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Detailed measured sections, bedrock aquifer/aquitard facies and potential bedrock aquifer systems of the Upper Cretaceous Nanaimo Group, Nanaimo Lowland, eastern Vancouver Island, British Columbia, Canada

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TABLE OF CONTENTS

ABSTRACT

Rapid population growth and expanding commercial developments are, and will continue to, put pressure on the limited groundwater resources of the Nanaimo Lowland. This study focused on the characterization of the bedrock aquifer potential of the Upper Cretaceous Nanaimo Group as a likely target of importance. This unit is a thick succession of 11 intertonguing sandstone-dominated and shale-dominated formations, of which only the lower 8 are present in the defined study area. The field study on eastern Vancouver Island incorporated observations from 61 surface outcrops and 1 subsurface core, comprising a total of 2480 m of measured section from all 8 formations in order to qualitatively evaluate the aquifer potential of these rocks. The Nanaimo Group displays a prominent regional-scale stratigraphic architecture of alternating coarse-grained (potential regional aquifer zones) and fine-grained (potential regional aquitard zones) units.

The irregular basal unconformity surface, with fracturing, high relief and weathered regolith forms a significantly-enhanced regional aquifer zone in the subsurface, and a recharge zone at surface. The overlying sandstone-and conglomerate-dominated formations (Comox, Extension, Protection, De Courcy) each represent regional aquifer zones with significant groundwater potential, whereas the intertonguing shale-dominated formations (Haslam, Pender, Cedar District, Northumberland) each represent regional aquitard zones with significant sealing potential. These alternating units are interpreted to compose a series of 3 stacked regional Bedrock Aquifer Systems. The Lower Aquifer System (up to 200 m thick and heavily fractured) comprises the extensive basal unconformity plus the lower Comox coarse-grained sandstone and conglomerate fluvial facies plus the upper Comox fine- to medium-grained sandstone shoreline facies. These deposits are overlain by the Haslam Formation shale, up to 200 m thick, which forms a Regional Aquitard Zone and renders this System the highest potential for both subsurface aquifer storage which underlies the entire field area, and for surface recharge where it outcrops in the west. The Medial Aquifer System (up to 600 m thick) comprises a combination of Extension Formation conglomerate and coarse sandstone facies plus Pender Formation interbedded sandstone and siltstone plus Protection Formation medium- to coarse-grained sandstone. These units are overlain by the Cedar District shale, up to 300 m thick, which forms a Regional Aquitard Zone that seals this very thick, but heterogeneous, significant Aquifer System which underlies most of the eastern part of the study area. The Upper Aquifer System (up to 300 m thick) encompasses the De Courcy Formation coarse-grained sandstone which is locally overlain by the Northumberland shale (only 50-100 m thick in the study area) and forms a local potential aquifer zone in one specific area. However, the De Courcy is the only aquifer unit for which we have actual subsurface core data (sandstone secondary porosity ranges 2-10%, av. 6.8%, permeability ranges 3-105 mD, av. 24 mD) and therefore provides a crucial analogy for the likely characteristics of the others. Additionally, fracture-related porosity and permeability are undoubtedly important in the subsurface setting, but have not yet been adequately studied.

INTRODUCTION

Rationale

Expanding population, agriculture and commercial development have focussed attention on the potential groundwater resources of the Nanaimo Lowland region. In 2010, the British Columbia Ministry of Environment, related local municipalities, and the Geological Survey of Canada began a joint project called "Groundwater Assessment in the Nanaimo Lowlands". The purpose of this effort was to bring together researchers with varied and multiple expertises to produce a qualitative evaluation of the future groundwater supply and quality in the greater Nanaimo Basin of eastern Vancouver Island. Studies related to surface water, shallow Quaternary aquifers, and deep bedrock aquifers are included, and will be summarized by Grasby et al. (in prep.). Subsurface borehole data for aquifers of the surficial deposits, and some bedrock data, were provided by Crow et al. (2014). A detailed 3-D hydrostratigraphic model of the Quaternary aquifers in the northern part of the field area provided important analysis of this potential (Benoit et al., 2015). However, another component of this joint project was to attempt to understand the aquifer potential of the bedrock of the Upper Cretaceous Nanaimo Group, which underlies large portions of the study area, and is tapped by numerous groundwater wells.

As a first step, Hamblin (2012) summarized the most relevant information from the previously-published geological literature (especially that of Mustard, 1994) for the 8 formation-rank units that occur in the field area, focussing on the zones and areas of most likely bedrock aquifer potential. That paper concluded that the basic geology of the Upper Cretaceous Nanaimo Group suggests that the coarser-grained formations (Comox, Extension, Protection and De Courcy formations) may present significant zones of regional-scale aquifer potential for new groundwater resources mappable in both surface outcrops and subsurface wells/seismic. This situation provides good potential for multiple, vertically-stacked regional-scale aquifer zones. Conversely, the intertonguing finer-grained formations (Haslam, Pender, Cedar District and Northumberland formations) may provide significant zones of regional-scale potential aquitard seals, also mappable in both surface outcrops and subsurface wells/seismic. The presence/absence of adequate porosity, permeability and fracturing on regional scales will also influence the characteristics and potential of both aquifer and aquitard zones.

In the next logical step, Hamblin and McCartney (2014) and Zhai and Grasby (2015) provided more detailed geological evidence related to the characterization and variability of the aquifer potential of one of the bedrock aquifer zones, based on a new 112.5 m core. Conclusions drawn from this study may serve as a regionally-valid analogy, applicable to the other high-potential aquifer zones for which we have no core. Based on this core study, the De Courcy Formation sandstone-dominated aquifer zone includes a) about 65% of thick bedded, fine- to coarse-grained sandstone in units up to 6 m thick, with porosity ranging 2 to 10 % (av. 6.8%) and permeability ranging 2 to 105 mD (av. 24 mD), and b) about 35% of thinly interbedded siltstone and very fine- to medium-grained sandstone in units up to 6 m thick, with porosity ranging 4 to 10 % (av. 7%, mostly microporosity) and permeability ranging 2 to 40 mD (av. 13 mD). In addition, fracturing, visible in many surface outcrops and in this core at depth, may influence aquifer potential. These characteristics are mirrored, and confirmed, in outcrops measured and reported here. Evidently, within each regional, sandstone-dominated aquifer zone, there is significant internal variability and alternation of coarse-grained aquifer horizons and fine-grained aquitard horizons, visible in both outcrop and subsurface sections, suggesting that each contains multiple, stacked aquifers.

