Aquifer, to be between 26,100 ± 400 ^{14}C years and 28,800 ± 740 ^{14}C years old (GSC, 1963). Overlying the extensive Quadra Sand exposures of the Comox Bluff are the glacial deposits of the Vashon Drift, forming a confining layer of till and fine-grained glaciomarine sediment that protects the groundwater resource from potential sources of surface contamination. Spatially pinching and thickening deposits of sand and gravel rest atop the Vashon Drift and are correlated to Capilano or Salish Sediments (See Chapter 2) (Fyles, 1963; Clague, 1977).

3.4 Methodology

3.4.1 Field Methods

Descriptions of exposures within the Comox-Merville Aquifer were completed along the southeastern coast of the aquifer at Willemar and Lazo bluffs throughout the spring, summer and autumn seasons of 2005 and 2007 (Figure 3.2). Data recorded at the exposures included location, unit descriptions, unit thicknesses, and approximate lateral extent. Vertical elevations for individual contacts were calculated using a TruPulse 200 laser inclinometer. Detailed stratigraphic sections were created from field observations along Willemar and Lazo bluffs and are included as Figures 3.3 and 3.4, respectively, with individual sections compiled in Appendix 3.1.

Samples were collected along the exposed bluffs for all of the major units safely accessible, and a minimum of two samples per unit were analyzed for grain size distribution. Samples of the finer grained units were sent to GeoSea for laboratory analysis. Eight samples were analyzed by GeoSea, with an additional duplicate randomly selected that showed a percent similarity of 98.8%. Disaggregation of the samples was achieved by both mechanical stirring, or mortar and pestle if necessary, and mild ultrasonic dispersion. GeoSea used a Malvern Mastersizer 2000 laser particle sizer for the grain size analysis of these sediments. Sand units were dry sieved by the author in the BC Ministry of Energy, Mines and Petroleum Resources' Victoria laboratory using phi value intervals -1 (2 mm) , 0 (1 mm), 1 (0.5 mm), 2 (0.25 mm), 3 (0.125 mm), and 4 (0.0625 mm) after splitting the field samples into representative sub-samples of approximately 250 to 450 grams dry weight. Two samples were analyzed for the lowermost sand unit exposed at Willemar Bluff, and four samples were analyzed for the upper sand unit; two from Willemar Bluff and two from Lazo Bluff. Three trials of each sample were conducted for quality assurance. Grain size data and analysis for the lower four units accessible at Comox Bluff are included in Appendix 3.2.

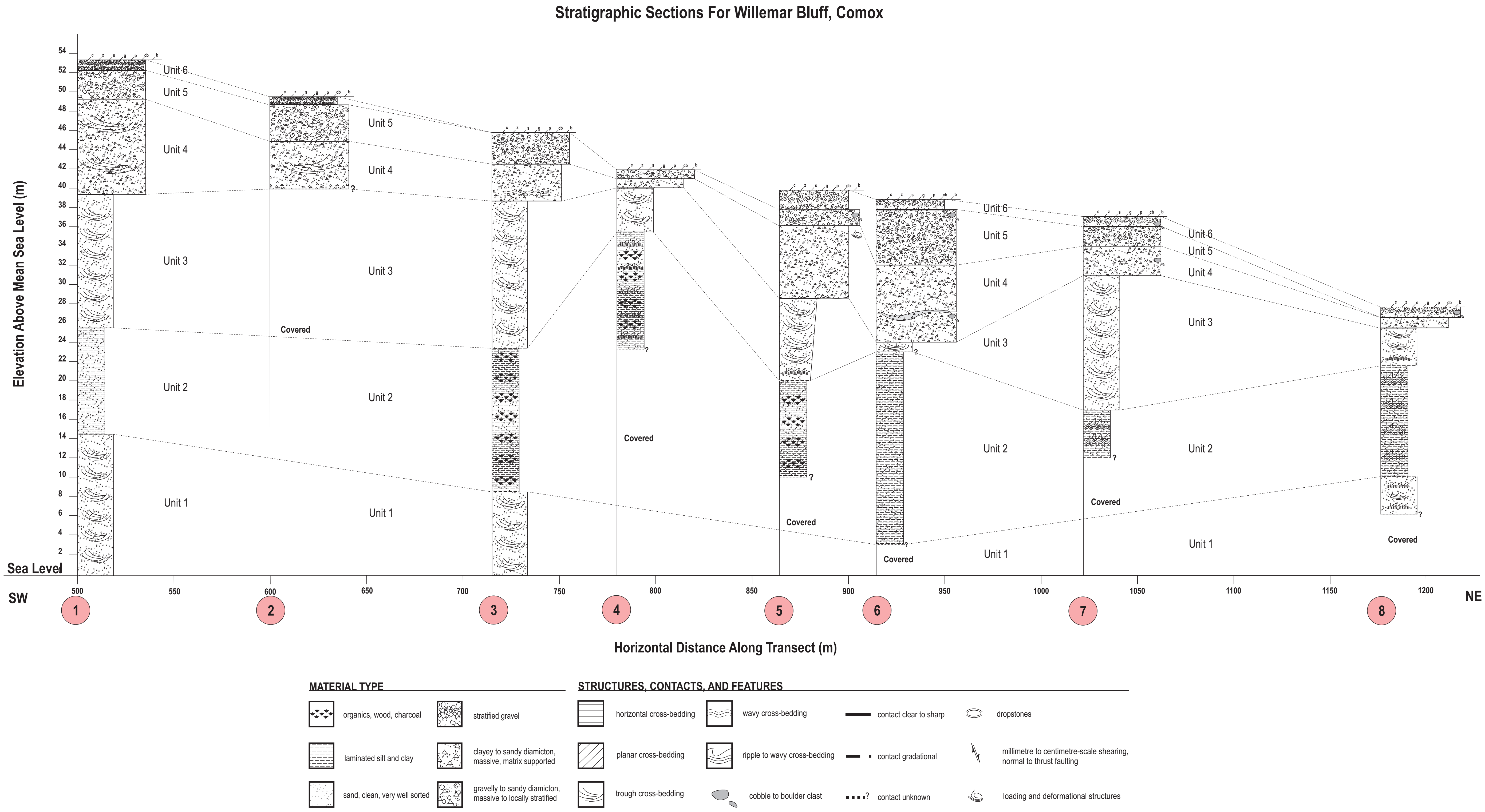


Figure 3.3. Stratigraphic sections along Willemar Bluff, Comox. Refer to Figure 3.2 for section site locations.

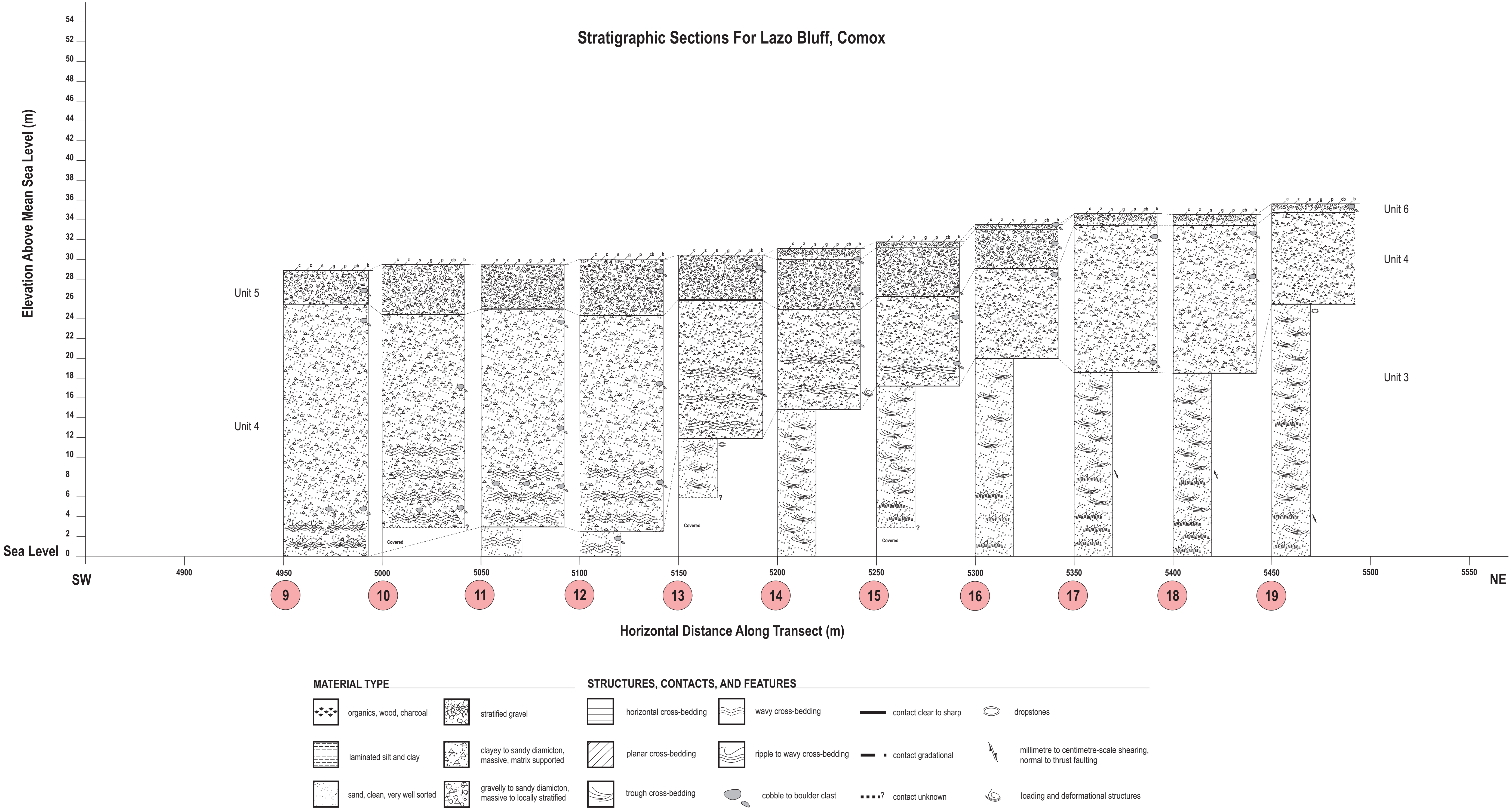


Figure 3.4. Stratigraphic sections along Lazo Bluff, Comox. Refer to Figure 3.2 for section site locations.

3.4.2 Analysis of Water Well Logs

Groundwater well logs submitted to the Province were accessed through the BC Ministry of Environment's *BC Water Resources Atlas* (BC MoE, 2001). Lithological and hydrogeological data included in the well logs vary widely in quality and detail depending, in part, on the thoroughness of the driller's records. Groundwater well logs can provide the only information in areas devoid of any knowledge of the subsurface environment, or merely act as indicators to the existence of a well at a particular location, while providing no other subsurface detail. Due to the vast range in each driller's knowledge regarding geology and hydrogeology, every well record must be scrutinized and assessed before it can be incorporated within the dataset. The process used for this analysis in this work is described below.

The southeastern region of the Comox-Merville Aquifer (Figure 3.2), an area approximately 13 km^2, was chosen as the focus of this study due to its proximity to extensive coastal bluff exposures where field investigations could be conducted to "ground truth" the water well log data. 196 groundwater wells completed within the southeastern region of the aquifer were used as the sample-set for this study. This included all of the wells situated within the region adjacent to the coastal bluffs and, therefore, there was no need for a statistical selection procedure. The logs were standardized in order to simplify descriptions as well as to gauge the validity of the driller's observations and subsequent interpretations recorded in the logs (Russell *et al.*, 1998). Certain assumptions and indicators were developed to aid in this process. Initially, the logs were differentiated into three classes: (i) "Red" indicating that they are completely unusable and would have to be culled from the dataset; (ii) "Yellow" requiring minor interpretation; and, (iii) "Green" for logs that can be used with confidence. Numerous indicators and corresponding responses were developed for each data classification, as detailed in Tables 3.1 and 3.2. This standardization approach exemplifies an expert-driven system of enhancing the data quality and utility through the

Table 3.1: Groundwater well logs flagged Yellow, requiring interpretation. Well logs may be flagged for multiple indicators; indicator frequency is greater than 100%, cumulatively.

Yellow Indicator	Response	Indicator Frequency
"Hardpan" or "Till > 5 metres"	Units are considered impermeable layers, denoted as a diamicton, and are visually compared with neighbouring wells in cross-section for validation	42%
Lithology given but listed as "0 to 0" depth	Unit thickness given entire well depth (these wells only have one unit logged and are not very deep)	40%
Total depth of well does not equal maximum depth of recorded lithology	Total depth of well given the greater of either the maximum depth of recorded lithology or hydrologic data (e.g. Static Water Level (SWL))	14%
No lithologic log given, but hydrologic information provided	Lithologic log given "No Sample" for the entire well depth	4%
Well has been deepened, so the original well depth has no lithology log	Only the newly exposed deeper section is described (e.g. well lithology starts at 50 feet)	3%
Within lithology logs, the last unit is not given a thickness (e.g. 69 feet to 69 feet)	Unit above is decreased by 1 foot, which is given to the underlying unit for mention	2%
Lithology given but listed as "0 to 0" depth, and total well depth is "0", but SWL is given a value	Unit thickness and well depth is given the SWL depth	2%
Material x "with some" material y	Unit is described as yX (i.e. silty sand = zS)	2%
"Rock"	Description substituted as the general material term "Gravel"	2%
Material x with y at the bottom logged within one unit– unit thickness unclear (e.g. Well Tag no. 1243: 0' to 26': hardpan with sand at the bottom)	Lower unit given a thickness of 1 foot if directly underlying an aquifer (i.e. if considered an aquitard/aquiclude), otherwise given a thickness of 6 feet representing the average length of a well screen – thicknesses given to the lower unit are subtracted from the overlying unit so as to maintain original well depth	1%
Unit is not given a material, only a description (e.g. "loose water-bearing blue")	Unit is given the same material as the unit above and/or below, ensuring that the description and material are rational (e.g. sand, matching the overlying units)	1%

Table 3.2: Groundwater well logs flagged Red, culled from dataset. Well logs may be flagged for multiple indicators; indicator frequency is greater than 100%, cumulatively.

Red Indicator	Response	Indicator Frequency
Lithology log given, but no lithologic, hydrologic, or well depths given	Culled	46%
Material x over substrate y; no unit thicknesses given	Culled	35%
No lithologic or hydrologic data given	Culled	19%
Only "glacial" is given, no material logged	Culled	4%

addition of indicator and response interpretation. For this research, the indicators and subsequent responses developed were applied for a site-scale study; however, these indicators, as well as the standardization process itself, can be used to provide guidelines for subsurface mapping applications in other locations.

Of the 196-well sample set, 13 % or 26 wells were flagged Red and culled, 67% or 132 wells were flagged Yellow, and 20% or 38 wells were flagged Green. This standardizing process necessitated certain assumptions, including:

- Unit descriptions that include at least three grain size classes (clay, silt, sand, and gravel) are denoted as a diamicton;
- Many of the wells not given proper unit thicknesses are assumed to be due to mere haste, since “0 to 0” automatically begins each line unless the driller takes the time to enter a specific depth range; and,
- The colloquial term “hardpan” is defined differently between drillers, and may correspond to anything from hard-packed wet silty sand or clay to overconsolidated glacial till. It is therefore assumed that this term refers to a relatively impermeable layer with respect to hydrostratigraphy, and is denoted as a diamicton. Drillers’ logs listing “Till” with a thickness greater than 5 metres were also flagged for further comparison to neighbouring wells. As both of these terms are legitimate sedimentary materials there were no alterations or substitutions made; however, they were considered suspect indicators for exaggerated thickness or insufficient unit description, such as is the case for “hardpan”.

The standardized dataset was refined to 170 wells, consisting of 132 wells (78%) of interpreted well logs (yellow), and 38 wells (22%) taken without modification from the drillers’ observations (green).

3.4.3 Computer Modeling Methods

Using Viewlog (Viewlog Systems, 2004), a 2.5-D subsurface stratigraphic modeling software package, discreet lithologic units logged in the drillers’ records were graphically displayed in cross-section and referenced to each well’s position in plan view. A Terrain Resource Inventory Mapping (TRIM) digital elevation model (DEM) was used as the ground surface to which the groundwater well dataset was referenced. Upper contacts were identified for each well log in cross-section for the major hydrostratigraphic units that are extensive throughout the Quaternary sedimentary sequence at Comox, including unconfined source aquifers, confining layers, and confined aquifer units. The contact elevations were chosen in cross-section in Viewlog because viewing multiple wells together provides a more accurate representation of the subsurface stratigraphy. All well logs along the cross-section and within 5 m on either side of the cross-section were incorporated into the hydrostratigraphic interpretation for each well's analysis. For example, a north-south transect cutting through the entire study area, when viewed in cross-section, can depict all of the wells north and south along the transect line and within 5 m east and 5 m west. This method allows for the consideration of both the vertical and lateral hydrostratigraphy across the study area within ten metre wide swaths at one time. Furthermore, the cross-section is moved across the study area (i.e. shifted east or west, given the north-south transect example) in 1 m intervals, thereby ensuring that every well log in the dataset is considered. The advantage of viewing numerous well logs across a wide area is coupled with decreased precision in visually pinpointing the contact elevations on each individual well log in the cross-section. Therefore, the data is exported to Microsoft Excel, where the UTM coordinates and contact pick elevations from the Viewlog cross-section are corrected to precisely match the logged elevations and spatial location of each well.

The Full Kriging method in Viewlog was chosen to create the hydrostratigraphic surfaces of the Comox Bluff geostatistical model. Full Kriging, a form of least squares estimation algorithms, estimates the value of an unknown real-valued function at a specified point given the values of the function at other points. In this case the function is spatial location, particularly vertical elevation. This geostatistical technique computes the best linear unbiased estimator based on a stochastic model of the variable in question. Consequently, kriging considers the spatial structure of the contact point, including the random variation or uncertainty of the real world. Estimates of interpolation error, in the form of standard deviations and variograms, are produced for the kriged elevation values for each interpolated hydrostratigraphic surface. This data interpolation method was selected as the best option for honouring the known data points provided, while also producing spatially realistic surfaces. (Baily and Gatrell, 1995; Wackernagel, 1995; Fetter, 2001; Anderson and Woessner, 2002; Heywood *et al.*, 2002; O'Sullivan and Unwin, 2003)

Interpreted hydrostratigraphic boundaries were originally identified based solely on the drillers' recorded observations, upon which the first interpolated surfaces were created. Each surface was subsequently clipped or cut off by the modeled surface of the upper layer, thereby observing Steno's Law of Superposition, ensuring that older units always lie beneath younger deposits inclusive of erosional surfaces (Pillans, 2007). Hydrostratigraphic contacts identified in the drillers' well logs require a unit above and below to be identified in order to verify that there is indeed an observed lithologic and/or hydrostratigraphic change at that point. Wells that are logged as a single lithologic unit throughout are, therefore, not considered in the initial interpolations as there are no observed contacts. Interpreted contact points can be added, however, to recognize erosion surfaces where overlying units are absent or where an otherwise extensive unit may pinch out. In this manner, the model can be directed to more accurately represent the subsurface observed in the well logs. This can be done by picking a contact point, termed a "pick", at the top or bottom of a logged well, for example, and with this addition to the modeling dataset the interpolation becomes more inclusive of all the identified subsurface lithostratigraphic and hydrostratigraphic units. Figure 3.5 illustrates a transect line through Willemar Bluff approximately perpendicular to the coastal Field Section #1 (see Figure 3.2 for location map). The upper profile in Figure 3.5 depicts the modeling scenario based solely on hydrostratigraphic boundaries identified by the drillers' logs, not including any additional interpreted contact points. This scenario

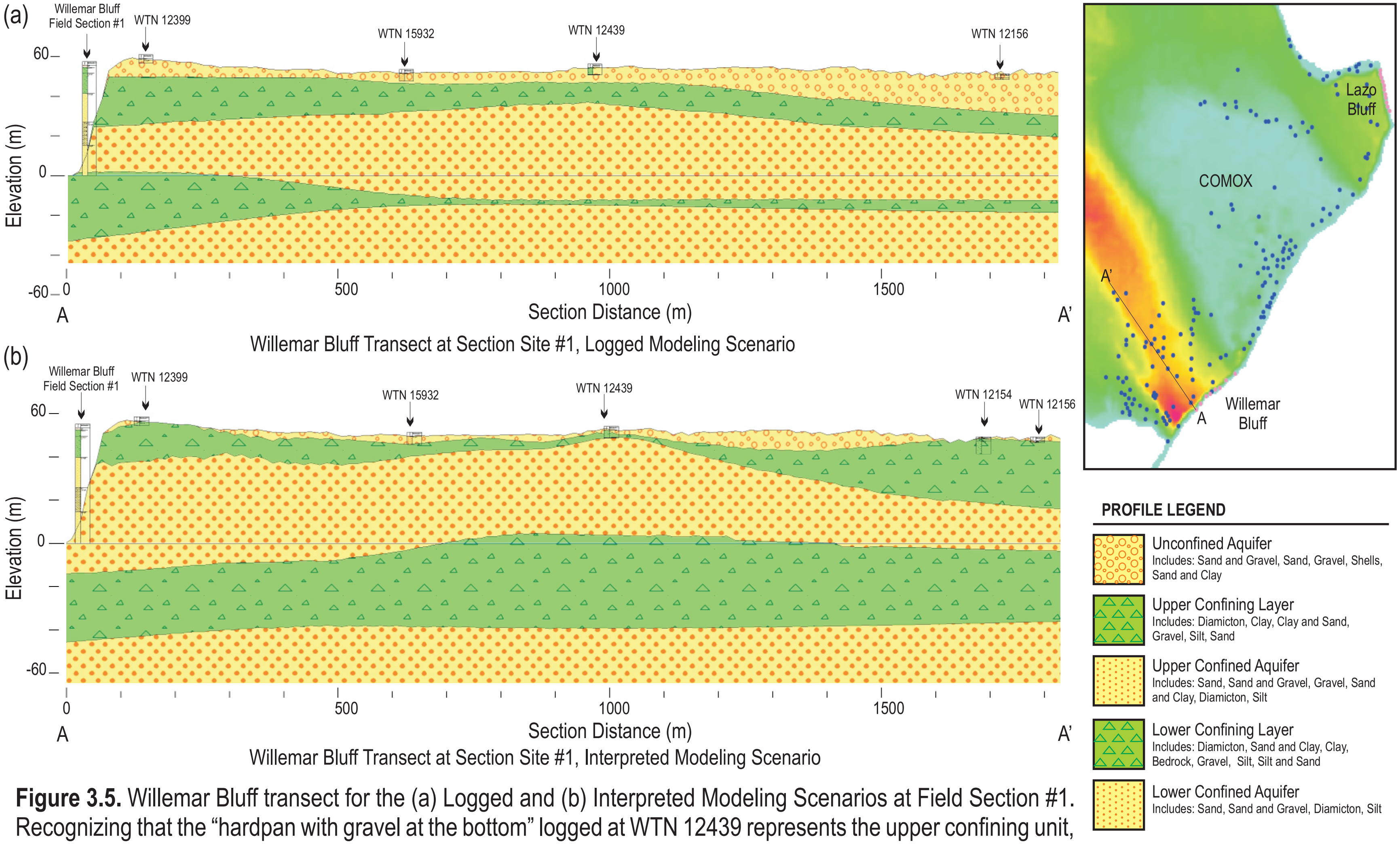


Figure 3.5. Willemar Bluff transect for the (a) Logged and (b) Interpreted Modeling Scenarios at Field Section #1. Recognizing that the "hardpan with gravel at the bottom" logged at WTN 12439 represents the upper confining unit, the top of the well was chosen to represent the lower contact of the overlying unconfined sand and gravel aquifer. Illustrated by the two profiles above, by adding the interpreted contact at WTN 12439 the model produces hydrostratigraphic surfaces that more closely matched the well log dataset.

included the diamicton well log of Well Tag Number (WTN) 12439 with the sand and gravel well logs of WTN 15932 and WTN 12156, and modeled all three wells within the unconfined sand and gravel aquifer. The lower profile in Figure 3.5 shows the modeling scenario that incorporates interpreted contact points with the logged drillers' contacts. By interpreting the upper contact of the uppermost confining unit to intersect the bottom of WTN 15932 and the top of WTN 12439, the model was successfully able to differentiate between the adjacent sand of WTN 15932 and hardpan of WTN 12439, and place each of the wells within the appropriate hydrostratigraphic units.

These interpreted contact points cannot always be verified as actual lithostratigraphic or hydrostratigraphic contacts, however, but rather are made based upon logical assumptions of the data. For example, it can be assumed that a driller would penetrate as much of a water-bearing unit as possible in order to place the well's screen in the optimal position to maximize the volume of accessible water. With that in mind, a well logged with the lowermost unit as water-bearing sand, such as is the case of WTN 50657 in Figure 3.6, would most likely be terminated close to the bottom of this unit, at a point where the driller notices a decrease in porosity or permeability. Similar to Figure 3.5, the upper profile in Figure 3.6 represents the modeling scenario based on the drillers' logged observations alone, while the lower profile incorporates additional interpreted picks. An interpreted point for the upper contact of the lowermost confining unit was placed at the bottom of WTN 50657 in the lower profile, and by doing so the model represented the entire depth of the logged sand unit within the confined sand aquifer (Figure 3.6).

Essentially, creating interpreted picks in cross-section adds new data points to the modeling scenario's dataset. In order to integrate these additional data points the model must re-interpolate each of the contact surfaces after very new interpreted point is added; this process is considered one "round". After each round is complete the modeling scenario is reassessed with respect to subsurface geology and hydrostratigraphy, and the level of agreement with contact

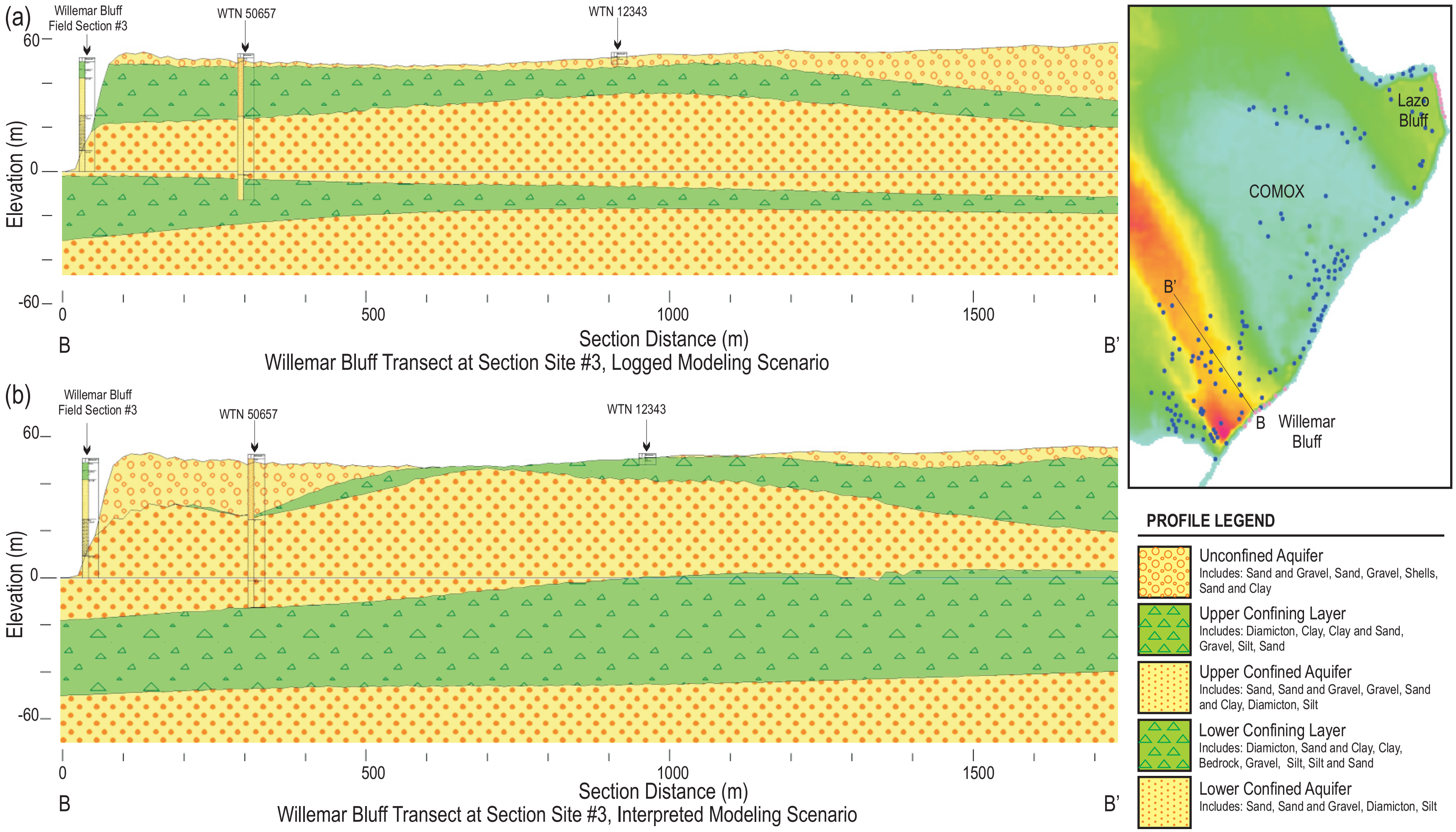


Figure 3.6. Willemar Bluff transect for the (a) Logged and (b) Interpreted Modeling Scenarios at Field Section #3. By assuming that the driller would most likely penetrate the entire aquifer, the bottom of WTN 50657 was interpreted to be the contact between the water-bearing sand aquifer and the underlying confining unit. As a result the lower sand unit logged at this well is modeled entirely within the confined sand aquifer, as opposed to the modeling scenario created using only contacts identified by the drilling logs.

points logged for each well. This entire process is, therefore, repeated in response to each new round of surfaces generated until the model accurately represents the groundwater well log dataset. Once satisfied, the resultant modeled surfaces are extrapolated to the southern coastline for comparison with the field reconnaissance at the exposed Willemar and Lazo bluffs. Through this comparison the conceptual hydrostratigraphic model is verified against the "real world" truth. Analytical measures developed for this model can then be evaluated for recommendations on subsurface modeling using groundwater drillers' logs as the sole source of subsurface data.

3.4.4 Geostatistical Modeling Limitations

Limitations in digital modeling are numerous regardless of the subject matter, particularly when spatially modeling real world environments. Sources of error for the Comox Bluff hydrostratigraphic model can be identified from five general areas: (1) secondary data sources such as base maps; (2) field instrumental error; (3) errors in the collection and logging of input data, both in the field and in the office; (4) formulaic errors computed in the kriging interpolation; and, (5) errors in modeling assumptions.

The first two sources as well as the fourth can be accounted for and are considered intrinsic to the model. The resolution of the TRIM digital elevation model is 10 m: spot elevations have 5 m accuracy and points interpolated from the DEM are within 10 m of their true elevation, both 90% of the time (BC MoE, 1992). The ground surface elevations of the groundwater well logs input for the Comox Bluff model are spatially referenced to the interpolated 1:20,000 scale DEM and, therefore, incorporate a spatial error of at least ±10 m with respect to their true surface elevations. The primary field instruments used in the reconnaissance work along Willemar and Lazo bluffs were a handheld geographical positioning system device and a TruPulse 200 laser inclinometer, the latter having a range accuracy of ±0.30 cm and ±1.00 m for high and low quality targets respectively (Laser Technology, Inc., 2008). Aside from selecting the most appropriate type of interpolation algorithm, Full Kriging, the mathematics behind Viewlog's interpolation choices are pre-designed; consequently, resultant surfaces are created relatively easily at the cost of this black box approach.

The third source of error, the collecting and logging of input data, can be divided into two areas: in the field and in the office. While drilling a groundwater well, for example, there is a time and depth delay between when the drill bit encounters a unit at depth and when the driller sees the material come out of the ground. Furthermore, drill rods that are used for such wells are typically 20 ft in length; the well is usually air-blown to clear the borehole and to check for groundwater when a new rod is attached. Unless a substantial amount of groundwater is intercepted, it is sometimes unclear where precisely the water-bearing unit is within the 20 ft interval. Variability in the drillers' geological and hydrogeological training and drilling experience influences the terminology that they use when describing the subsurface units encountered. This is particularly apparent for qualifiers like "marine or glaciomarine", or terms such as "hardpan or till". An example of this type of issue was encountered in one of the Comox Bluff well logs where "granite" was logged, suggesting that granite bedrock may have been penetrated. As the unit immediately underlying the granite was logged as unconsolidated sand it is likely that the "granite" was a large granite boulder contained within the surficial deposit. Data input error not only occurs in the field, but also when the well log field notes are input into the BC Ministry of Environment's digital database and when this information is transferred into the data management system used for the hydrostratigraphic model, such as Microsoft Access or Excel. Unfortunately, data entry errors can persist even in the most obsessively checked spreadsheets. These types of errors are accounted for in the modeling methodology, however, by visually cross-referencing each well log with others nearby during the contact picking process.

Additional limitations to the Comox Bluff model include assumptions made when interpreting the subsurface hydrostratigraphic units. Generalizations were necessary when assigning hydraulic properties for each lithologic stratum, and when deciding which lithologic units to include in the different hydrostratigraphic units. Type hydraulic properties were incorporated into the model on a conceptual level in order to aid in determining the relative difference in groundwater transmissivity and storativity between adjacent sedimentary deposits. As these properties were unable to be verified for the Comox sediments in particular, the assumptive generalizations are considered another source for error. In some cases, the same lithology may be incorporated into an aquitard in one well log and included in an aquifer at another well. This allocation decision considers the unit thickness at each well, the lateral extent with respect to neighbouring wells seen in cross-section, and the unit's stratigraphic relationship between the units logged above and below. Employing the shifting cross-section methodology to assist in the subsurface hydrostratigraphic interpretation and contact picking effectively addresses this concern. Where the hydrostratigraphic contacts are interpreted to be, however, is somewhat subjective and dependent upon the individual researcher. Due to the potential variability in interpreting the subsurface hydrostratigraphy, the model's level of repeatability is somewhat diminished and, therefore, is considered a source of error.

3.5 Comox Bluff - Lithostratigraphy

3.5.1 Unit 1

The lowermost unit exposed at Comox Bluff is very fine- to fine-grained sand, which is thought to extend below sea level (Figure 3.7 & 3.8). The sand unit is clean, very well sorted, and white to tan in colour with grains of varied lithology; biotite grains are particularly abundant. Bedding structure is primarily low angle, small to large scale, trough cross-bedding, with localized

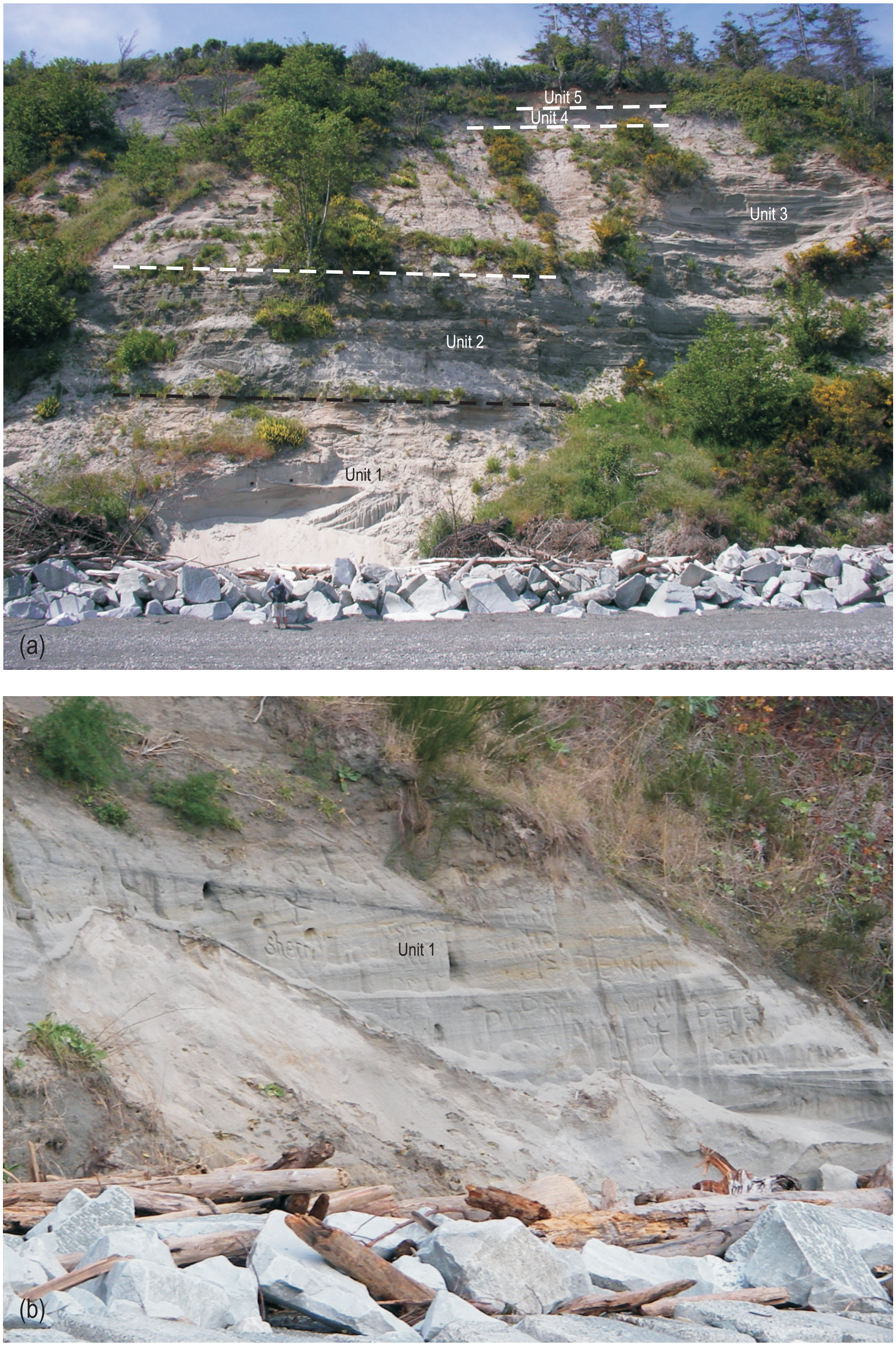


Figure 3.7. Lithologic Unit 1, Willemar Bluff, Comox. Figure 3.7a illustrates the extensive and very well sorted sand deposit, while Figure 3.7b exhibits the unit's large scale trough cross-bedding.

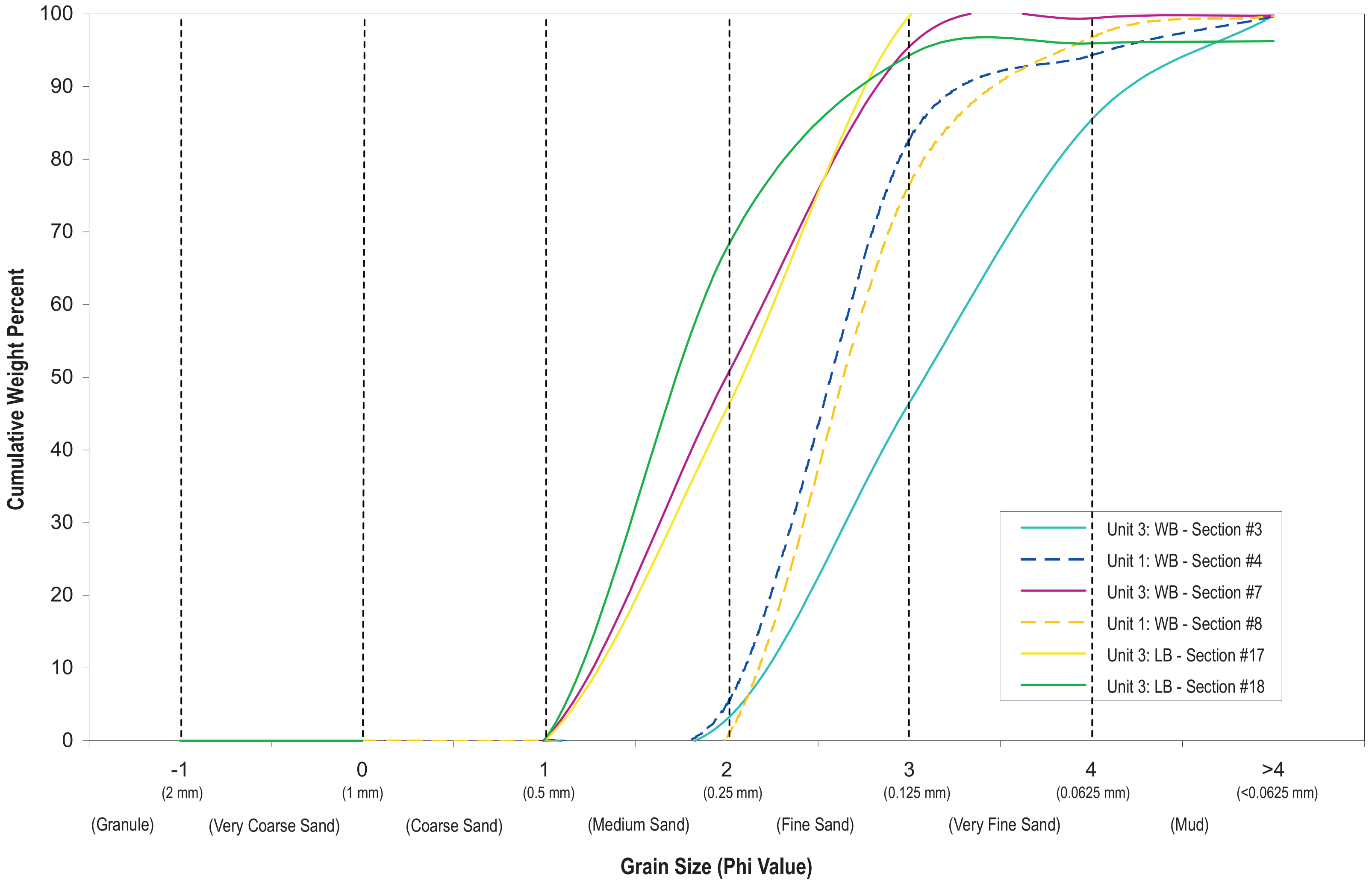


Figure 3.8. Units 1 & 3 Grain Size Analysis, Willemar and Lazo Bluffs, Comox

small scale ripple and wavy cross-bedding. The unit is unconsolidated and extends up from beach level to a mean elevation of 12 m above mean sea level (m +MSL). Although of substantial thickness and lateral extent, Unit 1 dips slightly down towards sea level along the northeast side of Willemar Bluff, and is not present at the Lazo Bluff exposure (Figures 3.9a & 3.9b).

3.5.2 Unit 2

Exposed above a gradational lower contact with Unit 1, Unit 2 is a very fine-grained sandy, silt (Figure 3.10 & 3.11). This unit exhibits small scale wavy to sub-horizontal laminations, small scale ripple bedding, as well as areas with interbedded silty clay or sand layers. There are also localized areas of soft sediment deformation and iron oxidation throughout this unit. Colours range from grey and green to brown and purple, with an overall greenish-grey dominating. This fine-grained unit hosts abundant organics; commonly discovered were intact wood pieces and black charcoal chips. The unit thickness across the bluff averages 10 m, with a lower contact elevation between 11 m and 20 m +MSL. Similar to Unit 1, Unit 2 laterally extends throughout the Willemar Bluff exposure while also dipping down to the northeast; Unit 2 is not observed at the Lazo Bluff exposure.

3.5.3 Unit 3

Above a clear, locally graded, contact with Unit 2 is the fine- to medium-grained sand of Unit 3. Similar to that of Unit 1, Unit 3 sediment grains are of varied lithology and contain abundant biotite and hornblende. The sand in this unit is a well sorted, white or light grey to light yellow or tan colour, predominantly white at Willemar Bluff and yellow at Lazo Bluff (Figures 3.8 and 3.12). The unit displays a slight coarsening-upwards-sequence overall. Bedding structure is sub-horizontal to horizontal at the base of the unit, changing to low angle, medium to large scale trough cross-bedding higher up the unit. Localized small scale ripple and wavy cross-beds, highlighted by

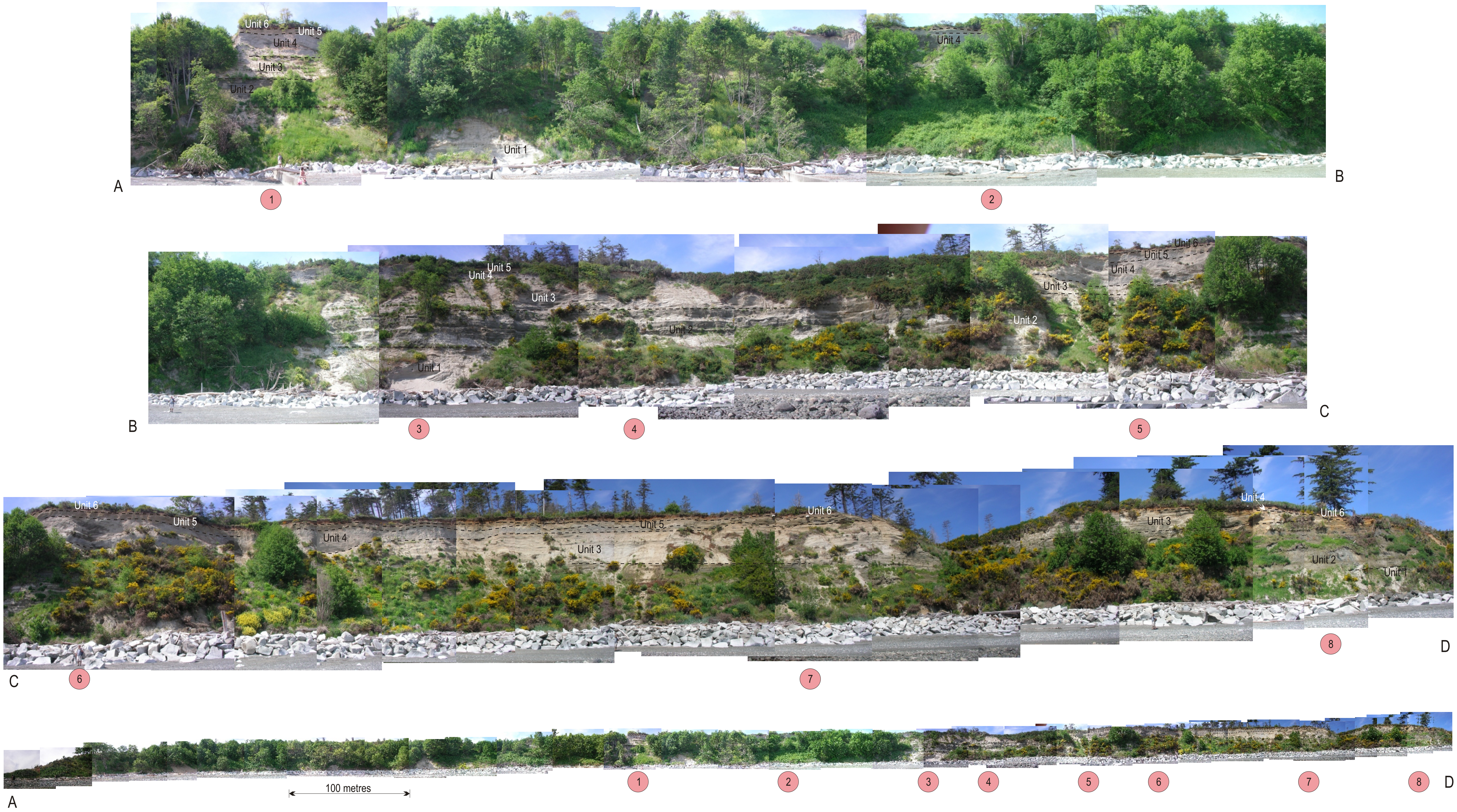


Figure 3.9a. Willemar Bluff Coastal Exposure, Comox, B.C. Distance from A to D is 1,200 metres. Refer to Figure 3.2 for location map.

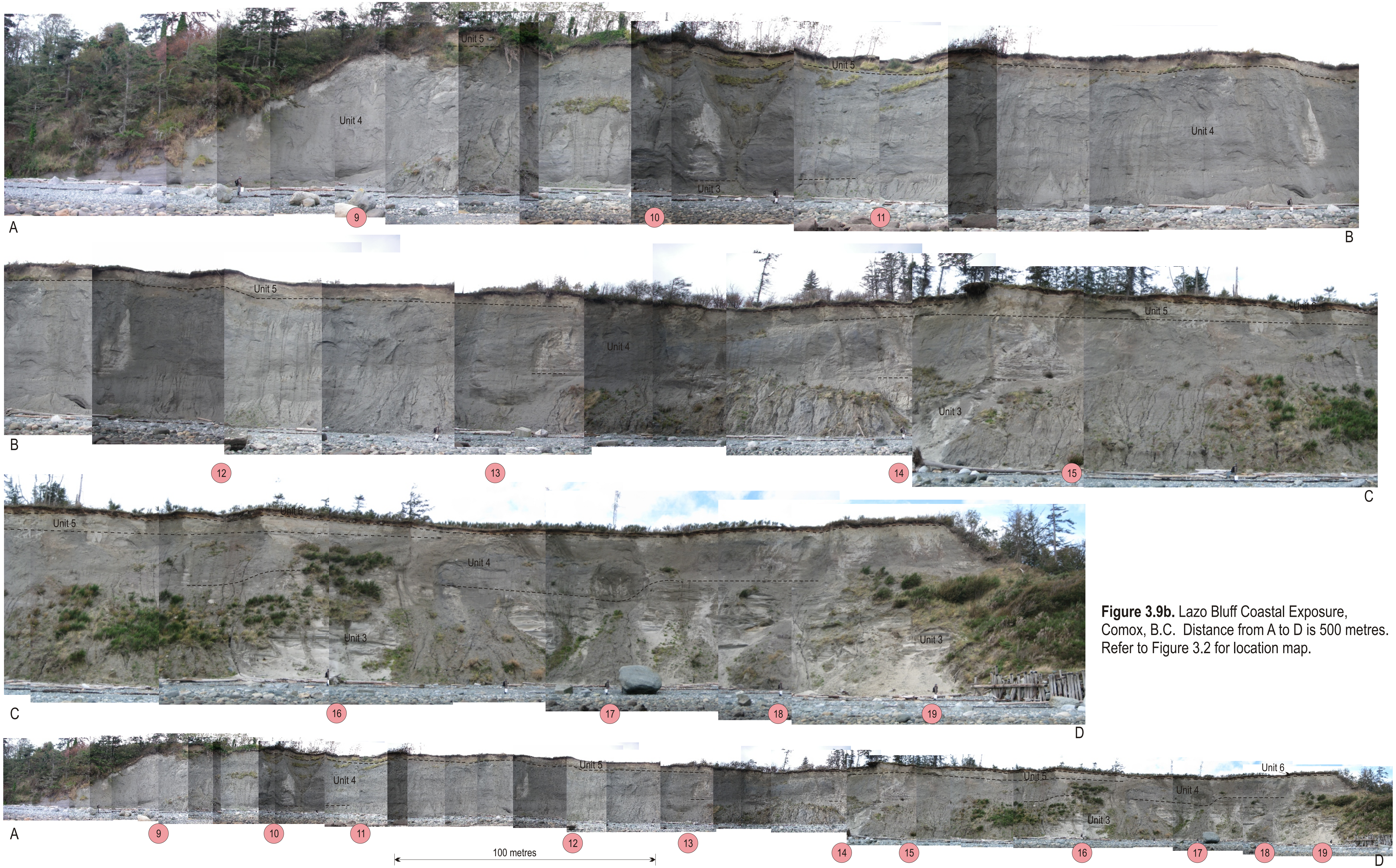


Figure 3.9b. Lazo Bluff Coastal Exposure, Comox, B.C. Distance from A to D is 500 metres. Refer to Figure 3.2 for location map.

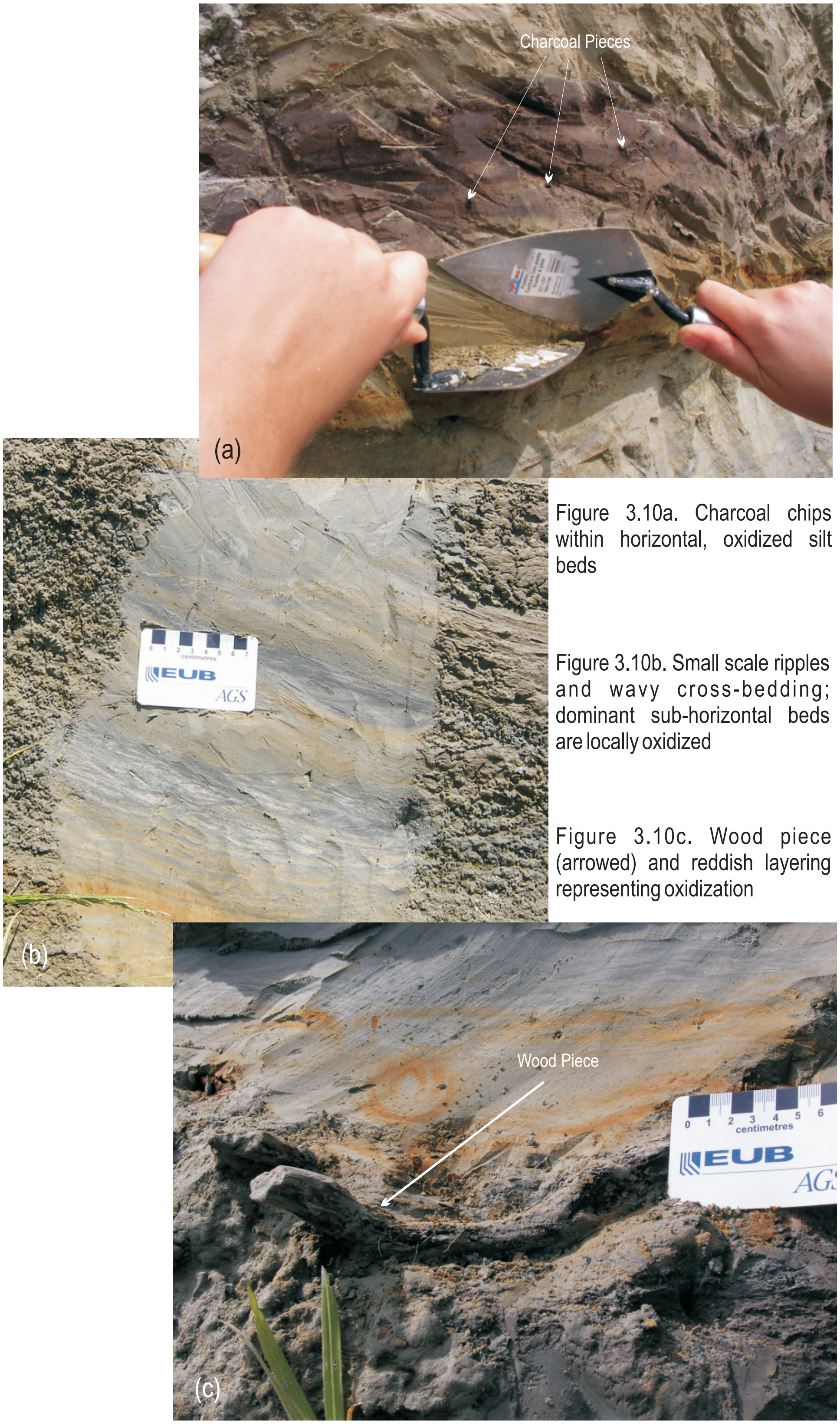


Figure 3.10a. Charcoal chips within horizontal, oxidized silt beds

Figure 3.10b. Small scale ripples and wavy cross-bedding; dominant sub-horizontal beds are locally oxidized

Figure 3.10c. Wood piece (arrowed) and reddish layering representing oxidization

Figure 3.10. Lithologic Unit 2, Willemar Bluff, Comox

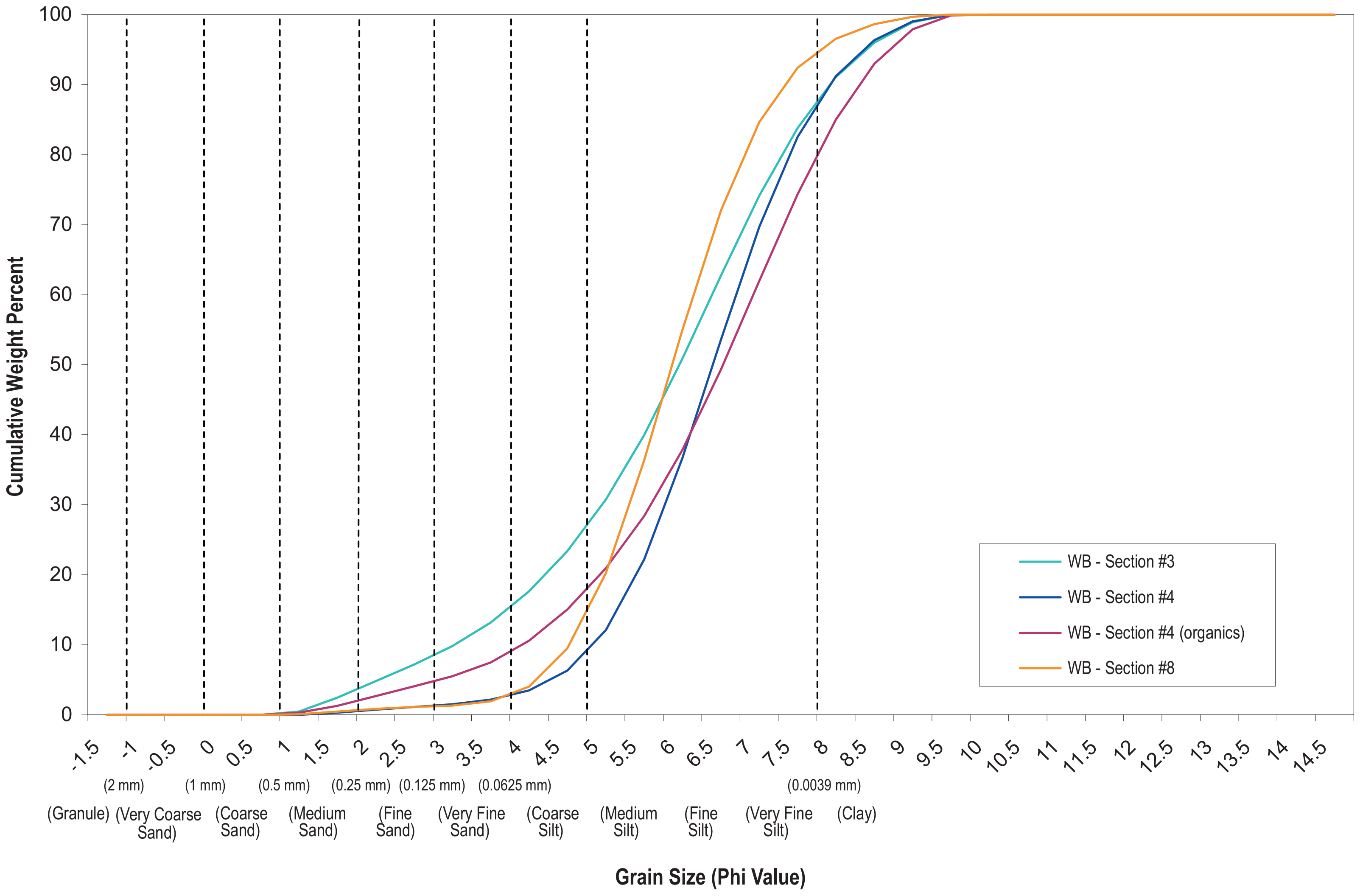


Figure 3.11. Unit 2 Grain Size Analysis, Willemar Bluff, Comox

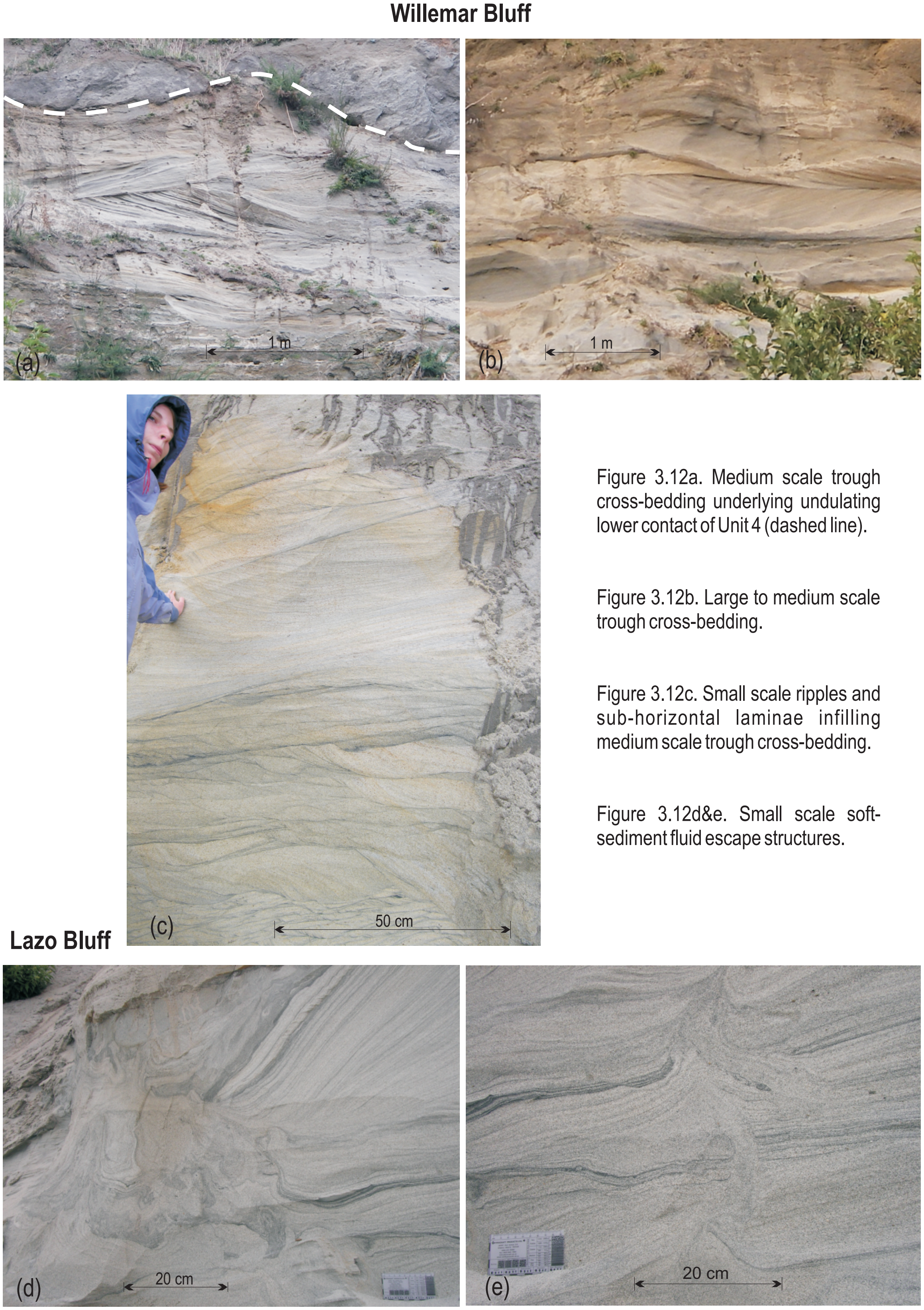


Figure 3.12a. Medium scale trough cross-bedding underlying undulating lower contact of Unit 4 (dashed line).

Figure 3.12b. Large to medium scale trough cross-bedding.

Figure 3.12c. Small scale ripples and sub-horizontal laminae infilling medium scale trough cross-bedding.

Figure 3.12d&e. Small scale soft-sediment fluid escape structures.

Figure 3.12. Lithologic Unit 3, Willemar and Lazo Bluffs, Comox

laminae with mafic mineral concentrations, are found within the larger scale troughs. Soft sediment deformation structures are also found near the upper and lower contacts of this unit (Figure 3.12 d & 3.12 e). At one particular location along Willemar Bluff, near Field Section #4, iron oxidation oriented at 220° (SW) was noticed when the sand was cut perpendicular to the bluff face, outlining a possible fluid flow pathway. The unit thickness across Willemar Bluff ranges between 1 m and 15 m, the lower contact occurring at approximate elevations of 17 m to 35 m +MSL. A similar unit was identified at Lazo Bluff, exposed from beach level up to 25 m +MSL, with the lower contact either covered by localized sediment slumps or below sea level.

3.5.4 Unit 4

Unit 4 is an overconsolidated silty, sandy, matrix-supported diamicton containing pebble to boulder sized clasts (Figure 3.13 and 3.15) interbedded with stratified silty and sandy lenses. Figure 3.14 depicts the grain size analysis of Unit 4 collected for the present study at both Willemar and Lazo bluffs. The diamicton matrix is poorly sorted, exhibiting a wide range of grain sizes. Three of the four samples analyzed display a significant mode at the medium-grained sand size; the fourth is a silt lense within the diamicton (Figure 3.13a and 3.14). The lower contact is generally sharp and erosional, with localized areas of pronounced undulation (Figure 3.12a). The unit is primarily light to dark grey in colour. Occasional lenses of finer grained material occur within the unit, and are typically less than ½ m thick and less than 10 m in lateral extent. Unit structure is dominated by wavy to low angle, inclined bedding in the lower five metres where silt and sand interbeds are common; the unit is more massive up section. Localized large scale flame-like structures and deformed beds occur near the upper contact with Unit 5 (Figure 3.16a and 3.17a). Unit thickness ranges between 1 m and 10 m; the unit's lower contact occurs at approximate elevations of 24 m to 40 m +MSL. A similar unit is recognized at Lazo Bluff, with thickness ranging

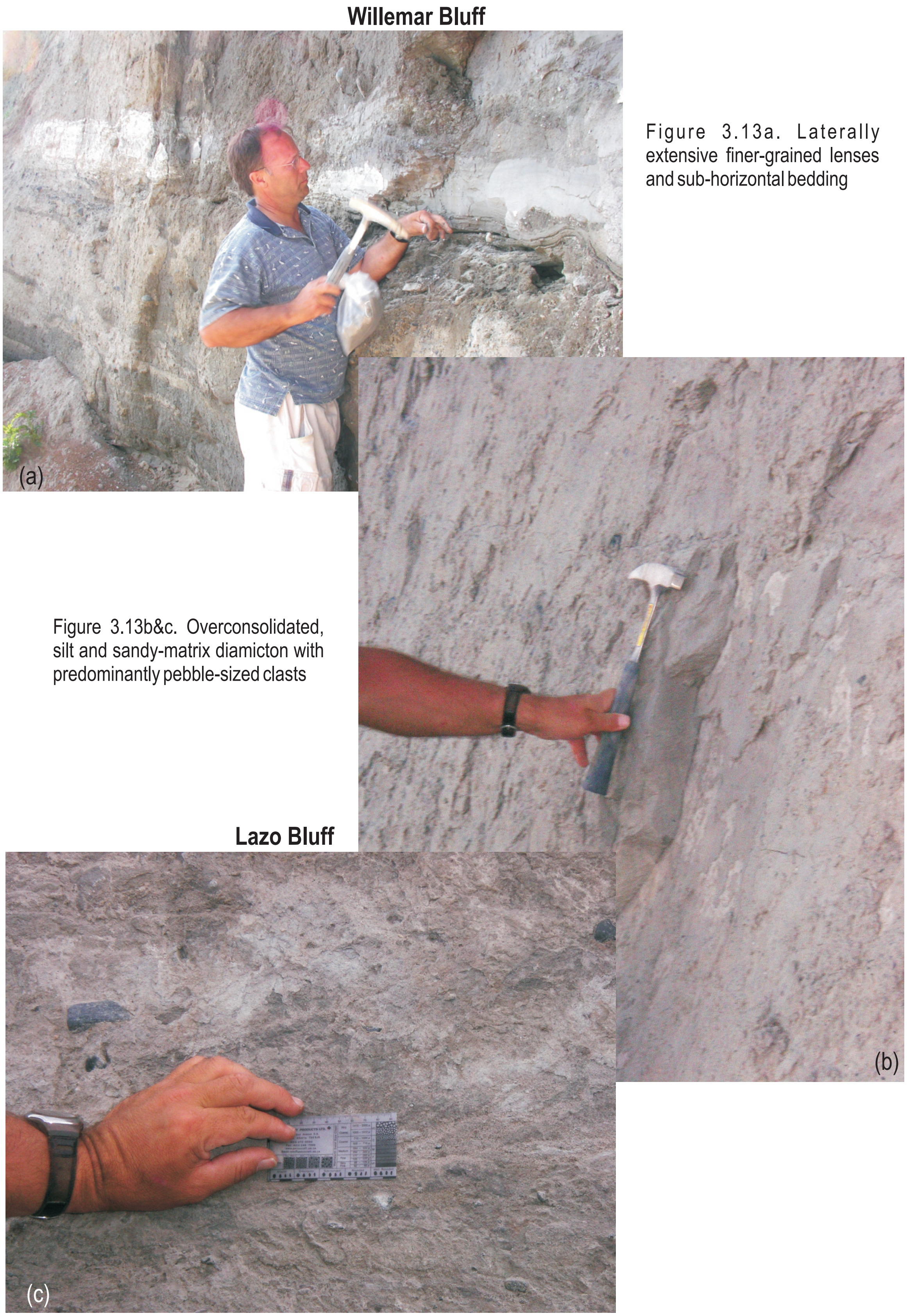


Figure 3.13a. Laterally extensive finer-grained lenses and sub-horizontal bedding

Figure 3.13b&c. Overconsolidated, silt and sandy-matrix diamicton with predominantly pebble-sized clasts

Figure 3.13. Lithologic Unit 4, Willemar and Lazo Bluffs, Comox

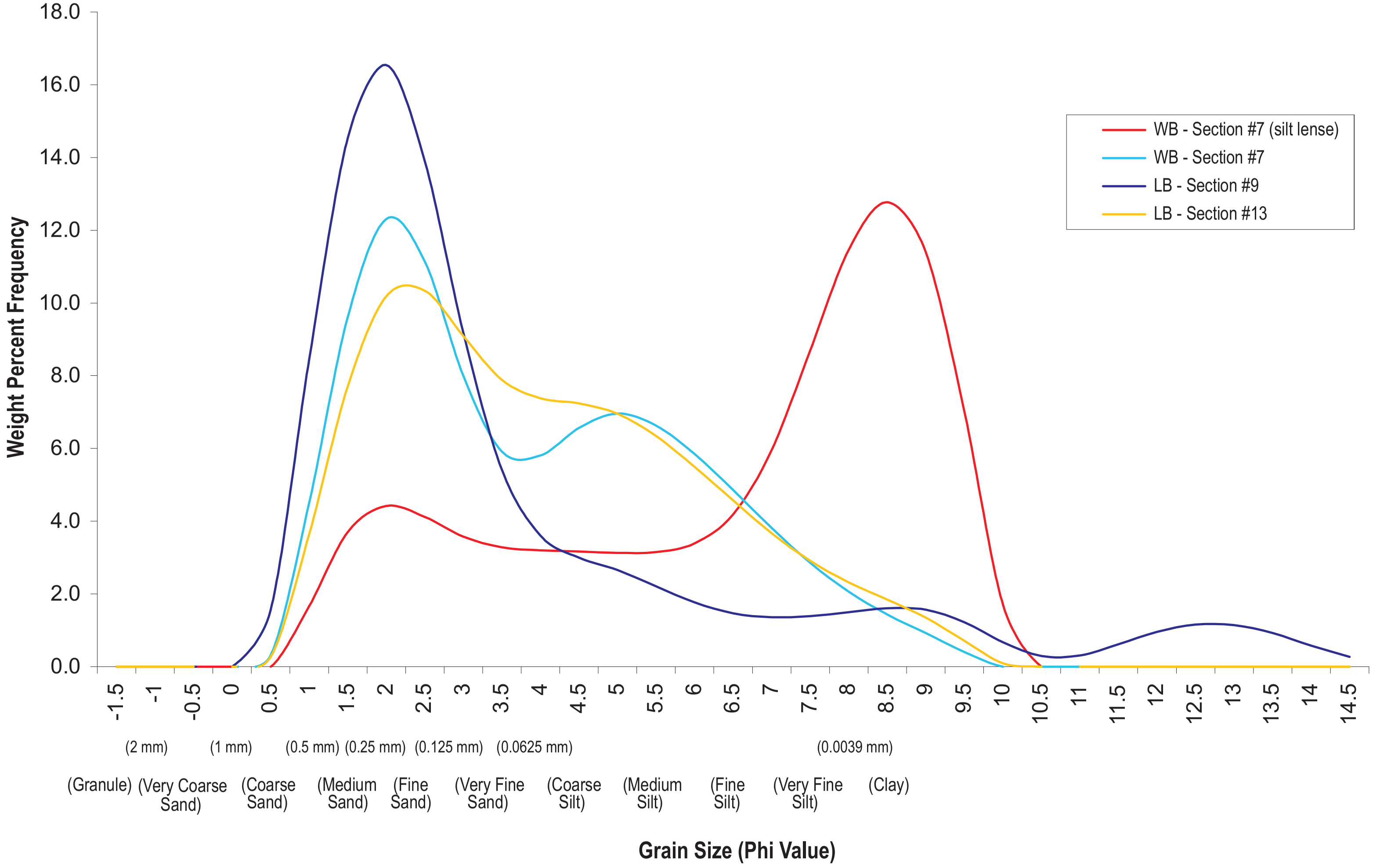


Figure 3.14. Unit 4 Grain Size Analysis, Willemar and Lazo Bluffs, Comox

Willemar Bluff

a) Willemar Bluff Section 1: 500 m along transect, GPS: 0363270, 5503737, vertical accuracy 6.3 m. Inclined bedding with an apparent dip northeast.

b) Willemar Bluff Section 2: 600 m along transect, GPS: 0363328, 5503806, vertical accuracy 6.0 m. Inclined bedding with an apparent dip south-southwest.

Lazo Bluff

c) Lazo Bluff Section 9: 500 m along transect, GPS: 0365863, 5507235, vertical accuracy 6.7 m. Wavy to sub-horizontal bedding, pebble to boulder sized clasts.

d) Lazo Bluff Section 11: 400 m along transect, GPS: 0365824, 5507335, vertical accuracy 7.1 m. Boulder rich layer within fine-grained, overconsolidated diamicton.

e) Lazo Bluff Section 12: 350 m along transect, GPS: 0365814, 5507389, vertical accuracy 7.0 m. Small-scale wavy to horizontal cross-bedding within the lower 5 m of the silt and sandy diamicton.

f) Lazo Bluff Section 14: 250 m along transect, GPS: 0365793, 5507485, vertical accuracy 7.0 m. Convoluted bedding, pebble to boulder sized clasts within the lower 5 m of the silt and sandy diamicton.

Figure 3.15. Variations in the structural features within Unit 4, Willemar and Lazo Bluffs, Comox. Refer to Figure 3.2 for location map.

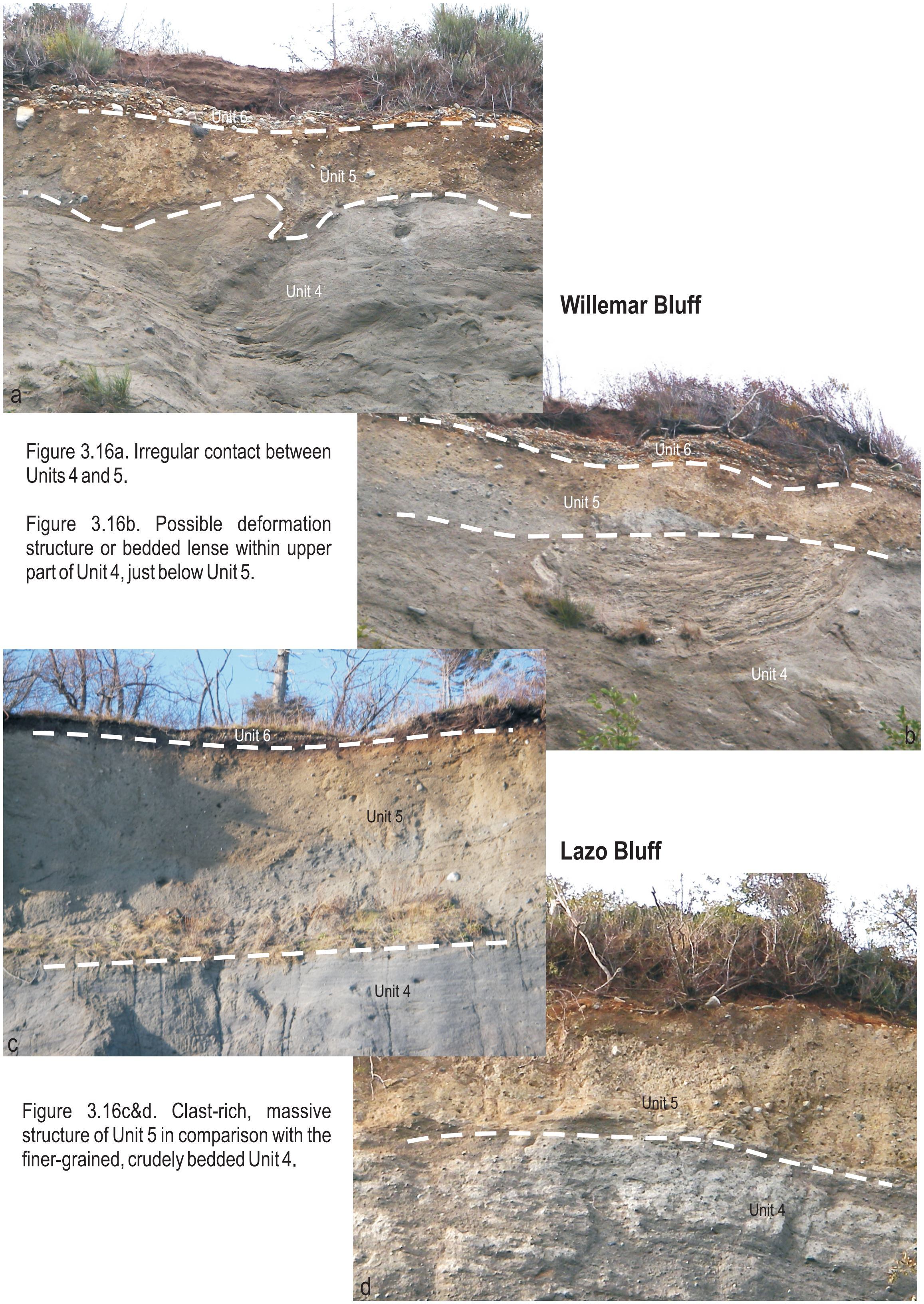


Figure 3.16a. Irregular contact between Units 4 and 5.

Figure 3.16b. Possible deformation structure or bedded lense within upper part of Unit 4, just below Unit 5.

Figure 3.16c&d. Clast-rich, massive structure of Unit 5 in comparison with the finer-grained, crudely bedded Unit 4.

Figure 3.16. Lithologic Units 5 & 6, Willemar and Lazo Bluffs, Comox

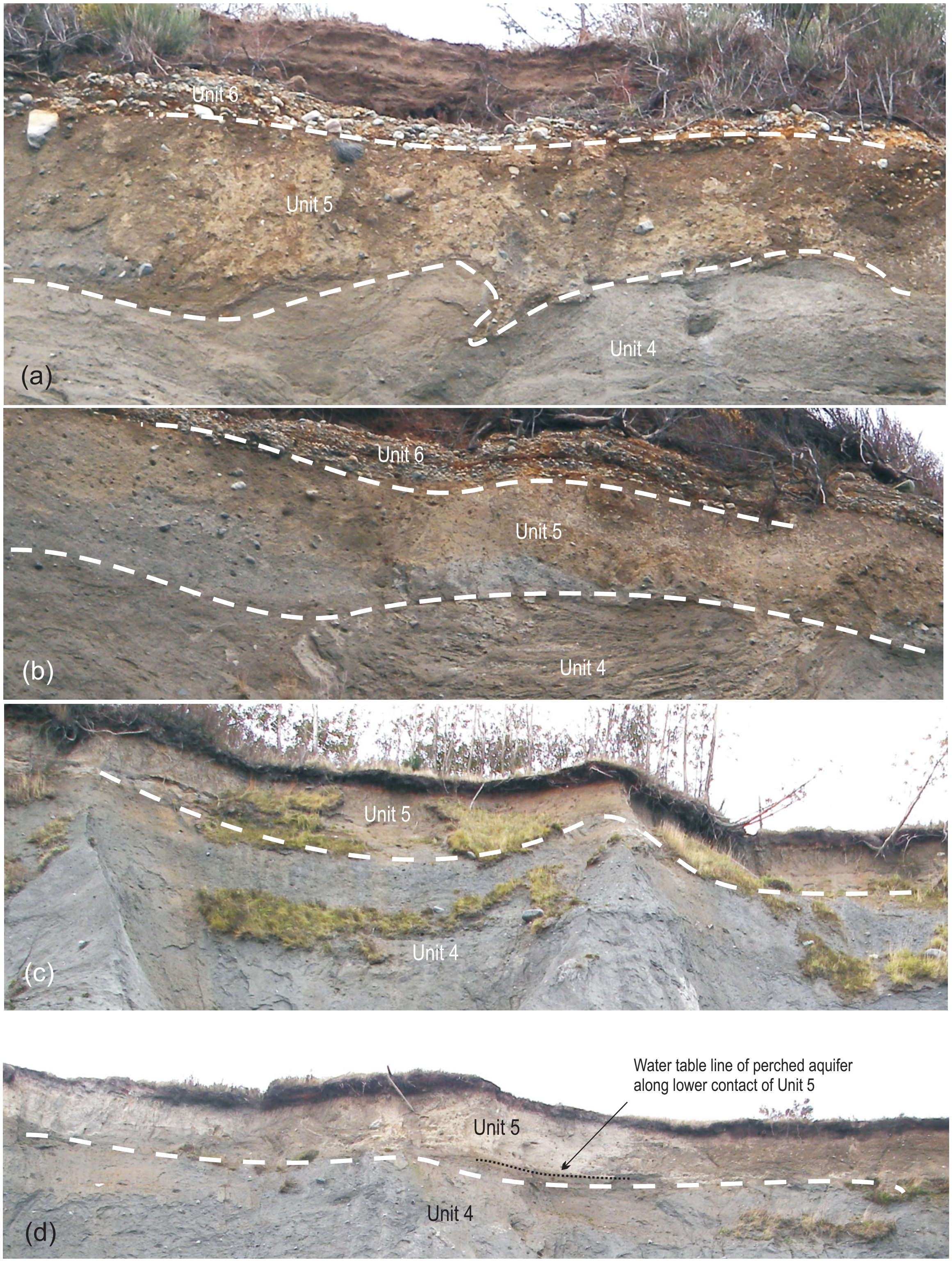


Figure 3.17. Texture variations within Unit 5 at Comox. Unit 5 exposed along Lazo Bluff (photographs c&d) appears finer grained and possibly less consolidated than the coarse-grained, overconsolidated and clast-rich exposure at Willemar Bluff (photographs a&b). Photograph (d) also shows a water table line along the unit's lower contact with Unit 4, indicative of a boundary to groundwater movement.

between 9 m and 25 m, and lower contact elevations from below sea level up to roughly 25 m +MSL. In some locations at Lazo Bluff, large, boulder-size clasts are concentrated in lense-shaped layers in the lowermost 10 m (Figure 3.15d), becoming more randomly distributed and predominantly cobble-size up section.

3.5.5 Unit 5

Unit 5 comprises an overconsolidated sandy diamicton, abundant in pebble to boulder sized clasts (Figure 3.16 & 3.17). The lower contact varies from sharp and irregular to gradational; in places units 4 and 5 are interfingered (Figures 3.16a and 3.17a). The unit is buff to tan in colour and is predominantly massive in texture, with little to no internal structure, and in places becomes blocky towards the top of the unit. Overall, Unit 5 is distinguished from Unit 4 by Unit 5's coarser grained texture, tan colour and massive structure. Unit thickness across Willemar Bluff ranges from 1 m to 6 m with the base of the unit exposed at approximate elevations of 32 m to 49 m +MSL; the same unit at Lazo Bluff, ranges from 3.4 m to 5.5 m thick, and lower contacts occur roughly from 24 m to 29 m +MSL.

3.5.6 Unit 6

The uppermost unit, Unit 6, consists of a sandy, pebble- to cobble-gravel, with occasional boulders (Figure 3.16). The unit is oxidized orange to brown in colour and has crude horizontal to inclined bedding. Unit thickness across Willemar Bluff ranges between 0.5 m to 1 m and the base is exposed at approximate elevations of 26 m to 52 m +MSL; the same unit occurs at Lazo Bluff, with thickness ranging between 0.3 m and 1 m, and lower contacts from roughly 30 m to 35 m +MSL.

3.6 Comox Bluff Interpretation

3.6.1 Lithostratigraphic Interpretation

The extensive exposures along Willemar and Lazo bluffs at Comox reveal a wide lateral extent for all six identified units. Given the fine grain size, exceptional sorting and dominant low angle, large scale trough cross-bedding of the sand units, a relatively distal, low relief, glaciomarine depositional environment is proposed for Unit 1 and Unit 3 identified at Comox. The thick sequences of uniform, predominantly fine-grained sand, suggest an environment distal to glacial influences. A subaerial glaciofluvial depositional environment is unlikely due to the lack of channels that would be evidenced by lag deposits, channel scours and lateral variations across the bluff exposures (Miall, 1992). Rather, the low angle and laterally prevalent cross-bedding suggests a glaciomarine environment such as a distal delta or pro-delta sequence (Bhattacharya and Walker, 1992). The fine grain size and horizontal stratification in Unit 2, traceable for several hundred metres, also supports the interpretation of a quiet, lower energy, glaciomarine depositional environment. The organic material found within Unit 2 furthers the argument against a glaciofluvial origin which would be typically devoid of organic material (Eyles and Eyles, 1992).

Previous research analyzing the mineralogy and grain surface textural characteristics of the lower units at Comox Bluff (Fyles, 1963; Clague, 1977) revealed a Coast Mountain provenance and a transport mechanism at least partly by glacial processes. Both Fyles (1963) and Clague (1977) interpreted the lower three units identified in this study at Comox Bluff to be sub-aerial, glaciofluvial, outwash deposits laid down in advance of the Fraser Glaciation. The considerable volume of sediment deposited at Comox does support a depositional environment influenced by glacial processes; however, the close proximity of the marine waters of the Strait of Georgia prompts the consideration of a glaciomarine depositional environment.

Unit 4 is interpreted as a proximal, glaciomarine deposit with glacially-derived diamicton units interbedded with glaciomarine silts and sands. This depositional environment is supported by the poor sorting of diamicton units, having a clay to coarse-grained sand matrix, and a wide range in clast sizes ranging from granules to boulders. Over-consolidation and the significant vertical and lateral extent of the unit also support this interpretation. Furthermore, bedding observed in the unit, combined with the presence of scattered boulder-sized clasts at Lazo Bluff, support a proximal glaciomarine depositional environment. The unit likely formed at the margins of the Cordilleran ice sheet as it advanced southwest down the Georgia Depression. Flame-like structures and deformed beds in the upper part of Unit 4 at Willemar Bluff (Figures 3.16a and 3.17a) may reflect loading of Unit 5 onto Unit 4.

Fyles (1963) described a characteristic sandy till of the coastal lowland that corresponds closely to the distribution of the underlying Quadra Sand, the lithostratigraphic unit that includes Units 1-3 at Comox (Fyles, 1963; Clague, 1977). Fyles's grain size analysis of various till deposits in the area revealed a dominant sediment population mode of between 8-25% medium-grained sand with a minor mode of gravel size material (Figure 3.18). The grain size analysis of Unit 4 samples collected at Comox (Figure 3.14) yields a very similar grain size distribution to that of Fyles's work, supporting a glacial origin for diamicton beds in Unit 4.

Unit 5 was not safely accessible for sampling and so the unit's interpretation is primarily based on observations through binoculars and digital photographs (Figures 3.16 & 3.17). The unit is interpreted to be a till on the basis of its massive structure, over-consolidation, high proportion of pebble- to boulder-sized clasts, and generally sharp and erosive lower contact. The interfingering of Unit 4 and Unit 5 in places along the Comox Bluff probably reflects loading of the till into the underlying saturated ice proximal sediments. The unit's massive structure supports a ground-

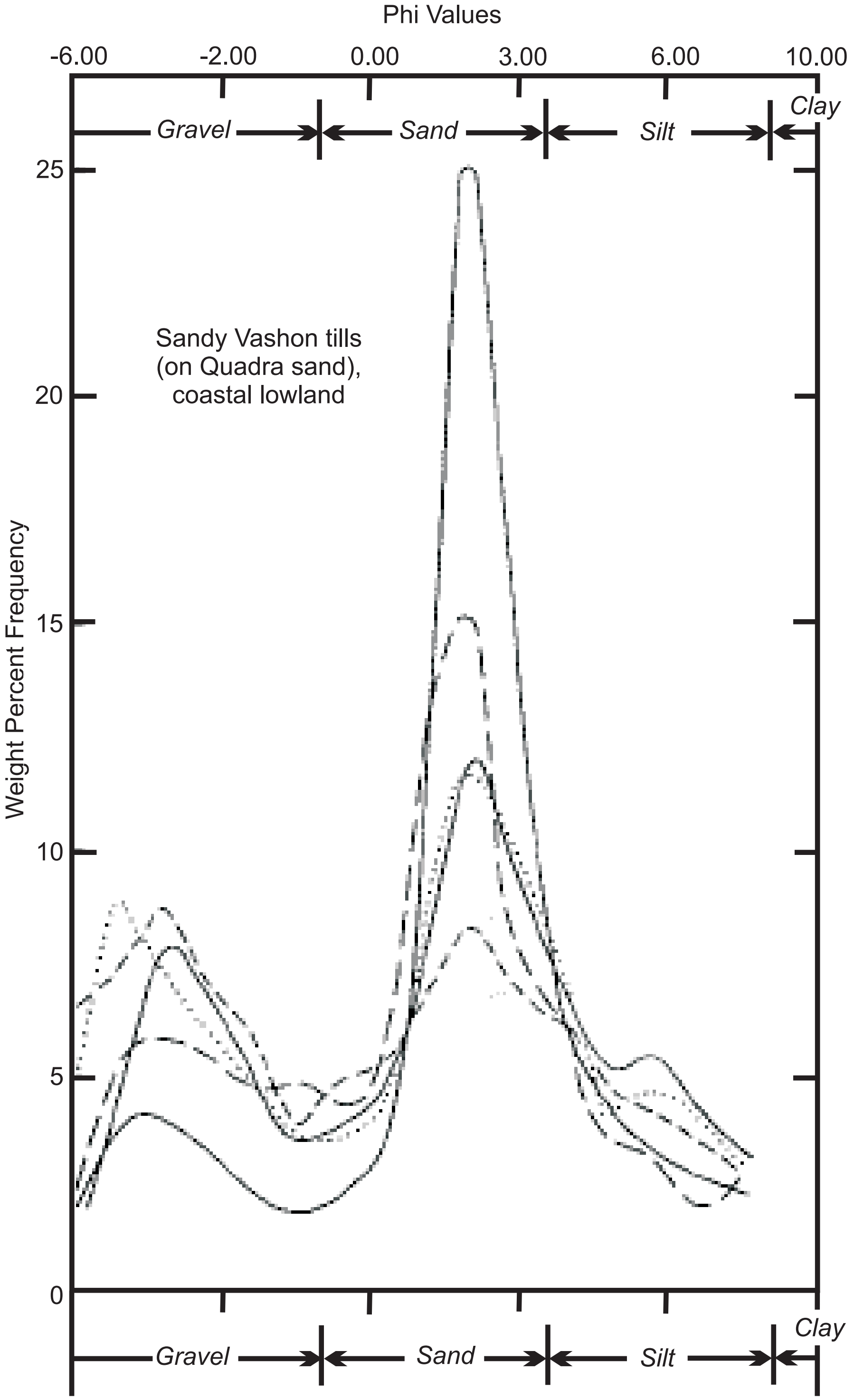


Figure 3.18. Grain size distribution of sandy Vashon tills of the coastal lowland. Amended from Fyles (1963).

moraine glacial deposit, probably equivalent to the sandy till identified by Fyles (1963) as the Vashon Drift laid down during the Fraser Glaciation.

The thin veneer of the oxidized sand and gravel of Unit 6 intermittently overlying Unit 5 can be deduced to be either a glaciofluvial or post-glacial fluvial deposit, or the winnowed remains of recessional glacial deposits eroded by glacial winds and transgressing sea level. Unit 6 does reveal crude bedding, which would support a water-lain interpretation. However, as the vertical thickness of the deposit is less than one metre, a winnowed lag origin seems more plausible. Furthermore, the continuous occurrence of the unit for hundreds of metres atop both Willemar and Lazo bluffs does not support the lateral variation normally associated with fluvial processes (Miall, 1992).

3.6.2 Hydrostratigraphic Interpretation

Lithosratigraphic units identified in the coastal exposures at Comox are correlated to hydrostratigraphic units based on significant differences between each unit's hydraulic properties. Such properties can be approximated for hydrostratigraphic units using grain size distribution data as an indicator. Grain size analysis of samples collected at Willemar and Lazo bluffs were used to calculate hydraulic conductivity, K, estimates based on the Hazen method, $K = C(d_{10})^2$ (Hazen, 1911). The effective grain size (d_{10}), the grain size of the finest 10% of the representative sample, is multiplied by a coefficient, C, that considers grain size and degree of sorting. Hydraulic conductivity estimates for the lower four lithostratigraphic units exposed at Comox are summarized in Table 3.3, using a coefficient value of 60.

Table 3.3. Hydraulic conductivity estimates for Comox Bluff (Hazen, 1911).

Lithostratigraphic Unit	Effective Grain Size (d_{10})	Hydraulic Conductivity, K; C = 60
Unit 4 (over-consolidated diamicton)	2.8×10^{-4} cm	4.7×10^{-6} cm/s
Unit 3 (fine- to medium-grained sand)	1.3×10^{-2} cm	9.4×10^{-3} cm/s
Unit 2 (very fine-grained sandy, silt)	3.9×10^{-4} cm	9.1×10^{-6} cm/s
Unit 1 (very fine- to fine-grained sand)	6.3×10^{-3} cm	2.3×10^{-3} cm/s

The Hazen method is most applicable for unconsolidated sands with effective grain sizes between approximately 0.1 and 3.0 mm (Fetter, 2001). Even with this limitation, however, the method produces hydraulic conductivity estimates consistent with values attributed to more general material descriptions (See Tables 3.5, 3.6 and 3.7) for all four lithostratigraphic units (Fetter, 2001; Anderson and Woessner, 2002). Transmissivity, T = bK, can be approximated using the calculated K estimates and average unit thickness, b, exposed at Willemar and Lazo bluffs. Table 3.4 summarizes the transmissivity estimates for the lithostratigraphic units at Comox Bluff.

Table 3.4. Transmissivity estimates for Comox Bluff (Fetter, 2001).

Lithostratigraphic Unit	Average Thickness, b	Hydraulic Conductivity, K	Transmissivity, T
Unit 4 (overconsolidated diamicton)	11 m	4.7×10^{-6} cm/s	5.2×10^{-3} cm^2/s
Unit 3 (fine- to medium-grained sand)	15 m	9.4×10^{-3} cm/s	1.4×10^{1} cm^2/s
Unit 2 (very fine-grained sandy, silt)	10 m	9.1×10^{-6} cm/s	9.1×10^{-3} cm^2/s
Unit 1 (very fine- to fine-grained sand)	12 m	2.3×10^{-3} cm/s	2.8×10^{1} cm^2/s

Specific yield values can also be approximated by grain size distribution for unconsolidated sediments by considering the relative proportion of sand, silt and clay sized fractions (Fetter, 2001). Specific yield estimates based on grain size distributions for Comox Bluff lithostratigraphic Units 1 through 4 are 40%, 7%, 35%, and 25%, respectively.

Tables 3.5, 3.6, 3.7, 3.8, and 3.9 summarize generalized hydraulic properties for fine-grained sand, silt, fine- to medium-grained sand, glacial till, and unconsolidated sand and gravel, which approximate the six lithostratigraphic units identified at Comox Bluff. Again using the average unit thickness observed across the coastal exposures, the storativity, $S = S_s b$, can be calculated. Ranges of storativity for the Comox Bluff lithostratigraphic Units 1 – 3 are: 1.2×10^{-2} to 5.9×10^{-3}; 2.0×10^{-1} to 2.6×10^{-2} for plastic clay, and 2.0×10^{-3} to 1.3×10^{-3} for dense sand (values for silt were unavailable; however, the unit contains between approximately 10-20% clay and 10-20% very fine-grained sand as per Figure 3.11); and, 1.5×10^{-2} to 7.4×10^{-3}, respectively.