In addition, Crow et al. (2014) included study of new geophysical logs from a single 92 m older (1984) bedrock borehole of the shale-dominated aquitard zone Haslam Formation, including Gamma Ray, Conductivity, and Optical Televiewer logs. These logs all indicated prevalence of dark grey shale, but with many thin sandstone interbeds, arranged into coarsening-upward sequences. Closed high-angle joints were also visible. These characteristics are mirrored, and confirmed, in many outcrops measured and reported here. Evidently, within each regional, shale-dominated aquitard zone, there is significant internal variability and fracturing, with dominance of fine-grained aquitard horizons, but with minor sandy horizons with higher permeability, visible in both outcrop and subsurface sections, suggesting that each regional-scale aquitard zone contains some variability and possibly some thin permeable horizons, and that fracturing is possible. All these features can affect the sealing potential of these aquitard zones.

Clearly, analogous knowledge of the detailed sedimentology, aquifer characteristics, presence of internal permeability barriers and fracture patterns for each formational-rank unit is important in evaluation of groundwater potential. To obtain a clear picture of aquifer potential, these varying characteristics must be studied on both regional and localized scales, as well as in both vertical and lateral dimensions. To that end, the field study needed to attempt to characterize the detailed geology of both aquifer and aquitard units, for all 8 formations in the study area, based on outcrop description – the only extensive window we currently have on the geology of these units. Therefore, for this study, a total of 61 outcrops and 1 long core of Nanaimo Group rocks, comprising 2480 m of total stratigraphic section, were measured and described during the course of 12 weeks of field work, over 2010-2013. These spanned the entire Nanaimo Basin study region, including locations on nine different 1:50,000 map sheets, and all eight formations present in the study area. The results of this study are reported here.

The prime purpose of the work was to qualitatively evaluate the aquifer potential of these rocks. However, it is important to note that bedrock aquifers with appropriate porosity and permeability (primary, secondary, or fracture-related) not only act as subsurface storage reservoirs, but also are prime loci for infiltration recharge by runoff when outcropping at surface, especially at higher elevations, or where fracturing is present. Therefore, it is also of crucial long-term consequence to understand the disposition and characteristics of potential bedrock aquifer zones in their surface outcrop belts.

Study Area and Methods

The regional study area for this project is centred on the City of Nanaimo, and lies on the eastern side of Vancouver Island, between Mill Bay/Saanich Peninsula to the south and Deep Bay/Denman Island to the north (Figure 1). Lowland areas of eastern Vancouver Island are underlain by Upper Cretaceous bedrock, which extends from the shore of the Strait of Georgia westward for several tens of kilometres. The field area spans a northwest-southeast-oriented region, roughly 110 km long by 50 km wide, along the eastern coastal plain margin of Vancouver Island. This study area occupies portions of three 1:250,000 sheets (Victoria, 92B; Vancouver, 92G; Port Alberni, 92F) and nine 1:50,000 sheets (Sidney, 92B/11; Shawnigan Lake, 92B/12; Duncan, 92B/13; Mayne Island, 92B/14; Nanaimo Lakes, 92F/1; Horne Lake, 92F/7; Parksville, 92F/8; Comox, 92F/10; Nanaimo, 92G/4).

The 61 outcrop sections are generally easily-accessed and represent a selection of the eight Nanaimo Group formations present (in stratigraphic order, from base to top; Comox, Haslam, Extension, Pender, Protection, Cedar District, De Courcy, Northumberland), scattered over the entire study area (Figure 1). Certain sub-areas (e.g. Qualicum, Duncan) have few outcrops due to extensive and thick Quaternary cover. The single 112 m long core, located 10 km SE of the City of Nanaimo, includes only part of the De Courcy Formation (Figure 1). Outcrop measured sections range in thickness from 3 m to 214 m. They include coastal cliff, tidal platform, stream cut and roadcut exposures employing standard field methods. Individual Nanaimo Group detailed measured sections with their locations are listed in Appendix I. Links to each drafted section in Adobe® pdf format are included. A single pdf file containing all of the detailed measured sections is included in Appendix II.

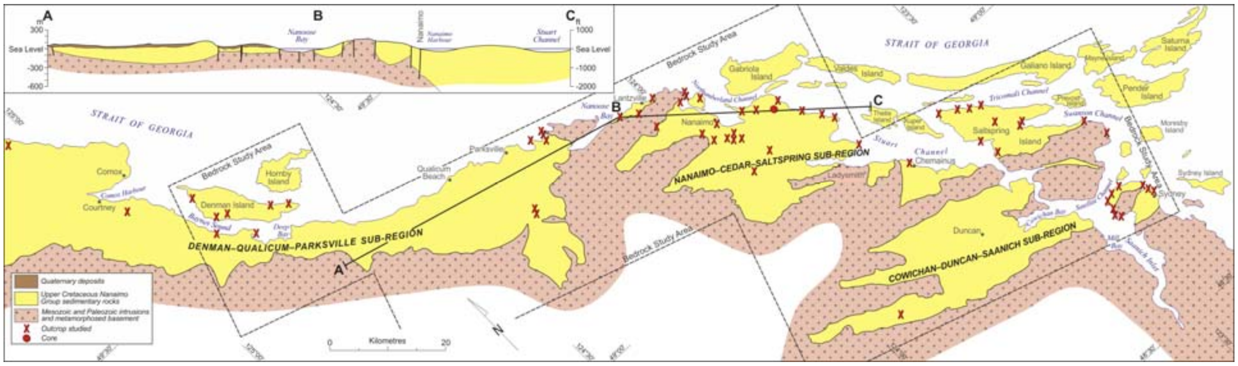

Figure 1. Outcrop and core locations, Nanaimo Lowland Bedrock Aquifer Study field area (geology simplified from Muller and Jeletzky, 1970). Click here or on figure for full-size version.