Table 3.5. Generalized hydraulic properties for fine-grained sand.
(Fetter, 2001; Anderson and Woessner, 2002)

Property	Unit Value
Porosity (n)	25-50 %
Specific Yield (S_y)	1-46 %; 33 % (arithmetic mean)
Specific Retention ($S_r = n - S_y$)	4-49 %; 17 % (arithmetic mean)
Specific Storage (S_s)	$1.0 \times 10^{-3} - 4.9 \times 10^{-4}$ m^{-1} for loose sand
Intrinsic Permeability	$1.0 \times 10^{-2} - 1.0$ darcys
Hydraulic Conductivity (K)	$1.0 \times 10^{-5} - 1.0 \times 10^{-3}$ cm/s

Table 3.6. Generalized hydraulic properties for a silt dominated unit.
(Fetter, 2001; Anderson and Woessner, 2002)

Property	Unit Value
Porosity (n)	35-50 %
Specific Yield (S_y)	1-39 %; 20 % (arithmetic mean)
Specific Retention ($S_r = n - S_y$)	11-49 %; 30 % (arithmetic mean)
Specific Storage (S_s)	$2.0 \times 10^{-2} - 2.6 \times 10^{-3}$ m^{-1} for plastic clay; $2.0 \times 10^{-4} - 1.3 \times 10^{-4}$ m^{-1} for dense sand
Intrinsic Permeability	$1.0 \times 10^{-3} - 1.0 \times 10^{-1}$ darcys
Hydraulic Conductivity (K)	$1.0 \times 10^{-6} - 1.0 \times 10^{-4}$ cm/s

Table 3.7. Generalized hydraulic properties for fine- to medium-grain sand.
(Fetter, 2001; Anderson and Woessner, 2002)

Property	Unit Value
Porosity (n)	25-50 %
Specific Yield (S_y)	16-46 %; 32 % (arithmetic mean)
Specific Retention ($S_r = n - S_y$)	4-34%; 18 % (arithmetic mean)
Specific Storage (S_s)	$1.0 \times 10^{-3} - 4.9 \times 10^{-4}$ m^{-1} for loose sand
Intrinsic Permeability	$1.0 - 1.0 \times 10^{2}$ darcys
Hydraulic Conductivity (K)	$1.0 \times 10^{-3} - 1.0 \times 10^{-1}$ cm/s

Table 3.8. Generalized hydraulic properties for glacial till.
(Fetter, 2001; Anderson and Woessner, 2002)

Property	Unit Value
Porosity (n)	10-20 %
Intrinsic Permeability	$1.0 \times 10^{-3} - 1.0 \times 10^{-1}$ darcys
Hydraulic Conductivity (K)	$1.0 \times 10^{-6} - 1.0 \times 10^{-4}$ cm/s

Table 3.9. Generalized hydraulic properties for sand and gravel. (Fetter, 2001)

Property	Unit Value
Porosity (n)	20-50 %
Specific Yield (S_y)	13-26 %; 23 % (arithmetic mean)
Intrinsic Permeability	1.0×10^2 – 1.0×10^3 darcys
Hydraulic Conductivity (K)	1.0×10^{-2} – 1.0 cm/s

Hydrostratigraphic units can be determined by comparing the estimated hydraulic properties of the six lithostratigraphic units identified at Comox Bluff. Hydrostratigraphic units can include one or multiple lithostratigraphic units, and *vice versa*. Table 3.10 summarizes the correlation of lithostratigraphic and hydrostratigraphic units for the Comox Bluff. The significant differences in hydraulic conductivity, transmissivity and specific yield between the stacked stratigraphic units provide convincing evidence to support an interpretation of aquitard for Units 2, 4, and 5; semi-confined to confined aquifer for Units 1 and 3; and, an unconfined aquifer, or due to its relatively thin thickness, a vertical transmission layer for Unit 6 at surface.

Table 3.10. Hydrostratigraphic Unit interpretation for Comox Bluff. (Fetter, 2001)

Unit	Lithostratigraphy	Hydrostratigraphy (calc.)	Hydrostratigraphic Interpretation
6	Glaciofluvial sand and gravel (oxidized sand and gravel)	Porosity = 20-50% K = 1.0×10^{-2} – 1.0 cm/s	Unconfined Aquifer
5	Glacial, sandy till (over-consolidated sandy diamicton)	Porosity = 10-20% K = 1.0×10^{-6} – 1.0×10^{-4} cm/s	Aquitard
4	Distal glaciomarine diamict (over-consolidated, silty & sandy diamicton)	K = 4.7×10^{-6} cm/s T = 5.2×10^{-3} cm^2/s S_y = 25%	Aquitard
3	Glaciomarine outwash sand (fine- to medium-grained sand)	K = 9.4×10^{-3} cm/s T = 1.4×10^{1} cm^2/s S_y = 35%	Semi-Confined to Confined Aquifer
2	Distal glaciomarine sand and silt (very fine-grained sandy, silt)	K = 9.1×10^{-6} cm/s T = 9.1×10^{-3} cm^2/s S_y = 7%	Aquitard
1	Glaciomarine outwash sand (very fine- to fine-grained sand)	K = 2.3×10^{-3} cm/s T = 2.8×10^{1} cm^2/s S_y = 40%	Semi-Confined to Confined Aquifer

The lowermost hydrostratigraphic unit, extending from below sea level to an average of 12 m +MSL at Willemar Bluff, is interpreted here as a semi-confined unconsolidated sand aquifer.

Although the unit is relatively protected from surface contamination by the overlying units, Unit 1 is considered semi-confined as opposed to confined due to the potential for hydraulic communication with Unit 3 in areas where Unit 2 is unusually thin or relatively coarse grained (see below). Considering the exposed thicknesses at Willemar Bluff and the delineated area of the Comox-Merville Aquifer, the very well sorted, dominantly fine-grained sand of Unit 1 and fine- to medium-grained sand of Unit 3 are hypothesized to store a significant amount of groundwater (Humphrey, 2000).

The unconsolidated organic-rich very fine-grained sandy silt of Unit 2 has been interpreted to be an aquitard based primarily on its fine grain size, significant thickness and wide lateral extent. Though this unit is considerably finer grained than the units above and below, the variability in thickness across the exposures and lack of interstitial cementation suggests the unit may not be entirely confining and may store and / or transmit some amount of groundwater. Consequently, Unit 2 may not always act as a barrier to groundwater movement between Units 1 and 3, but rather slowly leak water between the two sand units. Furthermore, interbedded sand and silt/clay layers within the unit potentially create preferential groundwater flow horizons in the sands and perched water tables above the silt/clay beds. However, the exposed surface of Unit 2 was often observed to be quite wet at various sites along Willemar Bluff, revealing a predominant perched water table along the unit's upper contact. This laterally extensive "wet" upper contact establishes Unit 2 as an aquitard, able to primarily block the vertical transmission of groundwater flow across its upper and lower contacts.

Unit 3, consisting of an unconsolidated fine- to medium-grained sand is interpreted as a semi-confined to confined aquifer. This sand aquifer is thought to be entirely confined with respect to its upper hydraulic boundary, as the thickness and over-consolidation of Unit 4 above sufficiently separates the groundwater storage and flow within Unit 3 from that of the overlying units. Although this aquifer is protected from surface contamination, Unit 3 may be in hydraulic communication with the underlying units and, therefore, is considered semi-confined with respect to its bottom contact. As noted above, however, groundwater is primarily seen to collect atop the Unit 2 – Unit 3 boundary, thereby suggesting that the lower hydrostratigraphic contact of Unit 3 is primarily confining.

Unit 4, consisting of over-consolidated silty and sandy diamicton is interpreted to be an aquitard, primarily separating groundwater flow above and below the unit. In addition to the hydraulic parameters calculated above using the unit's grain size distribution, this interpretation is supported by a perched water table line observed at the unit's upper contact seen at Lazo Bluff (Figure 3.17d). The average exposed thickness of Unit 4 across Willemar and Lazo bluffs is 11 m, and the lower contact extends from below sea level up to 25 m above sea level. The hydraulic properties of glacial deposits are difficult to generalize as these properties vary considerably depending on sediment distribution, degree of sorting and cementation, as well as depositional environment. Processes such as fluvial or marine re-sedimentation create highly variable deposits. As this unit has been interpreted as a glaciomarine deposit with interbedded glaciogenic diamicton, silt/clay units and sands, typical hydraulic properties for till would not apply.

The over-consolidated sandy diamicton of Unit 5 is considered an aquitard. Unlike the unconsolidated silt aquitard, Unit 2, the generalized porosity values for glacial till are roughly between 10% and 20%, which is significantly lower than values listed for Units 1 – 3 (Tables 3.5, 3.6 and 3.7) (Fetter, 2001). The comparatively coarse grained matrix and lack of visible interstitial cementation supports the interpretation that Unit 5 is capable of hosting some quantity of water as opposed to a confining aquitard, such as the over-consolidated silt and sand diamicton of Unit 4. Figure 3.17 shows variability in Unit 5's texture across Willemar and Lazo bluffs. Finer grained, less consolidated parts of the unit would be areas of preferential flow and storage, whereas areas of significantly reduced hydraulic conductivity would occur where the unit is more strongly cemented or more highly consolidated. Therefore, based on the noted perched water table, textural variability and inferred glacial derivation, Unit 5 is interpreted to be an aquitard.

The thin winnowed sand and gravel deposit of Unit 6 is considered to be a vertical water transmission layer, transmitting precipitation infiltrating the overlying soil horizons down into Unit 5. Unconsolidated sand and gravel deposits generally have considerable porosity and permeability enabling them to host and transmit water; however, the unit's restricted thickness limits its ability to be a substantial aquifer. Furthermore, the direct contact with the surface above leaves the unit unprotected from surface contamination sources.

3.7 Geostatistical Modeling Results

3.7.1 Interpolated Hydrostratigraphic Surfaces

The expert-driven iterative process of interpolating the Comox Bluff hydrostratigraphic model surfaces to best fit the groundwater well log dataset, as previously outlined in the methods section, was repeated five times based on the original full kriging of the logged dataset. Consistent improvement, assessed primarily with respect to agreement with the logged hydrostratigraphic contacts at each well, was observed with each consecutive iteration. For the fifth interpolation the model significantly deviated from the dataset; this is thought to be in response to the increasing constraint on the kriging interpolation process due to the addition of interpreted data points. The resultant surfaces of the fifth interpolation were unrealistic with respect to conventional lithostratigraphic deposition as well as when compared to what was recorded in the well logs. Therefore, the fourth interpolated model was selected as the best estimation of the subsurface hydrostratigraphic boundaries based on the groundwater well logs in the area. Appendix 3.3 tabulates all of the hydrostratigraphic surface picks – both drillers' and interpreted – and the author's rationale for each of the interpretations. Figures 3.19 a, 3.19 b, 3.20 a, and 3.20 b depict the modeled subsurface environments at Willemar and Lazo bluffs, using solely the logged drillers' observations as one scenario (Figure 3.19), and the drillers' observations as well as the additional interpreted picks of the fourth trial as the other scenario (Figure 3.20), henceforth referred to, respectively, as the Logged and Interpreted modeling scenarios.

Five hydrostratigraphic units were identified for both modeling scenarios, based on significant changes in inferred hydraulic properties of the logged lithologic units, unit thickness at each well location, stratigraphic correlation of units above and below, lateral extent by comparing multiple wells in cross-section, and whether or not the unit was noted as water-bearing in the drill log. At surface, an unconfined source aquifer was identified in the well logs to be comprised primarily of sand and gravel and includes, to a lesser degree, sand, gravel, shells, and sand and clay. Two confining layers were also identified in the logs and, subsequently, were interpreted to be aquitards. Although locally they can be discontinuous with variations in inferred hydrogeological confining properties, these units are nevertheless consistently identified in the well logs throughout the study area. The confining layers are predominantly comprised of diamicton units. Other sedimentary materials identified in the well logs and included in the aquitard units are clay, sand and clay, gravel, silt, sand, and sand and silt. Again, occasionally thin units of sediment that would otherwise be considered an aquifer are included in a confining layer, or vice versa, based on the unit's thickness, lateral extent when viewed with neighbouring wells in cross-section, and stratigraphic relationship with the units above and below. Two major aquifers have also been identified in the well logs, both ranging from vertically unconfined to confined units depending on the above strata. The aquifers are comprised primarily of sand; however, other sedimentary materials that are locally included in these regional units are sand and gravel, gravel, sand and clay, diamicton, and silt. Being the lowest unit identified by the model, the thickness of the

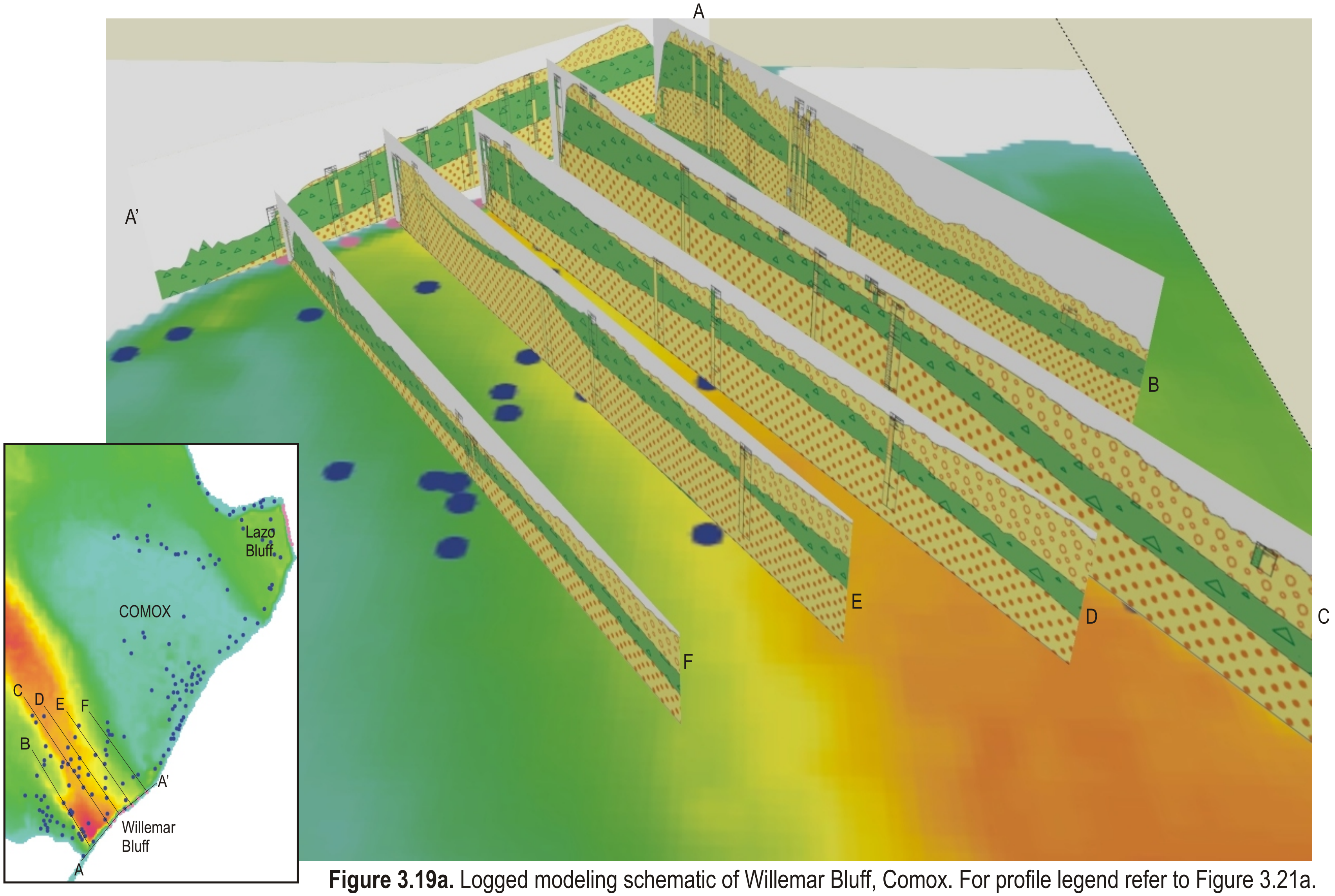


Figure 3.19a. Logged modeling schematic of Willemar Bluff, Comox. For profile legend refer to Figure 3.21a.

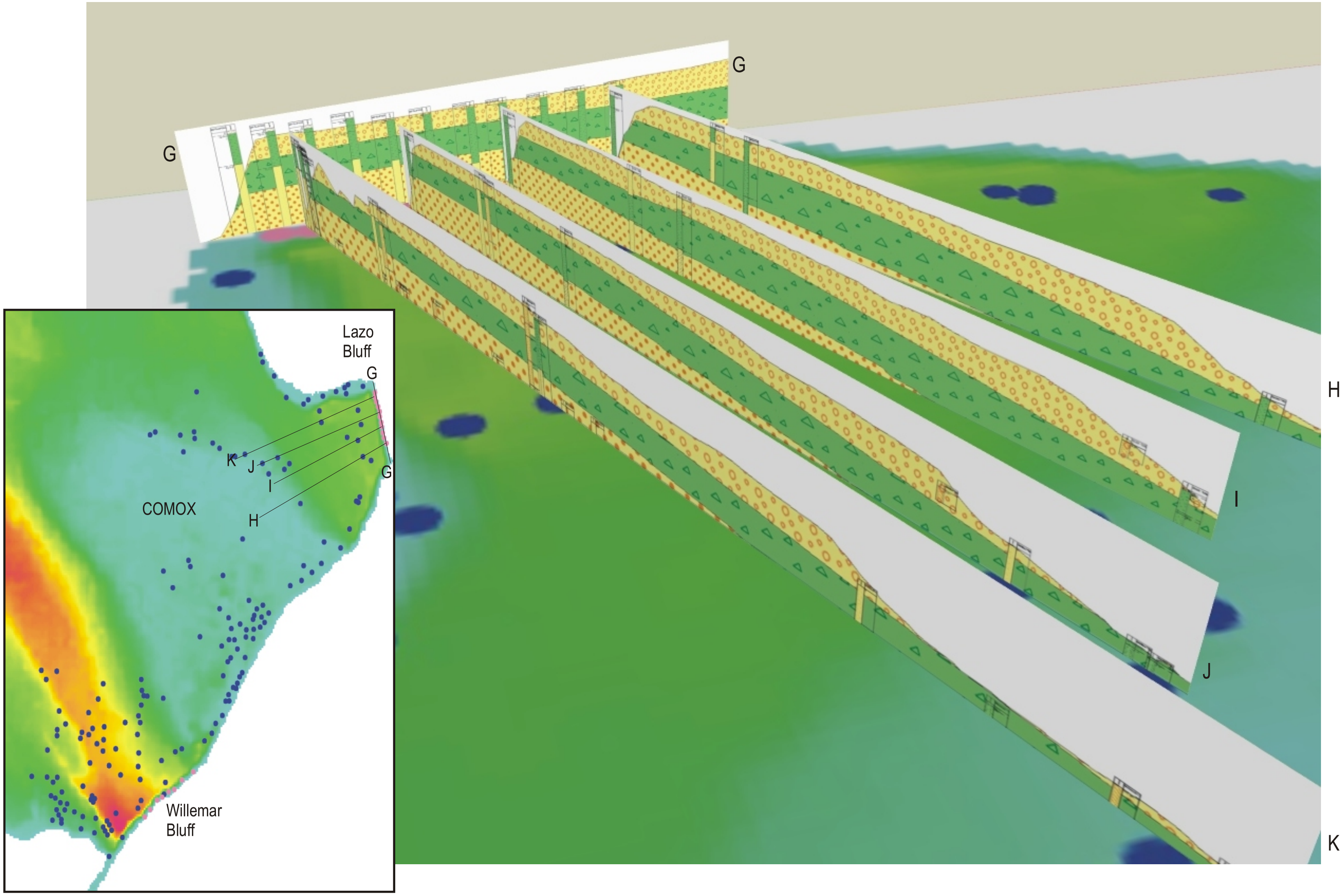


Figure 3.19b. Logged modeling schematic of Lazo Bluff, Comox. For profile legend refer to Figure 3.22a.

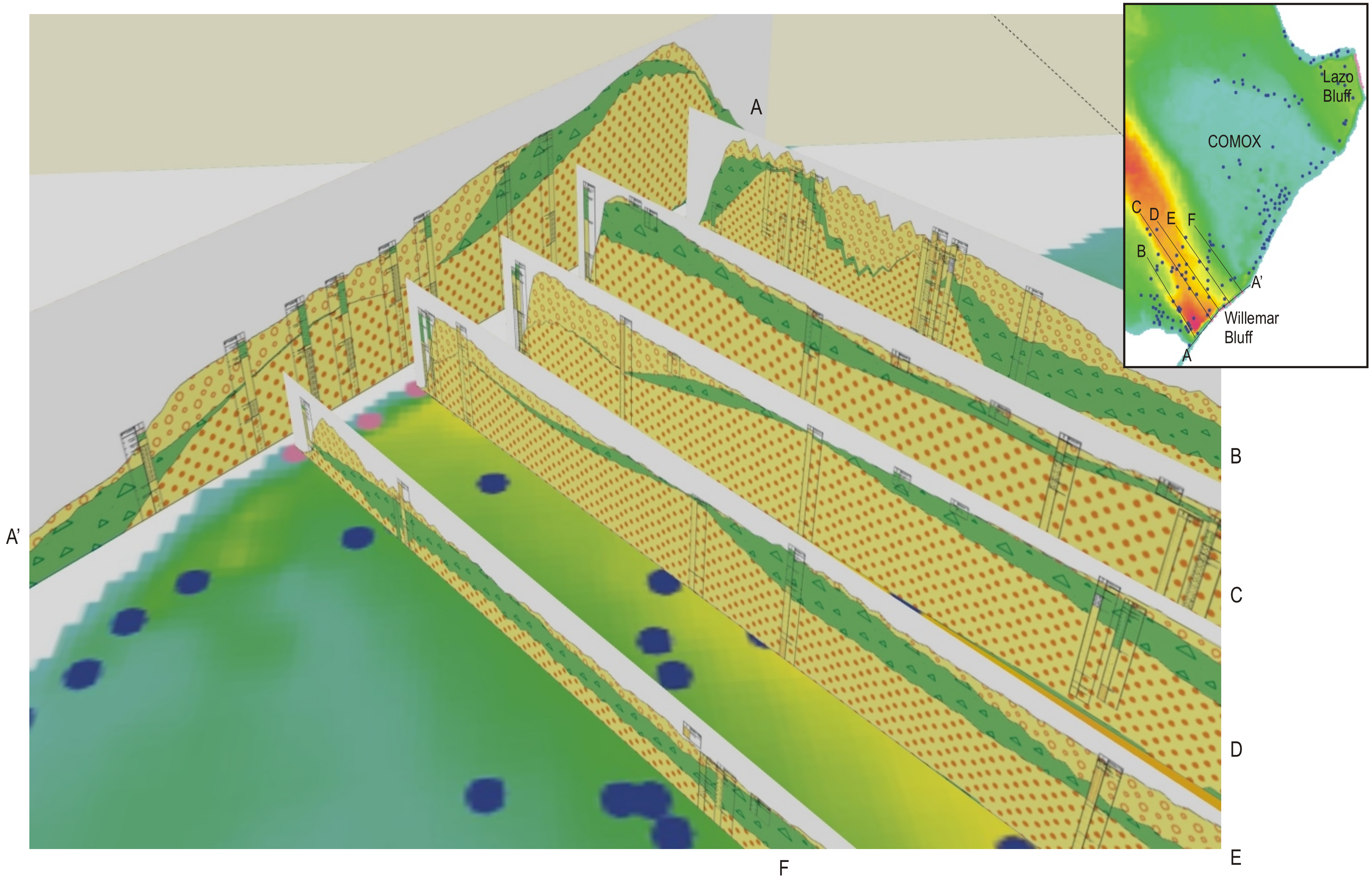


Figure 3.20a. Interpreted modeling schematic of Willemar Bluff, Comox. For profile legend refer to Figure 3.21b.

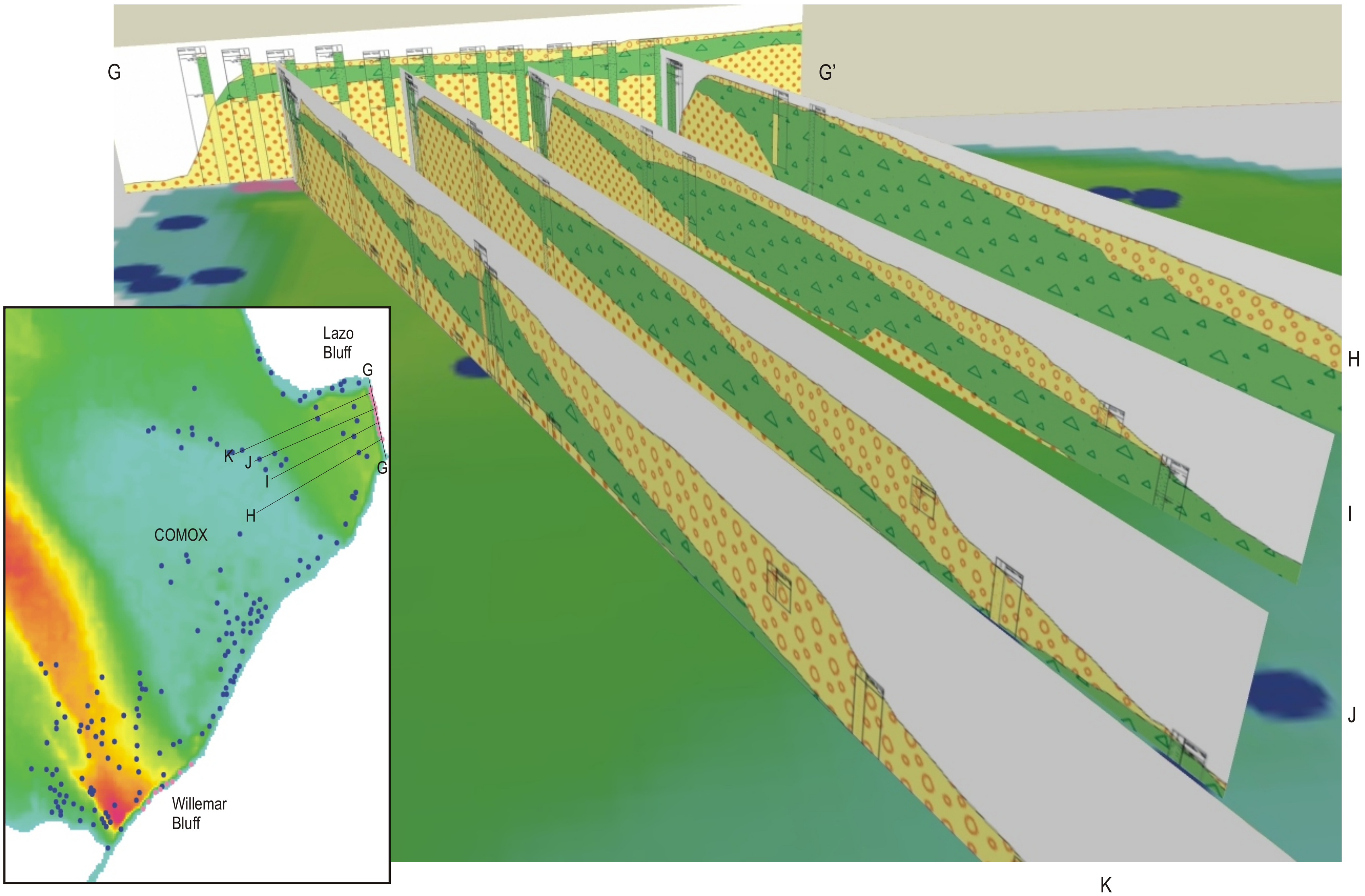


Figure 3.20b. Interpreted modeling schematic of Lazo Bluff, Comox. For profile legend refer to Figure 3.22b.

lowermost aquifer has been arbitrarily set at 30 m. This allows the model to have a “bottom” as well as ensures that all the well logs within the dataset are accounted for. Even though all five hydrostratigraphic units are spatially extensive throughout the study area, localized variability with respect to unit thickness and composition make it so that none of the units can be verified as being hydrogeologically independent from one another. This is demonstrated in Figure 3.6 where the upper confining layer is interpreted to pinch out at WTN 50657 and the unconfined sand and gravel aquifer is in hydraulic communication with the upper confined sand aquifer, making it no longer confined at that location.

3.7.2 Modeling Statistics

The resultant interpolated hydrostratigraphic surfaces of both the Logged and Interpreted modeling scenarios were schematically compared with each of the groundwater well logs by viewing cross-sections of the model’s scenarios. Three categories were created to determine the level of agreement between the modeled surfaces and the well logs in cross-section: (1) the modeled surface is more than 5 m above or below the picked contact; (2) the modeled surface is between 2 m and 5 m above or below the picked contact; and, (3) the modeled surface is within 2 m of the picked contact.

For the modeling scenario incorporating interpreted contact points as well as those identified in the well logs, the interpolated surfaces were more than 5 m above or below the picked contacts for 1% of the wells; between 2 m and 5 m for 3% of the wells; and, within 2 m of the identified points for 96% of the wells. For well logs providing static water level values, the Interpreted modeling scenario shows levels of agreement with the modeled hydrostratigraphic surfaces as per the above three categories as 5%, 11%, and 84%, respectively. Similarly, the interpolated surfaces are within 2 m for all of the well logs providing elevations of screened intervals, correctly modeling these intervals within the aquifer units. For the modeling scenario based solely on the drillers' logged contacts, the interpolated surfaces were more than 5 m above or below the picked contacts for 52% of the wells; between 2 m and 5 m for 15% of the wells; and, within 2 m of the identified points for 33% of the wells.

Auto-fit variograms that describe the spatial autocorrelation of the dataset (O'Sullivan and Unwin, 2003; Viewlog Systems, 2004) were created in Viewlog for each of the interpolated surfaces for both modeling scenarios. Tables 3.11 and 3.12 summarize the statistical analysis of the input data, with expanded tables included in Appendix 3.3.

Table 3.11. Statistical analysis of Logged input data and variogram

Statistical Analysis	Top of Confining Layer 1	Top of Confined Aquifer 1	Top of Confining Layer 2	Top of Confined Aquifer 2
Number of Data Points	22	53	13	6
Sample Mean	20.58	8.17	-10.41	-26.95
Standard Deviation	17.41	18.19	12.19	15.82
Skewness	0.32	0.70	0.19	-0.48
Coefficient of Variation	0.85	2.23	-1.17	-0.59
Goodness of Fit	69%	72%	23%	-134%
Correlation Coefficient	0.83	0.85	0.48	0.00

Table 3.12. Statistical analysis of Interpreted input data and variogram

Statistical Analysis	Top of Confining Layer 1	Top of Confined Aquifer 1	Top of Confining Layer 2	Top of Confined Aquifer 2
Number of Data Points	119	78	29	8
Sample Mean	18.84	12.51	-12.45	-31.58
Standard Deviation	20.35	22.07	11.86	17.12
Skewness	0.20	0.29	0.13	-0.22
Coefficient of Variation	1.08	1.76	-0.95	-0.54
Goodness of Fit	56%	73%	80%	187%
Correlation Coefficient	0.75	0.86	0.90	1.37

What is immediately clear by this analysis is that even though the data are spread across a wide variance interval with high standard deviation values, the Skewness values indicate that the data are normally distributed for both modeling scenarios. Interestingly, as seen by the Goodness of Fit percentages and Correlation Coefficient values for the upper surfaces of the uppermost two units, the results do not necessarily improve with more than a doubling of data points, an outcome that would be expected and which is seen for the upper contact of the third surface, the “Top of Confining Layer 2”. Comparing the “Correlation Coefficient” results for the “Top of Confining Layer 1” and the “Top of Confined Aquifer 1” of the Logged and Interpreted modeling scenarios, the lack of marked improvement could be indicative of quality concerns with the data or non-uniform distribution across the study area. Disconcertingly low sample numbers, such as those defining the upper contact of the lowermost confined aquifer unit (Top of Confined Aquifer 2), reveal nonsensical analytical results that cannot be trusted as demarking the true unit surface. Rather, these points can act as an indication for the unit’s existence. In general, however, it is clear that of the two modeling scenarios, the Interpreted modelling scenario, with hydrostratigraphic surfaces interpolated from both the interpreted and logged data points, best represent the subsurface hydrostratigraphy of the Comox Bluff area.

3.7.3 Model Verification

The Comox Bluff hydrostratigraphic model was verified using three methods: (1) variance analyses of the interpolated surfaces with respect to the input data; (2) comparison with field sections along the Willemar and Lazo bluffs; and, (3) comparison with the surficial aquifer previously identified by the BC Ministry of Environment in the central depressed region of the study area.

3.7.3.1 Variance Analysis

One of the key relationships being correlated for the Comox Bluff model is whether or not elevation values of the hydrostratigraphic surfaces can be accurately predicted based on a limited number of known, nonuniformly distributed data points. The Pearsonian correlation (r) calculates the significance level of the correlation coefficient, i.e. the predicted elevation, which can be expressed as 0.05/C, where C is the number of coefficients to be tested (Garson, 2008). As elevation is the only coefficient being tested in this relationship, and the model meets all of the necessary assumptions for Pearson's r, the significance level for correlation is 0.05/1 = 0.05 or 5%, meaning a minimum confidence limit of 95%. The correlation coefficients produced by Viewlog's variogram analysis for the upper three interpolated surfaces of the Logged and Interpreted modeling scenarios are 0.83, 0.85, 0.48, and, 0.75, 0.86, and 0.90 respectively (Tables 3.8 & 3.9). Although neither model successfully overcame the 95% confidence limit, the upper two surfaces in the Logged modeling scenario and all three surfaces for the Interpreted scenario demonstrated noteworthy values nonetheless. The hydrostratigraphic surfaces predicted by groundwater well logs were successful an average of 7 out of 10 times, and 8 out of 10 times for the Logged and Interpreted modeling scenarios, respectively. Due to a very limited number of data points, the fourth surface for both modeling scenarios was concluded to be unreliable with respect to Viewlog's statistical analyses.

3.7.3.2 Field Sections

By extrapolating the modeled surfaces to the southern coastline of the Comox Bluff study area it was possible to compare the stratigraphy observed in the exposures at Willemar and Lazo bluffs with the hydrostratigraphic surfaces predicted by the model. Unfortunately, there are very few wells completed within the coastal area immediately adjacent to the bluffs. Consequently, the interpolated data points and subsequent hydrostratigraphic surfaces become less reliable moving towards the coastline. Moving inland from the coastline at Willemar Bluff, the first 10 groundwater wells are located within 183 m inland. Moving inland from Lazo Bluff's shoreline the 8 eight wells are situated between 184 m and 626 m inland. Given the sparse groundwater well population along the coastline bordering the bluffs, and the consequent unreliable surfaces modeled adjacent to the coast, the field sections are compared to the modeled hydrostratigraphy inland from the coast where the model would provide a more accurate representation of the subsurface. Therefore, the coastal field sections are compared with the modeled hydrostratigraphy approximately 100 m inland from the southern coast at Willemar Bluff (Figures 3.21 a & 3.21 b) and at Lazo Bluff (Figures 3.22 a & 3.22 b).

Although neither of the modeling scenarios precisely match the stratigraphic sections identified along the coastal exposures, the upper semi-confined sand aquifer, the upper diamicton aquitard, and the unconfined sand and gravel aquifer at surface can be correlated to the field-interpreted hydrostratigraphic Units 1-3, 4/5, and 6, respectively. Spatial resolution of the model is unable to differentiate between the finer grained Unit 2 from the sand of Units 1 and 3. As the spatial distribution is so broad for the groundwater wells completed in the coastal region of Lazo Bluff, Figures 3.23 a & b depict the Lazo Bluff cross-section at approximately 400 m inland from the coastline for both the Logged and Interpreted modeling scenarios. Once again the modeled surfaces do not precisely correspond to the contact elevations observed along the coastline; however, the observed thickening of Unit 4 toward the southern end of the Lazo Bluff exposure is evident in the Interpreted modeling scenario’s Upper Confining Layer at this cross-section.

Interestingly, both scenarios model a relatively vertical and laterally extensive lower confining unit below sea level (Figures 3.21 – 3.23). Based on the lithostratigraphic interpretation of the units exposed at Comox, the Quadra Sand unit (Units 1-3 from this study) is modeled to extend on average -20 m +MSL (Fyles, 1963; Clague, 1977). Underlying the Quadra Sand is the nonglacial Cowichan Head deposit, which overlies the glacial sediments of the Dashwood Drift (Fyles, 1963; Clague, 1976; 1994). The lower aquitard interpreted in the Comox Bluff model is primarily comprised of diamicton, “hardpan”, clay and silt. Therefore, the unit may be that of the Cowichan Head estuarine or marine deposits rather than the glacial till of the Dashwood Drift. This

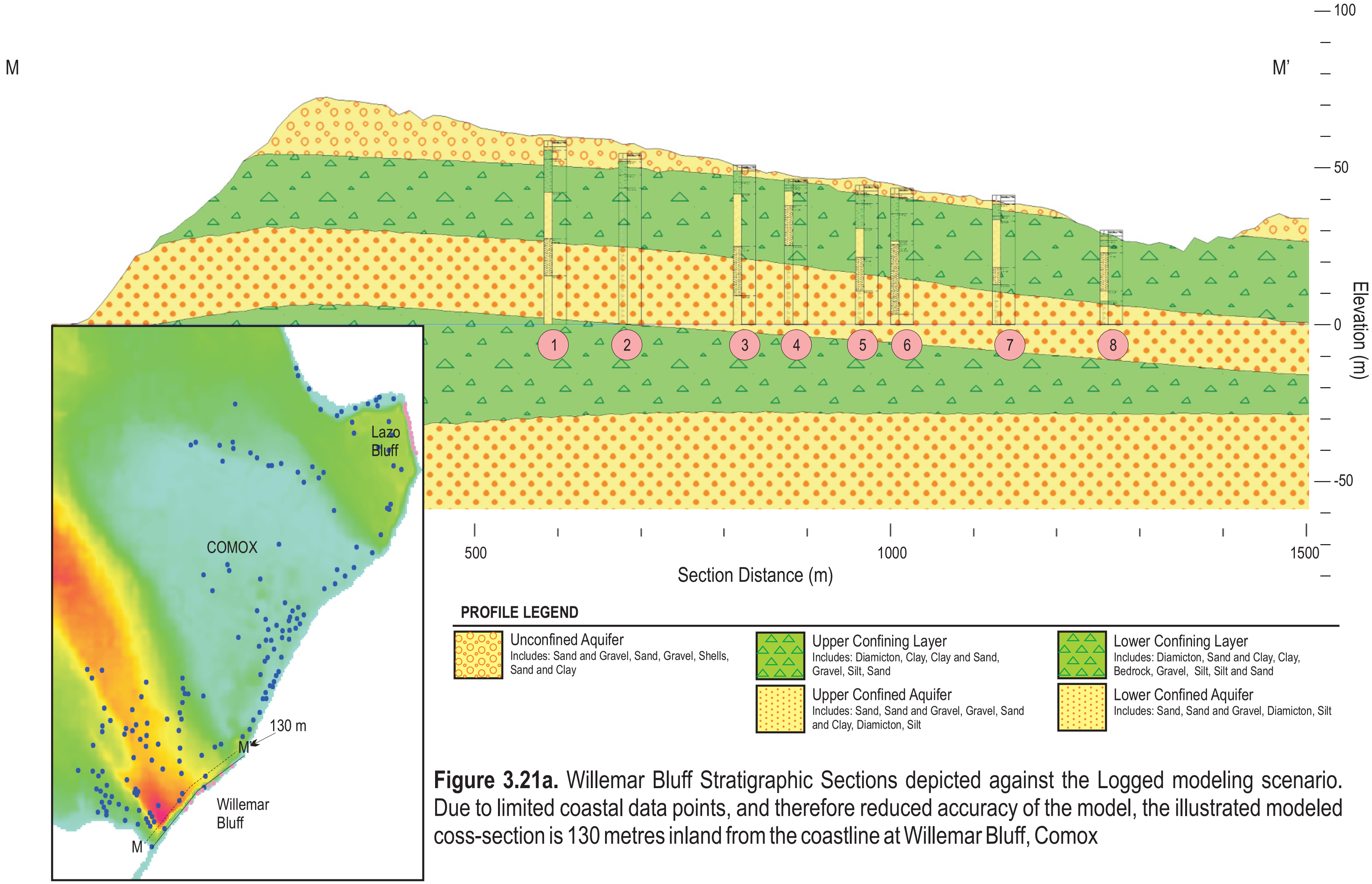


Figure 3.21a. Willemar Bluff Stratigraphic Sections depicted against the Logged modeling scenario. Due to limited coastal data points, and therefore reduced accuracy of the model, the illustrated modeled coss-section is 130 metres inland from the coastline at Willemar Bluff, Comox

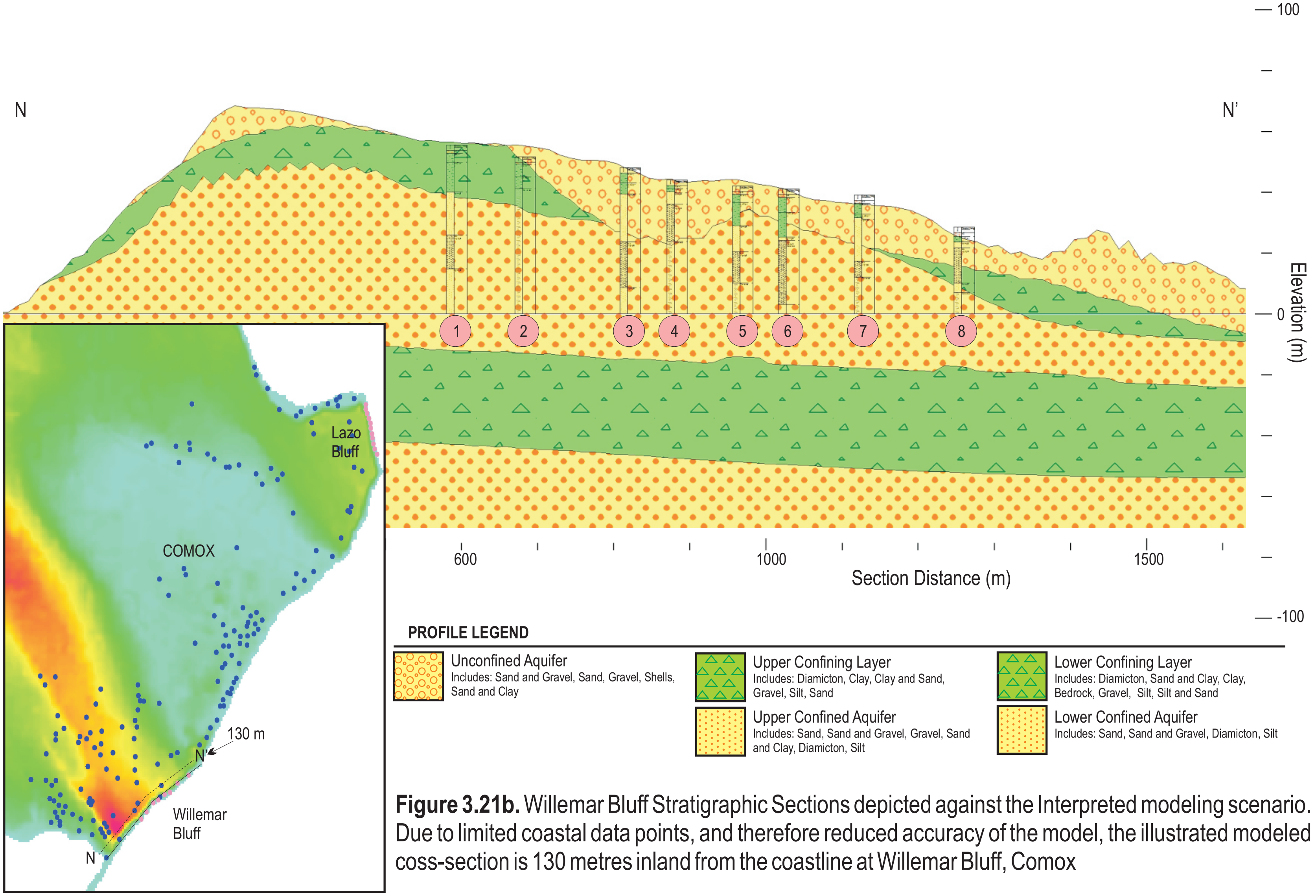


Figure 3.21b. Willemar Bluff Stratigraphic Sections depicted against the Interpreted modeling scenario. Due to limited coastal data points, and therefore reduced accuracy of the model, the illustrated modeled coss-section is 130 metres inland from the coastline at Willemar Bluff, Comox

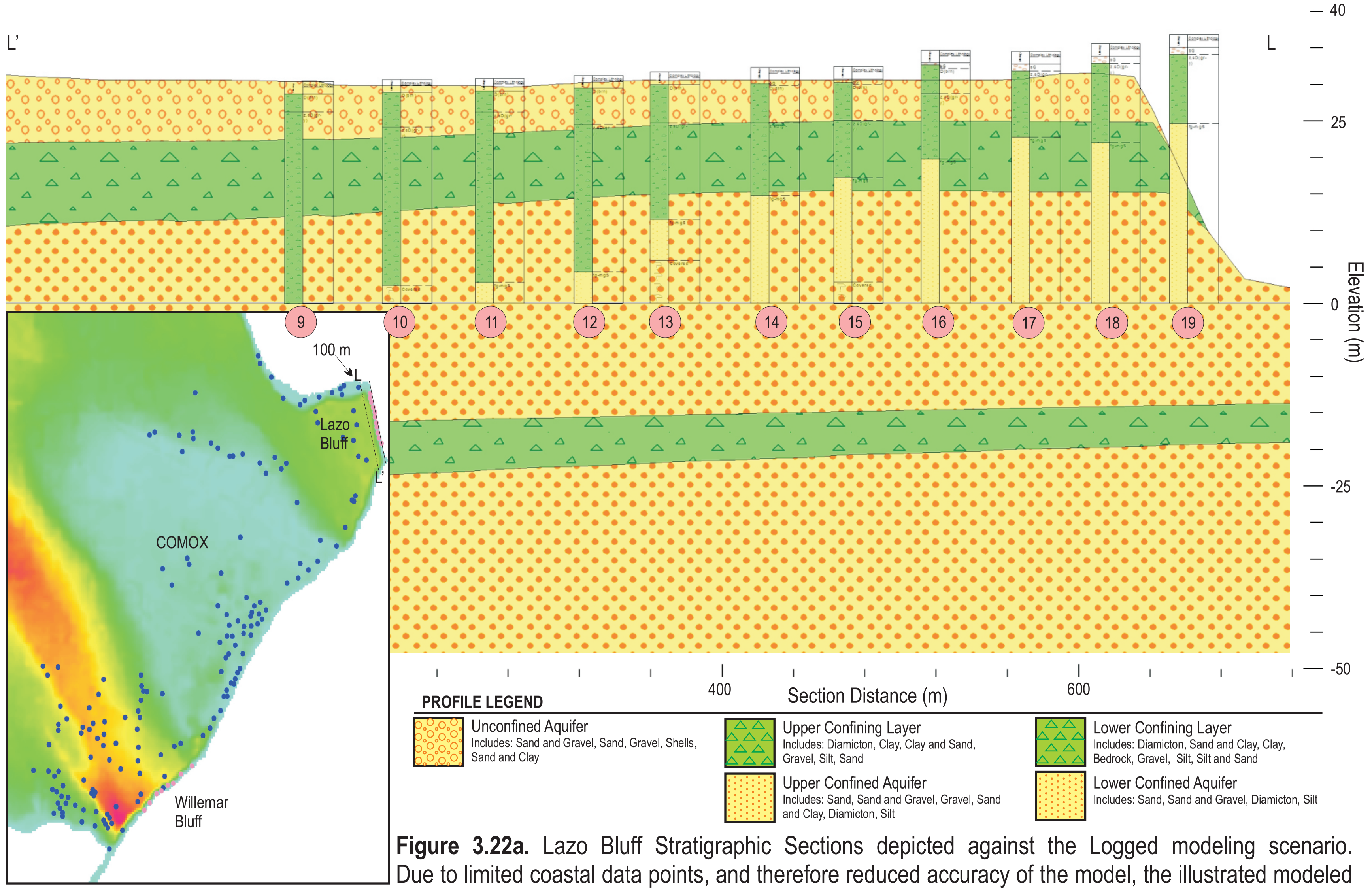


Figure 3.22a. Lazo Bluff Stratigraphic Sections depicted against the Logged modeling scenario. Due to limited coastal data points, and therefore reduced accuracy of the model, the illustrated modeled coss-section is 100 metres inland from the coastline at Lazo Bluff, Comox