The following brief summary descriptions of the 8 formations present in our study area are based on these measured sections, but also include information from the comprehensive work of Mustard (1994) with supplemental information from a variety of authors, as applied only to the aquifer potential of the currently-defined Nanaimo Basin study area. The Nanaimo Group displays an important prominent, regional-scale stratigraphic pattern of successive formations dominated by alternating coarse-grained (potential aquifer zones) intertonguing with fine-grained (potential aquitards zones) facies. This is illustrated by a simplified geological map and cross-section (Figure 2) in the Nanaimo sub-region and in the generalized stratigraphic chart of the Nanaimo Group stratigraphy (Figure 3). Additionally, within this regional framework, each formation includes both aquifer and aquitard units nested in three dimensions on a more local scale. The formations are described from base to top, and only those present in the study area are discussed.

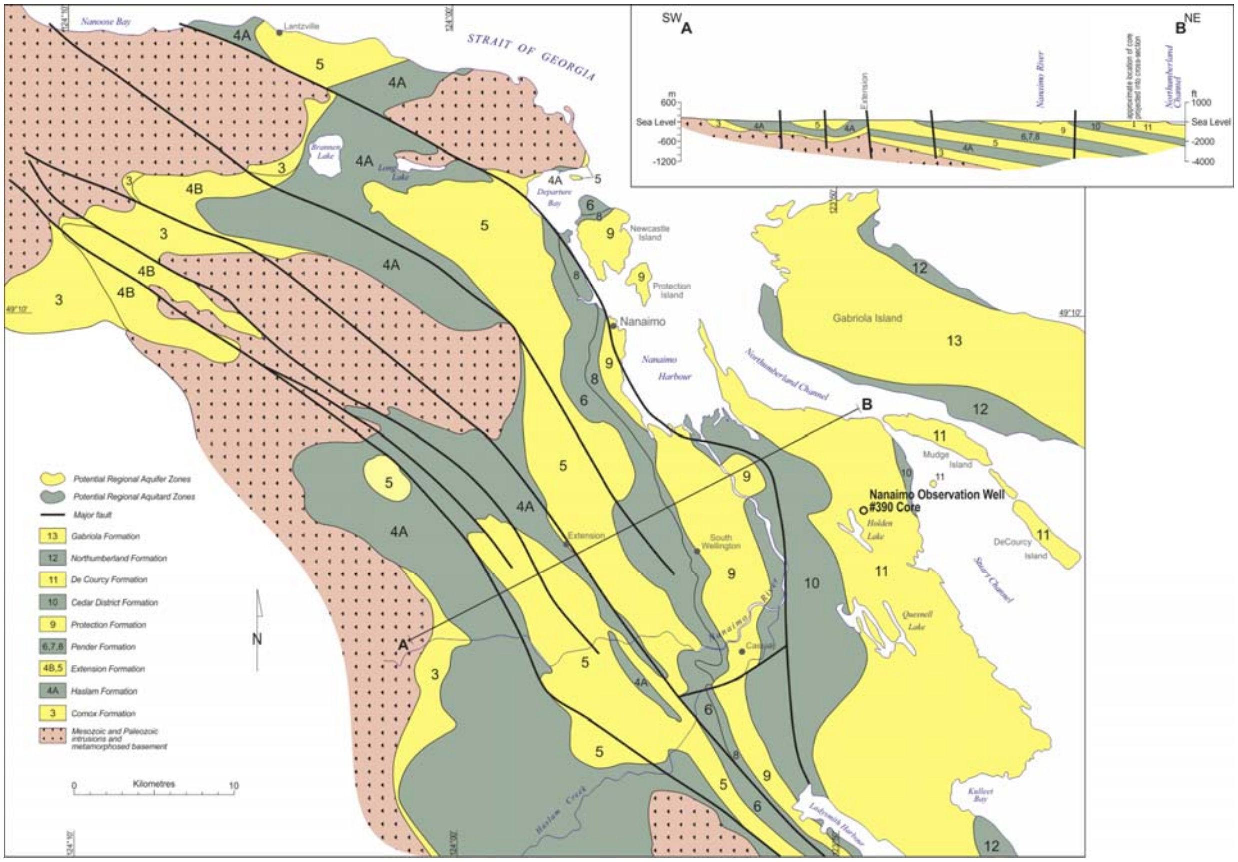

Figure 2. Geology of Nanaimo sub-region, with location of studied core, illustrating monoclinal eastward-dipping ramp structure and alternating coarse- and fine-grained units (geology simplified from Clapp, 1914; Buckham, 1947; Muller and Jeletzky, 1970). Click here or on figure for full-size version.

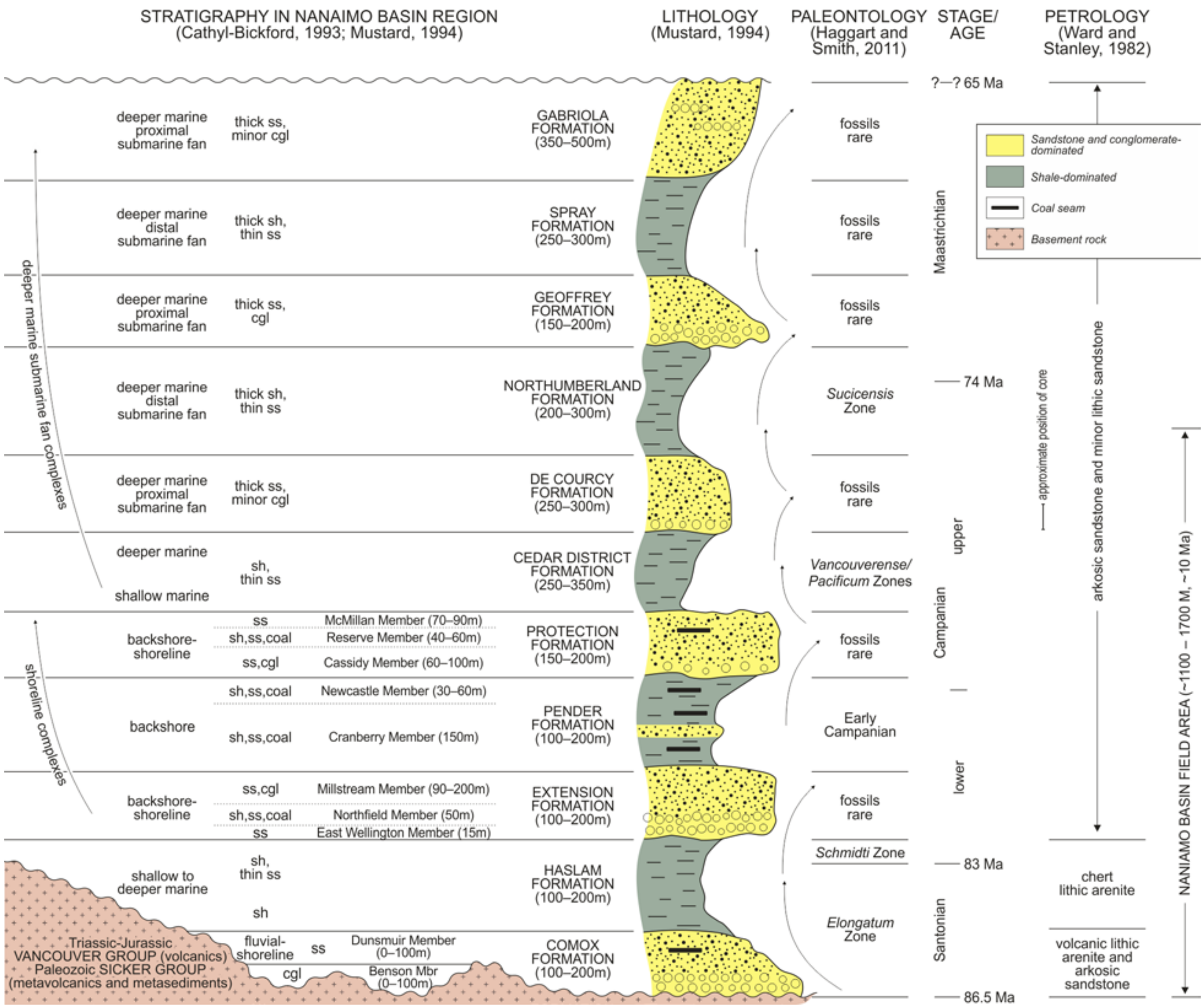

Figure 3. Simplified stratigraphy of the Upper Cretaceous Nanaimo Group of eastern Vancouver Island (simplified from Muller and Jeletzky, 1970; Cathyl-Bickford, 1993; Mustard, 1994). Click here or on figure for full-size version.

REGIONAL BEDROCK GEOLOGICAL SETTING

Regional Tectonics

The Nanaimo Group, first named by Dawson (1890), is the direct result of the Jurassic-Cretaceous evolution of the Canadian Cordillera, a tectonic collage of allocthonous terranes (Monger, 1989). Late Cretaceous docking of the oceanic/volcanic/plutonic Insular Superterrane (Alexander/Wrangellia Terranes which underlie the Nanaimo Group), immediately prior to Nanaimo Group deposition, led to rapidly intensifying tectonic loading, consequent deformation of the continental margin, and rapid sedimentation into the resulting depositional basin (Monger, 1989; Cant and Stockmal, 1989; Stockmal et al., 1993; Journeay and Morrison, 1999). The Upper Cretaceous Nanaimo Group was deposited within the Georgia Basin, the erosional remnant of a single northwest-trending structural and topographic depression which presently occupies Georgia Strait, the Gulf Islands and eastern Vancouver Island (Mustard, 1994). The current preserved extent of the Georgia Basin is about 250 x 100 km, but the original depositional extent was probably much greater (Mustard and Monger, 1991). Mustard and Monger (1991) suggested that a foreland basin model is appropriate for the Nanaimo Group basin fill. The thick Wrangellia Terrane of Devonian to Jurassic metamorphosed arc volcanic and sedimentary rocks provided a semi-rigid basement which was loaded and flexurally-deformed in front of the westerly-propagating thrust stacks of Coast/Cascade belts, positioned to the east of the depocentre during Late Cretaceous orogenesis (Mustard and Monger, 1991; Mustard, 1994; Journeay and Morrison, 1999). In this model, early thrust loading on the east side would provide a rapidly subsiding basin of deposition, with a northwest-southeast-oriented basin axis. Each subsequent phase of thrusting would cause renewed basin subsidence and develop each coarsening-upward sequence of deposition, with progressive deepening of facies through time, and predominant westward and northwestward sediment transport from sediment sources in the east and southeast (Mustard, 1994). Nanaimo strata were subsequently deformed by post-depositional, Tertiary-aged (Late Oligocene-Early Miocene) dextral strike-slip and transpressive thrust compression (Mustard, 1994; Journeay and Morrison, 1999), which induced complex folding, faulting, thrust repeats and fracturing.

Regional Structure

Much of the study area of eastern Vancouver Island is characterized by gentle east- or northeast-dipping beds, and similarly-oriented thrust slices, forming an overall monoclinal ramp sloping into the adjacent Georgia Strait. Consequently, lower stratigraphic units are present in surface outcrops to the west, and higher stratigraphic units are present in surface outcrops to the east. Therefore the more complete sequence of potential aquifer units is present toward the eastern margin of the study area. However, in numerous locales, all components of the Nanaimo Group are deformed into linear, northwesterly-trending folds (Clapp, 1914; Yorath et al., 1992; Mustard, 1994). In addition, a major northwest-trending set of post-Nanaimo, listric northwesterly-trending, northeast-dipping thrust faults are prominent throughout the region and affect both the Wrangellia basement and the overlying Nanaimo Group (Gabrielse and Yorath, 1992; Mustard, 1994; Journeay and Morrison, 1999). As a result, well-exposed, continuous outcrop sections of Nanaimo Group successions are uncommon: therefore understanding the local extent, distribution and disruptions of potential aquifer continuity is difficult and will require more detailed study.