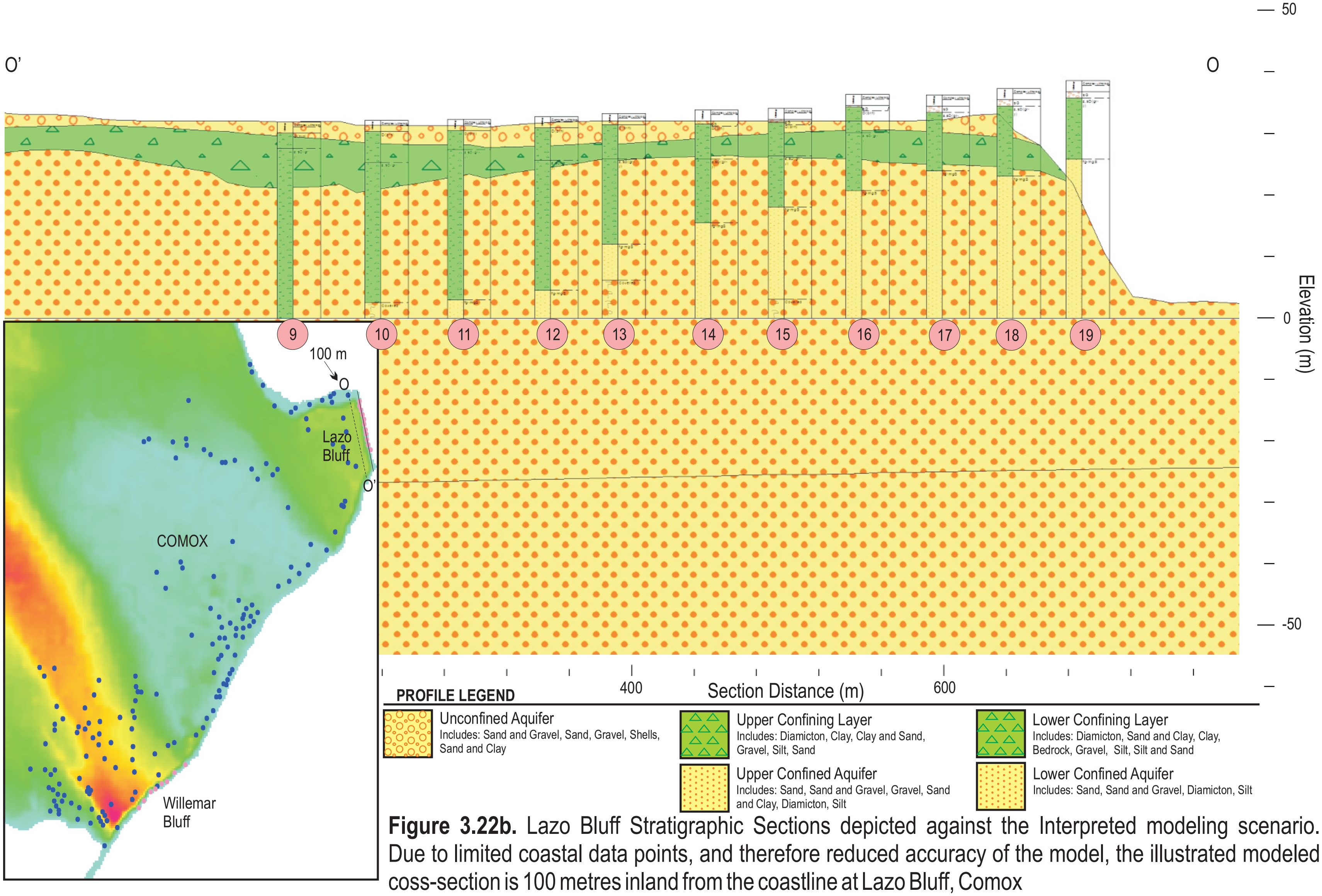


Figure 3.22b. Lazo Bluff Stratigraphic Sections depicted against the Interpreted modeling scenario. Due to limited coastal data points, and therefore reduced accuracy of the model, the illustrated modeled coss-section is 100 metres inland from the coastline at Lazo Bluff, Comox

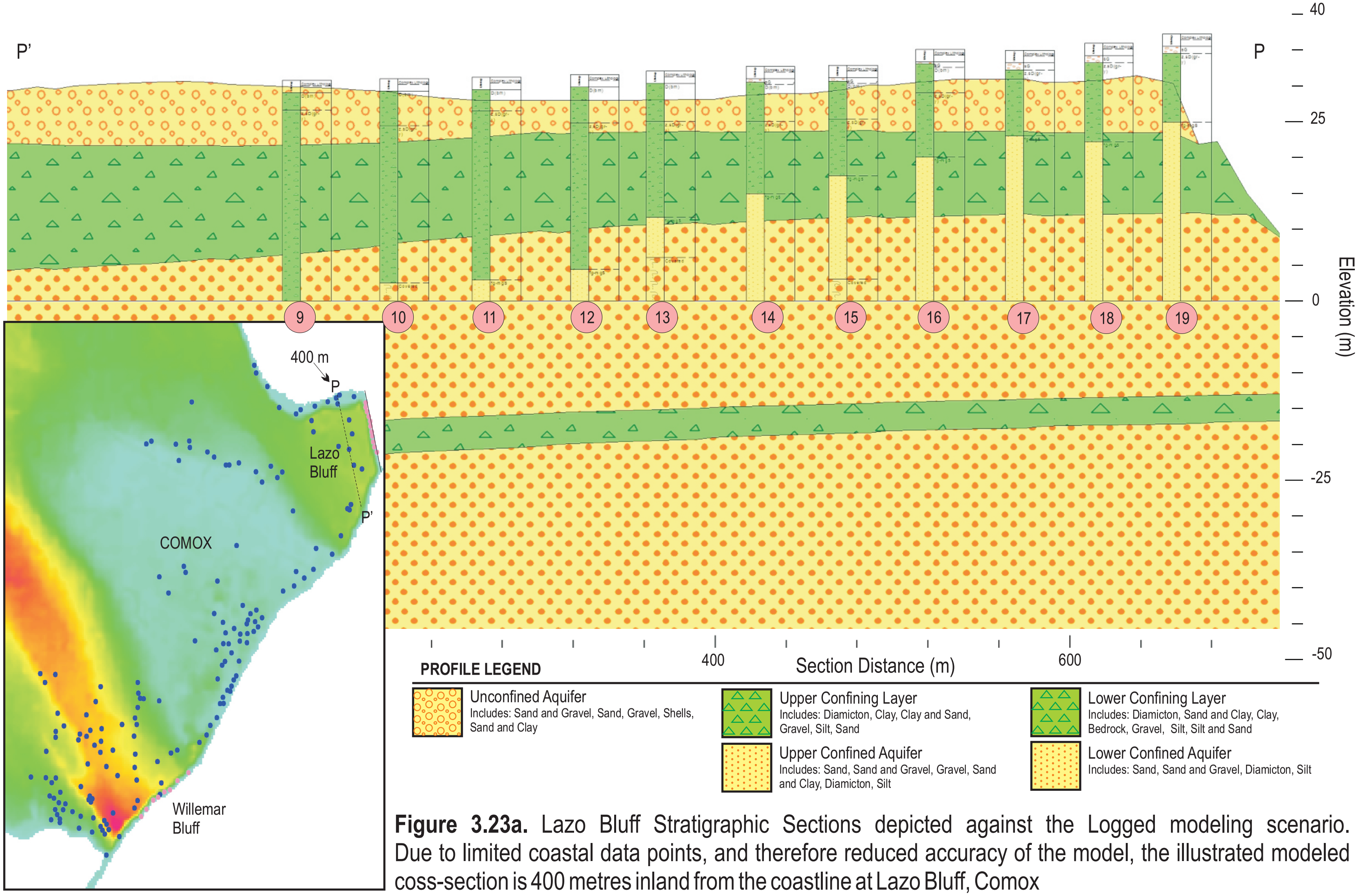


Figure 3.23a. Lazo Bluff Stratigraphic Sections depicted against the Logged modeling scenario. Due to limited coastal data points, and therefore reduced accuracy of the model, the illustrated modeled coss-section is 400 metres inland from the coastline at Lazo Bluff, Comox

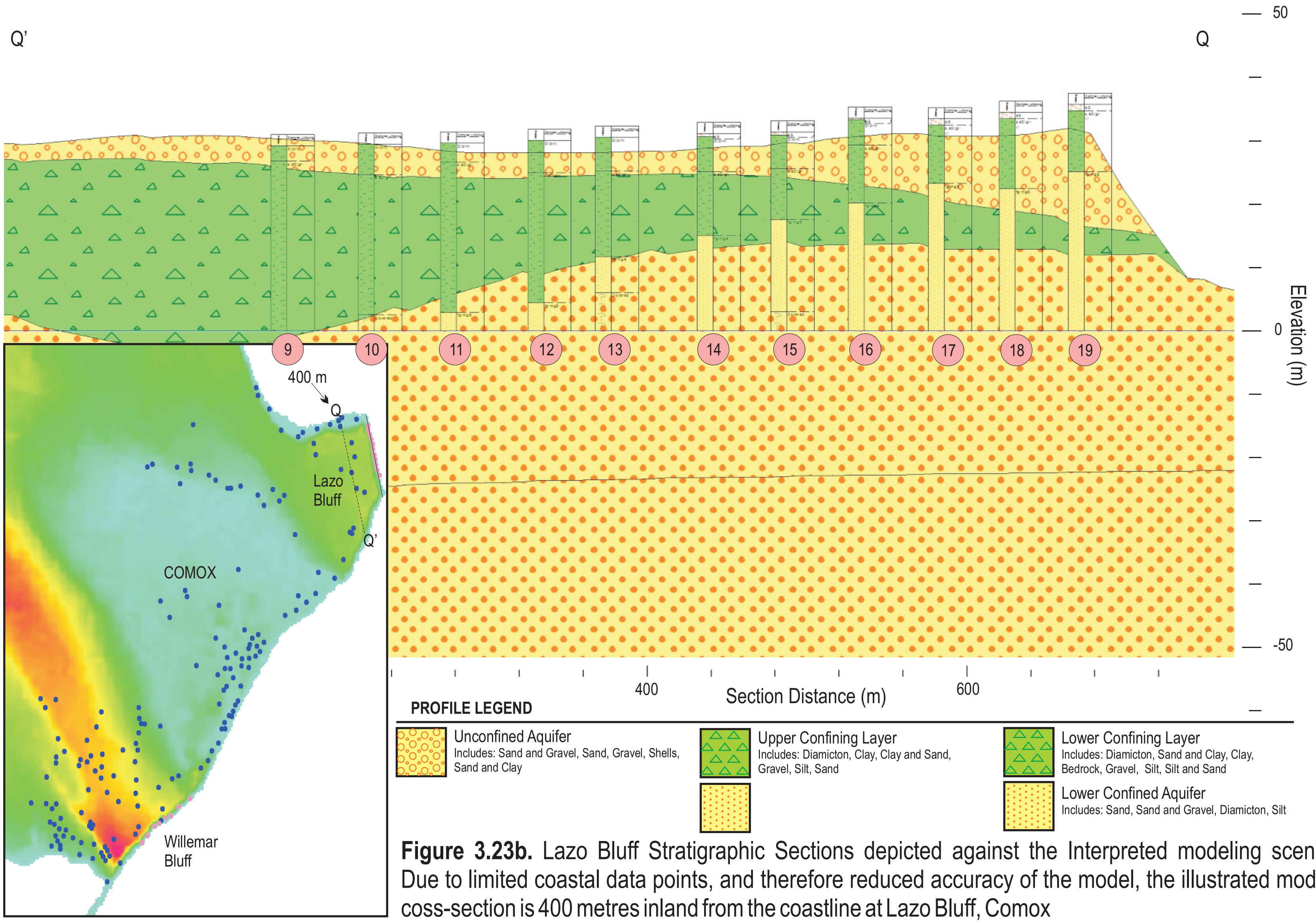


Figure 3.23b. Lazo Bluff Stratigraphic Sections depicted against the Interpreted modeling scenario. Due to limited coastal data points, and therefore reduced accuracy of the model, the illustrated modeled coss-section is 400 metres inland from the coastline at Lazo Bluff, Comox

hypothesis is further supported by the use of the term “till” logged for the upper confining aquitard considered to be Vashon Drift. Without a sediment or organic sample to date this deposit, however, further interpretation is premature at this time.

3.7.3.3 Surficial Aquifer

The BC Ministry of Environment has differentiated a surficial unconfined aquifer, separate from the surrounding Comox-Merville Aquifer, which is approximately 1.9 km^2 and is situated in the topographically depressed region of the Comox Bluff area (Figure 3.24). Thought to be comprised of Salish Sediments, this sand and gravel aquifer is classified as having a low level of demand, moderate productivity, and high vulnerability to surface contamination (Humphrey, 2000). The Comox Bluff hydrostratigraphic model was assessed as to whether or not it was able to accurately delineate this aquifer with respect to the input data, as well as illustrate the strata to be that of sand and gravel. The modeling scenario based solely on the drillers’ logged contacts was only able to delineate a portion of the surficial aquifer, with many of the logged strata inaccurately depicted in cross-section (Figure 3.25a). The Interpreted modeling scenario, however, was able to accurately delineate the entire area, appropriately showing the well logs within the uppermost sand and gravel unconfined aquifer (Figure 3.25b). The effective representation of a hydrostratigraphic unit independently identified by the BC Ministry of Environment supports the verification of the Interpreted modeling scenario of the Comox Bluff model.

3.8 Conclusion

The Comox Bluff hydrostratigraphic model can be considered somewhat successful as a predictor of subsurface hydrostratigraphy. An accurate portrayal of the subsurface hydrogeological environment based solely on groundwater drillers’ well logs is idealistic; rather, such a model can

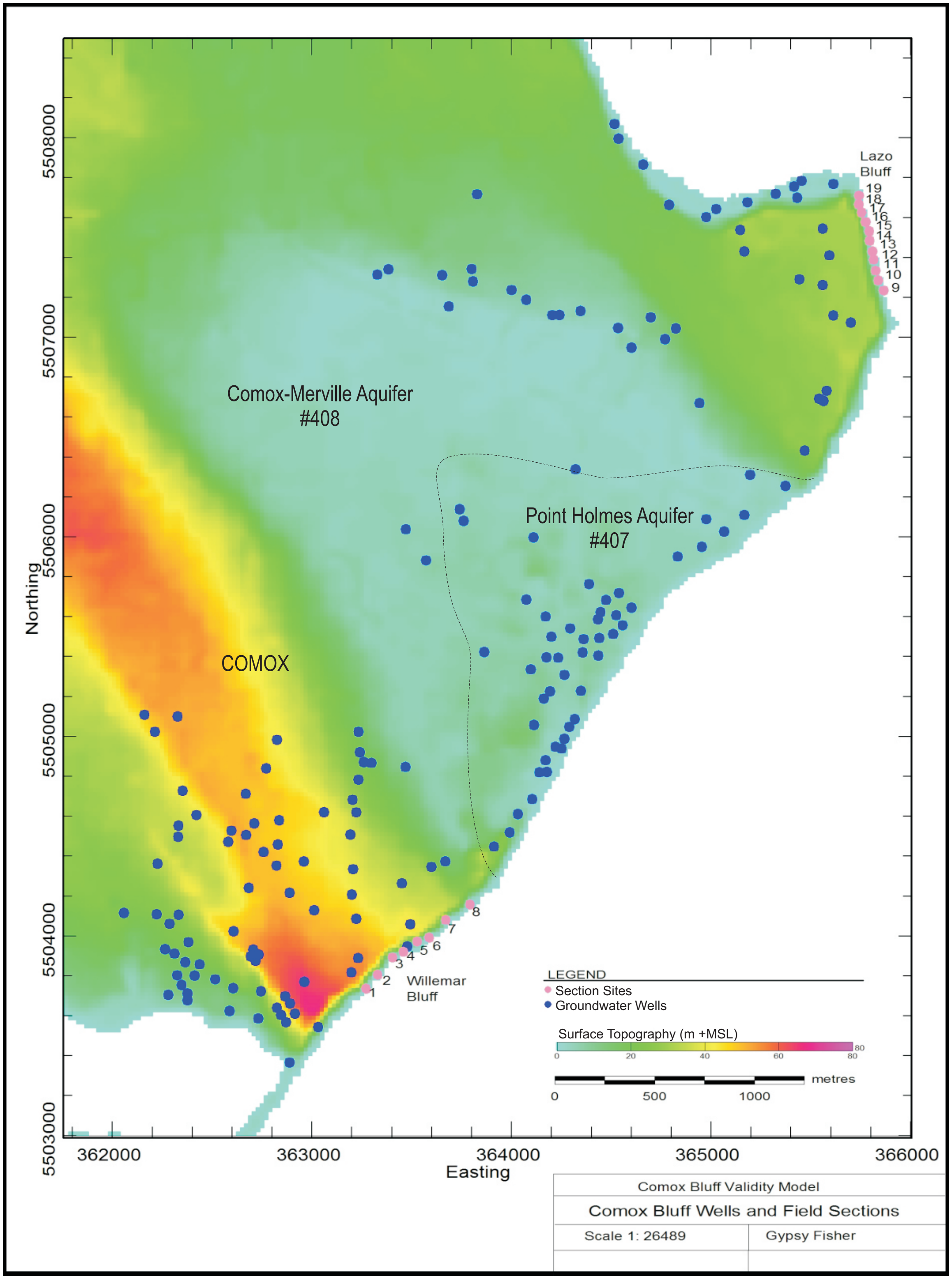


Figure 3.24. Comox Bluff Surficial Aquifers.
As delineated by the BC Ministry of Environment (Humphrey, 2000; MOE, 2001)

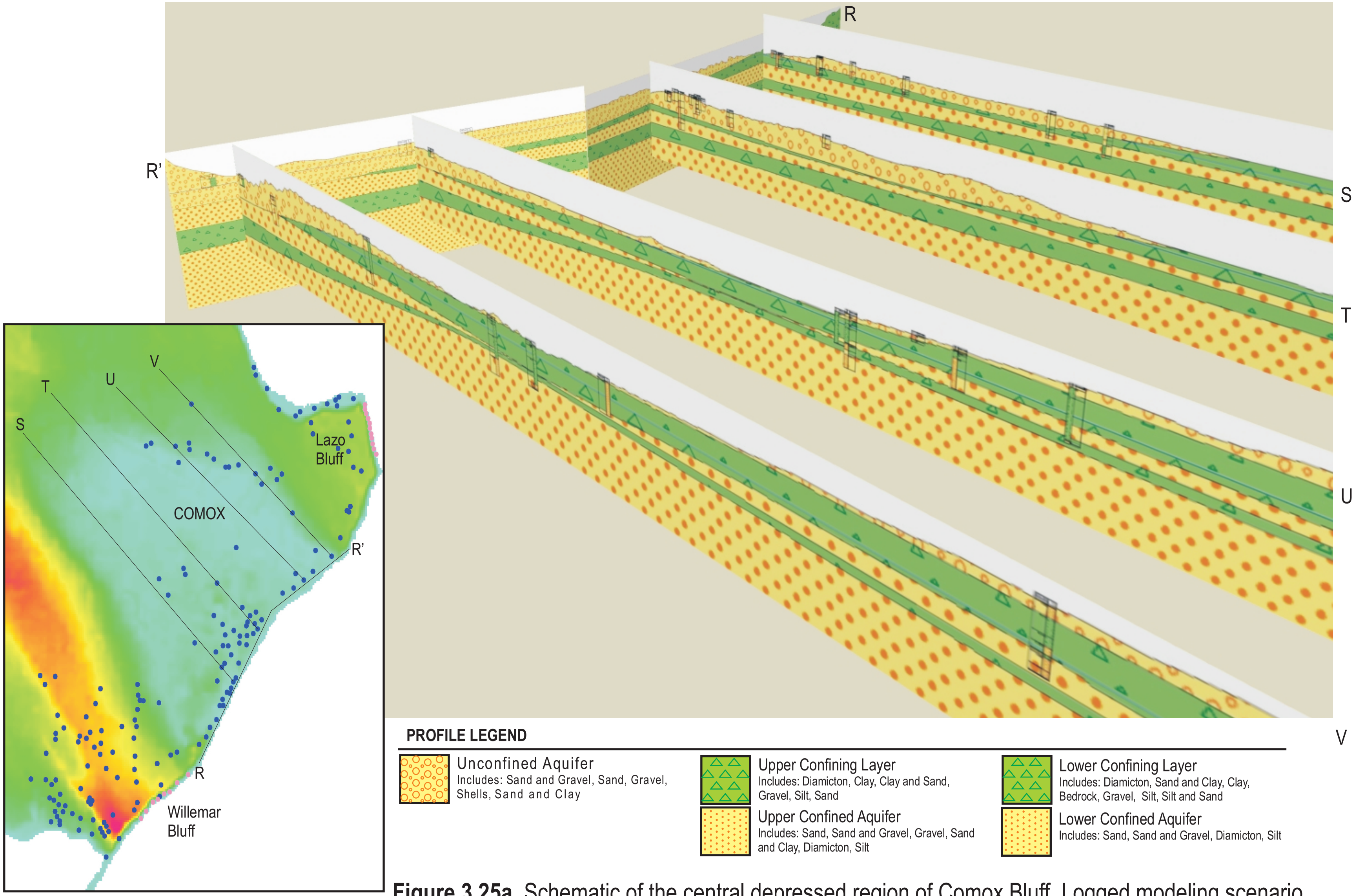


Figure 3.25a. Schematic of the central depressed region of Comox Bluff, Logged modeling scenario.

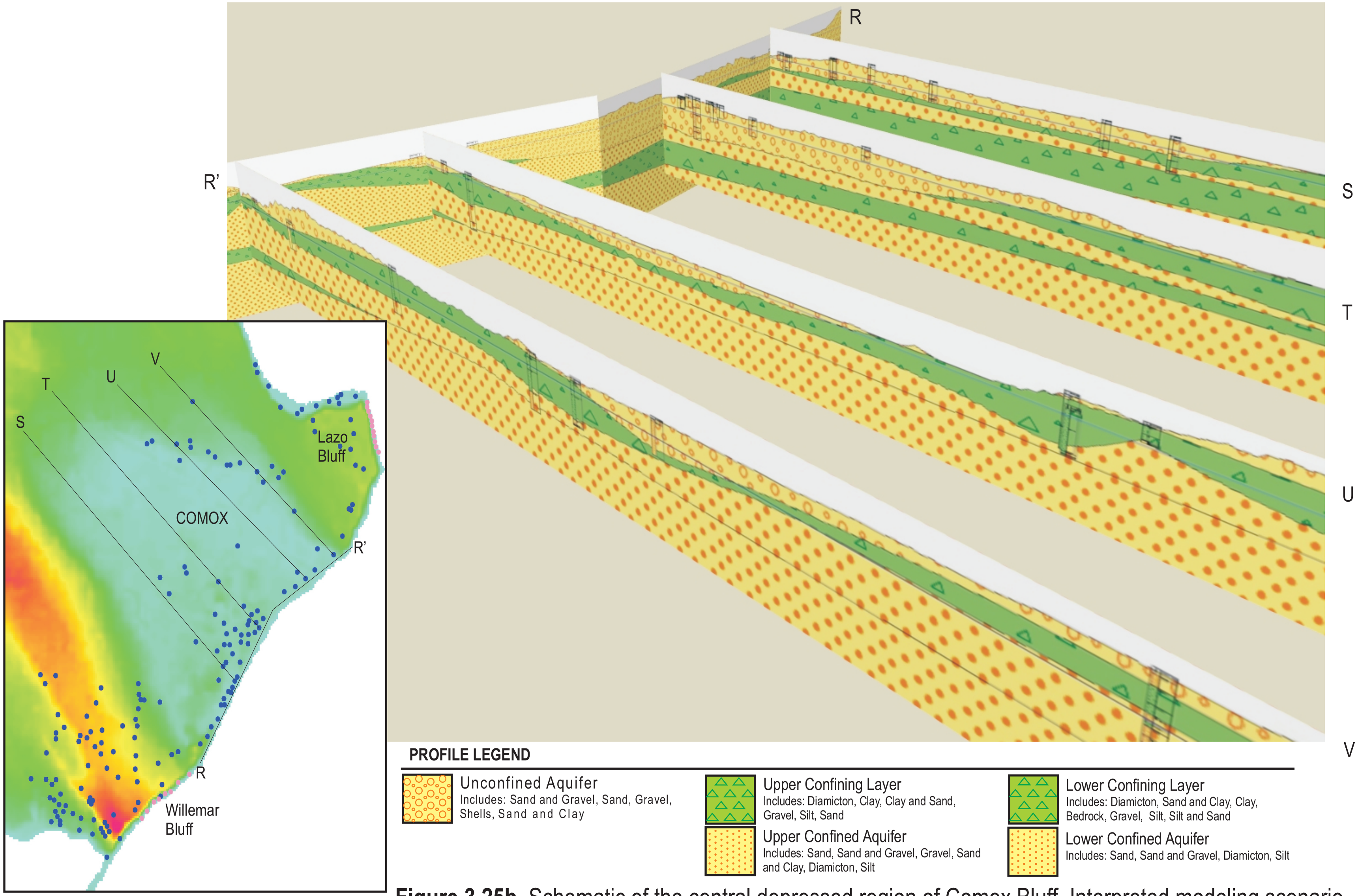


Figure 3.25b. Schematic of the central depressed region of Comox Bluff, Interpreted modeling scenario.

be used as insight for future drilling giving the approximate locations and general depth zones of surficial aquifers and aquitards. While neither the Logged nor the Interpreted modeling scenarios precisely match the stratigraphic sections identified along the coastal exposures, both generally recognize the hydrostratigraphic units identified in the field. Overall, it is clear that of the two modeling scenarios the hydrostratigraphic surfaces interpolated from both the interpreted and logged data points best represent the subsurface hydrostratigraphy of the Comox Bluff area.

The high confidence values produced by the model's autocorrelation variograms signify the strength of the predictive modeling process, although it was unable to surpass the 95% confidence limit. On average, over 80% of the time the Interpreted modeling scenario was successful in predicting the occurrences and vertical elevations of the upper contacts for the upper four hydrostratigraphic units identified from the well log dataset. The fact that this was not 100% of the time indicates the degree of error or noise in the system, or possibly describes other factors, such as the variability in spatial distribution of Quaternary deposits, that were not incorporated into the model. The Comox Bluff model considers one correlation coefficient: the spatial location of each data point. Already recognized as sources of error, the subjectivity with respect to the quality of the well logs and where the person conducting the subsequent model interprets the contacts to be are both possible factors influencing subsurface spatial correlation. However, this, combined with all of the other sources of error intrinsic to the model, is only significant less than 20% of the time.

Models representing natural environments cannot possibly incorporate every factor that influences a particular relationship. It is beneficial, therefore, that the model remains as simple and practical as possible while still being effective. The objective of this study was to demonstrate the standardization and evaluation process that allows for the conscientious use of groundwater well logs for subsurface hydrogeological investigations. Despite the modeling limitations, the Comox

Bluff hydrostratigraphic model did reasonably satisfy the main statistical and validation criteria tested for in this study. Hence, the research methodology can be considered a success and can be used to aid future subsurface mapping projects.

4 Hydrogeological Investigation of Stacked Quaternary and Late Cretaceous Bedrock Aquifers, Vancouver Island, British Columbia, Canada.

4.1 Introduction

This site-scale study investigates the hydrogeology of the inland Oyster River area of Vancouver Island, British Columbia. As part of this subsurface investigation, the potential for hydraulic connectivity between the fractured sedimentary bedrock of the Late Cretaceous Nanaimo Group and the overlying unconsolidated aquifers comprised of Quaternary sediments was assessed. Growing demand on groundwater resources in the region, both for domestic and industrial purposes, suggests an increasing risk of user conflict; consequently, investigating the region's hydrogeology and potential for aquifer communication will aid in management decisions regarding this communal natural resource.

4.2 Study Area

The study area is situated on the central-east coast of Vancouver Island, British Columbia. It is bounded by Oyster River to the north and Black Creek to the south (Figure 4.1). The Oyster River originates in the mountains of the Forbidden Plateau and drains an approximate area of 376 km^2 at its mouth before discharging to the Strait of Georgia (Nagpal, 1990).

As part of a regional study to assess the hydrogeology of the Comox Coallfield, two adjacent (paired) groundwater observation wells were completed in the study area. The well sites are located west of the Black Creek gravel pit, approximately 10 km inland from the Strait of Georgia, on the east side of the Inland Island Highway near kilometre 152 (in the Regional District of Comox-Strathcona, 35 km northwest of the village of Cumberland) (Figure 4.2). This area is within Vancouver Island's eastern coastal lowlands, between the Beaufort Mountain Range to the

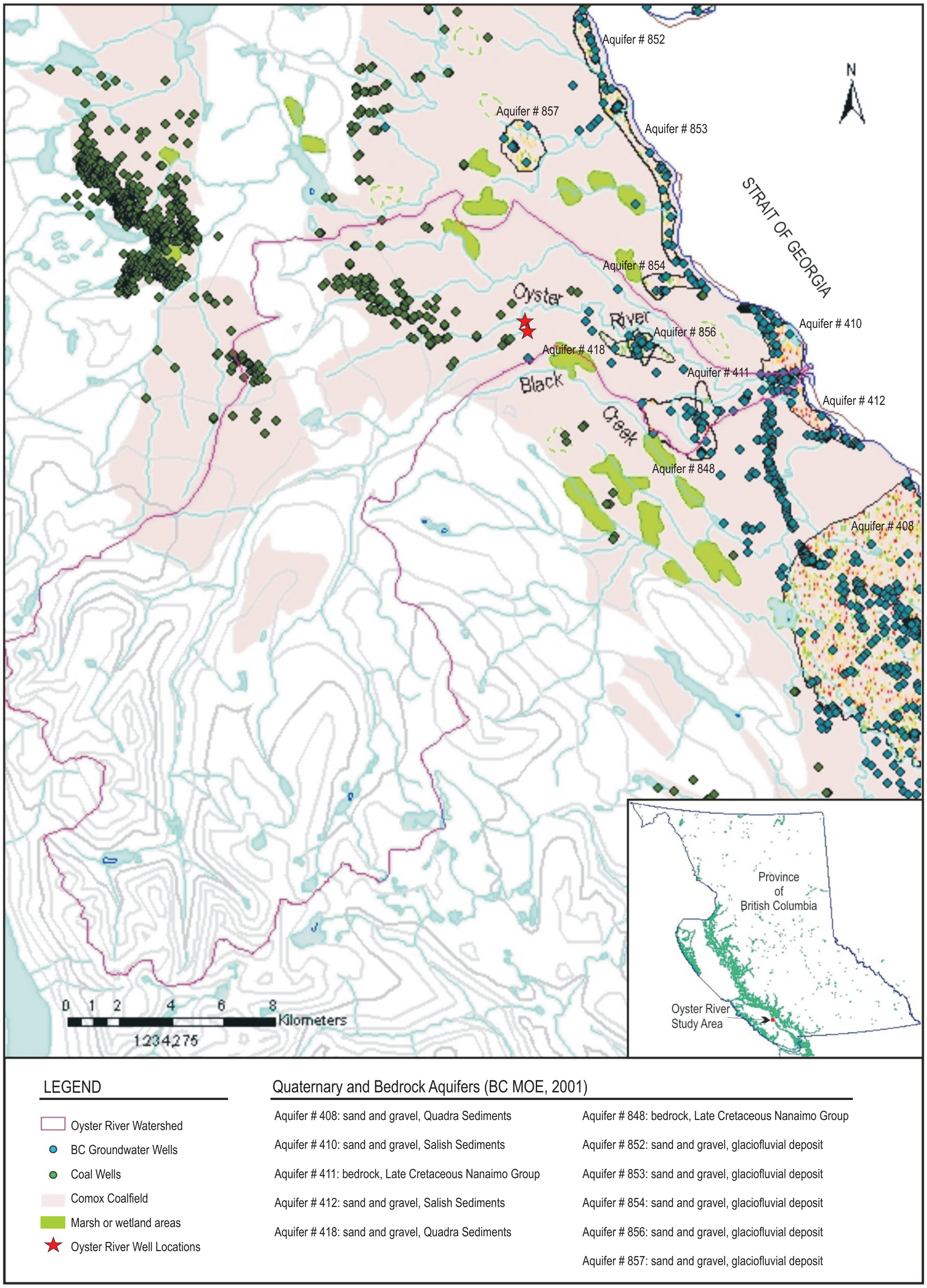


Figure 4.1. Location Map of Oyster River, Vancouver Island, British Columbia. Two paired groundwater observation wells were drilled for this study. The BC MoE has delineated numerous surficial and bedrock aquifers in the area. Coal exploration and groundwater wells are highlighted.

Figure 4.2. Location map for the Oyster River groundwater observation wells and the Black Creek gravel pit.

west and the Strait of Georgia to the east (Refer to Chapter 2 for detailed regional geology and physiography).

4.3 Previous Work

East of the study area are several discreet surficial and bedrock aquifers delineated by the BC Ministry of Environment (BC MoE) (Figure 4.1). These aquifers have been identified as Quaternary sand and gravel deposits, likely Capilano Sediments, or as the Nanaimo Group sedimentary bedrock sequence with local water-bearing fractures encountered within the upper 60 m. The bedrock and surficial geology of the region, primarily mapped by Fyles (1963), Jungen (1975), Bickford and Kenyon (1988), and Bickford (1989, 1990), has been compiled and summarized in Chapter 2. Hydrogeological studies on fractured aquifers within the Nanaimo Group sedimentary rock have been conducted in the region (Abbey and Allen, 2000; Allen *et al.*, 2001; Allen *et al.*, 2003; Surrette and Allen, 2008). Water quality assessments and monitoring programs have been conducted for major surface water streams throughout the Oyster River watershed and the Comox Coalfield (Nagpal, 1990; BC MEMPR, 2005), as well as for fractured bedrock aquifers on many of the Gulf Islands (Earle and Krogh, 2004; Allen and Suchy, 2001). To date, little research has been completed with respect to the hydrogeology of surficial sediments in the region.

4.4 Black Creek Gravel Pit Field Descriptions

The Black Creek gravel pit, managed by TimberWest Forest Corp., is situated 440 m to the east of the paired groundwater wells (Figure 4.2). The exposed gravel pit is subdivided into two areas (eastern and main exposures), which, combined, encompass an approximate area of 15,000 m^2 (0.015 km^2). Fieldwork for the Black Creek gravel pit was completed throughout the summer seasons of 2005 and 2007. Data recorded at the exposures included location, unit descriptions, unit thicknesses and approximate lateral extent. Representative sediment samples were collected along the exposed sections for the units that were safely accessible.

4.4.1 Main exposure

4.4.1.1 Unit 1a Descriptions

At the main exposure of the gravel pit (GPS: 0337911, 5527764, 7.7 m horizontal accuracy; Figure 4.3), Unit 1 is divided into two laterally equivalent subunits. Unit 1a is situated 75 m west of Unit 1b; however, both subunits are exposed at the same elevation and for roughly the same vertical extent. Unit 1a is interbedded gravel and diamicton, predominantly gravel at the base progressing to diamicton towards the top of the unit. The gravel beds are comprised of pebbles to small cobbles that are mainly openwork with little sand matrix. The diamict beds have a silty sand matrix with primarily subangular to subrounded clasts up to 2 m in diameter and that are of varied lithology. The diamicton is locally cemented and massive along the western exposure within the main gravel pit area. Containing roughly 20-40% gravel, these beds are up to 2 m thick and as thin as a few centimetres. The gravel beds vary from a few centimetres to about 1 m thick and are laterally discontinuous, pinching out in places across the section. Up to 4 m of the unit are exposed. Overall, the unit exhibits convoluted bedding with some beds locally dipping as steep as 45° (apparent dip). Numerous intraclasts of mud, showing both angular and rounded edges, are concentrated discontinuously along the unit's bedding. The unit also displays frequent deformation structures on the order of metres wide, including loading structures, convoluted bedding and folds.

4.4.1.2 Unit 1b Descriptions

Fairly clean coarse-grained gravel with little to no matrix occurs as the lowermost unit along the eastern exposure of the main gravel pit area. The unit is up to 2 m thick and can be traced laterally for over 70 m across the gravel pit's main exposed area. The unit exhibits steep

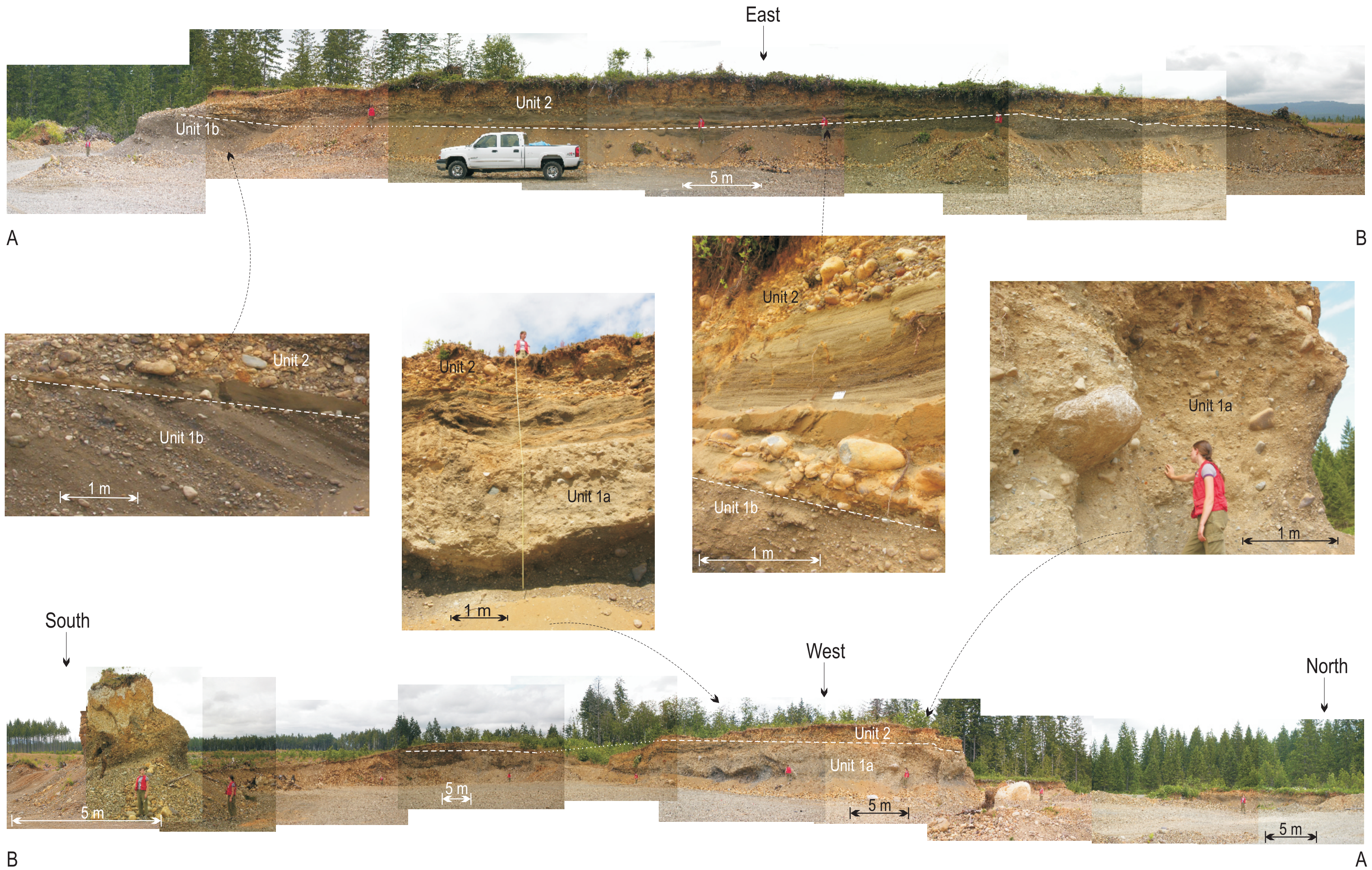


Figure 4.3. Black Creek Gravel Pit, main exposure.

inclined bedding dipping up to 30° (apparent dip) and smaller scale trough cross-bedding. Comparing Unit 1b exposed along the eastern side of the main area of the gravel pit to Unit 1 exposed at the eastern subsidiary area, it is evident that the unit is stratigraphically the same, laterally fining toward the east.

4.4.1.3 Unit 2 Descriptions

Unit 2, exposed at surface, can be traced to, and is considered equivalent to, the pebble- to cobble-sized gravel identified in the eastern subsidiary exposure described below. At the main exposure, the bottom 0.5 m – 1 m of the unit is coarse-grained sand displaying horizontal to wavy cross-bedding. The unit's lower contact is clear and erosional, cutting across the inclined bedding of Unit 1b, underlying. Up section the unit is a cobble to boulder gravel with coarse-grained sand matrix. Overall, the exposed unit at this location is up to 3 m thick and exhibits crude cross-bedding forming broad hummocks, approximately 20 m wide. At surface, the overall gravel pit area consists of many relatively elevated and depressed areas. Within this gently rolling topography, approximately 50 m to 100 m is measured from hill crest to the centre of an in-filled depression.

4.4.2 Eastern subsidiary exposure

4.4.2.1 Unit 1 Descriptions

The lowermost unit observed at the eastern exposure of the gravel pit (GPS: 0337990, 5527937, 6.0 m horizontal accuracy; Figure 4.4) is medium- to coarse-grained sand with up to 20% gravel beds. Numerous subrounded drop stones up to boulder-sized were also noted throughout the sand unit. Approximately 4 m of the unit is exposed above the covered lower contact. Numerous silt laminae within the upper metre of Unit 1 extend laterally up to several metres. Large scale trough cross-bedding laterally extends 10 to 15 m and beds are up to 3 m thick. A hummock shaped sub-unit is seen in one of the troughs, approximately 1 m thick and 5 m wide. Many

Figure 4.4. Black Creek Gravel Pit, eastern subsidiary exposure.

individual beds noted within the large scale troughs were laterally traceable for virtually the entire width of the troughs and exhibited normal grading. Below the dominant trough structures, beds were observed to be inversely graded.

4.4.2.2 Unit 2 Descriptions

Above a sharp and undulatory lower contact, is a large pebble- to cobble-sized gravel (Unit 2). The lower contact is clearly erosional, noticeably cutting across the bedding of Unit 1. The contact is undulatory with troughs that are approximately 0.5 m deep and 3 to 5 m wide. The gravel is moderately to very well rounded and clast lithologies are variable. The unit is approximately 2 m thick at the eastern exposure. Crude trough cross-bedding is present as well as lenses of small pebbles to small boulders up to 0.30 m in diameter. Also present are numerous small lenses of poorly sorted, fine- to coarse-grained sand about 0.10 m thick and 1 m wide. Purple manganese and orange to red iron staining highlights more permeable beds within Unit 2.

4.5 Black Creek Gravel Pit Geological and Hydrostratigraphic Interpretation

At the eastern exposure, Unit 1 shows both normal and reverse grading within the sand and gravel beds which is indicative of sediment gravity flows. A sub-aqueous environment is suggested by the absence of turbulent bed forms such as ripples or dunes; submergence within a large body of water would dampen turbulent flow and any associated bed form development. The unit fines toward the east and exhibits large scale, low-angle, trough cross-bedding as well as thin beds and laminae (Figure 4.5). This implies that the source of the sediment originated from the west, and fined toward the east. Numerous silt laminae within the upper metre of Unit 1 extend laterally up to several metres, further suggesting a subaqueous depositional environment.

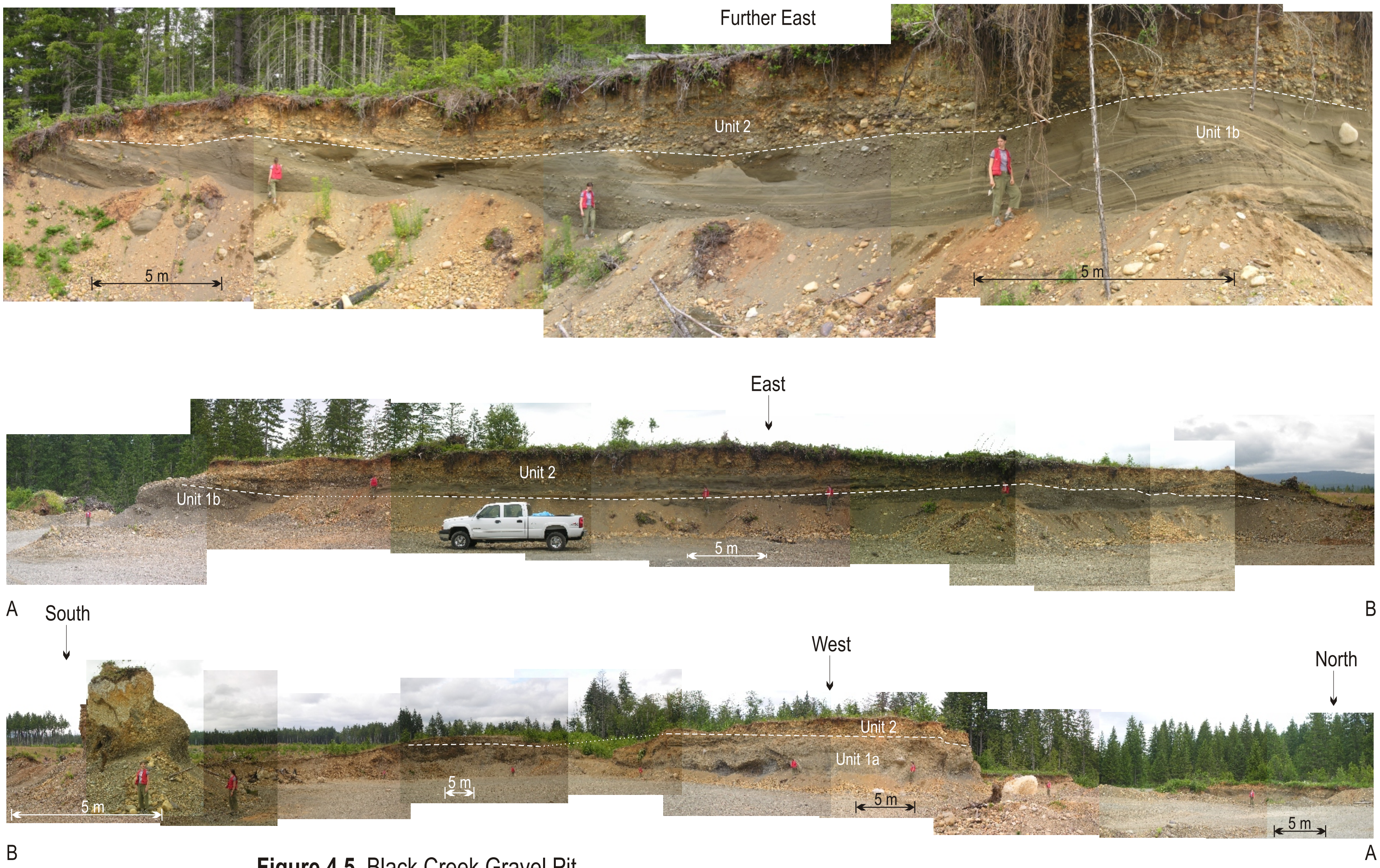


Figure 4.5. Black Creek Gravel Pit.
Uppermost profile of the eastern subsidiary exposure, lower two profiles of the main gravel pit.

Within the main gravel pit, Unit 1a is situated 75 m west of Unit 1b, both exposed at the same elevation and for roughly the same vertical extent. Unit 1a is texturally very different than Unit 1b and exhibits frequent deformation structures and mud intraclasts. That, coupled with the fine-grained, matrix-supported diamicton beds containing sub-angular to sub-rounded clasts, supports an interpretation of a glacially influenced formation for Unit 1a. Clearly related, Units 1a & 1b are hypothesized to represent a sub-aqueous formation influenced by lodged, stagnant glacial ice. The sediment was probably deposited around the ice by flowing water and as it melted sediment gravity flows off the ice filled in the freshly exposed voids. This process would explain the locally-massive diamicton in Unit 1a, the boulder-sized clasts, as well as the inclined and trough cross-bedded gravel of Unit 1b only 75 m away.

Unit 2, traceable across both gravel pit exposures, is considered to be formed by sub-aerial glaciofluvial deposition. This interpretation is based on the large low-angle trough cross-bedding, fluvial channel features evidenced by an erosional lower contact, and coarse-grained, well rounded clasts (up to cobble size) of varied lithology. Additional features that support a glaciofluvial depositional interpretation include the presence of sand and gravel lenses and significant oxidation observed at both gravel pit exposures.