Fracturing

Conversely, due to these post-depositional structural complications, most areas have extensive bedrock fracturing which may significantly enhance secondary subsurface aquifer porosity and permeability (Allen et al., 2003). Fractures at depth often exhibit artesian pressures, and surface springs are typically associated with fractures that extend from depth to surface (Wei et al., 2014). Mackie (2002) collected over 8000 fracture measurements from 157 stations on 8 islands, covering most of the Nanaimo Group formations, and observed that fracture density is greatest near regional-scale faults, especially in sandstone lithologies, creating wide fracture zones (10's of metres wide) of enhanced permeability (Mackie, 2002; Allen et al., 2003). However, overall fracture densities were much greater and more uniformly distributed in fine-grained, thinly-bedded units (Allen et al., 2003). Mackie (2002) identified 4 major types of fractures: 1) small-scale pre-folding deformation bands; 2) bedding-perpendicular joint fractures with NE-SW orientations formed during Tertiary transpression, with significant secondary permeability in mudstone lithologies; 3) NW-SE-trending faults and fracture zones of both reverse and normal styles, with significant secondary permeability; and 4) bedding-parallel fractures formed during later uplift (Allen et al., 2003). Furthermore, fracturing is spatially heterogeneous, with thinner bedding styles (i.e. the thin interbedding of sandstone and mudstone typical of mudstone-dominated units) displaying denser fracture development, whereas thick and massive sandstone-dominated aquifer zones display less dense, more focussed fracture spacing (Wei et al., 2014). Thus, fracture-enhanced permeability in sandstone-dominated aquifer zones should be more confined to discrete, mappable fracture zones.

In addition to that previous work, this current study gathered 163 measurements of fracture sets from 29 different Nanaimo Group outcrops scattered through all areas, and representing data from all 8 formations present (Figure 4) (primarily "bedding-perpendicular joint fractures" of Mackie, 2002). These data revealed a consistent NE-SW orientation to primary fracture sets throughout the region (similar to that observed by Mackie, 2002), with an average orientation of ~ 30°/210° (Figure 5). Although no fracture sets from basement metamorphosed volcanic rocks were measured in this study, these rocks are certainly affected by significant fracturing and faulting at the unconformable contact with overlying Nanaimo Group strata. Mackie (2002), Allen et al. (2003) and Wei et al. (2014) contend that the Nanaimo Group represents an aquifer system of low primary permeability and superimposed locally-enhanced fracture secondary permeability, better visualized by a hydro-structural model than a simple porous media model. Although there is now significant evidence for subsurface secondary porosity and permeability in these sandstones (Hamblin and McCartney, 2014; Zhai and Grasby, 2015), further refinement of the fracturing aspect is clearly very important and should allow better predictability of subsurface Nanaimo Group aquifer trends.

Figure 4. Protection Fm porous and permeable medium- to coarse-grained sandstone with two intersecting natural fracture sets (NE/SW and NNW/SSE), Medial Bedrock Aquifer System, Beachcomber Park near Parksville.

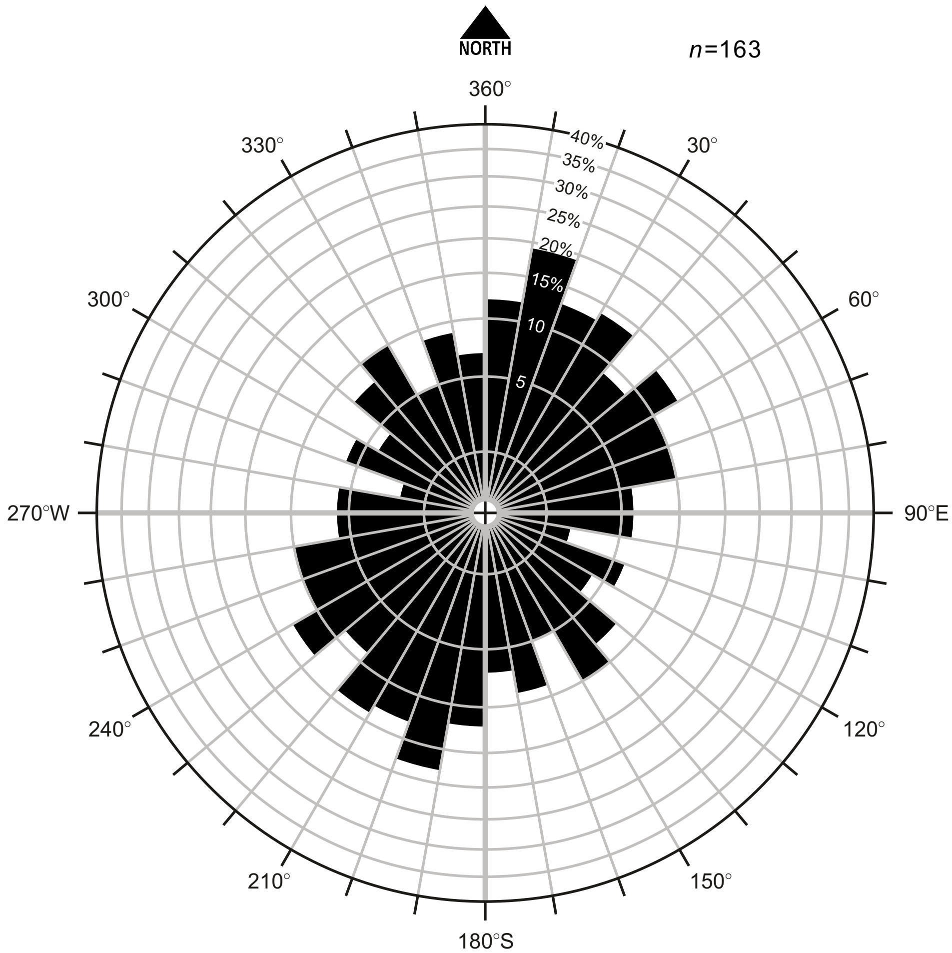

Figure 5. Orientation of bedding-perpendicular fracture sets from 29 Nanaimo Group outcrops of all eight formations studied.