The Black Creek gravel pit reveals a large relatively flat topped feature that is most likely an ice-proximal glaciofluvial deltaic deposit. Closed depressions on the surface of the feature are interpreted to be small kettles. Prograding east toward the Strait of Georgia and therefore fining to the east as is seen in the exposures, the overall sedimentary formation corresponds with that of a river-dominated deltaic succession. Unit 1b exhibits classic deltaic bedding features, such as foreset beds dipping steeply, up to 30 degrees, to the east, consistent with an eastward prograding delta. The underlying sediments exposed in the eastern area (Unit 1) are interpreted to be subaqeous beds deposited in deeper water, probably lower down in the foreset bed sequence, as suggested by the fine grain size, lateral continuity of beds and abundant silt laminae. The coarse-grained nature of Unit 2 supports an ice-proximal interpretation as opposed to a strictly fluvial delta. An ice-proximal origin for the deposits is supported by the presence of diamicton beds interpreted to be glaciogenic debris flows, extensive deformation of bedding, and numerous large boulders inferred to be supraglacially transported clasts or ice rafted boulders. Sediment re-worked and redistributed during downslope movement by sediment gravity flows into ice-melted voids can explain the localized structural complexity apparent in Unit 1a.

The area in which the Black Creek gravel pit and Oyster River wells are located has been mapped as a large elongate landform described as a gravelly, level fluvial terrace that is gently undulating and moderately rolling (gFtl/be) (Jungen, 1975). The studied gravel pit exposures occur on the eastern edge of the landform, bordered by marine deposits downslope and morainal sediments elsewhere nearby. The observations and subsequent interpretations provided here for the Black Creek gravel pit exposures, agree with Jungen's interpretation of the surficial geology encompassing both the Black Creek gravel pit and the two groundwater observation wells.

The overall hydrostratigraphy of the Black Creek gravel pit can be considered to be a laterally variable, unconfined, surficial aquifer. The uppermost pebble to cobble gravel (Unit 2) would act as a highly permeable source aquifer, transmitting water down to the underlying sand and gravel (Unit 1b and Unit 1 for the main and eastern exposures, respectively). Both units would be able to store and transmit groundwater, acting together as a regional, unconfined, surficial aquifer. The considerable variability in the textures of Units 1a and 1b exposed in the main gravel pit area indicates that the groundwater flow pattern would be influenced by highly conductive areas, and sections of little to no permeability that would act as barriers to flow. As the two units are exposed at the same elevation, roughly 75 m apart, it is conceivable that groundwater flow would be accelerated through the gravel of Unit 1b, and would likely travel beneath the less permeable diamictic components of Unit 1a by way of the unit's basal gravel or perhaps the presently unknown unit below. Given the significant geographic extent of the surficial deposit exposed at the Black Creek gravel pit, it is believed to potentially be a significant groundwater resource for the local area.

4.6 Borehole Subsurface Methods

4.6.1 Well Drilling and Completion

The drilling and completion of the groundwater observation wells at the site was co-supervised by the author, Michael Gallo of EBA Engineering Consultants Ltd., and Gwyneth Cathyl-Bickford of Westwater Mining Ltd. The wells were drilled by Drillwell Enterprises' Rig #4, the Foremost DR-12 machine, under the direction of driller Scott Burroughs and his assistant Aaron Jameson. The drilling commenced on March 17, 2005 and was completed by March 23, 2005. Two wells, drilled 10 m apart, were completed to different depths. BC MoE Observation Well #368 (Well Tag Number (WTN) 83156) was drilled to a total depth of 146.9 m (482 ft) and BC MoE Observation Well #369 (Well Tag Number (WTN) 83157) was drilled to a depth of 7.3 m (24 ft). These wells are henceforth referred to as WTN 83156 and WTN 83157 or as the deep and shallow wells, respectively.

The dual rotary drill was driven by pressurized air; however, due to high frictional temperatures at the bit, water was intermittently injected into the well as a coolant. Ten inch steel surface conductor pipe was initially used to keep the boreholes open through the overburden, whereupon six inch casing replaced the conductor pipe, and was surrounded with bentonite to seal the annulus down to bedrock for WTN 83156 (deep well). The deep well is open hole throughout the bedrock, without a screen in place. In order to keep the borehole open within the unconsolidated sediments, the six inch steel casing was left in place for the full length of the shallow well (WTN 83157) down to the four and a half foot (1.4 m) stainless steel screen placed at the well's bottom. With 1/8 inch screen slots, the screen is capable of keeping out sediment particles greater than 3 mm in size. The shallow well was then bailed out several times using two differently sized bailers to remove sediment from the water column.

Both wells are currently part of the provincial groundwater observation network and are being monitored for ambient groundwater quality conditions as well as continuous water level by the BC Ministry of Environment.

4.6.2 Drill Cutting Sampling

Drill cutting samples were taken every 2 ft (0.6 m) for overburden and every 5 ft (1.5 m) for bedrock. Samples were retrieved *in situ* using a hand sieve as the cuttings were blown from the drill pipe by the drillers. Some fines were potentially lost through the hand sieve used to collect the drill chips or during the washing procedure undertaken to separate the sample from the mud formed by the produced groundwater or added drilling water. Additionally, the driller was unable to sufficiently cover the discharge pipe mouth with the sampling bucket in order to collect a complete sample when the pipe was at significant heights at the start of each drill rod (Figure 4.6). Samples collected at these times may not be representative. Collected drilling samples were air dried, and stored in clearly labelled, clean plastic bags.

4.6.3 Borehole Geophysics

Borehole geophysical logging was conducted in both wells at the Oyster River site; the work was co-supervised by David Sim of Electrolog Services Inc. Multi-parameter probes are commonly used for subsurface hydrogeological investigations (Allen *et al.*, 2001; Allen *et al.*, 2002; Allen *et al.*, 2003). The Comprobe 1¼" slim line, 4-function multipurpose probe was employed to measure natural gamma ray, density, relative formation electrical resistance, and borehole

Figure 4.6. Drill cuttings sampling. These pictures are of a well drilled in Union Bay, southeast of Oyster River in the Comox Coalfield (UB-1, see Figure 2.8a in Chapter 2). The drilling and sampling procedure is the same for the Oyster River wells.

diameter using a single-arm motorized caliper. The probe's total length is 3.31 m with a 0.03 m (1¼") diameter and is connected to a 4.8 x 10^{-3} m ($^{3}/_{16}$") 4-conductor cable (Figure 4.7) (Hawkins, 2009; Sim, 2009). The probe's configuration from bottom to top included a 0.06 m x 0.01 m (2½" by ½") sodium iodide crystal for natural gamma ray detection, an AM 241 americium density source with a sodium iodide single density detector 5 cm above, and a single formation resistance electrode joined with a single-prong motorized caliper at the top end. The resistance electrode emits a low, constant DC current (millivolts) into the formation and measures the returning current using the top of the cable to complete the circuit, 1.55 m above the resistance electrode. The spatial resolution of the geophysical probe is 5 cm for the natural gamma ray and density logs (Sim, 2009), and approximately 2-3 m for the resistance log (Best, 2009a); however, the degree of accuracy cannot be fully determined due to variations in borehole effects for each individual well. To determine accuracy a section of the borehole would need to be logged twice and the resultant geophysical logs compared (Hawkins, 2009).

Beneficial attributes of borehole geophysical investigations include: (1) a continuous depth scale associated with a continuous series of measurements; (2) the undisturbed formation surrounding the borehole is sampled *in situ*; and, (3) geophysical logging equipment is designed in such a way that more than one measurement can be made in the same borehole (Paillet and Crowder, 1996).

Natural gamma radiation measures the natural radiation of the subsurface strata adjacent to the probe. Gamma rays are emitted by radioactive elements within the subsurface sediments, such as potassium 40 (^{40}K), uranium 238 decay series (^{238}U), and the thorium 232 decay series (^{232}Th) (Fetter, 2001). Clay and shale deposits as well as other rocks containing feldspar and mica minerals that are rich in ^{40}K reflect high gamma activity. Therefore, subsurface lithostratigraphic changes adjacent to the borehole can be detected using natural gamma radiation.

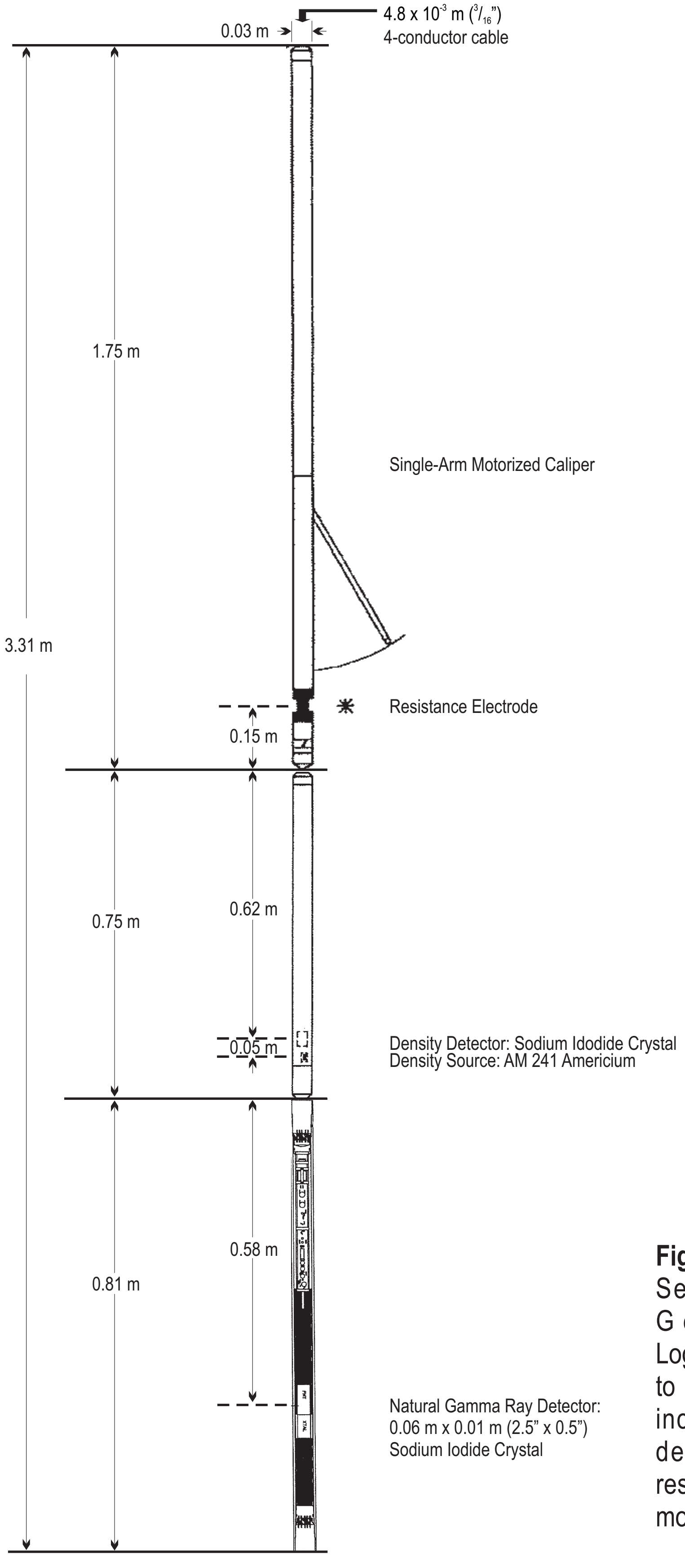


Figure 4.7. Comprobe 1¼” 1200 Series 4-Function Borehole Geophysical Probe. Logging from the bottom of the well to surface, this slim line probe included natural gamma ray, density, formation electrical resistance, and a single-prong motorized caliper. (Hawkins, 2009)

Geophysical density logs record variations in bulk formation density, which is a useful parameter to differentiate the lithostratigraphy encountered by the borehole. Sandstone (2.05-2.6 grams per cubic centimetre (g/cc)) is expected to be denser than shale (2.1-2.66 g/cc), while unconsolidated sediments (1.7-2.3 g/cc) are considerably less dense than the underlying bedrock strata (Kearney and Brooks, 1984; University of Melbourne, 2000). Gamma and density logs are the most powerful borehole geophysical logs in identifying subsurface lithostratigraphy (Paillet and Crowder, 1996).

Formation electrical resistance (used here) measures the total resistance of the subsurface materials between the Tx and Rx electrodes, while formation electrical resistivity is a specific property of a rock or unconsolidated sediment (Best, 2009b). Both resistance and resistivity depend on the rock or sediment and the interstitial pore waters (Fetter, 2001). The traces of the resistivity and resistance logs are similar, though resistivity can be calibrated and used quantitatively whereas resistance is a point value for the entire bedrock sequence. Increasing electrode spacing increases the lateral penetration of the resistivity measurement, thus a slower logging rate is desired to obtain a higher number of readings per metre.

A three- or four-pronged manual caliper is commonly used to measure variations in the diameter of an uncased borehole. A single-arm (prong) caliper is also typically employed for slim line borehole geophysical investigations, as the arm measures structural variations along one side of the borehole while pushing the probe to other side. Ensuring that the probe travels in direct contact with the formation minimizes any negative impacts to the resolution of the other geophysical sensors from the open space between the formation rock and the centre of the borehole. The nominal-hole diameter, equivalent to the drill bit, may be enlarged by formations caving into the hole or by formation minerals dissolving into solution due to drill or formation water (Fetter, 2001). Enlarged intervals can be associated with fracture zones and can also aid in determining architectural elements such as fracture orientation. The robust and versatile nature of the caliper allows for data collection in any open-hole conditions, i.e. dry or filled with water, making it a popular and useful tool for verification of other geophysical logs.

The data for the paired wells at Oyster River were recorded as the instrument traveled up from the bottom of the wells; the first readings were taken at 146.8 m and 7.0 m below ground surface (bgs) in the respective bedrock and surficial wells. Logging terminated 1.5 m bgs for both wells. The logging rate of the instrument as it moved up each borehole was 1.6 and 0.12 metres per minute for each respective well. The increased logging rate for the bedrock well was necessary due to the significant depth range; the weight and pressure inflicted onto the field winch by the cable and instrument was too great to go at a slower rate. A consequence of the difference in logging rates is that the logs of the shallow well may have higher resolution given the greater number of readings per metre distance.

4.6.4 Aqueous Geochemical Analysis

Groundwater samples from the shallow and deep observation wells were collected (Figure 4.8) on April 20th and 22nd, 2005 respectively, and immediately couriered to the CanTest laboratory for aqueous geochemical analysis. Subsequently, the BC Ministry of Environment Nanaimo regional office carried out sampling programs for the Oyster River wells, sampling each well once per year in 2006 and 2007. Sampling procedures for all three years followed those outlined in the June, 2004 draft of BC MoE's groundwater sampling manual (BC MoE, 2004). BC MoE's samples were analyzed by Maxxam Analytics Inc. laboratory. Both CanTest and Maxxam Analytics are analytical facilities that are accredited by the BC Ministry of Environment.

As coal was encountered during drilling, one of the objectives of the deep well's pumping test was to acquire a water sample that was representative of the groundwater associated with the

Figure 4.8. Water quality sampling for the Oyster River wells. Pump and water regulators were also employed for the pump tests of WTN 83156 and WTN 83157.

coal. Drill cutting interpretation identified that the “Comox Y” and the “Comox Y Lower” coal seams, both situated within the Dunsmuir Member of the Comox Formation, were encountered at 135.3 m (-5 m +MSL) and 138.4 m bgs (-8 m +MSL), respectively. The pump intake was placed at roughly 135 m bgs in order to sample the water as close as possible to the coal seams. It was hypothesized that the water located at the same depth and in direct contact with the coal would provide aqueous geochemical values most representative of the coal seams. Therefore, groundwater in the deep bedrock well was sampled after 1 min, 5 min and 60 min of pumping.

4.6.5 Groundwater Pumping & Recovery Test

A pumping and recovery test was conducted for the shallow well (WTN 83157) on April 20th, 2005. Drilling notes indicate the fine-grained sand aquifer may begin as shallow as 4.3 m bgs; however, the perforated screen was placed at the base of the well, approximately between 5.9 and 7.3 m bgs, still within the noted water-bearing sand units. The pump employed for the test was a ¾ horsepower AY McDonald, and a pumping rate of approximately 38 litres per minute (L/min) or 10 US gallons per minute (USgpm) was manually calculated using a 5 gallon bucket and stop watch. The pumping rate was not rerecorded over time during the test. The pump intake was placed approximately 0.5 m above the top of the perforated screen, roughly 4.6 m bgs. The pumping test continued for 4 hours and was immediately followed by a recovery period of 1 hour.

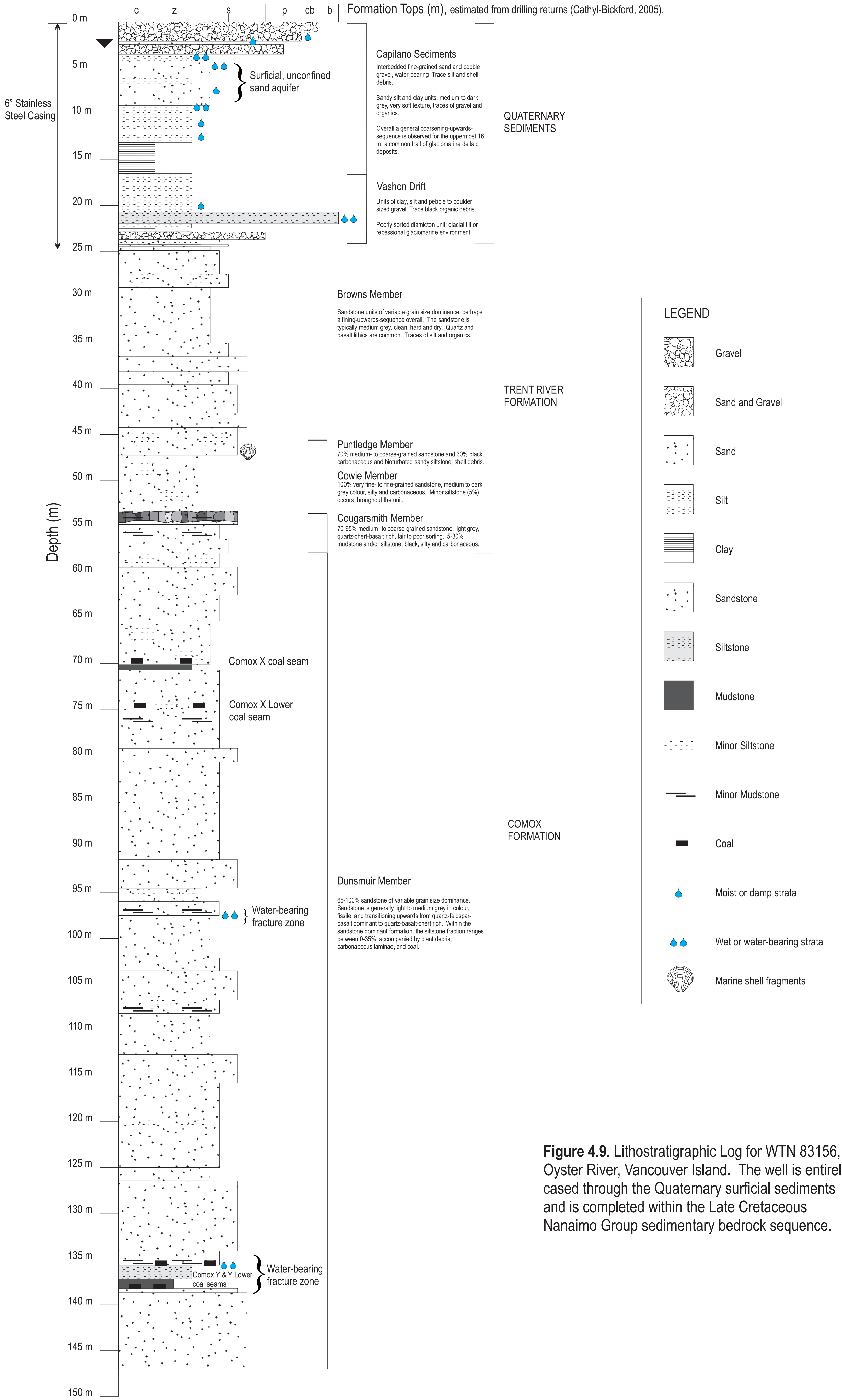
On June 22nd, 2005 a pumping and recovery test was undertaken for the deep bedrock well (WTN 83156). The pumping test was conducted for eighty minutes with an extended recovery period of just less than 14 days immediately following. Based on drill cuttings and depths of water-bearing fractures encountered during drilling, a fracture zone was identified at 135 m bgs (-5 m +MSL); the zone is approximately 3 m thick and includes two thin coal seams. The pump intake was situated at this approximate depth. The data for the pumping and recovery test were recorded every minute using a digital water level data logger placed approximately 100 m bgs (30.5 m +MSL). The Solinst Levelogger Gold 3001 (Model F300, M100) was used to monitor the water levels during the pumping and recovery test of the bedrock well. Given an elevation range of between 130.5 m and 30.5 m +MSL, the water level data logger has a resolution of 0.0006% at full scale, an accuracy of ± 5 cm, and a water fluctuation range of 99 m (Solinst Canada Ltd., 2008). The barometric data logger Solinst Barologger Gold 3001 (Model F5, M1.5) was placed at surface just beneath the well cap to record changes in barometric pressure throughout the test so that the water level measurements could be corrected for barometric pressure variations. Given a ground elevation of approximately 130.5 m +MSL, the barometric data logger has a resolution of 0.002% at full scale and an accuracy of ± 0.1 cm (Solinst Canada Ltd., 2008). Both loggers began their monitoring 6 hours before the pumping test began in order to gain accurate static water level readings. The pumping rate was manually calculated using a 5 gallon bucket and stop watch, and was rerecorded 16 times throughout the pumping test.

4.7 Borehole Subsurface Results

4.7.1 Drilling Cuttings Description

This section provides an overview of the lithologic descriptions determined on the basis of drill cuttings collected in both wells. Appendix 4.1 details the lithologic drilling logs for both wells at this site, while Figures 4.9 and 4.10 a & b summarize the wells' lithostratigraphy.

The uppermost lithologic unit was identified as interbedded sand and gravel and occurs in both wells for approximately the first 6 m bgs. The gravel beds are largely comprised of pebbles, up to 50 mm in diameter, that are predominantly subrounded to rounded with traces of sand and silt. The sand beds are typically very fine- to fine-grained or fine- to medium-grained, and are comprised of grains of varied mineralogy, including some basaltic lithics. The unit also contained



Capilano Sediments

Interbedded fine-grained sand and cobble gravel, water-bearing. Trace silt and shell debris.

Sandy silt and clay units, medium to dark grey, very soft texture, traces of gravel and organics.

Overall a general coarsening-upwards-sequence is observed for the uppermost 16 m, a common trait of glaciomarine deltaic deposits.

Vashon Drift

Units of clay, silt and pebble to boulder sized gravel. Trace black organic debris.

Poorly sorted diamicton unit; glacial till or recessional glaciomarine environment.

Browns Member

Sandstone units of variable grain size dominance, perhaps a fining-upwards-sequence overall. The sandstone is typically medium grey, clean, hard and dry. Quartz and basalt lithics are common. Traces of silt and organics.

Puntledge Member

70% medium- to coarse-grained sandstone and 30% black, carbonaceous and bioturbated sandy siltstone; shell debris.

Cowie Member

100% very fine- to fine-grained sandstone, medium to dark grey colour, silty and carbonaceous. Minor siltstone (5%) occurs throughout the unit.

Cougarsmith Member

70-95% medium- to coarse-grained sandstone, light grey, quartz-chert-basalt rich, fair to poor sorting. 5-30% mudstone and/or siltstone; black, silty and carbonaceous.

Dunsmuir Member

65-100% sandstone of variable grain size dominance. Sandstone is generally light to medium grey in colour, fissile, and transitioning upwards from quartz-feldspar-basalt dominant to quartz-basalt-chert rich. Within the sandstone dominant formation, the siltstone fraction ranges between 0-35%, accompanied by plant debris, carbonaceous laminae, and coal.

Figure 4.9. Lithostratigraphic Log for WTN 83156, Oyster River, Vancouver Island. The well is entirely cased through the Quaternary surficial sediments and is completed within the Late Cretaceous Nanaimo Group sedimentary bedrock sequence.

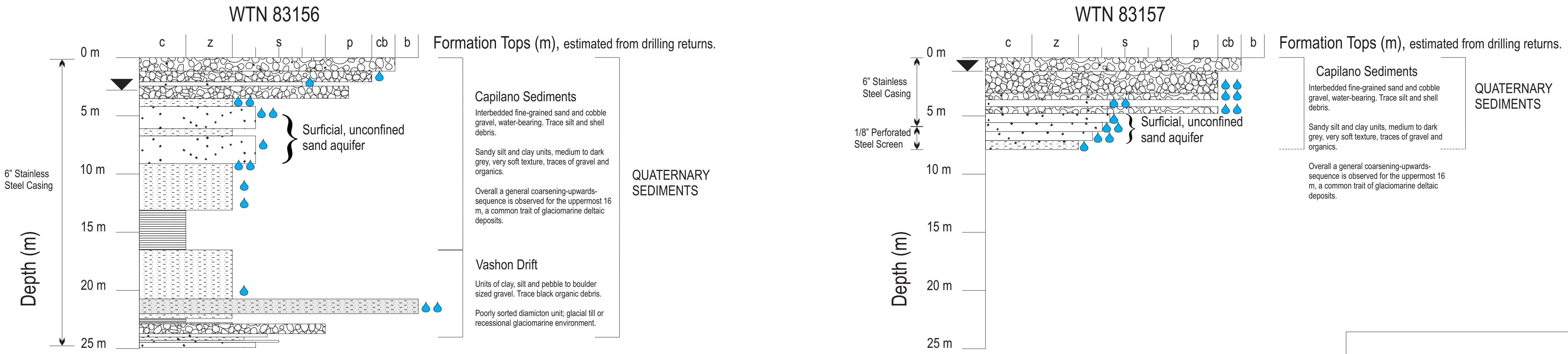


Figure 4.10a. Lithostratigraphic logs for the surficial Quaternary sediments penetrated by the two wells completed at Oyster River, Vancouver Island. The deep bedrock well is WTN 83156 and the shallow surficial well is WTN 83157. The two wells are situated 10 m apart.

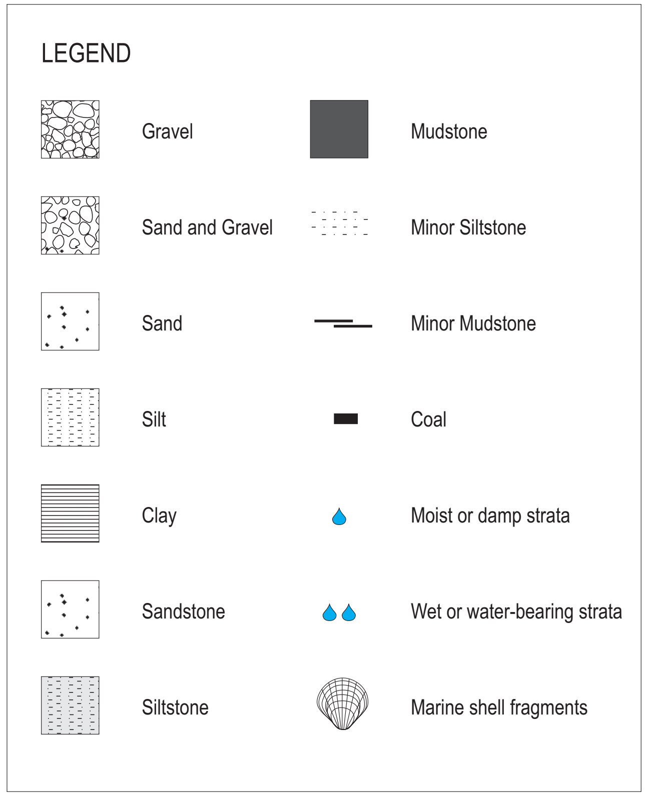


Figure 4.10b. Lithostratigraphic correlation for the surficial Quaternary sediments penetrated by the two wells completed at Oyster River, Vancouver Island. The deep bedrock well is WTN 83156 and the shallow surficial well is WTN 83157. The two wells are situated 10 m apart.

minor silt, with increasing fraction with depth, and trace shell debris. The shallow well encountered water at approximately 4 m bgs in a unit that was estimated to be 50% sand and 50% gravel. The gravel fraction was angular and poorly sorted with pebble grain sizes dominant. The sand fraction was fine- to medium-grained, well sorted, brown in colour and of varied mineralogy. A water-bearing sand layer was identified between 5 and 7 m bgs for WTN 83157 (shallow well), producing approximately 1.6 x 10^{-1} litres per second (L/s) or 2.5 USgpm as estimated by the driller. The deep well exhibits either wet or moist strata at the same elevation as the sand aquifer identified for the shallow well, although the sand is slightly finer grained at the deeper well.

Between 7 m and 20 m bgs the mean grain size at WTN 83156 progressively fines from silty sand to sandy silt and clay. The silt and clay units are medium to dark grey in colour, very soft, with traces of sand, granule-size gravel, and black, shell and peaty organic debris. Alternating units of silt and boulders of siltstone and sandstone were encountered between 21 m and 24 m bgs, at which point it was determined that bedrock had been reached (106.5 m +MSL).

The uppermost bedrock encountered at this location was identified from predominantly fissile chip fragments of dark grey to black siltstone (65%) with coarse-grained, light to medium grey sandstone (35%). Within the first metre of bedrock, sandstone became the dominant lithology (100%). It has the following characteristics: fine- to medium-grained, medium grey, chert-lithic, clean and moderately hard. The sandstone unit remained fairly consistent in composition for roughly 20 m; traces of basalt, quartz, glauconite and plant matter laminae were observed. Fissile carbonaceous siltstone remained a minor component (10%).

Between 45 m and 55 m bgs the deep well encountered a sequence of siltstone and sandstone alternating with solely sandstone. At approximately 45 m bgs the sample was estimated as 60% medium- to coarse-grained sandstone that was moderately hard, and slightly silty with traces of quartz-chert. Drill cuttings from this depth included an estimated 30% siltstone that was fissile, sandy, poorly sorted, black, carbonaceous and bioturbated. At roughly 48 m bgs the sample showed 70% silty, very fine- to fine-grained sandstone that was medium grey in colour, moderately hard to fissile, and quartz-chert-basalt dominant. The cuttings at this depth also showed 30% dark grey, sandy, siltstone that was carbonaceous with traces of shell debris. Over the following 5 m the sandstone became dominant, ranging between 85-100%, with 5% siltstone. At approximately 53 m bgs the siltstone fraction increased back up to 30%. Below this, however, the sample consists 95-100% of alternating fine- to medium-grained and medium- to coarse-grained sandstone, with 5-10% mudstone or siltstone. The mudstone cuttings were black, slightly carbonaceous and laminated.

Between 67 m and 70 m bgs the siltstone fraction is up to 20 or 30%. The 70-80% sandstone is very fine- to fine-grained, light to medium green-grey in colour and appears friable or fissile. The first coalified rootlets were observed at 70 m bgs (60.5 m +MSL) together with a dark grey, carbonaceous sandy siltstone, a minor fraction of the bedrock at this depth (5%). Immediately below this sample the drilling became quite fast and what appeared to be a 100% mudstone bed, light green-grey in colour was retrieved from the drilling returns for between 1 m to 2 m. Below this, however, the samples returned to the alternating 100% sandstone units and combined 55% sandstone and 45% siltstone fractions.

Alternating finer and coarser grained 85-100% sandstone units were encountered between 77 m and 95 m bgs. The sandstone coarsened and fined throughout this interval, progressing with depth from quartz-chert-basalt to quartz-feldspar-basalt dominant. Occasional oxidized surfaces were noted on the rock chips. Plant debris and carbonaceous laminae were also frequently observed throughout this interval.

At 96 m bgs the siltstone fraction increased to 45%, with 50% very fine- to fine-grained sandstone, and 5% medium-grained sandstone that is light grey and quartz-feldspar-basalt dominant. This unit was followed by 95% fine- to medium-grained sandstone and 5% carbonaceous and sheared mudstone. A possible fracture zone at 97.8 m bgs was indicated by the sheared mudstone cuttings and was immediately followed by water production a metre below. The water-bearing fracture zone is estimated at less than a metre thick.

Between 99 m and 106 m bgs the lithology is 100% sandstone exhibiting an overall coarsening-upwards-sequence. Trace plant debris and coal were identified at 100 m bgs. The sample at 108 m bgs was comprised of 55% fine- to medium-grained sandstone, 40% sandy siltstone, and 5% fissile mudstone. Below this, and continuing down to 135 m bgs, the bedrock samples consisted of alternating finer and coarser grained sandstone with occasional occurrences of siltstone (<10%).

Significant production of saline water was encountered at 135.3 m bgs (-5 m +MSL). With drilling paused, well yield was initially estimated at 1.0×10^{-1} L/s (1.6 USgpm); however, after 5 minutes of production the yield decreased to an estimated 1.7×10^{-2} – 3.3×10^{-2} L/s (3.0×10^{-1} – 5.0×10^{-1} USgpm). The rapid reduction in flow rate suggested limited permeability at this elevation. In addition to being saline, the water was turbid, iron-rich (yellow in colour) and contained silty flocculates. A coal seam was encountered at this water production zone. The drilling cuttings showed the bedrock composition at this depth as 50% very hard fine- to medium-grained sandstone, 40% black coaly mudstone, 5% black, dull, dirty, and blocky coal, and 5% carbonaceous sandy siltstone. The width of the coal seam was approximately 2 m, signified by 90% platy, medium grey siltstone and 10% very fine-grained, silty sandstone with traces of coal. Within a further 2 m, however, fine coal dust was seen in the drill returns, along with the production of more salt water. Although only briefly evidenced in the drill cuttings, a second lower coal seam was penetrated at 138.5 m bgs (-8 m +MSL).

Medium- to coarse-grained, light grey sandstone immediately followed the second coal seam. The sandstone was noted as being disaggregated, clean, quartz and feldspar rich, with a minor amount of basalt. This sandstone unit continued from 138.7 m down to the bottom of the well at 146.9 m bgs (-16.4 m +MSL).

4.7.2 Borehole Geophysical Analysis

Borehole geophysical logging conducted in WTN 83156 and WTN 83157 included natural gamma ray, density, formation electrical resistance, and a single-arm motorized caliper. The steel casing in place throughout the overburden significantly mutes the signal strength of the electrical logs, as well as negates the caliper entirely, for this depth interval at both wells. Furthermore, it is believed that the formation resistance measurements for the deep bedrock well, WTN 83156, were effected by the saline water produced at this well (Hawkins, 2009). Considering the influence of the saline water in the deeper well and the effects of the steel casing for both wells, the formation resistance logs for both wells were excluded from the analyses. Appendix 4.2 includes original analog logs as well as the digital data of the borehole geophysical investigation at both wells. The proceeding borehole geophysical analysis is entirely based on the analog logs as the digital data is presently uncorrected data and require further processing in order to effectively interpret the subsurface environment.

The geophysical logs for the unconsolidated surficial sediments encountered by both of the Oyster River wells recognize similar subsurface patterns regardless of the difference in logging rate or consequent resolution. The natural gamma radiation logs for the paired wells reflect an interbedded unit for the uppermost 4 m that contains significant fractions of silt and / or clay minerals. This unit is thought to be considerably porous with interstitial pore spaces largely filled with air. For both wells, the range in gamma response for this depth interval is between 10 counts per second (CPS) and 30 CPS. These readings drop to between 5 CPS and 15 CPS at the bottom of WTN 83157, and at 10 m bgs at the deeper well, WTN 83156. A noticeable decrease in the density log of WTN 83157 between 4.25 m and 5.5 m bgs corresponds with the observed drop in gamma readings. Between 10 m bgs and the upper bedrock contact at 24 m bgs, the gamma readings for the deep well increase slightly with depth but remain between approximately 10 CPS and 32 CPS. The drilling notes for this depth interval are interbedded silt and clay units with a few metres of silt and boulders at the upper bedrock contact. Silt and clay sediments are typically expected to give relatively high natural gamma readings. As the stainless steel casing lines the entire length of the shallow well and down to bedrock for the deeper well; however, the gamma ray signal is considerably muted throughout this interval. A signal dampening of 20% is the general rule of thumb (Sim, 2009), indicating that the upper range of natural gamma ray emissions for the surficial sediments at Oyster River would be roughly 40 CPS.

The natural gamma ray readings at the upper bedrock contact (24 m bgs) immediately jump up from approximately 20 CPS to 100 CPS. The uppermost 11 m of bedrock encountered by WTN 83156, between 24 m and 35 m bgs, record gamma readings in the range of 60 CPS to 100 CPS and density values between 2.5 g/cc and 2.65 g/cc. Between 35.5 m and 48.5 m bgs there is a noticeable decrease in gamma ray counts, generally ranging between 50 CPS and 70 CPS. Throughout this depth interval the density recordings for WTN 83156 alternate frequently between 2.45 g/cc and 2.625 g/cc, with occasional highs of 2.65 g/cc. The transition depth of approximately 35 m bgs demarks a contact between medium- to coarse-grained sandstone below, and very-fine- to fine-grained sandstone above in the drill logs. Finer gained sandstone would be expected to contain higher fractions of silt and clay minerals and therefore emit elevated amounts of natural gamma rays, a correlation evidenced in the geophysical logs of WTN 83156. Elevated gamma readings, between 60 CPS to 100 CPS, are also noted for the depth interval between 48.5 m and

52 m bgs; the elevated gamma recording again correlates with drilling logs of predominantly fine-grained sandstone with siltstone fractions up to 30%.

Water-bearing zones were encountered during drilling at 97.8 m and 135.3 m bgs. Drilling logs for the 97th m record 95% medium- to coarse-grained sandstone with 5% carbonaceous and sheared mudstone. The gamma readings are approximately 60 CPS at 97.6 m bgs and 90 CPS at 97.9 m bgs, possibly reflecting a mudstone rich lens underlying a sandstone dominant bed. A relative density low of roughly 2.58 g/cc corresponds to this depth interval, also thought to reflect the sheared mudstone. Based on the borehole geophysical and drilling logs the groundwater produced at this elevation is thought to be transmitted by the sheared mudstone. The water-bearing fracture zone encountered at 135 m bgs (-5 m +MSL) is thought to span a vertical thickness of 3 m and include two thin coal seams noticed in the drilling logs at 135.6 m and 138.4 m bgs. Drilling logs record 100% coarse-grained sandstone at 134.1 m bgs; water production at 135.3 m bgs; 50% fine- to medium-grained sandstone, 45% mudstone, and 5% coal at 135.6 m bgs; 90% siltstone and 10% very fine-grained sandstone with traces of coal at 137.2 m bgs; coal dust and more water production at 138.4 m bgs; and 100% medium- to coarse-grained sandstone down to the total depth of the well at 146.9 m bgs. Relatively low gamma ray values are recorded between 134.5 m and 136.5 m bgs, ranging between 45 CPS and 60 CPS; however, within this interval there is a noticeable high of 68 CPS at 135.6 m bgs corresponding to the upper of the two coal seams. There is also a relatively low measure in the density log at 135.6 m bgs, approximately 2.5 g/cc. Immediately below this, between 135.7 m and 136.3 m bgs, there is a brief interval of significantly elevated density, up to 2.65 g/cc. The variation in density between 135.6 m and 136.3 m bgs is interpreted to reflect the density difference between the mudstone and coal seam and the fine- to medium-grained sandstone. Gamma ray values are also somewhat elevated at 138.4 m bgs, corresponding to the lowermost coal seam intercepted at Oyster River; however, there is no significant variation observed in the density log at this depth.

Little variation was observed by the single-arm caliper throughout the borehole completed within the bedrock sequence. The caliper measurements remained between 130 mm and 140 mm throughout the entire length of the deep borehole, slightly less than the 152 mm equivalent to a 6”-diameter borehole. A variation of less then a centimetre demonstrates a considerably competent borehole. The lack of variation at the fracture zones encountered while drilling may reflect infilling of borehole cavities by mud formed from the occasional addition of water introduced during drilling. Alternatively, the fracture zones may not be significant enough to form noticeable cavities or simply not cause any caving at the borehole.

4.7.3 Aqueous Geochemical Analysis

Both wells completed at the Oyster River site were sampled and analyzed for aqueous geochemical constituents relating to drinking water quality, hydrocarbons, volatile organic carbons (VOCs) and methane gas dissolved in water. Tables 4.1 and 4.2 summarize the constituents that exceed the BC MoE drinking water criteria, and list the VOCs and hydrocarbons present in the well water. Appendix 4.3 tabulates the complete results of the aqueous geochemical analysis sampled just after well completion in 2005, as well as BC MoE’s 2006 and 2007 samples.

The water of the shallow, unconfined sand aquifer (WTN 83157) is near drinking water quality with respect to the typical ambient water quality parameters with the exception of total iron, which remained above the drinking water threshold for all three years. The VOCs and hydrocarbons present in the shallow well’s water samples do not have guidelines with respect to drinking water criteria. As the concentrations of these constituents are quite low, just above detection limits, they are considered a low concern with respect to drinking water quality.

Table 4.1. Aqueous Geochemical Constituents Exceeding BC MOE Drinking Water Guidelines (BC MoE, 2008)

WTN 83156 (deep bedrock well)

		22-Apr-05 (1 min)	22-Apr-05 (5 min)	22-Apr-05 (60 min)	30-Oct-06	07-Feb-07	Units	Detection Limit	BC MOE Criteria for Drinking Water
Misc. Inorganics									
Fluoride	F	<	**12.7**	<	0.82	0.81	mg/L	1	**1.5**
Anions									
Dissolved Sulphate	SO_4	25.7	<	13.0	16.9	25.4	mg/L	0.5	500
Chloride	Cl	**9310**	**12200**	**12800**	**2310**	**289**	mg/L	0.5	**250**
Dissolved Metals by ICPMS									
Dissolved Barium	Ba	**26000**	**28900**	**19000**	**4690**	281	µg/L	0.1	**1000**
Dissolved Manganese	Mn	**1190**	**1170**	**1360**	**208**	27.4	µg/L	0.04	**50**
Dissolved Selenium	Se	**14**	0	**16**	<	<	µg/L	1	**10**
Total Metals by ICP									
Total Iron	Fe	<	<	<	**1.83**	**1.68**	mg/L	0.005	**0.3**
Physical Properties									
Total Dissolved Solids		**16900**	**23400**	**24600**	**4320**	**698**	mg/L	10	**500**
Leachable Metals									
Total Sodium	Na	**3570**	**3860**	**2990**	**778**	**218**	mg/L	0.05	**200**

< less than detectable limit

WTN 83157 (shallow surficial well)

				20-Apr-05	30-Oct-06	07-Feb-07	Units	Detection Limit	BC MOE Criteria for Drinking Water
Dissolved Metals by ICPMS									
Dissolved Manganese	Mn			16	**51.6**	42.1	µg/L	0.08	**50**
Anions									
Dissolved Sulphate	SO_4			1.6	1.1	1.0	mg/L	0.5	500
Chloride	Cl			3.4	1.6	1.3	mg/L	0.5	250
Physical Properties									
pH, Laboratory				7.29	**4**	7.6	mg/L	0.1	**6.5:8.5**
Total Metals by ICP									
Total Iron	Fe			<	**1.41**	**1.80**	mg/L	0.005	**0.3**

< less than detectable limit

Table 4.2. Volatile Organic Compounds and Hydrocarbons in Water (BC MoE, 2008)

WTN 83156 (deep bedrock well)

	22-Apr-05 (1 min)	22-Apr-05 (5 min)	22-Apr-05 (60 min)	30-Oct-06	07-Feb-07	Units	Detection Limit	BC MOE Criteria for Drinking Water
Monocyclic Aromatics								
Benzene	2.7	2.1	2.3	1.2	<	µg/L	0.5	5
Ethylbenzene	**7.7**	<	<	<	<	µg/L	0.5	**2.4**
Toluene	**560**	**150**	**63**	12	14	µg/L	0.5	**24**
Xylenes (Total)	3.4	<	<	<	<	µg/L	1	300
Polycyclic Aromatics								
Low Molecular Weight PAH's	-	-	-	0.37	0.09	µg/L	0.05	-
High Molecular Weight PAH's	-	-	-	<	<	µg/L	0.02	-
Total PAH	-	-	-	0.37	0.09	µg/L	0.05	-
Napthalene	<	<	<	0.31	0.06	µg/L	0.01	-
2-Methylnapthalene	-	-	-	0.05	0.02	µg/L	0.01	
Permanent Gases (in Water)								
Methane	-	-	-	44	5.05	L/m³	0.005	-
Calculated Methane	-	-	**2123**	**29**	**3.3**	mg/L	0.003	-

< less than detectable limit
- not analyzed for

WTN 83157 (shallow surficial well)

	20-Apr-05	30-Oct-06	07-Feb-07	Units	Detection Limit	BC MOE Criteria for Drinking Water
Polycyclic Aromatics						
Low Molecular Weight PAH's	-	0.09	0.07	µg/L	0.05	-
High Molecular Weight PAH's	-	<	<	µg/L	0.02	-
Total PAH	-	0.07	0.07	µg/L	0.05	-
Napthalene	-	0.05	0.05	µg/L	0.01	-
2-Methylnapthalene	-	0.03	0.03	µg/L	0.01	-
Permanent Gases (in Water)						
Methane	-	0.107	0.009	mg/L	0.005	-
Calculated Methane	-	**0.069**	**0.006**	mg/L	0.003	-

< less than detectable limit
- not analyzed for

As expected, the saline water produced from the deep fractured bedrock aquifer (WTN 83156) is not suitable as a drinking water source. High levels of total dissolved solids, chloride, and sodium exceeded the BC MoE criteria for drinking water for all three years of sampling (BC MoE, 2008). Dissolved barium and manganese also exceeded drinking water thresholds for 2005 and 2006 samples. High concentrations of VOCs and hydrocarbons, particularly methane gas, were also found in the first year of sampling. However, by 2006 these constituents were within concentration ranges acceptable of drinking water quality. Relatively high levels of manganese, iron, sulphate and dissolved methane gas are indicative of an anoxic aqueous environment.