Regional Stratigraphic Setting

Basement beneath the Nanaimo Group in the study area consists of dark green volcanic rocks of the Triassic Karmutsen Formation, the eroded paleosurface of which may have had topographic relief up to 220 m and rocky shorelines during Cretaceous time (Cathyl-Bickford, 1993; Johnstone et al., 2006). Clapp (1914) reported that most basement rocks are thoroughly fractured. This basement topography likely influenced the presence, distribution and thickness of the unconformably-overlying lower Nanaimo Group units (Ward and Stanley, 1982; Johnstone et al., 2006). The present distribution of the Nanaimo Group is preservational only, and does not reflect the entire original depositional basin. In addition, the current distribution of Nanaimo Group rocks is separated into several outcrop/subcrop regions by the later uplift of fault-bounded basement blocks. Within our study area, these outcrop/subcrop regions are, from south to north 1) Cowichan-Duncan-Saanich, 2) Nanaimo-Cedar-Saltspring, and 3) Denman-Qualicum-Parksville regions.

The Nanaimo Group comprises a stratigraphic thickness of as much as 4 km, with ages ranging from Turonian (~ 90 my) to Maastrichtian (~ 70 my), a depositional rate of about 1 m/5,000 years. The Nanaimo Group is subdivided into 11 intertonguing formations, in ascending order; Comox, Haslam, Extension, Pender, Protection, Cedar District, De Courcy, Northumberland, Geoffrey, Spray and Gabriola. However, only the lower 8 formations of Santonian-Campanian age (~86-74 my, a duration of about 12 Ma) are present in the eastern Vancouver Island study area, so the following discussion is confined to these units.

Stratigraphic/Sedimentologic Succession

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

However, in contrast, according to Mustard (1994) numerous studies since have failed to identify the key unconformities, and indeed, have documented coarsening-upward transgressive-regressive sequences on several scales, typical of foreland basin successions. In this interpretation, each depositional sequence began with marine transgression due to a phase of significant tectonic subsidence (lower part of each fine-grained unit), followed by lesser subsidence and regression (development of most of the coarsening-upward sequence). Thus, the identifiable T-R sequences are: I) Comox-Haslam-Extension, II) Pender-Protection, III) Cedar District- De Courcy, IV) Northumberland-Geoffrey, V) Spray-Gabriola, the first three being most important to this study. In addition, most biostratigraphic and lithostratigraphic studies to date have concluded that all of the units dominated by fine-grained facies, and most of the units dominated by coarse-grained facies were deposited in shelf to slope to bathyal depths (Mustard, 1994). The exceptions to this are the Comox Formation everywhere, and other, lower, coarser-grained units (Extension, Protection formations) in the Nanaimo area where coal is present.

Thus, the succession present in our study area represents a sequence from a regionally extensive high-topography erosional surface (sub-Nanaimo unconformity), through a wide variety of nonmarine and coastal/marginal marine facies intertonguing with lesser, deeper marine deposits (Comox to Protection), to predominantly deeper marine coarse-grained and fine-grained facies (Cedar District to Northumberland): an overall deepening-upward succession (Figure 3). Published paleocurrent data (Mustard, 1994) is abundant in several of the coarse-grained formations of the Nanaimo Group, and rather sparse in the fine-grained units. However, taken together, most data suggest predominantly westward, north-westward, and south-westward transport of sediment into the Nanaimo Basin during Comox to Northumberland time. Paleocurrent information mentioned here is primarily gleaned from Mustard

(1994), but in addition, this study collected 142 measurements of flow indicators from 30 outcrops scattered through all areas and representing data from all 8 formations present, which essentially agree with Mustard's (1994) data. Mineralogical and detrital zircon studies likewise suggest that most sediment was derived from the Coast Belt to the east and the Northern Cascades to the southeast (Ward and Stanley, 1982; Pacht, 1984; Mustard et al., 1995). Locally-derived sources from the Wrangellia Terrane, exposed immediately west of the study area, are important only in the basal Comox Formation (Mustard, 1994), which also displays a more complex paleocurrent pattern, resulting from deposition onto the pre-Nanaimo, high-topography unconformity surface.

Petrography

Most Nanaimo sandstones are immature to submature, moderately-sorted feldspathic arenites with 10-15% matrix and calcareous cement (reducing surface primary porosity to less than 5% in most outcrops), with lesser chert-rich and lithic-rich sandstones (Mustard, 1994). Chert is particularly abundant in lower formations, and plagioclase is especially abundant in upper units, with volcanic rock fragments present throughout (Ward and Stanley, 1982; Mustard, 1994). Ward and Stanley (1982) identified 3 distinct petrologic intervals in Nanaimo Group rocks, in ascending order: 1) Comox Formation sandstones of volcanic lithic arenite and arkosic sandstones, 2) Haslam Formation chert lithic arenite, 3) Extension to Gabriola formations arkosic sandstones with minor lithic sandstones (Figure 3). For extensive detail, see Mustard (1994). Detailed data from a subsurface core of De Courcy Formation sandstones are summarized by Hamblin and McCartney (2014) and Zhai and Grasby (2015). In that core, sandstones displayed porosities (mostly secondary, after dissolution of feldspars) averaging 6-7% and permeabilities averaging 12-24 mD (see De Courcy Formation section below for more details). The information from this single subsurface data point is vitally significant because it suggests that subsurface aquifer quality is much better than that implied by the heavily-cemented condition of coarse-grained facies exposed in surface outcrops. These mineralogical characteristics may influence the subsurface primary porosity and permeability in different units, but will need to be merged with fracture analysis (e.g. Mackie, 2002; Allen et al., 2003) to produce a proper evaluation of aquifer potential.