Aqueous geochemical analysis of WTN 83156 can aid in determining the origin of the high concentration of methane gas found in the 2005 sample. Indicator constituents have been identified to provide a signature concentration relationship common to coalbed methane produced waters throughout North America (Van Voast, 2003). Milliequivalents per litre are used as a relative measure of chemical constituent concentrations and are displayed in Schoeller diagrams (Freeze and Cherry, 1979). Typical geochemical signatures of coalbed methane associated water exhibit high concentrations of sodium (Na), chloride (Cl) and bicarbonate (HCO_3), typically between 10 and 1000 milliequivalents; moderate levels of calcium (Ca) and magnesium (Mg), generally between 1 and 10 milliequivalents; and very low concentrations of sulphate (SO_4), commonly around 0.1 millequivalents (Van Voast, 2003). The Schoeller diagram (Figure 4.11b) of the deep bedrock well at Oyster River, WTN 83156, describes the general pattern seen in coalbed methane associated waters throughout North America (Van Voast, 2003). The concentrations of most of the key constituents are shown to decrease over the 2 years of monitoring. The concentration of dissolved methane gas significantly decreases over the monitoring period, reducing from 2,123 mg/L in 2005 when the bedrock well was drilled and the thin coal seams first penetrated, through 2006 (29 mg/L) to the latest values of 2007 (3.3 mg/L). The coincident decline of the dissolved

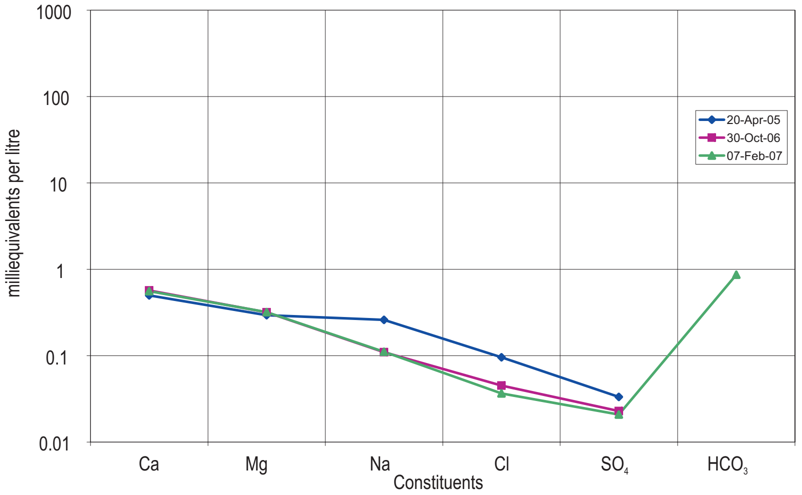


Figure 4.11a. WTN 83157 Schoeller diagram

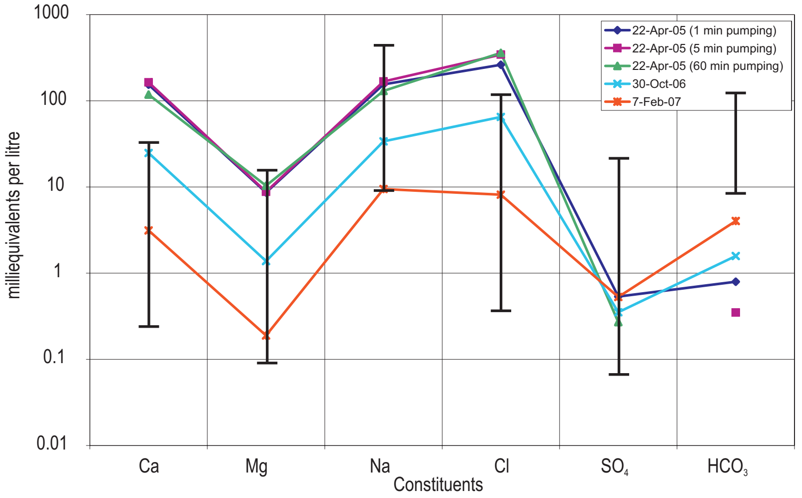


Figure 4.11b. WTN 83156 Schoeller diagram

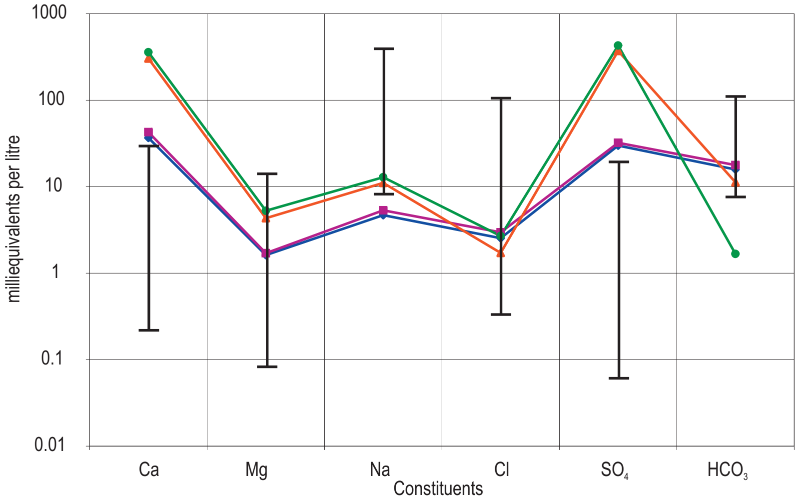


Figure 4.11c. Quinsam coal mine Schoeller diagram

Figure 4.11a-c. Schoeller diagrams for WTN 83156, WTN 83157 and Quinsam coal mine. Schoeller diagrams have been used to identify geochemical signatures for coalbed gas associated groundwater. The vertical black bars are concentration ranges for the illustrated constituents of coalbed gas associated groundwater across North America, compiled by Van Voast (2003).

methane gas and the key constituents identified to relate with coalbed methane support the interpretation that the water produced from the deep bedrock well at Oyster River is coal related. Furthermore, the significant and relatively rapid decrease in the dissolved methane gas and related constituents in the formation water of the deep well support the concept that the source of the coal related water are the coal seams encountered by the well, which due to their thinness degas over a short amount of time.

Conversely, the Schoeller diagram (Figure 4.11a) of the shallow well at Oyster River, WTN 83157, reflects both little change in constituent concentration over time and an entirely different relative concentration pattern. In spite of this, the groundwater produced from the surficial well did contain low concentrations of dissolved methane gas: 0.069 mg/L in 2006 and 0.006 mg/L in 2007. There is not a measure of dissolved methane gas for WTN 83157 in 2005; however, the decrease in concentration between 2006 and 2007 imitates the trend observed for the bedrock well. It is logical; therefore, to assume that the 2005 dissolved methane gas concentration for the surficial well would be significantly higher than that recorded in 2006.

Other geochemical constituents, such as selenium, have also been shown to be closely associated with coal throughout the world (Ryan and Dittrick, 2001; Ryan *et al.*, 2002; Yudovich and Ketris, 2005). Aqueous geochemical results from the 2005 sampling of WTN 83156 reveal dissolved selenium values of 14-16 μg/L. Although the selenium concentration of WTN 83156 drops to below 1 ppb (detection level) in the 2006 and 2007 samples, the initially elevated selenium levels further confirm geochemical association with the coal of the Comox Coalfield (Ryan *et al.*, 2002).

Data from the Quinsam coal mine (Ryan, 2008), the only presently active coal mine on Vancouver Island, located northwest of the Oyster River area in a subsidiary coalfield of the Comox

Coalfield, does not concur with the signature pattern reflective of coalbed methane associated groundwater (Figure 4.11c). Because the Quinsam samples were taken from coal exploration wells, their chemistries are clearly coal related. However, as these coal seams have been, and continue to be, actively mined for conventional coal, it is possible that the coalbed gases have escaped over time. Nevertheless, at this time it is not possible to conclude a definitive coalbed methane aqueous geochemical signature for the Comox Coalfield. The dissolved methane gas and aqueous geochemical concentrations obtained in this study for WTN 83156 can be combined with Quinsam's data, however, to advance coalbed gas characterization on Vancouver Island.

4.7.4 Groundwater Pumping and Recovery Test Analysis

The pumping test conducted for the shallow well (WTN 83157) at Oyster River drew the water level in the well down 1.51 m after four hours of pumping, from a static water level of 0.92 m to a maximum drawdown of 2.43 m. The water level was entirely recovered at the end of an hour's monitoring, indicative of a highly permeable hydrostratigraphic unit. As the pumping rate was not recorded over time a constant pumping rate cannot be verified. Assuming that the measured pumping rate of 10 USgpm did not vary, however, transmissivity and hydraulic conductivity values can be calculated from the pumping data and an aquifer thickness of 1.4 m, the height of the well screen.

Table 4.3. Pumping Test Analysis for WTN 83157. See Appendix 4.4 for data and analyses.

Analytical Method	Transmissivity, T (m^2/s)	Hydraulic Conductivity, K (m/s)
Theis Curve Matching (Theis, 1935)	5.9×10^{-5}	4.3×10^{-5}
Cooper-Jacob Straight Line (Cooper and Jacob, 1946)	6.0×10^{-5}	4.4×10^{-5}
Neuman Curve Matching (Neuman, 1975)	4.5×10^{-5}	3.2×10^{-5}
Theis Recovery Method (Theis, 1935)	1.3×10^{-4}	9.4×10^{-5}

The transmissivity and hydraulic conductivity values estimated by the Theis curve matching, Cooper-Jacob straight line matching, and Neuman curve matching methods are consistent with one another and are within the typical range of values for a well-sorted, clean, fine-grained sand aquifer (Fetter, 2001; Anderson and Woessner, 2002). The Theis recovery method was employed to analyze the recovery data (Theis, 1935). Transmissivity and hydraulic conductivity values approximated from the recovery data are 1.3×10^{-4} m^2/s and 9.4×10^{-5} m/s, respectively. Although these values are slightly higher than those estimated from the pumping test data they are still consistent with well-sorted sands, perhaps slightly coarser grained such as a medium-grained sand aquifer (Fetter, 2001; Anderson and Woessner, 2002). As the actual pumping rate for the full 4 hours of pumping is uncertain, the estimates using the recovery data may be more accurate. However, given the small overall drawdown it is thought that the pumping rate did not change significantly.

Specific and long-term well capacities for the surficial well are difficult to approximate due to the uncertainty in the pumping rate over time. Assuming a constant pumping rate of 10 USgpm, specific capacity calculations for mid (100 min) and late (200 min) pumping times give values of 2.57×10^{-1} L/s/m (1.24 USgpm/ft) and 2.59×10^{-1} L/s/m (1.25 USgpm/ft), respectively. Later time estimates reveal very consistent values, and although they do not differ considerably from the early time (10 min) estimate of 3.33×10^{-1} L/s/m (1.61 USgpm/ft), there is enough of a variation to suggest that the drawdown may have equilibrated by the latter half of the pumping test.

Long-term well capacity was calculated by considering 70% of the available drawdown (the water column within the wellbore) multiplied by the specific capacity. Based on the specific capacity at 200 minutes of pumping a long-term well capacity estimate of 0.91 L/s (14.4 USgpm) is estimated.

The static water level at the start of the pumping test of the deep bedrock well, WTN 83156, was recorded to be 14.6 m bgs (115.9 m +MSL). The initial height of the water column above the data logger was 85.4 m, well within the pressure range of the instrument to provide full resolution and accuracy. The water produced from the pumping test was discharged into a ditch at the side of the highway, roughly 5 m northwest of the bedrock well, and 15 m northwest of the shallow well.

The 80-minute pumping test drew down the water level 80.36 m (Figure 4.12). The water level continued to lower by an additional 3.07 m over a period of 18.9 hours following the termination of pumping. This is an unusual response in that the drawdown in the well continued to decrease for close to one day after the pump had been turned off. Thus, interpretation of the data proved difficult, as discussed below. Over the course of the following 36 hours, the water level recovered to the same elevation as at the time the pumping stopped (38.04 m +MSL). During the following 11.5 days, the water level recovered an additional 34.88 m. At the conclusion of the 14 day test the water level had risen to an elevation of 72.92 m +MSL, approximately 43 m below the original static water level. The fact that full recovery was not achieved, even after 14 days, attests to the low storage and hydraulic properties of the aquifer.

Analysis of the pumping test data revealed that the pumping test was affected by significant wellbore storage. Wellbore storage is typically characterized by a slope of one log cycle change in drawdown over one log cycle change in time during pumping (Figure 4.13). In addition, the pumping rate decreased over time due to the fact that the pumping rate was initially too high and the water level in the well dropped too quickly to maintain the pumping rate. Thus, the overall effect on the pumping test data was the combined effect of wellbore storage and changing pumping rates, making the pumping test data un-usable for determining the hydraulic properties of the

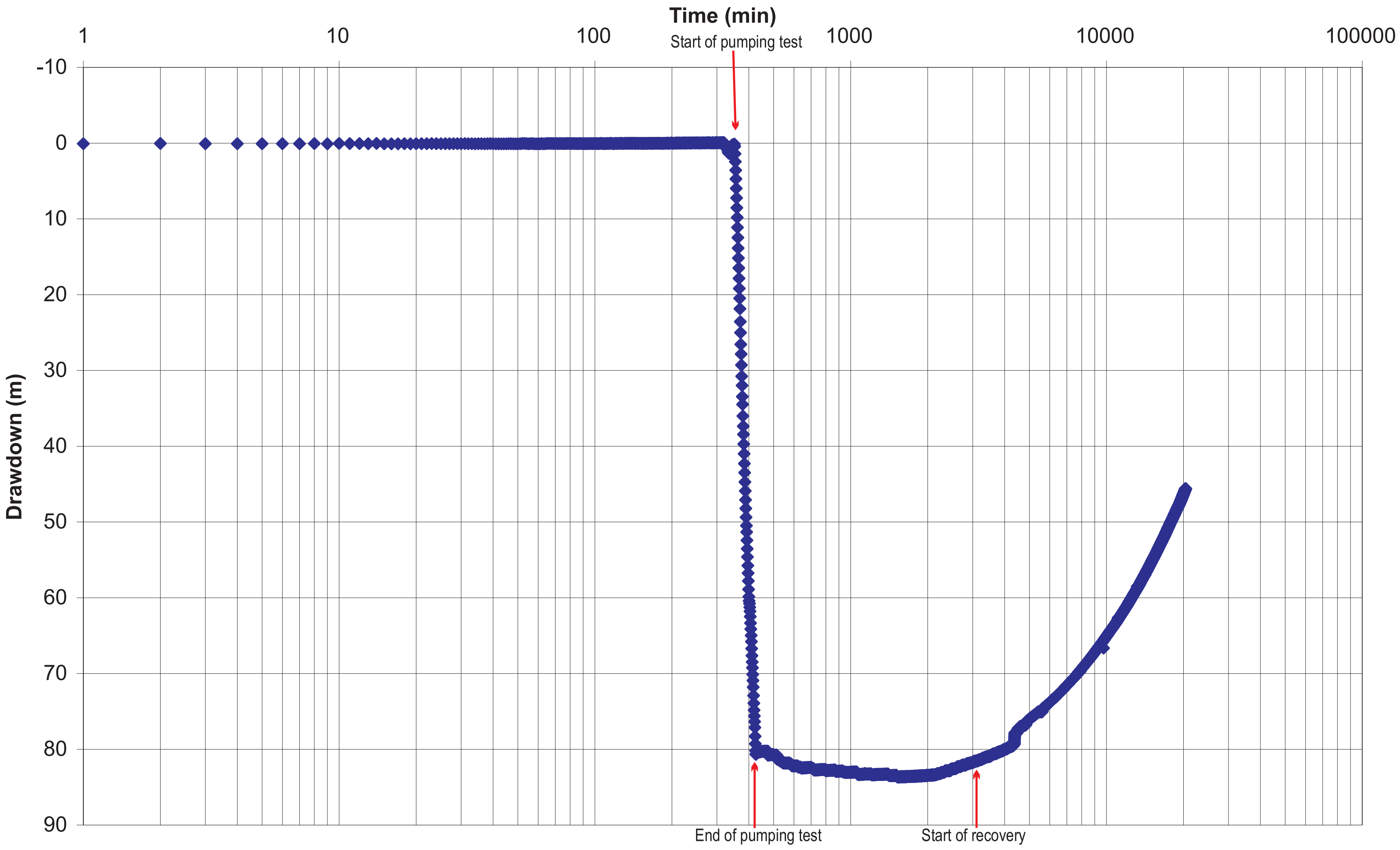


Figure 4.12. WTN 83156 pumping and recovery test, June 22, 2005 Oyster River, Vancouver Island, BC. The 80 min pumping test for the deep bedrock well drew the water column down 80.36 m, at which point the pump was turned off. The well's water level continued to decline 3.07 m over 18.9 hrs; therefore, the start of the recovery analysis was taken at this lowest level, 1,213 minutes after the start of pumping.

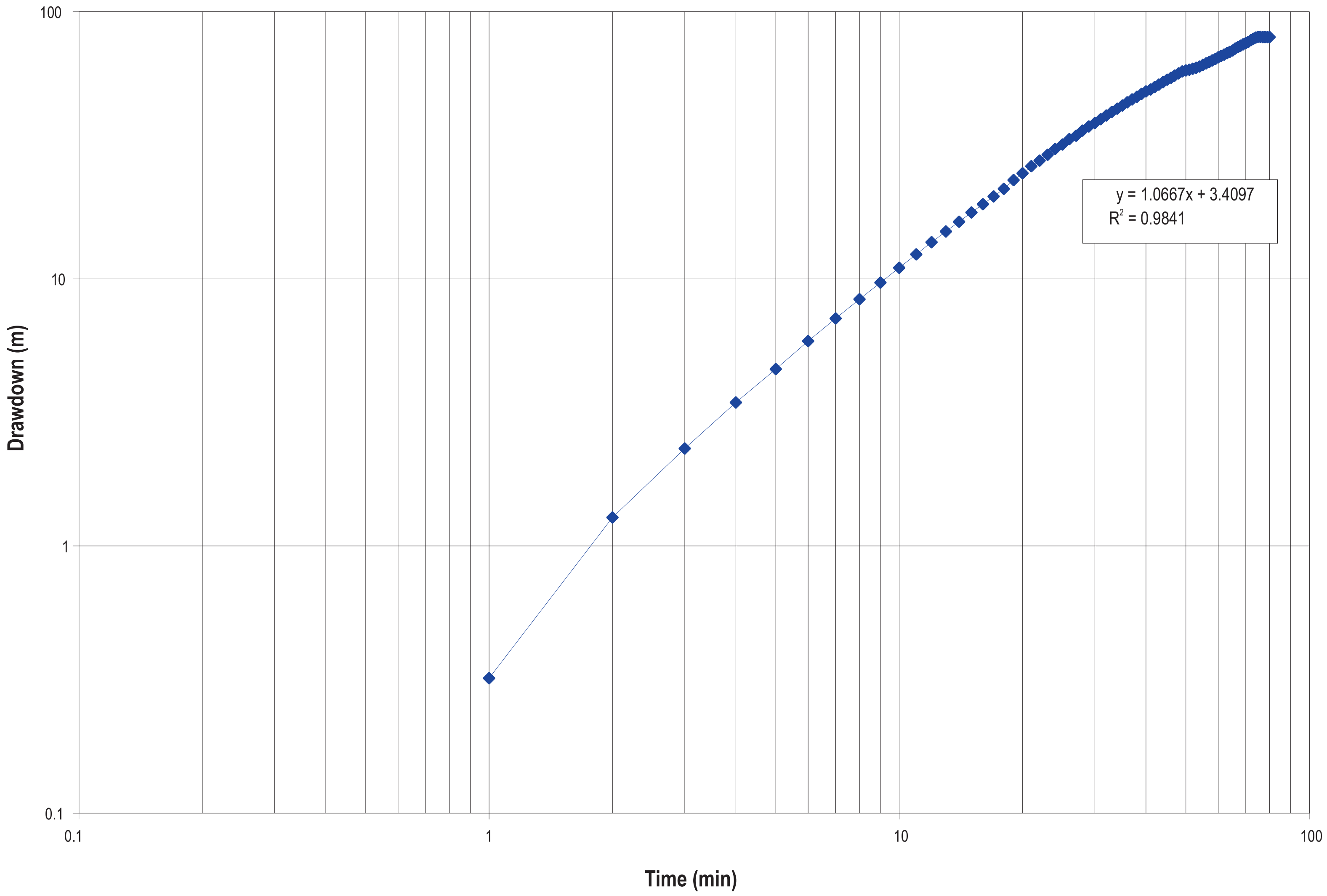


Figure 4.13. Pumping Test conducted on June 22, 2005 for the Oyster River deep bedrock well, WTN 83156. Wellbore storage is identified by a one log cycle drawdown for one log cycle time, as is apparent for this test.

aquifer. Consequently, only the recovery test data could be used for analysis, with the limitation that the analytical method used may not be entirely suitable, for reasons discussed later.

The Theis recovery method (Theis, 1935) was employed to estimate the fracture transmissivity (T) and hydraulic conductivity (K) for the confined, fractured bedrock aquifer penetrated by WTN 83156. The recovery analysis plots the residual drawdown (recovering water level) versus the logarithmic ratio of the total test time since pumping began, t, to recovery time, t' (log t/t'). The slope of the best fit line through the data is used to calculate the transmissivity of the aquifer (Kruseman and de Ridder, 1994). The method has some general assumptions, some of which are violated in this particular study. The most important assumptions are:

1. The aquifer must be confined, homogeneous and isotropic. This assumption is technically violated because while the aquifer may be confined and isotropic, it is not homogeneous, as fracture zones are encountered along the length of the open borehole. Nevertheless, the Theis Recovery method has been used in other studies under similar hydrogeological conditions (Allen, 1999).
2. There should be no borehole storage (that is, the aquifer should respond to pumping by taking water out of storage within the aquifer and not from the borehole itself). This condition was clearly violated, and it is unclear what effect this might have on the results.
3. The well must be pumped at a constant rate. This was clearly not the case for this test. However, it is possible to take an average of the pumping rate and set this value for analysis of the recovery data (Neville, 2006). Even if the average pumping rate is used, it is not clear what effect this will have on the results.
4. The well must fully recover to its original level. This did not occur, and it is unclear what effect this will have on the results.

For the analysis, the lowest water level attained during the test was used (Figure 4.14); thus, the recovery period began at 1,213 minutes after the start of the pumping test. Transmissivity, T, was estimated by the Theis recovery method at 6.10×10^{-2} m^2/d (7.06×10^{-7} m^2/s or 4.91 USgpd/ft) based on the final recovery trend, $\Delta s_3' = 60$ m (Figure 4.14). Hydraulic conductivity, K, was estimated assuming that the width of the fracture zone was equal to the aquifer thickness (3 m) and was estimated at 1.98×10^{-2} m/d (2.29×10^{-7} m/s or 6.50×10^{-2} ft/d).

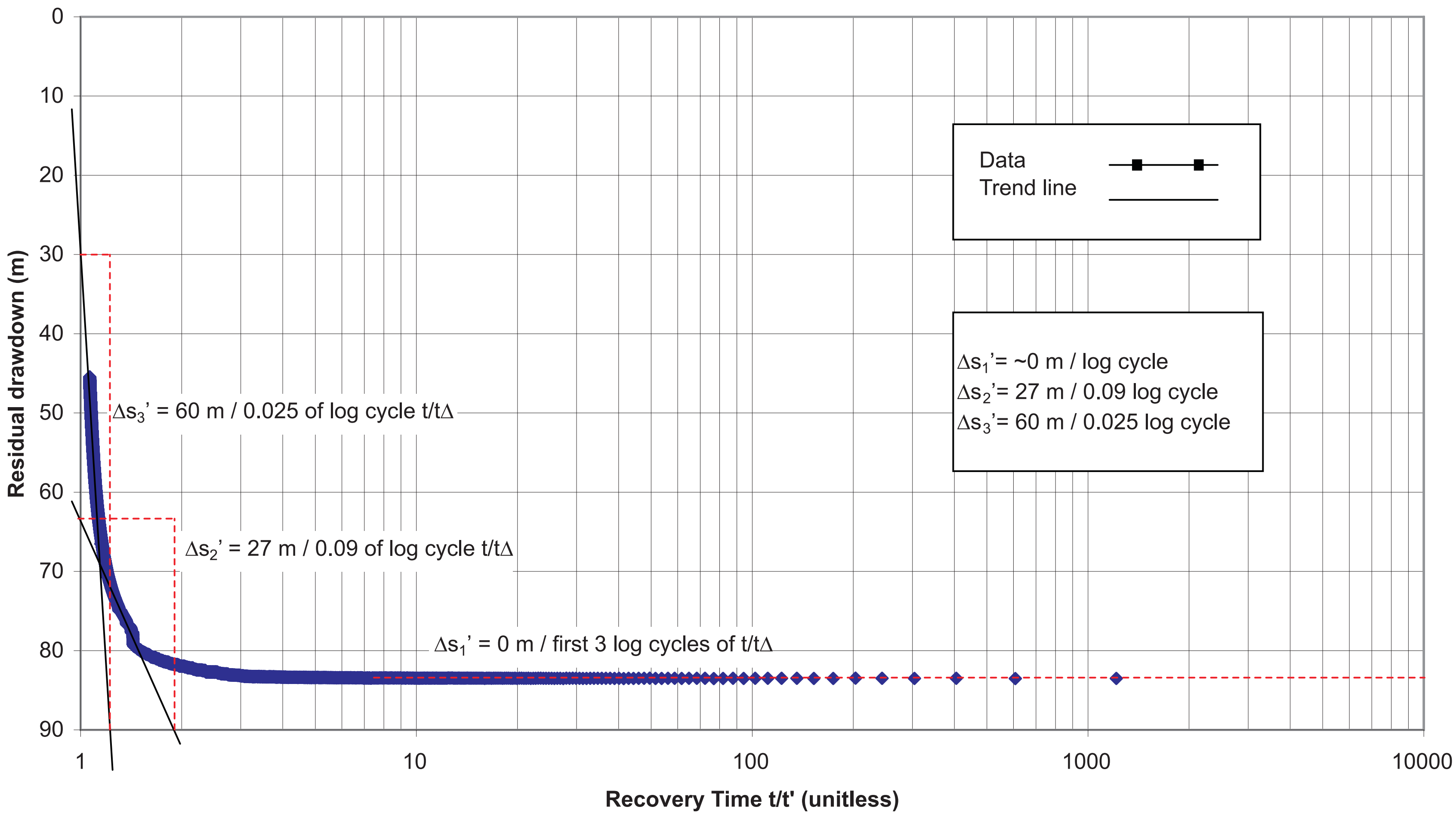


Figure 4.14. WTN 83156 Theis Recovery Curve (semi-log plot of residual drawdown versus recovery time, t/t' from t = 1213 min, t' = 0 min). The final recovery stage, $\Delta s_3' = 60$ m, was used to calculate fracture transmissivity and hydraulic conductivity estimates for the fractured bedrock aquifer.

Typically, however, the entire open-hole fractured bedrock sequence is considered the aquifer, as opposed to the individual fracture zones identified during drilling (Surrette and Allen, 2008). Therefore, if the entire open-hole bedrock sequence encountered at Oyster River is taken for the aquifer thickness, an interval of 123 m, the calculated conductivity is 5.0 x 10^{-4} m/d (5.79 x 10^{-9} m/s or 1.63 x 10^{-3} ft/d). Aquifer storativity cannot be estimated using the Theis recovery method.

Specific and long-term well capacities are difficult to approximate for the bedrock well due to the decline in pumping rate over time. Specific capacity calculations for mid (50 min) and late (70 min) pumping times give values of 5.31 x 10^{-3} L/s/m (2.56 x 10^{-2} USgpm/ft) and 3.02 x 10^{-3} L/s/m (1.46 x 10^{-2} USgpm/ft), respectively. Late time estimates reveal significantly more consistent and conservative values in comparison to the early time (1 min) estimate of 1.36 x 10^{-1} L/s/m (6.58 x 10^{-1} USgpm/ft), suggesting that the drawdown may have begun to equilibrate with the lower pumping rates at later time. Early time pumping illustrates significant wellbore storage effects and thus exaggerated specific capacity estimates. Thus, the best estimate for specific capacity is that obtained from late time data: 3.02 x 10^{-3} L/s/m (1.46 x 10^{-2} USgpm/ft).

Long-term well capacity was calculated by considering 70% of the available drawdown (the water column within the wellbore) multiplied by the specific capacity. Based on the specific capacity at 70 minutes of pumping a long-term well capacity estimate of 0.28 L/s (4.4 USgpm) is estimated.

Spot checks during each of the pumping tests were conducted to monitor the static water levels within the well that was not being pumped at the time. During the pumping test of the shallow well (WTN 83157), the static water level within the deep bedrock well (WTN 83156) was 48.5 m bgs before pumping began, 48.0 m bgs after 73.5 minutes of pumping, and 47.7 m bgs after 4 hours of pumping and 1 hour of recovery. During pumping of the deep bedrock well, the static water level within the shallow surficial well was recorded to be 1.40 m bgs at the start of pumping, and then 1.52 m bgs, 1.45 m bgs, 1.37 m bgs, and 1.38 m bgs throughout the first 30 minutes of pumping. Appendix 4.4 tabulates the data and analyses for the pumping and recovery tests of WTN 83156 and WTN 83157.

4.8 Borehole Subsurface Interpretation

4.8.1 Groundwater Well Log Interpretation

The lithostratigraphy logged during drilling of the surficial and bedrock wells at Oyster River is interpreted to include surficial Quaternary sediments as well as Nanaimo Group sedimentary bedrock (Figures 4.9 and 4.10 a & b). Chapter 2 details the regional surficial and bedrock geology of Vancouver Island, inclusive of the Oyster River area.

At surface through to a minimum of 7 m bgs, the interbedded sand and cobble-sized gravel units are thought to represent glaciofluvial deltaic deposits of the Capilano Sediments prograding into a glaciomarine environment. The minor silt and calcitic shell debris supports this interpretation. Within this deposit, water-bearing, fine-grained sand units were encountered between approximately 4.5 m and 9 m bgs, and are interpreted to comprise an unconfined, surficial aquifer. Thick units of silt and clay were penetrated by the deep well, WTN 83156, from 9 m to 20 m bgs. The units were sandy, well-sorted, and had traces of gravel and organics. In between the unconsolidated silt and clay sequence and the top of bedrock at 24 m bgs are boulders of siltstone and sandstone. The boulders are accompanied by sand, granule- to pebble-sized gravel, as well as shell and organic debris.

A coarsening-upwards-sequence is identifiable from the clays at 15 m depth up to the surface. One possible interpretation of this sequence is that it represents a prograding glaciomarine delta sequence. This depositional environment is consistent for Capilano Sediments. The lower boundary with the underlying Vashon Drift glacial sediments is most likely within the lower silt unit between 17 m and 21 m bgs. The silt and boulder unit would be within the Vashon Drift deposit. Alternatively, the shell and organic debris at 22 m bgs could also be a part of the Olympia nonglacial period. The coarseness and wide range of sediment grain size is indicative of glacial influence, as is the presence of shells and thick sequence of silt and clay of marine origin. Consequently, the Quaternary deposits encountered at Oyster River are interpreted to reflect a glaciofluvial delta overlying glaciomarine sediments and glacial deposits associated with the Vashon Drift. However, without further investigation into dating the surficial sediments a more definitive interpretation is not possible.

The uppermost bedrock unit intercepted by WTN 83156 is interpreted to be the Browns Member, a middle sandstone member of the Trent River Formation, the third formation of the Nanaimo Group sedimentary sequence (Bickford *et al*., 1990; Cathyl-Bickford, 2001; 2005). The Browns Member is characterized by sandstone and minor siltstone. The bedrock down to approximately 45 m bgs at WTN 83156 is predominantly clean sandstone of variable grain-size with minor siltstone. Shell debris and an increase in the siltstone fraction (30%) were encountered at 46 m bgs. This unit has been suggested as the Puntledge Member of the Trent River Formation (Cathyl-Bickford, 2005), which is a shale unit characterized by siltstone and mudstone (Cathyl-Bickford, 2001). Immediately underlying what has been interpreted to be the Puntledge shale, is fine-grained, bioturbated sandstone with up to 30% siltstone. The fine-grained sandstone unit occurs between 46 m and 53 m bgs, and is interpreted to be the Cowie Member of the Trent River Formation. The Cowie Member is characterized by bioturbated sandstone and minor siltstone. Between 53 m and 57 m bgs the sandstone remains dominant (95%) with 5% mudstone. The Cougarsmith Member, the lowermost member of the Trent River Formation, is proposed for this interval as the type shale is typified by the presence of mudstone (Cathyl-Bickford, 2001; 2005).

Thick sequences of clean sandstone of varying grain sizes characterize the bedrock encountered at Oyster River below 60 m bgs. Occasional increased fractions of siltstone, mudstone and coal occur down to 147 m bgs, the total depth of WTN 83156. Based on the thick sandstone, minor siltstone and coal, the Dunsmuir Member, the uppermost member of the Comox Formation, is interpreted for this sequence. The Comox X, X Lower, Y, and Y Lower coal seams have been identified based on situation within the coalfield and stratigraphic relationship with the overlying sediments (Bickford *et al*., 1990; Cathyl-Bickford, 2001, 2005). Two water bearing fracture zones were encountered within what is interpreted as the Dunsmuir Member, at approximate depths of 97.5 m and 135.3 m bgs. The lowermost fracture zone was coincident with the Comox Y and Y Lower coal seams, which combined span a total bedrock aquifer thickness of 3 m.

4.8.2 Borehole Geophysical Interpretation

The natural gamma ray and density borehole geophysical logs were particularly useful in correlating with drilling notes in the identification of transitions in grain size dominance, such as differentiating between sandstone and mudstone or coal. The natural gamma ray logs of the paired wells at Oyster River agree with the drilling logs in identifying interbedded, porous gravel beds at surface that overlie relatively cleaner, less dense deposits such as the water-bearing sand unit encountered during drilling. The gamma log of the deeper well, WTN 83156, also clearly confirms the depth of the contact between the Quaternary surficial sediments and the Nanaimo Group sedimentary bedrock. Allen *et al.* (2002) found that low gamma readings reflected the relatively clean sandstone formations of Saturna Island, one of the local Gulf Islands that is also comprised of the Nanaimo Group bedrock sequence. Small spikes in their gamma logging were thought to potentially recognize the mudstone stringers identified in the study's rock chip analysis.

The gamma and density logs of WTN 83156 are interpreted to differentiate the mudstone and uppermost coal seam from the dominant fine- to medium-grained sandstone within the fracture zone encountered at 135 m bgs.

4.8.3 Aqueous Geochemical Interpretation

Following from the correlations found in the preceding aqueous geochemical analyses of WTN 83156, coalbed methane was detected in the fractured bedrock aquifer. The individual coal bed sourcing this methane gas is unclear at this time. The two primary hypotheses at present are: (1) the two thin coal seams intercepted by the deep well; and, (2) hydraulic and/or gaseous communication with a more distant coal bed through the fracture network of the Nanaimo Group bedrock. Observing the significant decline in dissolved methane concentration between when the well was drilled and the thin coal seams first penetrated in 2005 through to 2007, the former hypothesis comes into favour. If a distant coal bed has been contributing methane to the bedrock groundwater over time, the significant drop in concentration during the well's first year would be unlikely. Therefore, given the data available at present, it can be proposed that the source of the coalbed methane detected in WTN 83156 is the two thin coal seams intercepted at 135 m bgs (-5 m +MSL).

The source of the dissolved methane gas present in the surficial well is hypothesized to be from groundwater produced during the drilling of the deep bedrock well that recharged the surficial aquifer in which the shallow well is completed. Alternatively, given the conservative nature of dissolved chloride and the relatively high and low chloride concentration for the bedrock and surficial wells, respectively, cross-contamination between the wells may not be the source of the dissolved methane gas in the surficial aquifer. To further assess whether or not the shallow methane gas is associated with coal at depth or produced from surficial organic decay, ^{14}C and/or

^{12}C-^{13}C isotopic analysis is recommended. Although it is theoretically possible for gases escaping up the borehole of the bedrock well to move into fracture openings in the adjacent bedrock and into the surficial sediments and aquifer above, it is thought to be unlikely. The release of pressure as the gas escapes up the borehole would be the strongest force upon the gas and, therefore, the most direct route to the least pressurized environment would be expected. A similar path may be necessitated for the source of the methane gas at WTN 83157 to be distant coal; however, due to the Comox coals outcropping at surface in areas throughout the Coalfield and also being conventionally mined at shallow depths, it is possible to have groundwater associated with distant coal to be in hydraulic communication with the surficial sediments at Oyster River. Based on the data and preceding analyses of the paired wells it is thought that the origin of the dissolved methane gas in the water of the shallow well is due to either water produced during the drilling of the bedrock well recharging the surficial aquifer, or methane produced from the recent decay of organic matter at surface.

4.8.4 Groundwater Pumping & Recovery Interpretation

The pumping and recovery testing at the surficial and bedrock wells at Oyster River provide an initial approximation of the hydraulic properties of stacked surficial and bedrock aquifers. The recovery test of the bedrock well, WTN 83156, approximates the transmissivity and hydraulic conductivity of a fractured bedrock aquifer within the Nanaimo Group sedimentary bedrock sequence. A recent study on Mayne Island, one of the Gulf Islands within the Strait of Georgia, southeast of the Oyster River area, calculated fracture transmissivity values for the Nanaimo Group sedimentary bedrock sequence (Surrette and Allen, 2008). By mapping fracture trace lengths and aperture estimates at outcrop, the study used a stochastic fracture modeling approach to calculate transmissivity values for the fractured bedrock aquifers (Snow, 1968).

Surrette and Allen's modeling research, including 12 discrete fracture models situated close to pumping test well sites, resulted in transmissivity values between 7.78 x 10^{-6} m^2/s and 1.74 x 10^{-4} m^2/s (Surrette and Allen, 2008; Allen, 2009). Pumping test data at the well sites estimated transmissivity values in the range of 10^{-6} and 10^{-4} m^2/s, closely matching modeling estimates (Allen, 2009). These values can be compared with 7.06 x 10^{-7} m^2/s, the transmissivity value estimated from the recovery data of the bedrock Oyster River well, WTN 83156. Both Mayne Island and the Oyster River studies approximate similar fracture transmissivity values for the Nanaimo Group sedimentary bedrock sequence. Surrette and Allen (2008) determined that the primary source of groundwater within the Nanaimo Group is by way of interbedded mudstone and sandstone deposits and by fault or fracture zones. Considering the mudstone and coal seams associated with the water-bearing fracture zone identified at 135 m bgs at WTN 83156, it would seem that the hydrogeology of the Nanaimo Group at Oyster River is similar with that of the same bedrock formation at Mayne Island.

The analysis of the pumping and recovery test of the shallow well, WTN 83157, characterizes a spatially extensive unconfined aquifer that is thought to be comprised of the Capilano Sediments. Corresponding to generalized values for fine- to medium-grained sand aquifers, the surficial well at Oyster River contributes to the characterization of glaciomarine deltaic deposits that commonly occur on Vancouver Island and in the Comox Coalfield region (Fyles, 1963; Fetter, 2001; Anderson and Woessner, 2002).

Based upon the data collected in this study, hydraulic connection between the two wells is thought to be unlikely. Very little variation in the water levels was noticed at the observation wells, and the variation that was recorded was a slight increase in the static water levels. If the surficial and bedrock aquifers were indeed hydraulically connected, drawdown in the water level of the monitoring well would be expected. The discharge points of the water produced by the pumping tests were approximately 15 m away from the observation wells. Consequently, it is possible that the shallow observation well was affected by the produced water discharged from the deep well recharging the surficial deposits at surface. The hydrostratigraphic nature of surficial unconsolidated sand and gravel suggests that this may be likely. Recharge of the surficial aquifer from discharge at surface is different, however, than subsurface hydraulic communication between the surficial and bedrock aquifers.

A slight increase in the water level of the bedrock well was also noticed during the pumping test of the shallow surficial well. Assuming that the deep well was properly cased and sealed into bedrock, the water produced from pumping the shallow well would have to infiltrate the surficial sediments down to bedrock and then flow through bedrock fractures and into the open-hole bedrock well. For this to occur within 75 min, the time at which a slight increase in static water level was noticed in the bedrock well, is considered unlikely. This, combined with the expectation that the water level in the monitoring well would lower during the pumping test if the aquifers were hydraulically connected, leads to the interpretation that the aquifers are most likely not in hydraulic communication.

4.9 Oyster River Regional Hydrogeological Interpretation

The regional hydrogeology of the Oyster River region of the Comox Coalfield on Vancouver Island, BC, was assessed using drilling logs, borehole geophysics, aqueous geochemistry, pumping and recovery test data, and stratigraphic interpretation of surficial exposures. Coalbed gas potential in the Comox Coalfield occurs mainly between 450 m and 1,500 m depth; however, there is a potential for hydraulic communication between the deeper fractured sedimentary bedrock of the Late Cretaceous Nanaimo Group and the overlying unconsolidated Quaternary aquifers commonly used as community groundwater aquifers. To investigate this, two adjacent groundwater observation wells were drilled; one completed in bedrock (146.9 m) and one in the surficial sediments (7.3 m).

Quaternary sediments, including Vashon Drift and glaciofluvial Capilano Sediments, span 24 m from ground surface to bedrock. Laterally extensive (at least 0.3 km^2) surficial aquifers occur within the upper 10 m. The deep well penetrated the Trent River and Comox Formations of the Nanaimo Group sedimentary bedrock sequence. A water-bearing fracture zone approximately 3 m wide was encountered at 135 m bgs (-5 m +MSL), coincident with the Comox Y and Y Lower coal seams. Dissolved methane gas was detected in both aquifers. Shoeller diagrams reveal that the gas in bedrock is coal related. Fracture transmissivity (T) and hydraulic conductivity (K) for the confined, fractured bedrock aquifer are estimated at 6.10×10^{-2} m^2/d (7.06×10^{-7} m^2/s or 4.91 USgpd/ft) and 1.98×10^{-2} m/d (2.29×10^{-7} m/s or 6.50×10^{-2} ft/d), respectively, using the Theis recovery method.

A pumping and recovery test in the deep well suggests that it is unlikely there is hydraulic communication between the bedrock and surficial aquifers encountered at Oyster River. This assessment is based on infrequent water level measurements in the shallow well, which did not consistently draw down during pumping of the deeper well. However, the pumping rate was not sustainable for this test and it could not be held constant. As well, there may have been recharge to the shallow aquifer from discharged water. Therefore, another pumping test should be conducted at a lower pumping rate with discharge water directed further away to confirm the potential connection.

The localized study at Oyster River used a multidisciplinary approach to subsurface hydrogeological investigation. Employing various analytical techniques solidified the study's litho- and hydrostratigraphic findings. The data derived from the paired groundwater observation wells contributes to the hydrogeological understanding of both Quaternary sediments and the underlying fractured Nanaimo Group sedimentary bedrock sequence. Additionally, aqueous geochemical analysis correlating the bedrock water with local coal provides initial estimates of coalbed gas produced water for the Comox Coalfield. As interest in the region's groundwater resources and potential for coalbed gas development continue to grow, further research in the area will prove important information for subsurface resource management decisions.

5 Thesis Summary

As part of a study to assess the regional hydrogeology of the Comox Coalfield on Vancouver Island, British Columbia, two site specific geological and hydrogeological investigations were conducted. A 2.5-D modeling reconstruction and hydrostratigraphic analysis of the Quadra Sand Comox-Merville Aquifer is coupled with a hydrogeological investigation of stacked Quaternary and Late Cretaceous bedrock aquifers at Oyster River.

5.1 Comox-Merville Aquifer

A total of 196 pre-existing domestic-use groundwater wells completed within the southeastern region of the Comox-Merville Aquifer were incorporated into a 2.5-D geostatistical model. Well logs were standardized with respect to lithology and hydrogeological characteristics, and subsequently assessed for subsurface representativeness. An expert-driven data standardization process was developed for the drillers' descriptions in order to clarify the hydrogeological significance of the logged observations and build confidence in the subsequent interpretations. Once the logs were input into the model, contact surfaces were created for identifiable hydrostratigraphic units employing an iterative interpolation process that incorporated contact points logged in the well log dataset and additional interpreted points based on knowledge of the regional hydrogeology. Modeled hydrostratigraphic surfaces were compared to logged contacts at depth and to contacts mapped in the field at exposed sections along the southern coastal bluffs.

Field reconnaissance at Willemar and Lazo bluffs identified six lithostratigraphic units as follows: very fine- to fine-grained sand at the base (Unit 1); overlain by sandy silt (Unit 2) and fine- to medium-grained sand (Unit 3); erosively overlain by a thick sequence of over-consolidated silty and sandy diamicton (Unit 4); followed by a coarser grained sandy diamicton (Unit 5); and, capped by a thin veneer of sand and gravel at surface (Unit 6). Employing the Hazen method, hydraulic conductivity values were estimated for the lowermost four units exposed at Comox; K estimates for Units 1 – 4 are 2.3 x 10^{-3} cm/s, 9.1 x 10^{-6} cm/s, 9.4 x 10^{-3} cm/s, and 4.7 x 10^{-6} cm/s, respectively. Using the average unit thickness exposed across the bluffs, transmissivity values were calculated to be 2.8 x 10^{1} cm^2/s, 9.1 x 10^{-3} cm^2/s, 1.4 x 10^{1} cm^2/s, and 5.2 x 10^{-3} cm^2/s for Units 1 – 4, respectively. Based on differences in hydraulic properties of the Comox Bluff units, corresponding hydrostratigraphic units were interpreted to be confined to semi-confined aquifers for Units 1 and 3, confining aquitards for Units 2, 4 and 5, and a thin unconfined aquifer or vertical transmission layer for Unit 6 exposed at surface.

Two modeling scenarios were developed as a comparative exercise that exemplifies the iterative process of incorporating geological and hydrogeological knowledge to enhance the model's performance. The model was verified using statistical variance analysis, field reconnaissance data along the coastal exposures, and the identification of a separate surficial aquifer situated within the study area. Overall, the model identified the units mapped in the field as well as two units below sea level; these lower strata are interpreted to be a confined to semi-confined sand aquifer overlain by a confining aquitard primarily comprised of diamicton and clay sediments. These units are proposed to be deposits of the Cowichan Head Formation, laid down in estuarine or marine depositional environments. On the whole, the Comox Bluff successfully predicted, within 2 m vertically, subsurface hydrostratigraphic boundaries 80% of the time.

5.2 Oyster River

The hydrogeological investigation of the Oyster River area incorporated drilling logs, borehole geophysics, aqueous geochemistry, pumping and recovery test data, and hydrostratigraphic interpretation of surficial exposures. The potential for hydraulic communication between the deeper fractured sedimentary bedrock of the Late Cretaceous Nanaimo Group and the overlying unconsolidated Quaternary aquifers was examined. To explore this, two adjacent groundwater observation wells were drilled; one completed in bedrock (146.9 m) and one in the surficial sediments (7.3 m). Laterally extensive (at least 3 km^2) surficial aquifers occur within the upper 10 m of Quaternary sediments. The deep well penetrated the Trent River and Comox Formations of the Nanaimo Group. A water-bearing fracture zone approximately 3 m wide was encountered at 135 m bgs (-5 m +MSL), coincident with the Comox Y and Y Lower coal seams. Dissolved methane gas was detected in both aquifers. Schoeller diagrams reveal that the gas in bedrock is coal related. Fracture transmissivity (T) and hydraulic conductivity (K) for the confined, fractured bedrock aquifer are estimated at 6.10×10^{-2} m^2/d (7.06×10^{-7} m^2/s or 4.91 USgpd/ft) and 1.98×10^{-2} m/d (2.29×10^{-7} m/s or 6.50×10^{-2} ft/d), respectively, using the Theis recovery method.

Based on the data collected during this study, hydraulic communication between the bedrock and surficial aquifers encountered at the well sites at Oyster River is thought to be unlikely. Pumping test data showed little to no variation in the water levels of the second monitoring well. Due to the fact that spot checks, and not continuous measurements, were recorded for the water levels of the monitoring well during the pumping tests, this interpretation cannot be confirmed. This is further confounded by the difficulties in maintaining pumping rates and the potential recharge of the surficial aquifer from pumped water. For there to be hydraulic communication, however, drawdown of water levels in the monitoring well is expected; this was not seen during either of the pumping tests. It is the opinion of the author, therefore, that at the relative spacing and depths of the paired wells drilled at Oyster River, the fractured bedrock and overlying surficial aquifers are not in hydraulic communication.

5.3 Future Work and Discussion

The geological and hydrogeological research conducted at Comox and Oyster River highlights the effectiveness of a multidisciplinary approach for subsurface resource mapping. This thesis contributes site level and aquifer-scale data to begin to build regional hydrogeological inferences for the Comox Coalfield, Vancouver Island, British Columbia. A multi-layer and multi-scale conceptual model is recommended as an appropriate vehicle to allow for such regional hydrogeological interpretations to be upscaled from site specific data. Fluid flow can be hypothesized for discreet surficial deposits, as well as for potential fluid-path connectivity between different surficial units and between surficial deposits and the underlying fractured sedimentary bedrock.

A conceptual model is a schematic representation of the groundwater flow system, frequently in the form of a block diagram or a cross-section (Anderson and Woessner, 2002). However, owing to the complex nature of hydrogeological settings with respect to depth, depositional environment, and subsurface structure aiding or impeding flow, it is a significant challenge to generalize regional areas based upon discreet local situations (de Marsily *et al.*, 2005; Noetinger *et al.*, 2005; Hunt, 2006). Moreover, the complex deformational history of southwest British Columbia has resulted in the development of numerous faults and fractures that have the potential to connect surficial sediments and bedrock aquifers, further complicating the local hydrogeological environment (Mustard 1994; Mackie *et al.* 2001). A regional conceptual model can be developed, however, by undertaking detailed site investigations throughout the area and subsequently making broad inferences on the regional hydrostratigraphy through a process called “upscaling”.

Upscaling, or averaging as it is also referred to, is the process of describing the special variability of rock properties from site-specific observations and measurements (de Marsily *et al.*, 2005). This is commonly used to address issues concerning spatial heterogeneity by defining homogeneous equivalent properties in geostatistical models, such as facies, and by genetic modeling which incorporates geological, geophysical, and hydrogeological knowledge bases (de Marsily *et al.*, 2005). Upscaling is used for, and is limited by, its defined equivalent property for the entire aquifer; where one single parameter characterizes a system. When reality is represented by a series of small cells or volumes, upscaling groups these elementary cells and creates a single value that can be assigned (i.e., permeability). Calculations using these upscaled properties are then made, attempting to create a solution as close as possible to the original values, as if the small scale meshes had been kept.

Although upscaling is an important tool for hydrogeological investigations, the accuracy of the resulting subsurface representation is largely dependent and limited to the averaged theoretical values and the rigidity of the structured model grid; therefore, theoretical results may be inadequate for heterogenic subsurface environments that do not meet modeling assumptions (i.e., fractured media, anisotropy, etc.) (de Marsily *et al.*, 2005; Noetinger *et al.*, 2005). The issue is a nested or multi-scale problem that can be reduced with the incorporation of geological knowledge and connectivity of fluid pathways associated with heterogeneity.

Data derived from the detailed hydrostratigraphic assessments at Comox and Oyster River contribute to the hydrogeological database for the Comox Coalfield. The data standardization and iterative modeling processes developed for the Comox Bluff model demonstrates effective investigative techniques to manage pre-existing subsurface data. The localized study at Oyster River used a multidisciplinary approach to subsurface hydrogeological investigation. Employing various analytical techniques solidified the study's litho- and hydrostratigraphic findings. Although the objective to determine hydraulic communication between stacked surficial and fractured bedrock aquifers cannot be confirmed definitively by this study, the data derived from the paired groundwater observation wells contributes to the hydrogeological understanding of both Quaternary sediments and the underlying fractured Nanaimo Group sedimentary bedrock sequence. Additionally, aqueous geochemical analysis correlating the bedrock groundwater with local coal provides initial estimates of coalbed gas produced water for the Comox Coalfield. As interest in the region's groundwater resources and potential for coalbed gas development continue to grow, further research in the area will prove important information for subsurface resource management decisions.