BEDROCK FACIES AND AQUIFER POTENTIAL OF THE NANAIMO GROUP

Basal Unconformity (Potential Regional Aquifer Enhancement Zone)

Nanaimo Group strata rest directly on the very irregular, angular unconformity surface which marks the top of the metamorphosed basement volcanic rocks. On a regional scale, this surface is characterized by high relief up to several hundred metres, expressed as deep east-west-trending paleovalleys discernible on bedrock map patterns, and filled by Comox Formation deposits (Mustard, 1994; Johnstone et al., 2006). On a local scale, this surface and the detailed relationship with those Comox sediments, are exposed in several outcrops. Seven outcrops which expose this surface, overlain by Comox deposits, were described in this study, in the Nanaimo (e.g. Malaspina Roadcut) and Saanich (e.g. Towner Road Shoreline) areas, with an additional exposure of the surface, possibly overlain by Protection Formation, at Cottam Point near Parksville.

When exposed, this surface typically displays tilted and bedded greenish volcanics with a faulted/fractured, irregular geometry with up to several metres of topography and variable amounts of pre-depositional weathering/rotting and coarse lag/regolith development. It is sharply overlain by coarse clastic sediments which fill in the surface irregularities (Figure 6). This represents the pre-Nanaimo, rocky, exposed and weathered shorelines at which Nanaimo deposition began during Upper Cretaceous time (Johnstone et al., 2006). In the southern part of the study area, Johnstone et al. (2006) described 3 types of shorelines: storm-dominated rocky shorelines covered by thin coarse conglomerates and sandstones (as at all 8 sections measured for this study), low-energy rocky shorelines covered by fine- to medium-grained sandstones, and drowned fan-deltas of thick successions of coarse angular conglomerates. Interestingly, several of these exhumed 85 million year-old Upper Cretaceous rocky shorelines are now exposed and visible on *modern* rocky shorelines in the study area.

Figure 6. Comox Fm coarse-grained sandstone overlying basal unconformity and basement volcanics, Lower Bedrock Aquifer System, Pacific Biological Station near Nanaimo.

All the characteristics of this regionally-extensive surface (pervasive faulting/fracturing, locally and regionally irregular relief, zone of diagenetically-altered weathered/rotted rock, cover by coarse and poorly- to well-sorted regolith deposits, and ultimate blanketing by aquifer sandstones) suggest that this surface may significantly enhance the aquifer characteristics of this interval and the immediately-overlying Comox Formation sandstones (or other formations where the Comox is not present). In addition, these characteristics suggest that this zone may represent a major belt of recharge through surface infiltration where it can be mapped in outcrop, generally in the western higher-elevation parts of the field region, near the basement-cored highlands.

Comox Formation (Potential Regional Aquifer Zone)

The Comox Formation comprises thick sandstone and conglomerate which forms the base of the Nanaimo Group in almost all areas. The unit rests on a sharp, high-relief angular unconformity, overlying the metamorphosed, stratified, Devonian to Jurassic rocks of the Wrangellia Terrane, and displays great variability (Muller and Jeletzky, 1970). The formation is generally 100-200 m thick, but is quite variable due to filling topography on the underlying unconformity: in some places, it appears to be absent and younger units overlie the basement. The Comox Formation is well-exposed in the western portions of the study area and is present in 20 of the outcrops measured. Typically there are basal conglomerates (Benson Member of Cathyl-Bickford, 1993; Benson Formation of Clapp, 1914 and Clapp and Cooke, 1917) consisting of poorly- to fairly-sorted, matrix- to clast-supported, pebble to cobble conglomerate (locally-derived clasts dominated by volcanic and felsic intrusive lithologies), set in a medium- to coarse-grained arkosic sandstone matrix. These are characteristically overlain by thick bedded, medium to coarse-grained arkosic sandstone with minor interbedded siltstone and mudstone of the Dunsmuir Member (Cathyl-Bickford, 1993). Coal is present in the Comox area to the north (beyond the study area). There is generally an overall fining-upward succession, passing gradationally-upward into the overlying Haslam Formation.

Twenty outcrops of the well-exposed Comox Formation were measured and described for this study, primarily in the Nanaimo and Saanich areas. The Malaspina Roadcut and Auld's Roadcut in Nanaimo area, the Schwarz Bay Roadcut and Norris Road Shoreline in the Saanich area, and Beddes Beach cliffs on Saltspring Island provide particularly good views of the lithologies and extreme variations within this unit. Overlying the sharp, irregular basal unconformity, there is typically several to several tens of metres of dark, poorly-sorted, matrix-supported cobble to boulder conglomerate, with angular volcanic clasts, in thick beds with erosive bases and a matrix of coarse-grained sandstone to pebble conglomerate. This facies commonly gives way upward to thick sharp-based beds of dark clast-supported pebble conglomerate with fair to good sorting, sandy matrix and sandstone rip-up clasts (Figure 7). The bulk of the Comox Formation is typically represented by thick successions of grey, well-sorted medium- to coarse-grained sandstone in sharp-based, fining-upward, thin to thick beds (Figure 8). These strata feature scattered pebbles, siltstone rip-ups, coaly wood fragments, horizontal to low-angle lamination, trough cross bedding, abundant soft-sediment convolute lamination, some vertical to sub-horizontal burrows and minor ripple cross lamination. At many outcrops, minor, thin beds of dark grey, bioturbated sandy siltstone are present as interbeds between coarser beds. At several outcrops (e.g. Horsewell Bluff II), there are a few thick coquina beds of coarse-grained calcareous pebbly sandstone with abundant broken bivalve shell fragments. Throughout the Comox, faulting and fracturing are common.

Figure 7. Lower Comox Fm porous and permeable coarse-grained sandstone to pebble conglomerate (braided fluvial), Lower Bedrock Aquifer System, South Ruckle Park, Saltspring Island.

Figure 8. Upper Comox Fm porous and permeable fine- to medium-grained sandstone (shoreline), Lower Bedrock Aquifer System, Blunden Point near Lantzville.