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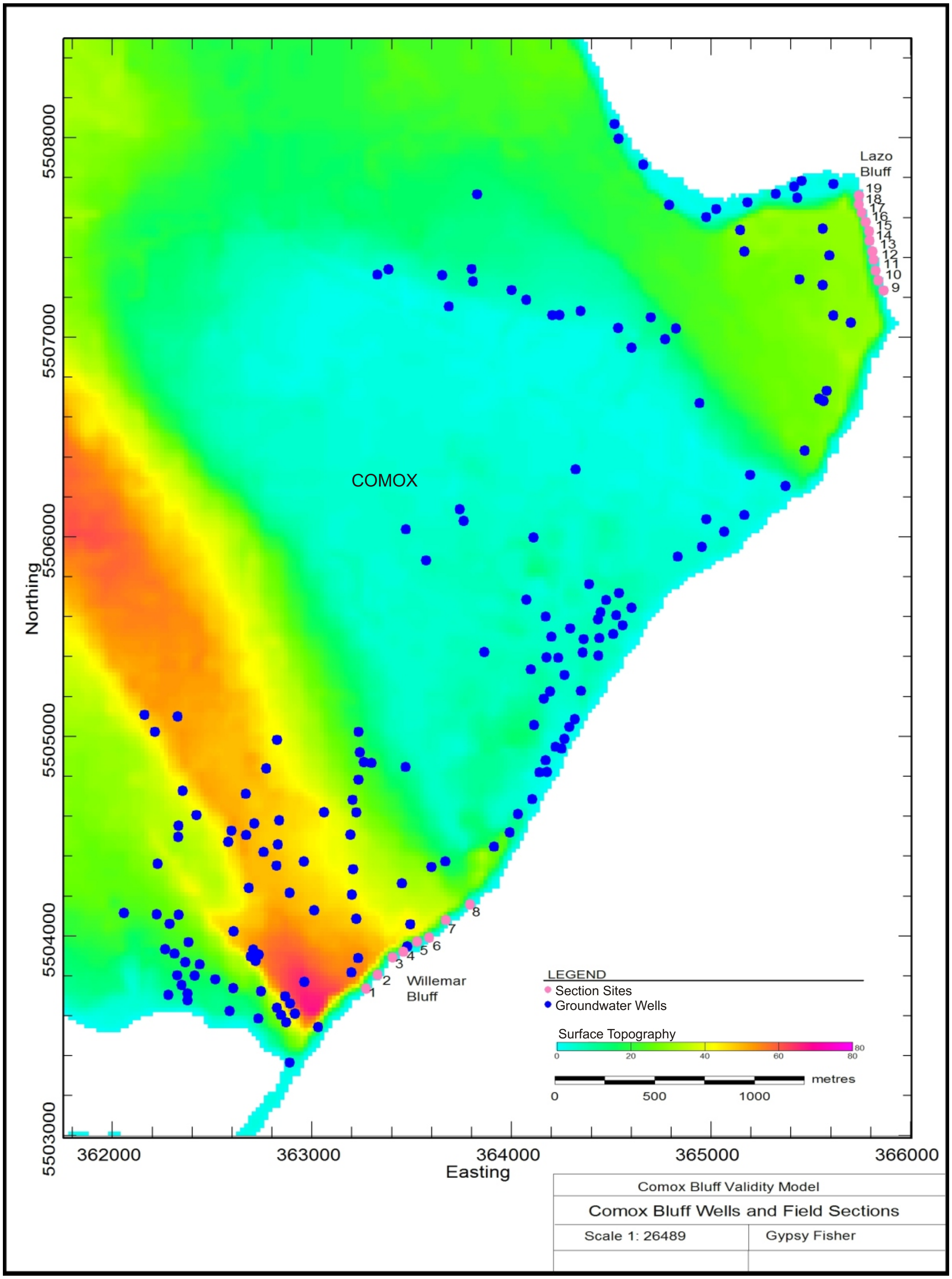
7 Appendices

Appendix 1.1 Terminology (from Fetter, 2001, unless otherwise indicated)

Aquiclude: A low-permeability unit that forms either the upper or lower boundary of a groundwater flow system.
Aquifer: Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.
Aquifer, confined: An aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer.
Aquifer, perched: A region in the unsaturated zone where the soil may be locally saturated because it overlies a low-permeability unit.
Aquifer, semiconfined: An aquifer confined by a low-permeability layer that permits water to slowly flow through it.
Aquifer, unconfined: An aquifer in which there are no confining beds between the zone of saturation and the surface.
Aquitard: A low-permeability unit that can store groundwater and also transmit it slowly from one aquifer to another.
Confining layer: A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers.
Drawdown: The lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of groundwater from wells.
Head, total hydraulic: The sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer.
Hydraulic conductivity: A coefficient of proportionality describing the rate at which water can move through a permeable medium.
Hydraulic gradient: The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.
Hydrogeology: The study of the interrelationships of geologic materials and processes with water, especially groundwater.
Hydrostratigraphic Units: Comprise geologic units of similar hydrogeologic properties. (Anderson and Woessner, 2002)
Hydrostructural Domains: Defined by using changes in fracture intensity to characterize the distribution of relative permeability in an aquifer system. (Surrette and Allen, 2008)
Natural gamma radiation log: A borehole log that measures the natural gamma radiation emitted by the formation rocks. It can be used to delineate subsurface rock types.
Neutron log: A borehole log obtained by lowering a radioactive element, which is a source of neutrons, and a neutron detector into the well. The neutron log measures the amount of water present, hence, the porosity of the formation.
Porosity: The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.
Porosity, effective: The volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.
Porosity, primary: The porosity that represents the original pore openings when a rock or sediment formed.
Porosity, secondary: The porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed.

Resistivity log: A borehole log made by lowering two current electrodes into the borehole and measuring the resistivity between tow additional electrodes. It measures the electrical resistivity of the formation and contained fluids near the probe.
Specific storage: The volume of groundwater that an aquifer absorbs or expels from a unit volume when the pressure head decreases or increases by a unit amount.
Specific yield: The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil.
Storativity: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, the storativity is equivalent to the specific yield.



Appendix 3.1. Comox Bluff Location Map

Willemar Bluff Section 1:
500 m along transect
GPS: 0363270, 5503737, accuracy 6.3 m

Unit 6
- Thickness
  - 1 m, lower contact is clear
  - contact elevation 52.3 m +MSL
- Description
  - sandy gravel to cobbles
  - orange to medium brown in colour
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

Unit 5
- Thickness
  - 3 m, lower contact is clear
  - contact elevation 49.3 m +MSL
- Description
  - diamicton with gravel to cobbles
  - buff to tan in colour
  - overconsolidated, little to no structural bedding
- Hydrologic Info
  - overconsolidated unit, potential aquitard

Unit 4
- Thickness
  - 9.7 m, lower contact is clear
  - contact elevation 39.6 m +MSL
- Description
  - silty, sandy diamicton with gravel to cobbles
  - grey to tan in colour
  - low angled trough cross-bedding
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3
- Thickness
  - 14 m, lower contact is graded
  - contact elevation 25.6 m +MSL
- Description
  - fine to medium grained sand
  - clean, light yellow to tan in colour
  - horizontal to low angle, large scale trough cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer

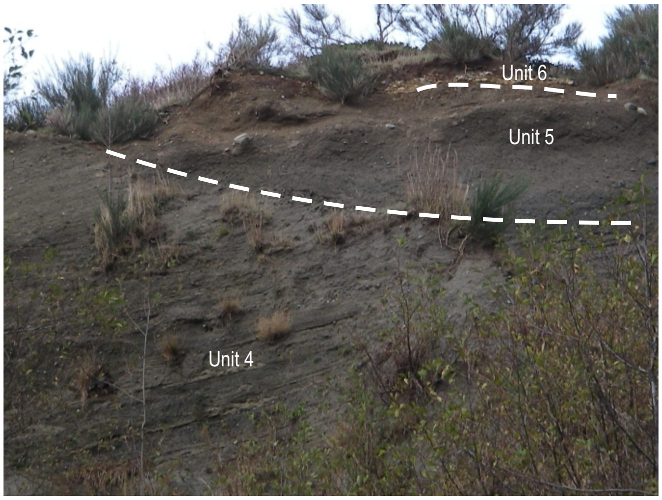
Unit 2
- Thickness
  - 11 m, lower contact is graded
  - contact elevation 14.6 m +MSL
- Description
  - silty, very fine grained sand
  - grey to tan in colour
  - laminar to horizontal cross-bedding
- Hydrologic Info
  - appears generally wet, potential aquifer sill or tight aquifer

Unit 1
- Thickness
  - 14.6 m, from beach level; may extend below sea level
- Description
  - fine to medium grained sand, clean and very well sorted
  - white to tan in colour
  - trough cross-bedding, mafic minerals demarking bedding
- Hydrologic info
  - loose unconsolidated sand, potential aquifer

Willemar Bluff Section 2:
600 m along transect
GPS: 0363328, 5503806, accuracy 6.0 m

Unit 6

- Thickness
  - 0.5-1 m, lower contact is clear
  - contact elevation 49 m +MSL
- Description
  - sandy pebble to cobble gravel
  - orange to medium brown in colour
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent



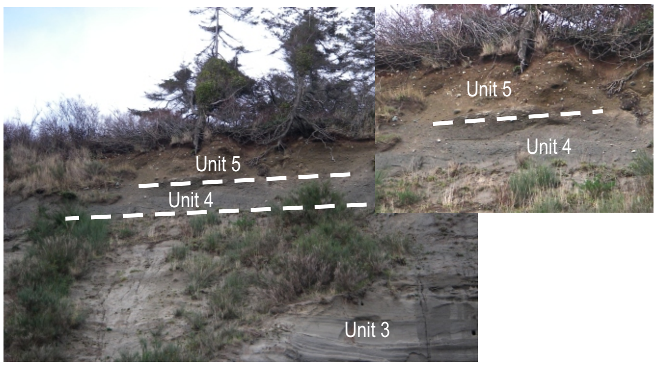
Unit 5

- Thickness
  - 4 m, lower contact is clear
  - contact elevation 45 m +MSL
- Description
  - diamicton with cobbles to boulders
  - buff colour
  - overconsolidated, blocky
- Hydrologic Info
  - overconsolidated unit, potential aquitard

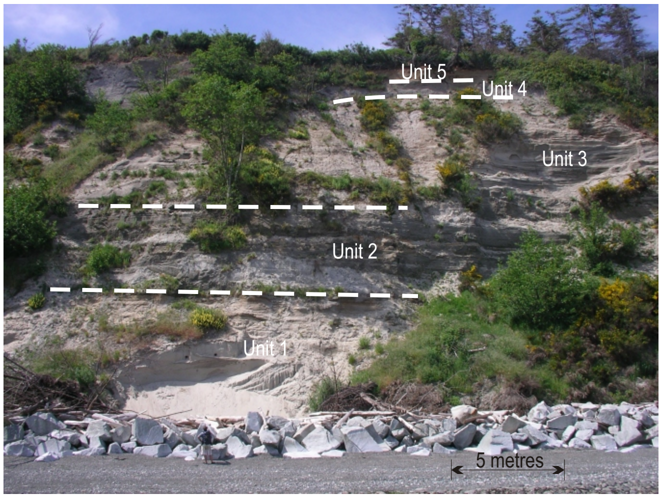
Unit 4

- Thickness
  - unit exposed at least 4 m, lower contact is unclear
- Description
  - silty, sandy diamicton with cobbles to boulders
  - grey to buff in colour
  - non-horizontal, parallel stratification (low angle trough?)
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Willemar Bluff Section 3:
715 m along transect
GPS: 0363404, 5503893, accuracy 5.9 m

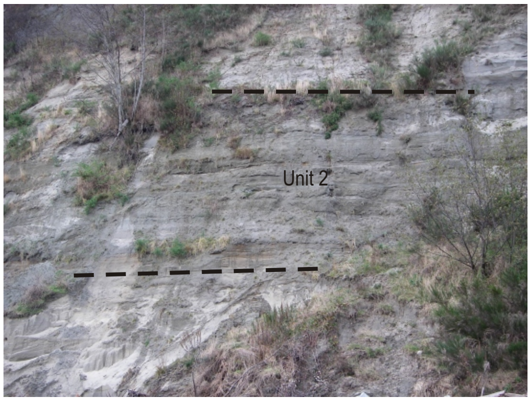


Unit 5
- Thickness
  - 3.3 m, lower contact is clear
  - contact elevation 42.5 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - brown to tan in colour
  - overconsolidated, little to no structural bedding
- Hydrologic Info
  - overconsolidated unit, potential aquitard



Unit 4
- Thickness
  - 3.5 m, lower contact is clear and sharp
  - contact elevation 39 m +MSL
- Description
  - silty, sandy diamicton with gravel to cobbles
  - grey colour
  - generally massive, potentially wavy cross-bedding
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, Potential aquitard

Unit 3
- Thickness
  - 15.7 m, lower contact is graded
  - contact elevation 23.3 m +MSL
- Description
  - fine to medium grained sand
  - clean, white to light grey in colour
  - low angle, large scale trough cross-bedding with small scale ripple bedding demarked with mafic minerals
  - iron oxidation reflects possible flow direction of 220 to 223 degrees (SW)
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer



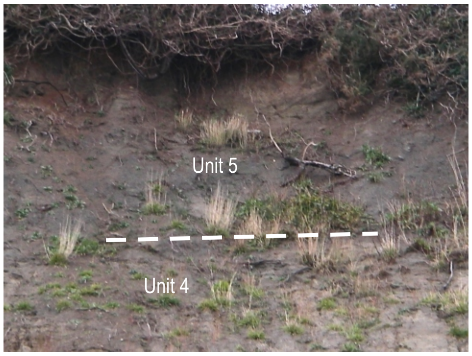
Unit 2
- Thickness
  - 14.7 m, lower contact is graded
  - contact elevation 8.6 m +MSL
- Description
  - silty, very fine grained sand
  - brown to grey in colour varying to purple in some beds
  - wavy to sub-horizontal laminar cross-bedding
  - iron oxidation, black organic chips (charcoal?)
- Hydrologic Info
  - appears wet, potential aquifer sill or tight aquifer

Unit 1
- Thickness
  - 8.6 m, from beach level; may extend below sea level
- Description
  - medium grained sand, clean and very well sorted
  - light yellow to tan in colour
  - low angle medium to large scale trough cross-bedding
- Hydrologic info
  - loose unconsolidated sand, potential aquifer

Willemar Bluff Section 4:
777 m along transect
GPS: 0363458, 5503922, accuracy 6.5 m

Unit 5

- Thickness
  - 1 m, lower contact is graded and perhaps the same unit as below
  - contact elevation 41 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - brown to light grey in colour
  - consolidated, little to no structural bedding
- Hydrologic Info
  - consolidated unit, potential aquitard



Unit 4

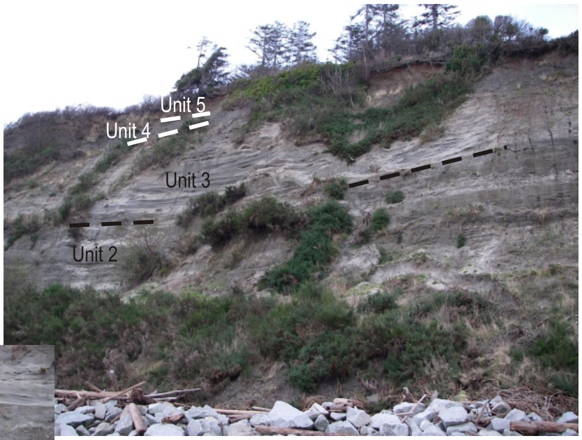
- Thickness
  - 1 m, lower contact is clear
  - contact elevation 40 m +MSL
- Description
  - silty, sandy diamicton with gravel to cobbles
  - grey colour
  - limited to no stratification
- Hydrologic Info
  - consolidated unit, likely silt-cemented, Potential aquitard

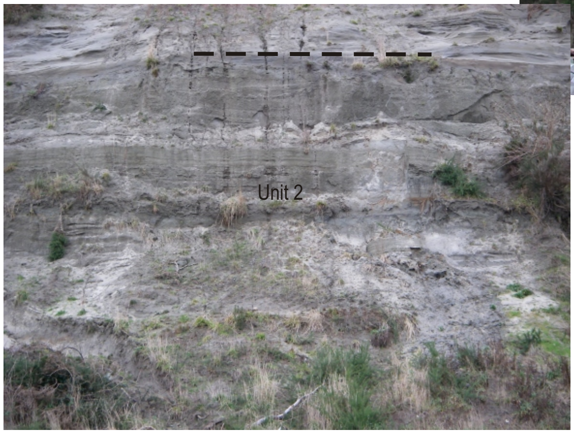
Unit 3

- Thickness
  - 4.5 m, lower contact is clear and graded
  - contact elevation 35.5 m +MSL
- Description
  - fine to medium grained sand
  - clean, white to light grey in colour
  - medium to large scale trough cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer

Unit 2

- Thickness
  - 12 m exposed above a sediment slump
  - lower contact is covered by lower slump (top of slump is 23.5 m +MSL)
- Description
  - silty, very fine to fine grained sand
  - grey to green in colour varying to purple to brown in some beds
  - wavy sub-horizontal laminar and small scale ripple cross-bedding
  - iron oxidation, wood samples and black chips of coalified wood
- Hydrologic Info
  - appears wet, potential aquifer sill or tight aquifer





Willemar Bluff Section 5:
861.5 m along transect
GPS: 0363575, 5503973, accuracy 6.8 m

Unit 6
- Thickness
  - ○ 1 m, lower contact is clear
  - ○ contact elevation 38.7 m +MSL
- Description
  - ○ sandy pebble gravel
  - ○ orange to medium brown colouring
  - ○ vague horizontal possibly wavy bedding; lag deposit?
  - ○ altered by modern soil development and vegetation
- Hydrologic Info
  - ○ unit is immediately beneath thin topsoil and is intermittent

Unit 5
- Thickness
  - ○ 2.6 m, lower contact is clear
  - ○ contact elevation 36.1 m +MSL
- Description
  - ○ sandy diamicton with cobbles to boulders
  - ○ buff to grey in colour
  - ○ overconsolidated, massive unit
- Hydrologic Info
  - ○ overconsolidated unit, potential aquitard

Unit 4
- Thickness
  - ○ 7.5 m, lower contact is sharp, erosive, and lobe-like
  - ○ contact elevation 28.6 m +MSL
- Description
  - ○ silty, sandy diamicton with gravel to cobbles
  - ○ grey to brown in colour
  - ○ deformation and loading structures in otherwise massive unit
  - ○ overconsolidated unit
- Hydrologic Info
  - ○ overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3
- Thickness
  - ○ 8.6 m, lower contact is graded
  - ○ contact elevation 20 m +MSL
- Description
  - ○ fine to medium grained sand
  - ○ clean, white to light grey in colour, coarsening up sequence
  - ○ sub-horizontal bedding at bottom grades up to medium scale trough cross-bedding with small scale ripples in bedding
- Hydrologic Info
  - ○ loose unconsolidated sand, potential aquifer

Unit 2
- Thickness
  - ○ 10-20 m, lower contact covered by either sediment slump or beach
- Description
  - ○ silty, very fine grained sand
  - ○ green to grey in colour varying to purple or brown in some Beds
  - ○ horizontal laminar cross-bedding
  - ○ iron oxidation, prominent wood pieces
- Hydrologic Info
  - ○ appears wet, potential aquifer sill or tight aquifer

Willemar Bluff Section 6:
913.4 m along transect
GPS: 0363587, 5503993, accuracy 6.9 m

Unit 6

- Thickness
  - 1 m, lower contact is clear
  - contact elevation 37.8 m +MSL
- Description
  - sandy pebble to cobble gravel, up to boulder size
  - orange to medium brown colouring
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

Unit 5

- Thickness
  - 5.8 m, lower contact is sharp and erosive
  - contact elevation 32 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - buff to grey in colour
  - overconsolidated, massive unit
- Hydrologic Info
  - overconsolidated unit, potential aquitard

Unit 4

- Thickness
  - 8 m, lower contact is sharp, erosive, and lobe-like
  - contact elevation 24 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - grey to brown in colour
  - unclear structures and bedding if any
  - consolidated unit with large overconsolidated silty lens
- Hydrologic Info
  - consolidated unit, potential aquitard

Unit 3

- Thickness
  - 1 m exposed, lower contact is obscured by vegetation
  - exposure elevation 23 m +MSL
- Description
  - fine to medium grained sand
  - clean, white to light grey in colour
  - sub-horizontal to medium scale trough cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer

Unit 2

- Thickness
  - ≤ 23 m, upper and lower contacts obscured by vegetation or beach
  - Unit 3 is exposed at approximately 23 m +MSL
- Description
  - silty, very fine grained sand
  - grey colour
  - horizontal laminar cross-bedding
- Hydrologic Info
  - appears wet, potential aquifer sill or tight aquifer

Willemar Bluff Section 7:
1019 m along transect
GPS: 0363671, 5504081, accuracy 7.1 m

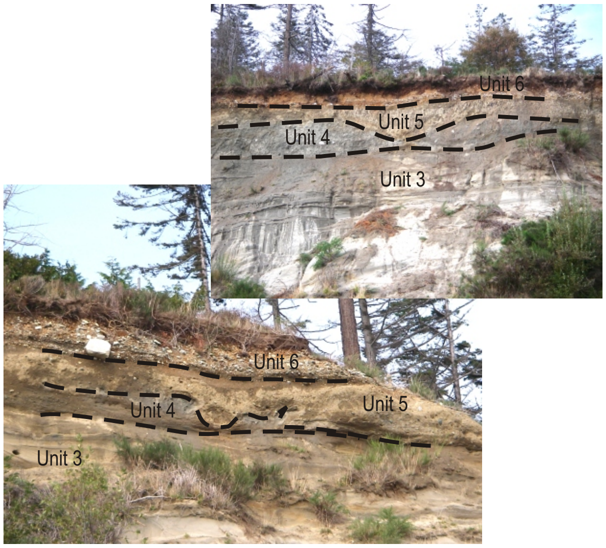
Unit 6
- Thickness
    - 1 m, lower contact is clear
    - contact elevation 36 m +MSL
- Description
    - sandy pebble to cobble gravel, up to boulder size
    - orange to medium brown colouring
    - vague horizontal possibly wavy bedding; lag deposit?
    - altered by modern soil development and vegetation
- Hydrologic Info
    - unit is immediately beneath thin topsoil and is intermittent

Unit 5
- Thickness
    - 2 m, lower contact is sharp and erosive, wavy?
    - contact elevation 34 m +MSL
- Description
    - sandy diamicton with cobbles to boulders
    - buff to grey in colour
    - overconsolidated, massive unit
- Hydrologic Info
    - overconsolidated unit, potential aquitard

Unit 4
- Thickness
    - 3 m, lower contact is sharp and erosive
    - contact elevation 31 m +MSL
- Description
    - silty, sandy diamicton with cobbles to boulders
    - grey colour
    - overconsolidated, massive unit
- Hydrologic Info
    - overconsolidated unit, potential aquitard

Unit 3
- Thickness
    - 14 m exposed, lower contact is graded
    - exposure elevation 17 m +MSL
- Description
    - fine to medium grained sand
    - clean, white to light grey colour grading up to light yellow to tan
    - low angle medium to large scale trough cross-bedding
- Hydrologic Info
    - loose unconsolidated sand, potential aquifer

Unit 2
- Thickness
    - ≤ 17 m, lower contact is covered by sediment slump or vegetation
- Description
    - silty, very fine grained sand
    - grey to brown in colour
    - horizontal laminar and small scale ripple cross-bedding
- Hydrologic Info
    - wet, potential aquifer sill or tight aquifer



Willemar Bluff Section 8:
1180 m along transect
GPS: 0363792, 5504159, accuracy 5.9 m

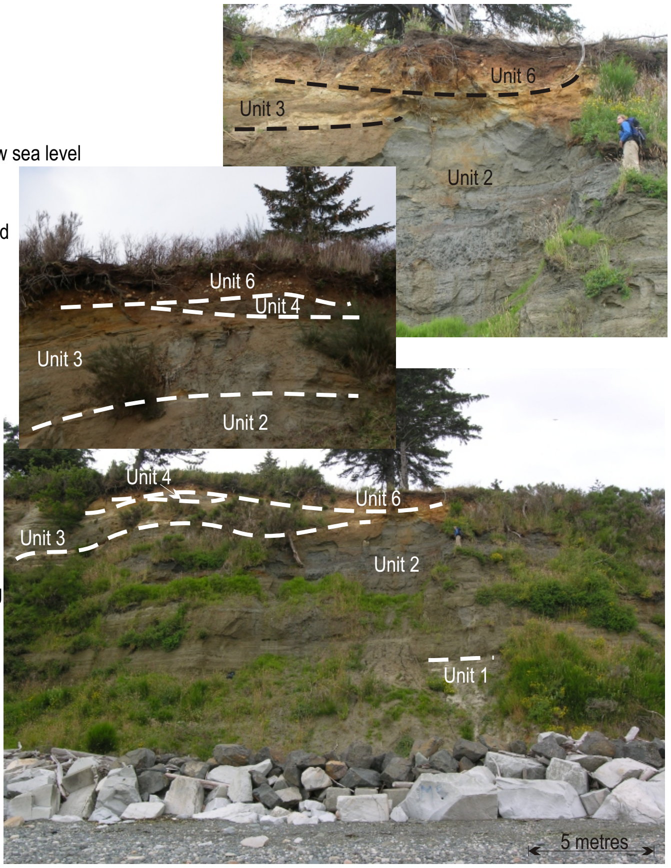
Unit 1
- Thickness
  - 3 m exposed above sediment slump, may extend below sea level
  - top of exposure is at 10 m +MSL
- Description
  - fine to medium grained sand, clean and very well sorted
  - white to tan in colour
  - small to medium scale trough cross-bedding
  - small scale ripple and wavy cross-bedding
- Hydrologic info
  - loose unconsolidated sand, potential aquifer

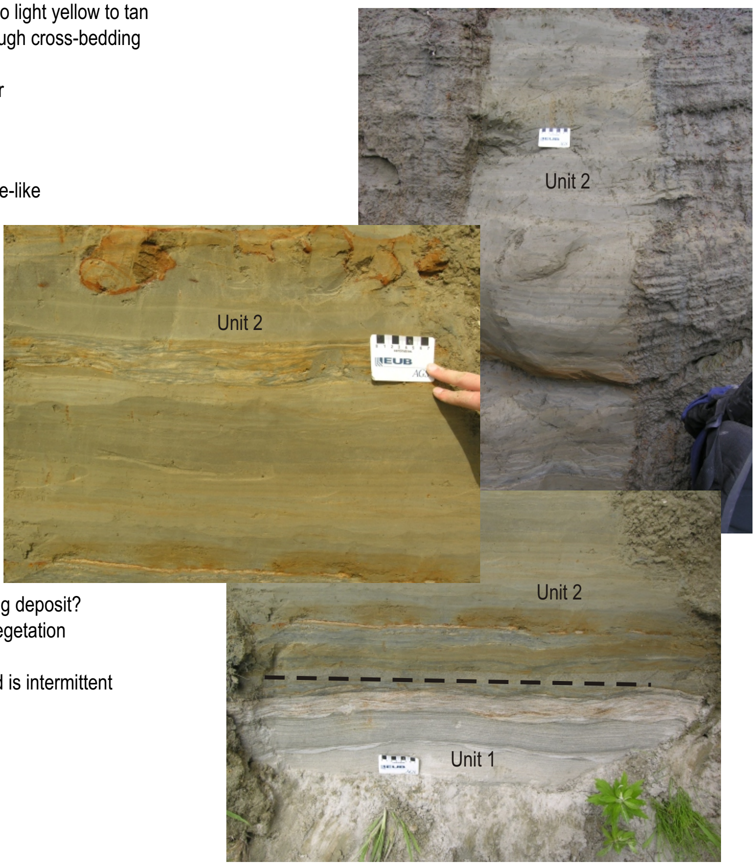
Unit 2
- Thickness
  - 11.5 m, lower contact is clear and graded
  - contact elevation 10 m +MSL
- Description
  - silty, very fine grained sand
  - blue-grey to green in colour
  - horizontal laminar and small scale ripple cross-bedding
  - iron oxidation, small scale deformation structures
- Hydrologic Info
  - wet, potential aquifer sill or tight aquifer

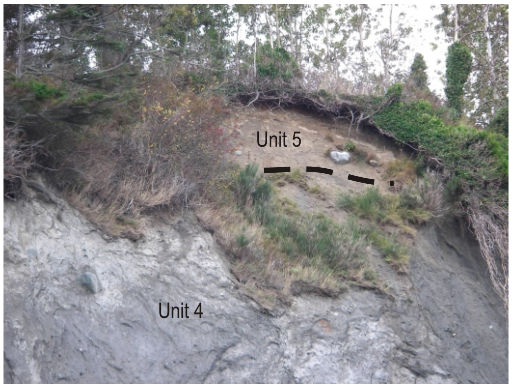
Unit 3
- Thickness
  - 4 m exposed, lower contact is clear and graded
  - contact elevation 21.5 m +MSL
- Description
  - fine to medium grained sand
  - clean, white to light grey colour grading up to light yellow to tan
  - planer grading to small to medium scale trough cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer

Unit 4
- Thickness
  - 1 m, lower contact is sharp, erosive and lobe-like
  - contact elevation 25.5 m +MSL
- Description
  - silty, sandy diamicton with gravel to cobbles
  - grey colour
  - overconsolidated, massive unit
- Hydrologic Info
  - overconsolidated unit, potential aquitard

Unit 6
- Thickness
  - 1 m, lower contact is clear
  - contact elevation 26.5 m +MSL
- Description
  - sandy pebble gravel
  - orange to medium brown colouring
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent







Lazo Bluff Section 9:
500 m along transect
GPS: 0365863, 5507235, accuracy 6.7 m

Unit 5

- Thickness
  - 3.4 m, lower contact is clear
  - contact elevation 25.6 m +MSL
- Description
  - sandy diamicton with sub-angular to sub-rounded cobbles to boulders
  - buff to brown in colour
  - overconsolidated, primarily massive texture
- Hydrologic Info
  - overconsolidated unit, potential aquitard

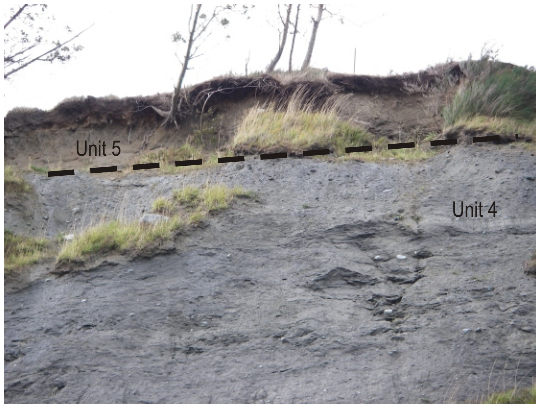
Unit 4

- Thickness
  - 25.6 m from beach level; may extend below sea level
- Description
  - silty, sandy diamicton with sub-angluar to sub-rounded cobbles to Boulders, occasional cobble lenses
  - light grey to bluey dark grey in colour
  - overconsolidated
  - sub-horizontal to wavy bedding
  - massive towards top of unit with increasing clasts
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Lazo Bluff Section 10:
450 m along transect
GPS: 0365837, 5507285, accuracy 7.6 m

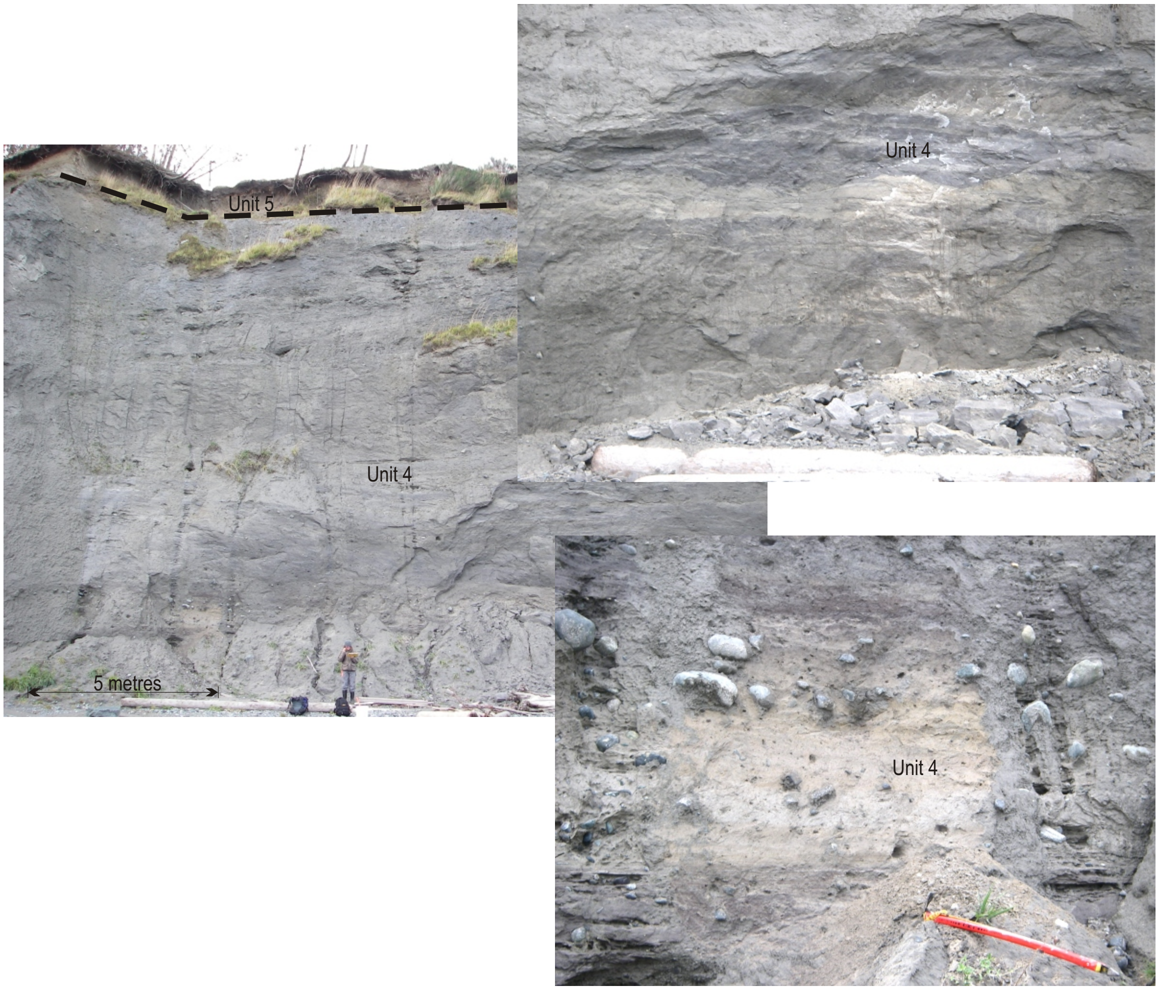
Unit 5

- Thickness
  - ○ 5 m, lower contact is clear and erosive
  - ○ contact elevation 24.5 m +MSL
- Description
  - ○ sandy diamicton with sub-angular to sub-rounded cobbles to boulders
  - ○ buff to brown in colour
  - ○ overconsolidated, primarily massive texture
- Hydrologic Info
  - ○ overconsolidated unit, potential aquitard



Unit 4

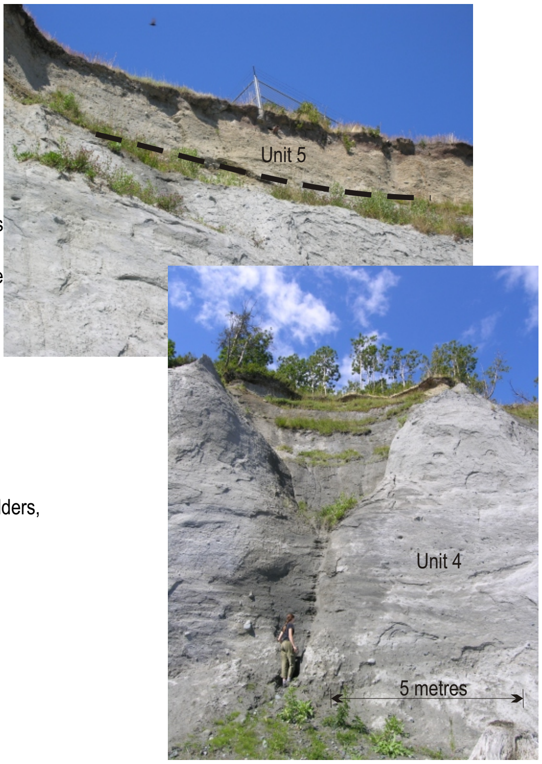
- Thickness
  - ○ 22 m exposed above lower sediment slump; may extend below sea level
  - ○ contact elevation 2.5 m +MSL
- Description
  - ○ silty, sandy diamicton with sub-angluar to sub-rounded cobbles To boulders, occasional cobble lenses
  - ○ light yellow to blue-grey in colour
  - ○ overconsolidated
  - ○ sub-horizontal to wavy bedding
  - ○ massive towards top of unit with increasing clasts
- Hydrologic Info
  - ○ overconsolidated unit, likely silt-cemented, potential aquitard



Lazo Bluff Section 11:
400 m along transect
GPS: 0365824, 5507335, accuracy 7.1 m

Unit 5

- Thickness
  - 4.5 m, lower contact is clear and erosive
  - contact elevation 25 m +MSL
- Description
  - sandy diamicton with sub-angular to sub-rounded cobbles to boulders
  - buff to brown in colour
  - overconsolidated, primarily massive with faint sub-horizontal structure
- Hydrologic Info
  - overconsolidated unit, potential aquitard

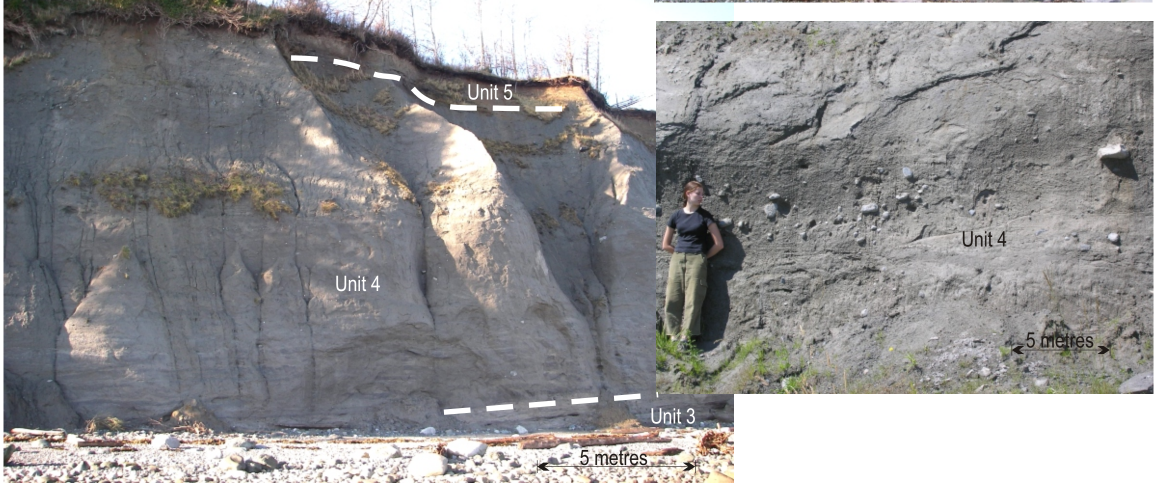


Unit 4

- Thickness
  - 22 m, lower contact is clear and perhaps graded
  - contact elevation 3 m +MSL
- Description
  - silty, sandy diamicton with sub-angluar to sub-rounded cobbles to boulders, occasional boulder lenses
  - light yellow to blue-grey in colour
  - overconsolidated
  - sub-horizontal to wavy bedding
  - massive towards top of unit
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3

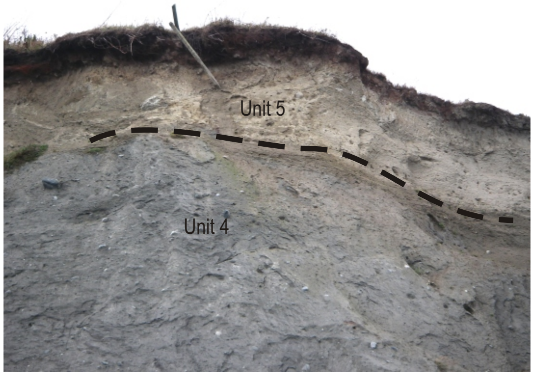
- Thickness
  - 3 m from beach level; may extend below sea level
- Description
  - fine to coarse grained sand
  - white to light yellow in colour
  - sub-horizontal planar to medium scale trough cross-bedding
  - poorly consolidated with some cobble to boulder sized drop stones
- Hydrologic Info
  - poorly consolidated sand, potential aquifer



Lazo Bluff Section 12:
350 m along transect
GPS: 0365814, 5507389, accuracy 7.0 m

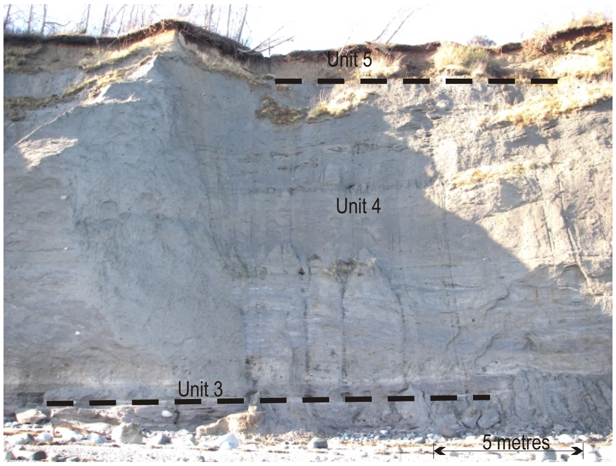
Unit 5

- Thickness
  - 5.5 m, lower contact is clear and erosive
  - contact elevation 24.4 m +MSL
- Description
  - sandy diamicton with sub-angular to sub-rounded cobbles to boulders
  - buff colour
  - overconsolidated, primarily massive with faint sub-horizontal structure, blocky towards top of unit
- Hydrologic Info
  - overconsolidated unit, potential aquitard
  - water line along lower contact indicative of decreasing permeability for water infiltrating from Unit 5 to Unit 4



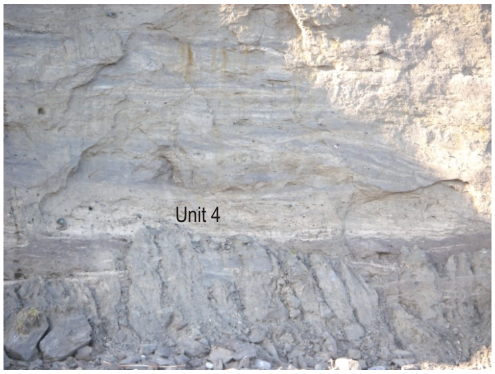
Unit 4

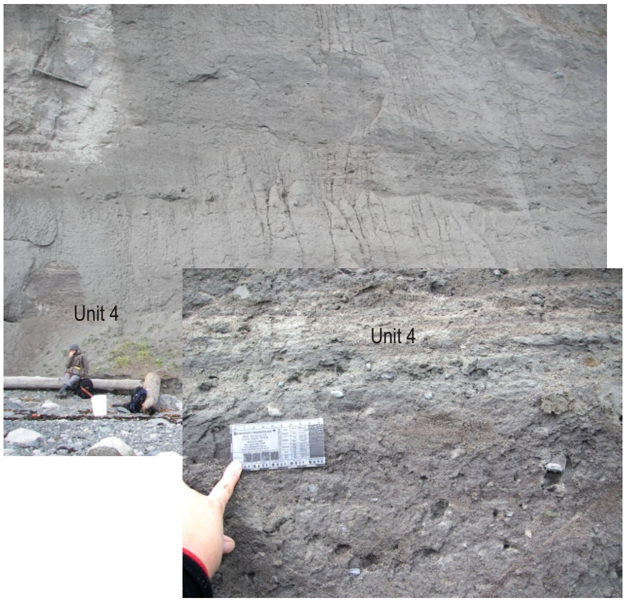
- Thickness
  - 20 m, lower contact is clear and perhaps graded
  - contact elevation 4.4 m +MSL
- Description
  - silty, sandy diamicton with sub-angluar to sub-rounded cobbles to boulders, occasional cobble lenses
  - light yellow to blue-grey in colour
  - overconsolidated
  - sub-horizontal to wavy bedding
  - small to medium scale ripple cross-bedding
  - massive towards top of unit
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

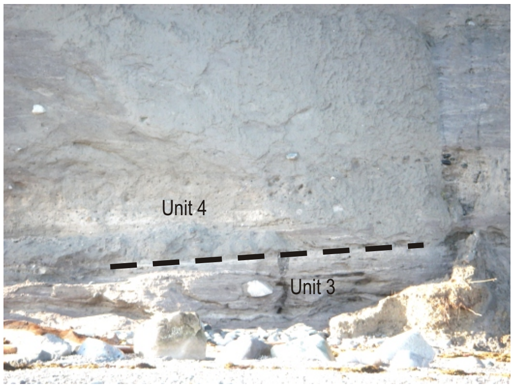


Unit 3

- Thickness
  - 4.4 m from beach level; may extend below sea level
- Description
  - fine to coarse grained sand
  - white to light yellow in colour
  - sub-horizontal planar to medium scale trough cross-bedding
  - poorly consolidated with some cobble to boulder sized drop stones
- Hydrologic Info
  - poorly consolidated sand, potential aquifer





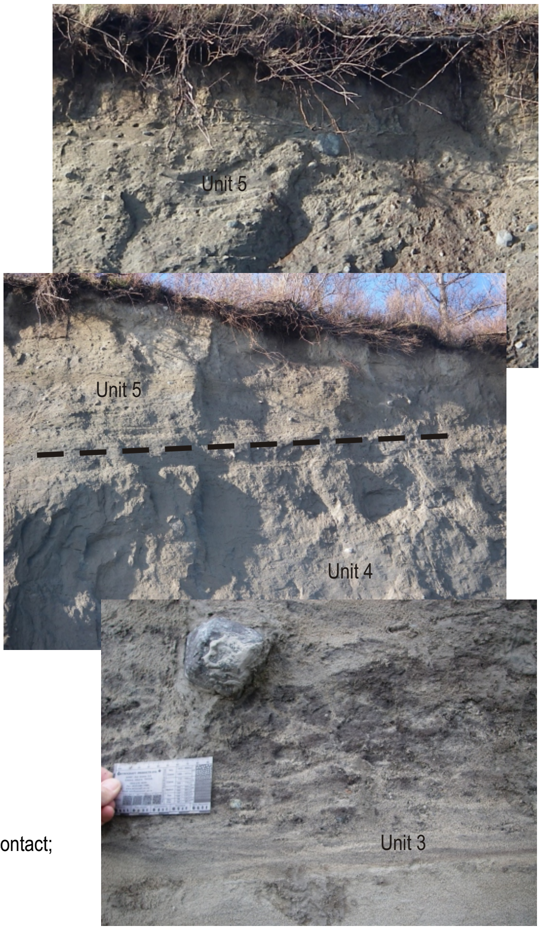


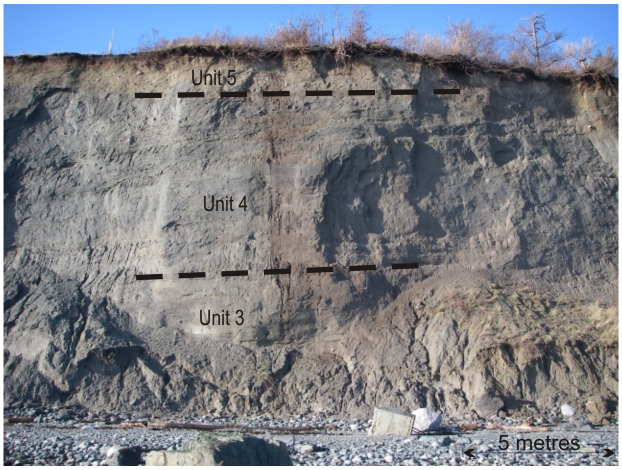
Lazo Bluff Section 13:
300 m along transect
GPS: 0365807, 5507431, accuracy 5.6 m

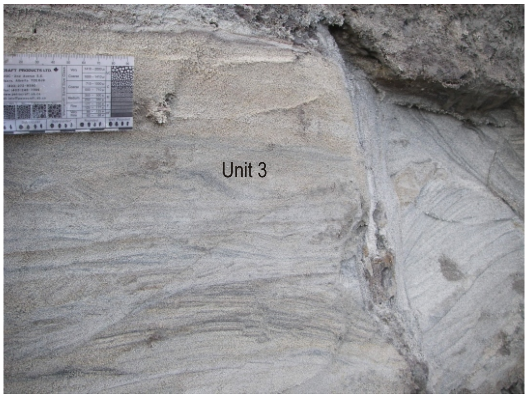
Unit 5
- Thickness
    - 4.3 m, lower contact is clear and graded
    - contact elevation 26 m +MSL
- Description
    - sandy diamicton with sub-angular to sub-rounded cobbles to boulders
    - buff colour
    - overconsolidated, primarily massive with faint sub-horizontal structure
- Hydrologic Info
    - overconsolidated unit, potential aquitard

Unit 4
- Thickness
    - 14 m, lower contact is clear and perhaps graded
    - contact elevation 12 m +MSL
- Description
    - silty, sandy diamicton with sub-rounded cobbles to boulders
    - grey to brown in colour
    - overconsolidated
    - faint sub-horizontal to wavy bedding
- Hydrologic Info
    - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3
- Thickness
    - 6 m exposed above a lower sediment slump that is covering the lower contact; May extend below sea level
- Description
    - fine to coarse grained sand
    - clean, white to light yellow in colour
    - medium scale trough cross-bedding
    - some cobble sized drop stones
- Hydrologic Info
    - loose unconsolidated sand, potential aquifer



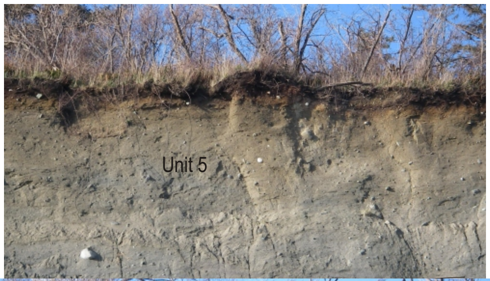




Lazo Bluff Section 14:
250 m along transect
GPS: 0365793, 5507485, accuracy 7.0 m

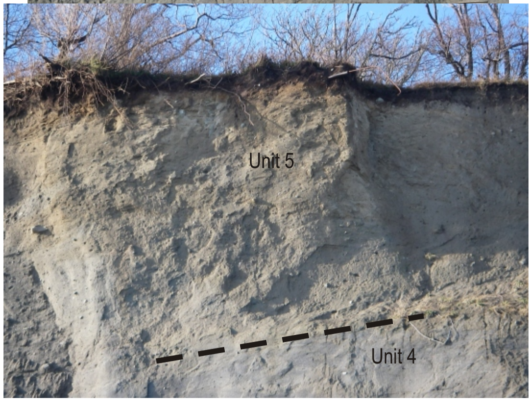
Unit 6

- Thickness
  - 0.50 m, lower contact is clear
  - contact elevation 30.5 m +MSL
- Description
  - sandy pebble gravel
  - orange to medium brown in colour
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent



Unit 5

- Thickness
  - 5.5 m, lower contact is clear and graded
  - contact elevation 25 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - buff colour
  - overconsolidated, massive with poor stratification
- Hydrologic Info
  - overconsolidated unit, potential aquitard

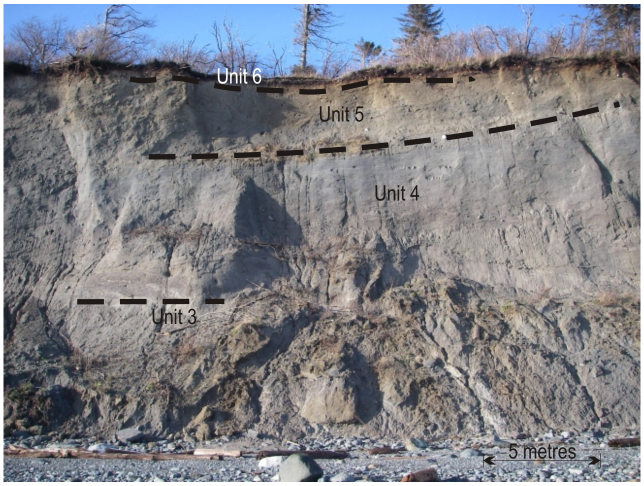


Unit 4

- Thickness
  - 10 m, lower contact is clear and perhaps graded
  - contact elevation 15 m +MSL
- Description
  - silty, sandy diamicton with sub-rounded cobbles to boulders
  - grey to buff in colour
  - overconsolidated
  - sub-horizontal to planar bedding with some wavy flow structures in areas
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3

- Thickness
  - 15 m, from beach level; lower contact is covered by sediment slump in places or may extend below sea level
- Description
  - fine to coarse grained sand
  - clean, white to light yellow in colour
  - medium scale trough cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer



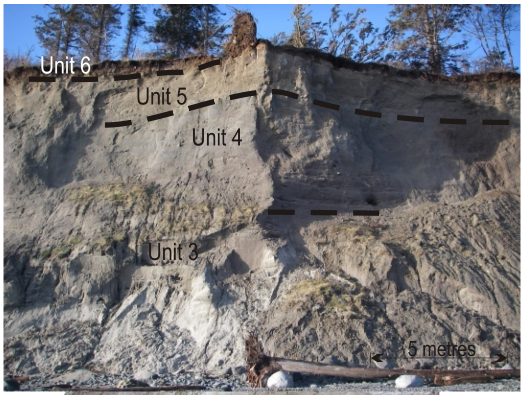
Lazo Bluff Section 15:
200 m along transect
GPS: 0365791, 5507532, accuracy 5.7 m

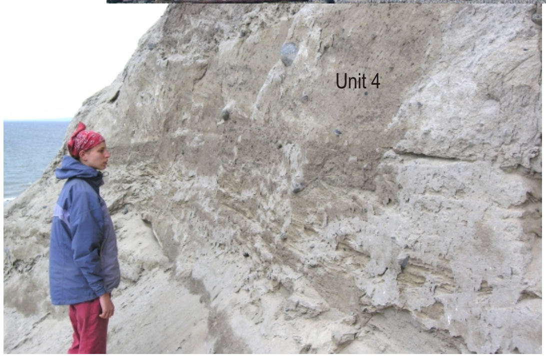
Unit 6
- Thickness
  - 0.50 m, lower contact is clear
  - contact elevation 31.25 m +MSL
- Description
  - sandy pebble gravel
  - orange to medium brown in colour
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

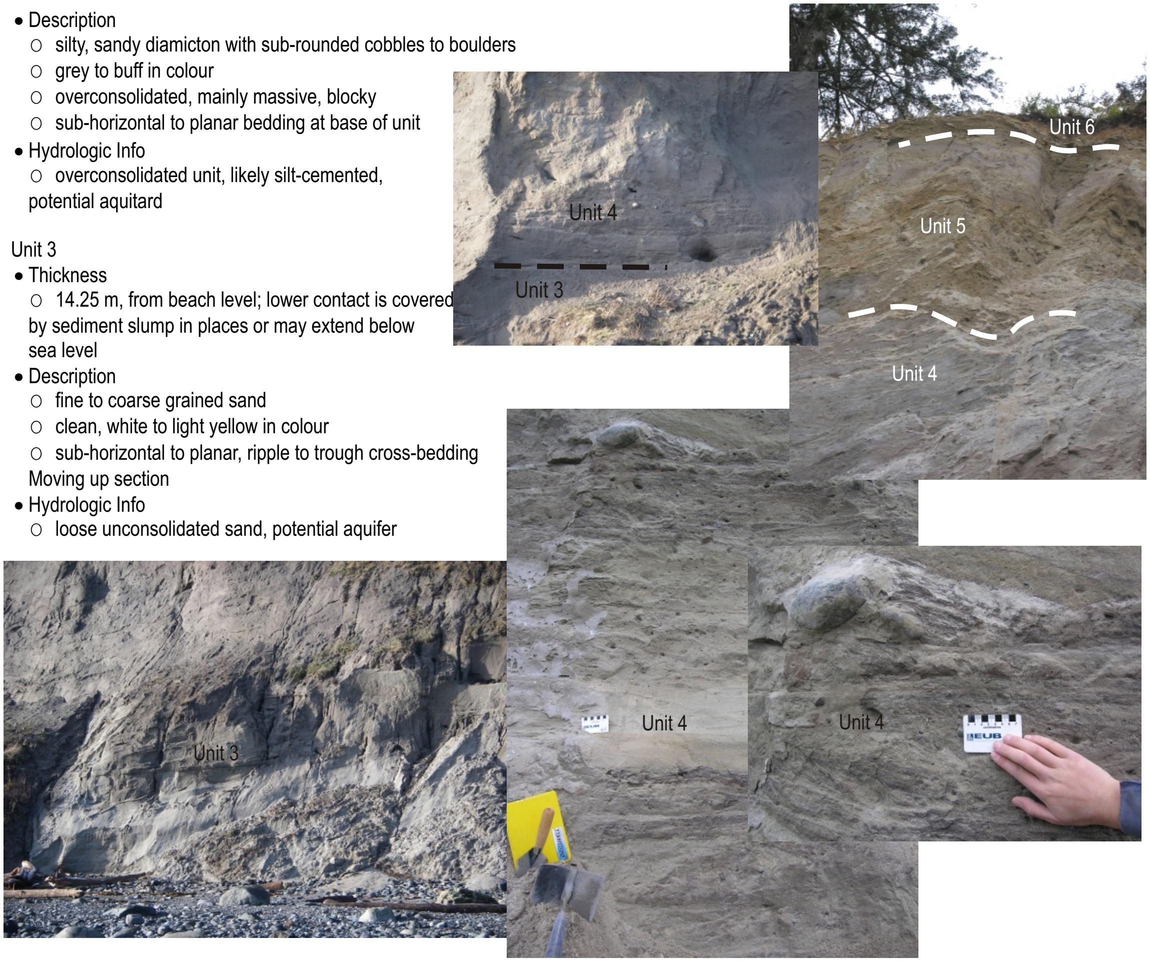
Unit 5
- Thickness
  - 5 m, lower contact is clear and graded
  - contact elevation 26.25 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - buff colour
  - overconsolidated, massive with poor stratification
- Hydrologic Info
  - overconsolidated unit, potential aquitard

Unit 4
- Thickness
  - 12 m, lower contact is clear and perhaps graded
  - contact elevation 17.25 m +MSL
- Description
  - silty, sandy diamicton with sub-rounded cobbles to boulders
  - grey to buff in colour
  - overconsolidated, mainly massive, blocky
  - sub-horizontal to planar bedding at base of unit
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3
- Thickness
  - 14.25 m, from beach level; lower contact is covered by sediment slump in places or may extend below sea level
- Description
  - fine to coarse grained sand
  - clean, white to light yellow in colour
  - sub-horizontal to planar, ripple to trough cross-bedding Moving up section
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer







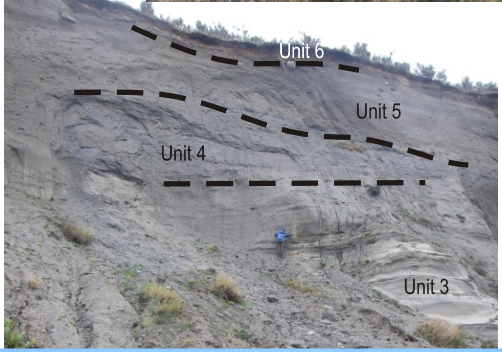
Lazo Bluff Section 16:
150 m along transect
GPS: 0365774, 5507578, accuracy 5.8 m

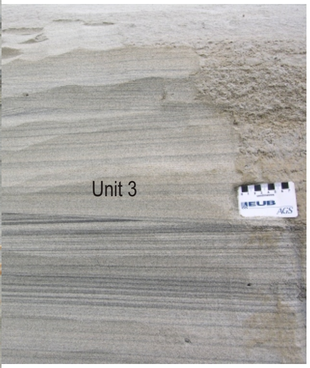
Unit 6
- Thickness
  - 0.30 m, lower contact is clear
  - contact elevation 33.1 m +MSL
- Description
  - sandy gravel up to angular boulders
  - orange to medium brown in colour
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

Unit 5
- Thickness
  - 4 m, lower contact is clear and graded
  - contact elevation 29.1 m +MSL
- Description
  - sandy diamicton with cobbles to boulders
  - buff colour
  - overconsolidated, massive with poor stratification
- Hydrologic Info
  - overconsolidated unit, potential aquitard

Unit 4
- Thickness
  - 9 m, lower contact is clear and erosive
  - contact elevation 20.1 m +MSL
- Description
  - silty, sandy diamicton with sub-rounded to sub-angular cobbles to boulders
  - grey to buff in colour
  - overconsolidated, mainly massive, blocky
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3
- Thickness
  - 20.10 m, from beach level; lower contact is covered by sediment slump in places or may extend below sea level
- Description
  - medium grained sand
  - clean, white to light grey in colour
  - medium to large scale trough cross-bedding
  - sub-horizontal to planar cross-bedding
  - yellow iron oxidation up section
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer



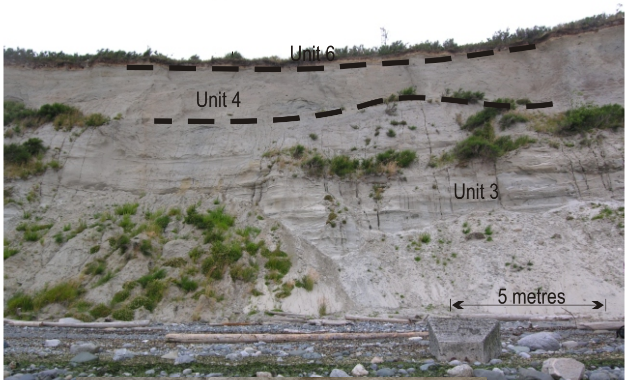


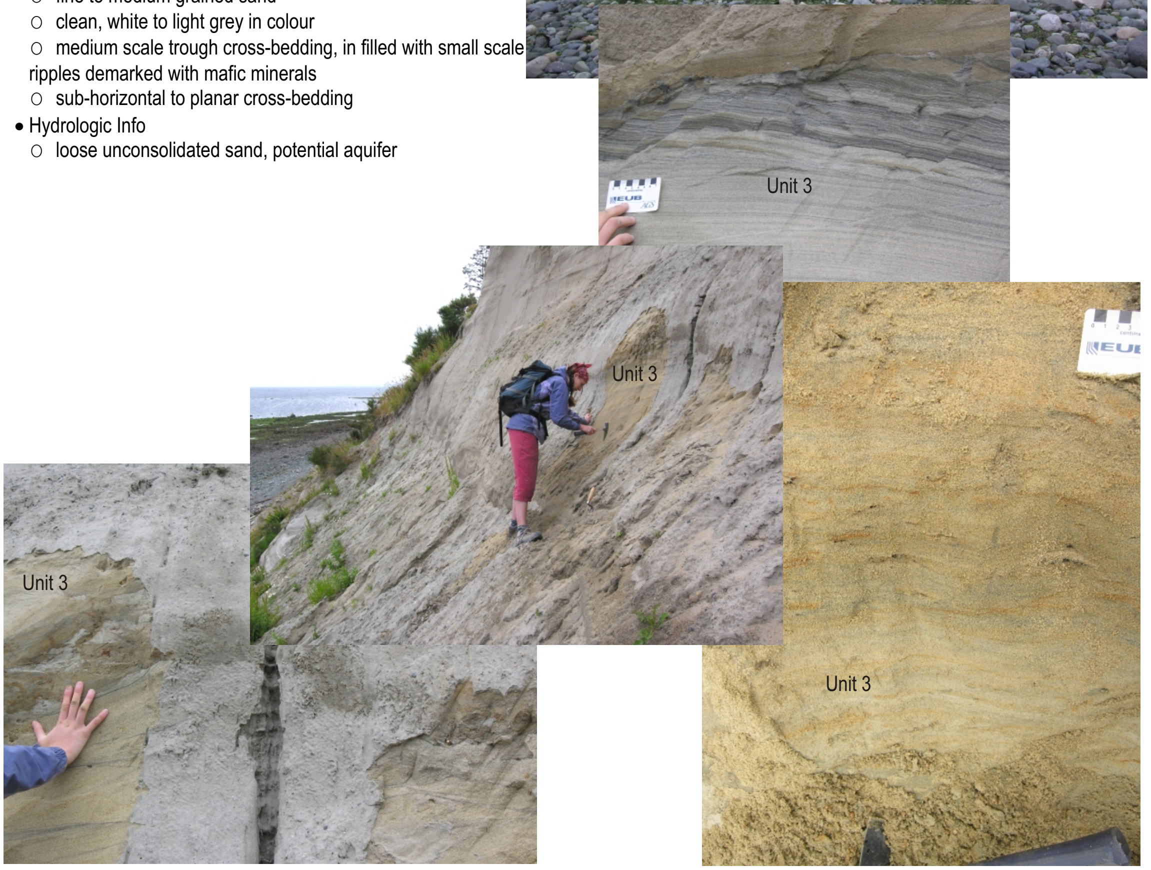
Lazo Bluff Section 17:
100 m along transect
GPS: 0365754, 5507625, accuracy 6.0 m

Unit 6
- Thickness
  - 1 m, lower contact is clear
  - contact elevation 33.5 m +MSL
- Description
  - sandy pebble gravel
  - orange to medium brown in colour
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

Unit 4
- Thickness
  - 15 m, lower contact is clear and erosive
  - contact elevation 18.6 m +MSL
- Description
  - silty, sandy diamicton with sub-rounded cobbles to boulders (drop stones?)
  - grey to brown in colour
  - overconsolidated, mainly massive
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3
- Thickness
  - 18.6 m, from beach level; lower contact is covered by sediment slump or may extend below sea level
- Description
  - fine to medium grained sand
  - clean, white to light grey in colour
  - medium scale trough cross-bedding, in filled with small scale ripples demarked with mafic minerals
  - sub-horizontal to planar cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer

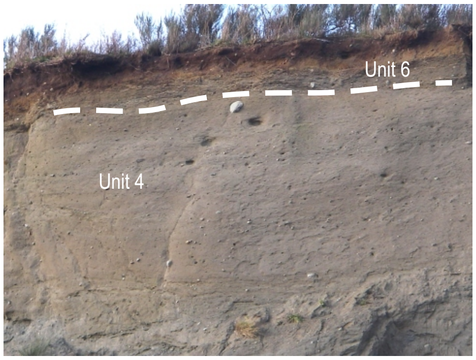




Lazo Bluff Section 18:
50 m along transect
GPS: 0365739, 5507667, accuracy 6.1 m

Unit 6

- Thickness
  - 1 m, lower contact is clear
  - contact elevation 33.5 m +MSL
- Description
  - sandy pebble gravel
  - orange to medium brown in colour
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

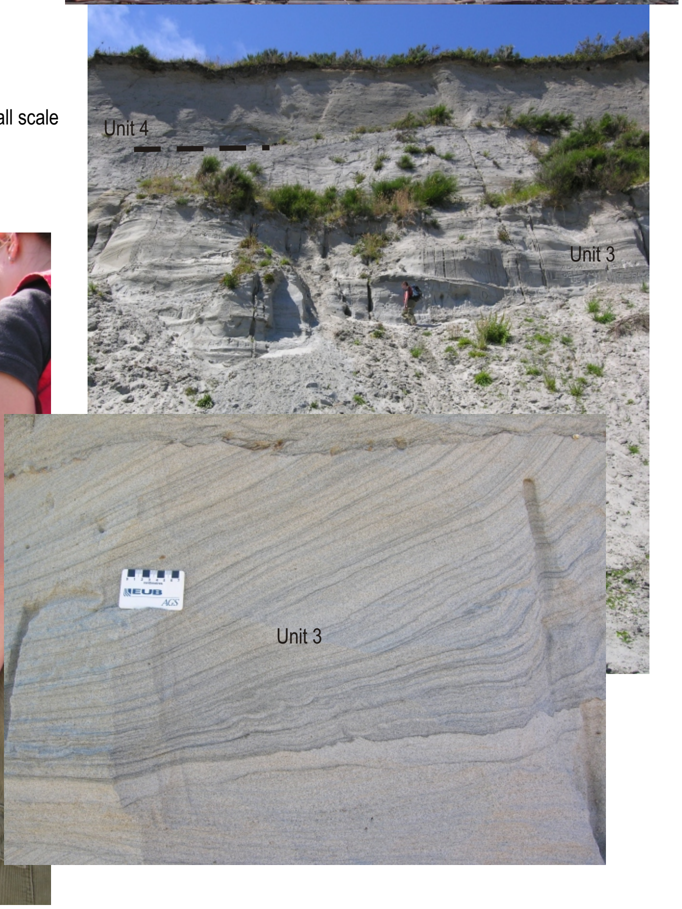


Unit 4

- Thickness
  - 15 m, lower contact is clear and erosive
  - contact elevation 18.6 m +MSL
- Description
  - silty, sandy diamicton with sub-rounded cobbles to boulders (drop stones?)
  - grey to brown in colour
  - overconsolidated, mainly massive
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard

Unit 3

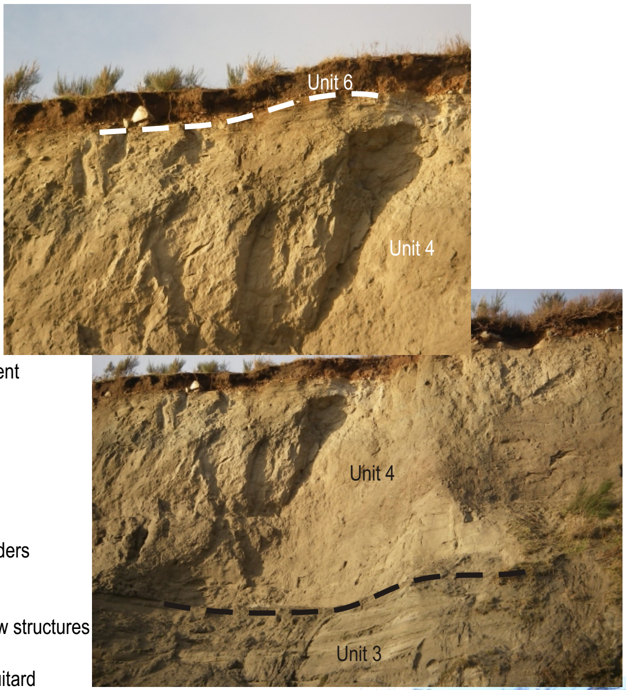
- Thickness
  - 18.6 m, from beach level; lower contact is covered by sediment slump or may extend below sea level
- Description
  - fine to medium grained sand
  - clean, white to light grey in colour
  - medium scale trough cross-bedding, in filled with small scale ripples demarked with mafic minerals
  - sub-horizontal to planar cross-bedding
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer



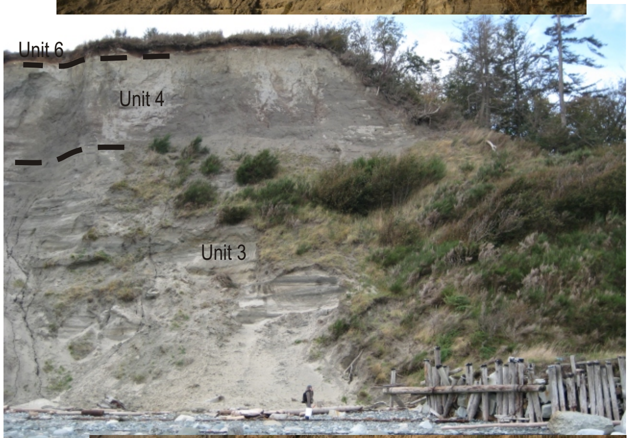
Lazo Bluff Section 19:
12 m along transect
GPS: 0365740, 5507712, accuracy 6.0 m

Unit 6
- Thickness
  - 1 m, lower contact is clear
  - contact elevation 34.75 m +MSL
- Description
  - sandy pebble gravel, up to boulders
  - orange to medium brown in colour
  - vague horizontal possibly wavy bedding; lag deposit?
  - altered by modern soil development and vegetation
- Hydrologic Info
  - unit is immediately beneath thin topsoil and is intermittent

Unit 4
- Thickness
  - 9.25 m, lower contact is graded, clear, and erosive
  - contact elevation 25.5 m +MSL
- Description
  - silty, sandy diamicton with sub-rounded cobbles to boulders (drop stones?), matrix supported (~95%)
  - white to light grey in colour
  - overconsolidated, blocky, mainly massive with some flow structures
- Hydrologic Info
  - overconsolidated unit, likely silt-cemented, potential aquitard



Unit 3
- Thickness
  - 25.5 m, from beach level; may extend below sea level
- Description
  - medium to coarse grained sand
  - clean, white colour
  - medium to large scale trough cross-bedding, In filled with small scale ripples
  - sub-horizontal to planar cross-bedding
  - normal soft-sediment faulting
- Hydrologic Info
  - loose unconsolidated sand, potential aquifer



Appendix 4.1 Oyster River Borehole Drilling Logs

WTN 83156 Drilling Logs

Elevation beneath ground surface (ft)	Elevation beneath ground surface (m)	Cuttings Descriptions (Cathyl-Bickford, 2005)	Lithostratigraphic Interpretation (Cathyl-Bickford, 2005)
4	1.22	100% cobbles, with some sand and silt.	Capilano Sediments (at surface)
7	2.13	100% gravel, coarse-grained (20 to 50 mm pebbles), rounded, brown, moist. trace silt.	
8	2.44	100% sand, coarse, brown, damp. trace gravel, fine-grained (20 mm).	
9.8	2.99	100% gravel, fine-grained (15 to 20 mm), brown, subrounded. trace sand.	Static water level at 9 feet (2.74 metres)
10	3.05	100% gravel, coarser (20 to 30 mm), subrounded, harder drilling. trace sand.	
11.5	3.51	100% gravel, as above.	
12	3.66	100% silt, brown, sandy, wet. trace gravel, fine-grained (up to 10 mm).	
13.7	4.18	100% silt, brown, slightly sandy, wet.	
15	4.57	100% sand, fine-grained, brown, slightly silty, wet. trace shell debris.	
16	4.88	100% sand, very fine-grained, brown, slightly silty, some basaltic grains. trace clay.	
19	5.79	100% sand, very fine- to fine-grained, brown, slightly silty, wet.	
20	6.10	100% sand, as above.	
22	6.71	100% silt, olive drab, sand, compact.	Vashon Drift? (sample top: 6.7 m)
24	7.32	100% sand, fine-grained, olive drab to brown, silty, moist.	
26	7.92	100% sand, very fine- to fine-grained, olive drab to brown, slightly silty, moist.	
28	8.53	100% sand, fine-grained, dark olive drab, fair to good sorting, basaltic, moist.	
30	9.14	100% sand, very fine- to fine-grained, dark olive drab. trace gravel (to 18 mm), rounded. trace silt, dark grey, slightly clayey, damp.	
32	9.75	100% silt, dark greenish-grey, sandy, wet.	
34	10.36	100% silt, dark grey, slightly sandy, very soft, wet.	
35	10.67	100% silt, dark grey, slightly clayey, damp.	
35.5	10.82	100% silt, medium to dark grey, sandy, damp. trace clay.	
39	11.89	100% silt, medium to dark grey, clayey, damp.	
40	12.19		Start water injection
42	12.80	100% silt, medium to dark grey, very clayey, very soft, wet.	Fast drilling
43	13.11	100% silt, very clayey, very soft, wet, as above.	
46	14.02	100% clay, medium grey, silty, very soft, wet. trace sand.	
48	14.63	100% clay, medium grey, silty.	
51	15.54	100% clay, medium grey. trace silt.	
52	15.85	100% clay, medium grey. trace silt.	
54	16.46	100% clay, dark olive drab to brownish-grey, sticky.	
56	17.07	100% silt, dark grey, with abundant gravel of dark grey, very fine- to fine-grained sandstone. trace organic debris, black, peaty.	
58	17.68		Dashwood Sediments? (sample top: 17.1 m)

60	18.29	100% silt, medium to dark grey, sandy, clayey, soft.	
62	18.90	100% silt, dark grey, slightly sandy, clayey. trace organic debris, black.	
64	19.51	100% silt, dark grey, pebbly, soft. trace clay. trace sand.	
65.5	19.96	100% silt, sandy. trace organic debris, black. trace pebbles, rounded, to 15 mm.	Harder drilling than before
66.2	20.18	100% silt, medium grey, sandy, pebbly. trace organic debris, black.	Hard drilling
68	20.73	100% silt, medium to dark grey, clayey, sand, sticky, damp.	
69.6	21.21	100% boulder of siltstone, dark grey, very sandy, platy, moderately soft. trace sandy silt or very fine-grained silty sand.	
71.5	21.79	50% boulders of sandstone, very fine-grained, dark grey, silty, platy. 50% silt, sandy, wet. trace organic debris, black.	Browns Member Sandstone?
72.3	22.04	100% boulder of sandstone, coarse-grained, light grey, with basalt pebbles.	Casing pushed down readily; driller thinks the hole is still in boulders and not yet at rockhead.
73.5	22.40	100% silt, medium to dark greenish-grey, gritty, sandy.	Very hard drilling from 73.5 to 73.7 feet. Faster below.
74.5	22.71	100% clay, olive drab, slightly sandy, softer. trace organic debris, black.	
75	22.86	70% siltstone – dark grey to black, platy. 30% sandstone – coarse-grained, light to medium grey. trace shell debris, fresh and unaltered.	Hard drilling again at 75 feet.
78	23.77	100% gravel; grit to 35 mm pebbles, subrounded to rounded. trace silt.	
78.5	23.93		Rockhead at 78.5 feet. Browns Member (sample top: 23.9 m)
79	24.08	65% sandstone, fine- to medium-grained, medium grey, chert-lithic, platy, clean. 35% gravel, unbroken pebbles to 15 mm, basaltic, rounded, clean, with no silt.	
79.5	24.23	65% silt, grey, sandy, sticky. 35% sandstone, fine- to medium-grained, medium grey, chert-lithic; may be cobbles.	Casing advancing slowly. Base of casing at 79.33 feet.
80	24.38	100% sandstone, medium-grained, medium grey, chert-lithic, clean, moderately hard. trace white quartz pebbles to >10 mm. trace silt, dark grey, sandy (cavings?).	
81	24.69	100% sandstone, fine-grained, medium greenish-grey, chert-basalt, hard, clean, dry. trace chert, red, as fine sand grains.	
85	25.91	100% sandstone, very fine-grained, medium grey, chert-basalt, moderately soft, dry.	
90	27.43	90% sandstone, fine- to medium-grained, medium grey, quartz-chert, trace basalt, clean, moderately soft. 10% sandstone, very fine-grained, light to medium grey, silty (possibly kaolinitic?), very soft.	
95	28.96	95% sandstone, medium-grained, medium grey, chert-basalt, silty, trace glauconite, moderately soft, dry. 5% siltstone, dark grey, platy.	
100	30.48	100% sandstone, fine-grained, medium to dark grey, silty with scattered fine broken plant trash concentrated in laminae; moderately hard.	
105	32.00	90% sandstone, fine-grained, as above. 10% sandstone, very fine-grained medium to dark grey, very silty, platy. trace iron-stained quartz grit.	
110	33.53	100% sandstone, fine-grained, as above, with occasional plant trash. trace siltstone, dark grey, carbonaceous, as very thin platy	

		chips (may be discrete laminae within the sandstone).	
115	35.05	100% sandstone, fine-grained, as above, medium grey, slight greenish cast, trace glauconite?, occasional disseminated fine plant debris.	
120	36.58	100% sandstone, medium-grained, medium grey, fair sorting, cleaner than above (less silt matrix). trace dark chert grit, well-rounded.	
125	38.10	100% sandstone, coarse-grained, light to medium grey, quartz-chert, friable, disaggregated soft, poorly cemented, fair to good intergranular porosity.	
130	39.62	100% sandstone, medium-grained, light grey, quartz-chert, friable, clean. Trace very coarse sand to rounded grit of dark grey chert.	
135	41.15	100% sandstone, medium- to coarse-grained, light grey, quartz-chert, minor basalt, clean, moderately soft, but harder than above; platy chips.	
140	42.67	100% sandstone, medium- to coarse-grained, as above, with occasional carbonaceous laminae; slightly harder than above. trace very coarse chert grains.	
145	44.20	100% sandstone, coarse-grained, light grey, quartz-chert, trace basalt, clean, moderately hard. trace very coarse rounded quartz grains.	
150	45.72	40% sandstone, medium-grained, quartz-chert, slightly silty, moderately hard. 30% siltstone, black, carbonaceous, sandy, very poorly sorted, bioturbated, platy (Puntledge shallow-marine facies) 30% sandstone, coarse-grained, as above (probably Browns Member).	Puntledge Member (sample top: 45.7 m)
155	47.24	100% sandstone, medium- to coarse-grained, quartz-chert-basalt, clean, fair intergranular porosity, moderately soft. Trace fine white calcite (shell hash?).	Cowie Member (sample top: 46.6 m) Dark grey to black drill returns from 150 to 153 feet. Drilling break at 153 feet.
160	48.77	70% sandstone, very fine- to fine-grained, medium grey, quartz-chert-basalt, silty, platy, moderately hard. 30% siltstone, dark grey, carbonaceous, very sandy. trace shell debris, orange-white. trace medium to coarse red chert grains.	Fast drilling from 155 to 160 feet.
165	50.29	70% sandstone, fine- to medium-grained, medium to dark grey, with abundant carbonaceous laminae. 30% sandstone, very fine- to fine-grained, medium grey, as above. trace siltstone, carbonaceous, as above.	
170	51.82	85% sandstone, fine-grained, medium to dark grey, carbonaceous, as above, platy, moderately hard. 10% sandstone, very fine- to fine-grained, medium grey, silty. 5% siltstone, black, sand, carbonaceous, fissile, brittle.	
175	53.34	70% sandstone, very fine- to fine-grained, medium grey, quartz-chert, silty, bioturbated, platy, brittle. 30% siltstone, dark grey, carbonaceous, platy.	
180	54.86	95% sandstone, medium- to coarse-grained, light grey, quartz-chert-basalt, clean, poor intergranular porosity, moderately hard (probably cavings of basal tidal-delta or channel-fill facies of the Cowie). 5% mudstone, black, silty, slightly carbonaceous (probably Cougarsmith).	Cougarsmith Member (sample top: 54.9 m)
185	56.39	95% sandstone, fine- to medium-grained, light to medium grey, quartz-chert, trace basalt, fair sorting, moderately hard (possibly cavings from Cowie). 5% mudstone, black, silty, slightly carbonaceous, laminated; thin platy chips.	
190	57.91	100% sandstone, medium-grained, light to medium grey, quartz-chert-basalt, slightly silty, fair to poor sorting, bioturbated, moderately hard. trace siltstone, black, sandy, carbonaceous, platy, very hard.	
195	59.44	90% sandstone, fine- to medium-grained, cleaner, otherwise	

		as above. 10% siltstone, black, fissile.	
200	60.96	100% sandstone, medium- to coarse-grained, quartz-chert, minor basalt, rare red chert grains, clean, moderately hard.	
205	62.48	100% sandstone, medium- to coarse-grained, clean, friable, disaggregated, otherwise as above.	
210	64.01	80% sandstone, medium-grained, light grey, quartz-chert, minor basalt, clean, friable, disaggregated. 20% sandstone, fine-grained, slightly silty, quartz-chert, minor basalt, platy, moderately hard.	
215	65.53	90% sandstone, medium-grained, friable, as above. 10% sandstone, very fine- to fine-grained, silty; platy chips (may be laminae or intraclasts).	
220	67.06	80% sandstone, very fine- to fine-grained, medium grey, silty, platy, brittle, moderately hard. 20% siltstone, dark grey, sandy, carbonaceous, splintery, small chips.	
225	68.58	70% sandstone, very fine- to fine-grained, medium greenish-grey, quartz-basalt, carbonaceous. 30% siltstone, medium to dark greenish-grey, very sandy, slightly carbonaceous. trace bentonite, light grey, silty, clayey, swelling (probable ash band).	Hard drilling at 225 feet, becoming softer at 226 feet.
230	70.10	95% sandstone, fine-grained, silty, light to medium greenish-grey, quartz-basalt, platy, hard. 5% siltstone, dark grey, very sandy, carbonaceous, with occasional coalified rootlets.	Comox X coal bed (horizon?)
232	70.71	100% mudstone, light greenish-grey, very soft, (possibly seatearth?). No sample.	Fast drilling in soft rocks from 230 to 232 feet. Light grey drill returns. Mudstone sloughing into well?
235	71.63	100% sandstone, fine- to medium-grained, quartz-basalt, silty, with occasional carbonaceous laminae; moderately hard. trace siltstone, dark grey, sandy, carbonaceous.	
240	73.15	85% sandstone, medium- to coarse-grained, medium grey, quartz-chert-basalt, friable, moderately soft. 15% sandstone, very fine-grained, medium grey, quartz-chert-basalt, silty, slightly carbonaceous, platy, moderately hard.	
245	74.68	65% sandstone, fine-grained, medium greenish-grey, quartz-basalt, slightly carbonaceous, platy. 35% siltstone, dark grey to brownish-grey, muddy, carbonaceous, soft.	Comox X Lower coal bed (horizon?) (sample top: 74.7 m)
250	76.20	85% sandstone, fine- to medium-grained, medium grey to greenish-grey, quartz-basalt, moderately soft, friable. 10% mudstone, dark grey, carbonaceous, silty, platy to fissile. 5% sandstone, very fine-grained, medium greenish-grey, quartz-basalt, platy, moderately hard.	Fast drilling 253 to 255 feet.
255	77.72	100% sandstone, very fine-grained, quartz-chert-basalt, silty, platy, moderately soft.	
260	79.25	100% sandstone, fine- to medium-grained, medium to slightly greenish-grey, quartz-basalt, slightly silty, with occasional rusty fracture surfaces; poor to fair fracture porosity.	
265	80.77	95% sandstone, medium- to coarse-grained, light to medium grey, quartz-chert-basalt disaggregated. 5% grit, platy, rounded, of black argillite (maybe Parsons Bay clasts).	Hard drilling at 268 feet.
270	82.30	85% sandstone, fine- to medium-grained, medium grey, quartz-chert-basalt. 15% grit and rounded pebbles of dark grey to black argillite as above.	
275	83.82	90% sandstone, fine- to medium-grained, as above. 10% sandstone, fine-grained, medium to dark grey, with abundant fine plant debris.	Fast drilling in very soft rock from 276 to 277 feet.
280	85.34	100% sandstone, very fine- to fine-grained, medium grey, slightly silty, with occasional fine plant debris; moderately	

		hard.	
285	86.87	100% sandstone, fine-grained, medium grey, quartz-chert, minor basalt. Occasional rusty fracture surfaces; poor fracture porosity.	
290	88.39	100% sandstone, fine- to medium-grained, medium grey, as above; no fractures.	
295	89.92	100% sandstone, fine- to medium-grained, as above, with occasional carbonaceous laminae.	
300	91.44	100% sandstone, fine- to medium-grained, as above.	
305	92.96	90% sandstone, medium- to very coarse-grained, medium grey, quartz-basalt, trace glauconite? 10% sandstone, medium-grained, light to medium grey, quartz-chert-basalt, with abundant plant trash (possible caving from above).	
310	94.49	80% sandstone, medium- to coarse-grained, as above, trace glauconite, hard. 15% sandstone, very fine- to fine-grained, medium greenish-grey, quartz-basalt, with carbonaceous laminae; occasional veined angiosperm leaf fragments; platy. 5% siltstone, black, carbonaceous, fissile.	Slow drilling at 310 feet.
315	96.01	50% sandstone, very fine- to fine-grained, carbonaceous, as above. 45% siltstone, dark grey, carbonaceous, sandy, platy. 5% sandstone, medium-grained, light grey, quartz-feldspar-basalt, hard.	Faster drilling from 315 to 320 feet.
320	97.54	95% sandstone, fine- to medium-grained, light grey, quartz-feldspar-basalt, slightly carbonaceous, with disseminated fine plant trash. 5% mudstone, dark grey to black, carbonaceous, slightly sheared.	Possible drilling break from 321 to 322 feet. Blowing water out of hole at 324 feet. Fault, possible, at 321 feet (97.8 m).
325	99.06	100% sandstone, fine-grained, light to medium grey, quartz-feldspar-basalt, platy; moderately hard. trace mudstone, as above, fine platy chips.	
330	100.58	95% sandstone, as above, moderately hard. 5% sandstone, very fine- to fine-grained, medium to dark grey, quartz-feldspar-basalt, with abundant plant debris. trace coal fines, in wash.	
335	102.11	100% sandstone, fine-grained, light to medium grey, quartz-feldspar-basalt, moderately hard, blocky chips. trace sandstone, carbonaceous, as above.	Faster drilling from 335 to 340 feet.
340	103.63	60% sandstone, fine-grained, as above; platy to blocky, moderately soft. 40% sandstone, fine- to medium-grained, quartz-feldspar-basalt, disaggregated, clean.	
345	105.16	95% sandstone, medium- to coarse-grained, light grey, quartz-feldspar-basalt, disaggregated, clean. 5% sandstone, fine- to medium-grained, light grey, poorly cemented, friable, as above. Trace siltstone, red, ferruginous, as fine sand grains; may be as fine sand-sized intraclasts.	Fast drilling from 345 to 350 feet.
350	106.68	90% sandstone, medium- to coarse-grained, clean, disaggregated, as above. 10% sandstone, fine-grained, light grey, slightly silty, platy, moderately soft.	
355	108.20	55% sandstone, fine- to medium-grained, light to medium grey to slightly greenish-grey, quartz-feldspar-basalt, moderately hard. 40% siltstone, dark grey to black, sandy, carbonaceous, platy, brittle. 5% mudstone, dark grey to black, silty, carbonaceous; fine platy chips.	
360	109.73	100% sandstone, fine-grained, light to medium grey, quartz-feldspar-basalt, slightly silty, with abundant carbonaceous laminae.	
365	111.25	100% sandstone, very fine- to fine-grained, light to medium greenish-grey, quartz-feldspar-basalt, platy, moderately hard. trace siltstone, black, carbonaceous, platy.	
370	112.78	100% sandstone, fine-grained, light to medium greenish-	Slower drilling from 373

		grey, quartz-basalt, with occasional carbonaceous laminae, platy to blocky; moderately hard.	to 375 feet.
375	114.30	60% sandstone, fine-grained, slightly silty, otherwise as above. 40% sandstone, coarse-grained, greenish-grey, quartz-basalt, with occasional rounded pebbles of dark grey argillite and chert.	Faster drilling from 376 to 378 feet.
380	115.82	100% sandstone, medium- to coarse-grained, light to medium greenish-grey, quartz-basalt, slightly silty in part, with occasional fracture-filling ferroan quartz; trace fracture porosity. trace chert grit.	
385	117.35	100% sandstone, fine- to medium-grained, light to medium greenish-grey, quartz-basalt, slightly silty, moderately soft, mostly disaggregated.	
390	118.87	70% sandstone, fine- to medium-grained, medium grey, quartz-basalt, disaggregated. 30% sandstone, fine- to medium-grained, medium grey, quartz-basalt, blocky, moderately hard.	
395	120.40	80% sandstone, fine- to medium-grained, blocky, as above. 10% sandstone, medium- to coarse-grained, light greenish-grey, quartz-basalt, clean, moderately hard. 10% siltstone, medium greenish- to brownish-grey, sandy, slightly carbonaceous.	
400	121.92	100% sandstone, fine- to medium-grained, medium grey, quartz-feldspar-basalt, slightly silty, with occasional carbonaceous laminae; moderately soft.	Fast drilling from 401 to 403 feet.
405	123.44	100% sandstone, fine- to medium-grained, medium grey, quartz-feldspar-basalt, cleaner than above but with occasional laminae of slightly carbonaceous siltstone; moderately hard.	
410	124.97	70% sandstone, fine- to medium-grained, medium greenish-grey, quartz-basalt, disaggregated (possible caving). 30% sandstone, very fine-grained medium, greenish-grey, quartz-basalt, silty, occasional carbonaceous laminae; brittle, platy.	Poor sample.
415	126.49	97% sandstone, fine-grained, light to medium grey, quartz-feldspar, minor basalt, slightly silty, platy to blocky, very hard. 3% siltstone, dark greenish-grey, sandy, subangular fragments (possible intraclasts).	
420	128.02	75% sandstone, medium- to coarse-grained, light grey, quartz-feldspar-basalt, friable. 25% sandstone, fine-grained, light to medium grey, quartz-feldspar-basalt, silty, platy, moderately hard. trace siltstone, medium to dark grey, carbonaceous, silty, quartz-basalt, moderately soft.	
425	129.54	80% sandstone, medium- to coarse-grained, friable, as above. 20% sandstone, fine-grained, silty, as above. trace ironstone, red, muddy.	
430	131.06	100% sandstone, medium- to coarse-grained, light grey, quartz-feldspar-basalt, friable. trace fragments of rounded pebbles (intraclasts?) of sandstone, very fine-grained, dark grey to greenish-grey, silty, carbonaceous. trace sandstone, fine-grained, silty, platy, as above.	
435	132.59	100% sandstone, medium- to coarse-grained, light grey, quartz-feldspar, minor basalt, clean, friable, soft.	
440	134.11	100% sandstone, coarse-grained, light grey, quartz-feldspar, minor basalt, clean, friable, with occasional very coarse fragments of dark grey argillite (clasts Parsons Bay?).	
444	135.33	Hole made water at 6 L/min at 444 feet. Flow rate declined to 1 to 2 L/min after 5 minutes, suggesting limited permeability and possibly a nearby flow barrier within the aquifer. Water is saline, turbid, and yellowish (iron-rich), with silty flocculates.	Dunsmuir Member (middle division) (sample top: 135.3 m) Roof of Comox Y coal bed (sample top: 135.3 m)
445	135.64	50% sandstone, fine- to medium-grained, light grey, quartz-	

		feldspar-basalt, a few rootlets; very hard. 40% mudstone, black, coaly, platy. 5% coal, dull, dirty, black, blocky. 5% siltstone, black, sandy, carbonaceous.	
450	137.16	90% siltstone, medium grey, muddy, platy. 10% sandstone, very fine-grained, medium grey, quartz-feldspar-basalt, very silty, slightly carbonaceous. trace coal, dull, blocky.	Floor of Comox Y coal bed
454	138.38	Fine coal dust in drill returns at 454 feet. Hole making more salt water.	Roof of Comox Y Lower coal bed (sample top: 138.4m). Floor of Comox Y Lower coal bed.
455	138.68	100% sandstone, medium- to coarse-grained, light grey, quartz-feldspar, minor basalt, clean, disaggregated.	Dunsuir Member (lower division) (sample top: 138.7 m) Hard drilling at 455 feet.
460	140.21	100% sandstone, coarse-grained, light grey, quartz-feldspar, minor basalt, disaggregated.	
482	146.9	100% sandstone, as above.	

WTN 83157 Drilling Logs

Elevation beneath ground surface (ft)	Elevation beneath ground surface (m)	Cuttings Descriptions (Fisher, 2005)	Lithostratigraphic Interpretation (Fisher, 2005)
2	0.61	100% gravel, sandy, brown.	Capilano Sediments (at surface)
4	1.22	100% gravel, some sand, brown, as above. Poor sample.	Static water level at 4 feet (1.22 metres)
6	1.83	100% gravel, coarse-grained (pebble to cobble size), brown covered, angular, poorly sorted, varied lithology (basalt?).	
8	2.44	100% gravel, coarser (~30 mm), subangular, poorly sorted. Hole produced water (lots).	
10	3.05	100% gravel, coarse-grained, as above, wet.	
12	3.66	50% gravel, coarse-grained, angular, poorly sorted, as above. 50% sand, fine- to medium-grained, brown, well sorted, varied mineralogy, wet.	
14	4.27	100% sand, fine- to medium-grained, brown, well sorted, varied mineralogy, wet. trace silt.	
16	4.88	50% gravel, finer grained than above (>15 mm), subangular. 50% sand, medium- to coarse-grained, dark brown, wet.	Water coming up with sand from 16 to 18 feet.
18	5.49	100% sand, fine- to medium-grained, brown, moist (less water than above).	
20	6.10	100% sand, fine-grained, brown, well sorted, varied mineralogy (basaltic or mafic mineral grains), slightly silty.	More water than above.
22	6.71	100% sand, very fine- to fine-grained, brown, silty, wet.	Drilling faster at 22 feet. More water coming up.
23.5	7.16	70% silt, coming up in aggregated chunks. 30% sand, fine-grained, brown, moist. Poor sample.	Driller's estimate: 2.5 GPM