The Comox Formation has been interpreted to represent high-energy deposition in alluvial fan to braided fluvial and coastal floodplain to shoreline facies, with an overall transgressive or deepening-upward trend (Mustard, 1994). These facies represent the depositional settings created when the foreland basin began rapid subsidence and the initial marine transgression advanced over the high-topography subaerial unconformity. The lower Comox is typically dominated by coarser-grained, alluvial fan to fluvial facies (with the lateral variability and facies variability associated with those settings), whereas the upper Comox is more likely to exhibit finer-grained, sandy, shoreline to shallow marine facies (with the lateral and facies consistencies more typical of those settings). Paleocurrent indicators display scattered directions, but generally suggest flow toward the western hemisphere (Mustard, 1994). Deposition may have been influenced locally by high-relief topography on the underlying unconformity surface (Ward and Stanley, 1982; Johnstone et al., 2006). Johnstone et al. (2006) described 3 distinct facies typical of deposition on rocky shorelines with cliffed headlands and protected coves: 1) locally-derived conglomerates representing gravel-dominated fans built out from coastal cliffs and gullies, 2) well-sorted sandstone facies reflecting deposition on storm-dominated shorelines, and 3) fine-grained units which reflect protected embayment settings.

The Comox Formation is the lowest coarse-grained unit of the Nanaimo Group, present in outcrop on the western margins of the basin and present in the subsurface at depth beneath most of the basin, and is considered here to present significant regional aquifer potential. Due to its widespread distribution, great thickness, general coarse-grain size and extensive regional seal (by the overlying Haslam Formation), these strata may represent the most important potential bedrock aquifer zone. This potential may be further augmented by the regional aquifer enhancement characteristics of the immediately underlying basal unconformity surface, as described above.

However, the possibility of local thinning/thickening and pinchouts of Comox sandstones against significant underlying basement topography may result in a less predictable/less continuous distribution at depth, and more facies/aquifer quality variation than expected. Whereas fluvial facies distributions in the lower Comox may imply rapid lateral facies changes and lesser sorting (and consequently less-continuous aquifers with variable characteristics), the upward transition to shoreline and shallow marine facies suggests more laterally-continuous aquifers in the upper Comox with more predictable and more favourable aquifer characteristics. In some areas, especially toward the east, this unit may reside at depths too great for economically-feasible groundwater extraction.

In addition, these characteristics suggest that this zone may represent a major belt of recharge through surface infiltration where it can be mapped in outcrop, generally in the western higher-elevation parts of the field region, near the basement-cored highlands.

Haslam Formation (Potential Regional Aquitard Zone)

The Haslam Formation is dominated by grey to dark grey siltstone and mudstone with thin interbeds of fine- to coarse-grained sandstone. The unit is generally about 100-200 m thick (thickening southward; Clapp and Cooke, 1917), and rests with a gradational and conformable contact on the underlying Comox, and is sharply overlain by the Extension Formation. However, in the Duncan/Cowichan area, there are places where the Comox Formation is not present (due to relief on the underlying unconformity), and the Haslam rests directly on underlying basement rocks (Clapp and Cooke, 1917). The Haslam Formation is present in 10 of the outcrops measured for this study. Fine-grained facies may be dark grey, organic-rich and laminated, are typically calcareous, with calcareous concretions (Clapp, 1914), but are more typically bioturbated. Shelly fossils are present, in distinct calcarenite beds in some locations (Clapp, 1914), but not usually abundant. Thin, interbedded sandstones are generally sharp-based, laminated and rippled, display partial (B-D) Bouma turbidite sequences, and are typically arranged into coarsening and thickening upward sequences several to tens of metres thick. In addition, overall there is a general coarsening-upward trend over the entire thickness (Ward and Stanley, 1982). To the southeast, sandstone and conglomerate facies are more prominent (Ward and Stanley, 1982).

Although not directly observed in this study, a water well located near the town of Coombs penetrated 90.8 m of Haslam Formation dark grey shale with minor thin sandstone beds (Crow et al., 2014). Based on the geographic location, this well likely penetrated the uppermost part of the Haslam. Closed high angle joints, although no open fractures, were observed by televiewer, but the rock is relatively impermeable (Crow et al., 2014). Based on these televiewer images and the concurrent Gamma-Ray and Conductivity logs (the only ones available in the bedrock units of this basin), this borehole appears to record several 5-15 m thick coarsening-upward sequences of interbedded dark grey shale and thin fine-grained sandstone in the lower half (47-90 m depth), a macro-characteristic of the Haslam Formation which is also evident in many outcrops.

Ten outcrops of the rather poorly-exposed Haslam Formation were measured and described for this study, primarily as tidal platform exposures in the Saltspring and Saanich areas, although the best sections are at Marie Canyon on Cowichan River and Beddes Beach cliffs on Saltspring Island. The formation is dominated by thick successions of grey to dark grey, bioturbated, organic-rich siltstone to silty mudstone interbedded with thin very fine- to fine-grained sandstone beds (Figure 9). Sandstone beds typically have sharp to scoured bases with sole marks, horizontal to low-angle lamination, rippled tops, convolute lamination and some burrows (interpreted as Bouma B, C and BC turbidite beds). These interbedded lithologies are commonly arranged in thickening- and coarsening-upward sequences 2 to 5 m thick, especially in the lower part of the formation, forming a transition from the underlying Comox Formation. There may be fewer sandstone beds, lesser bioturbation and more laminated shale in the middle part of the formation. Fossiliferous calcarenite beds are present in places. Faulting and fracturing are common.

The Haslam Formation has been interpreted to represent low-energy deposition in marine shelf to relatively deep slope depositional facies (Mustard, 1994). Muller and Jeletzky (1970) suggested a relatively nearshore shelf setting. Certainly, the Haslam represents the culmination of the initial Nanaimo marine transgression over most of the basin, resulting from the initial foreland subsidence phase. Whereas the dominant shale facies represents low-energy continuous background deposition in deeper water, the thin sandstone and calcarenite beds are interpreted as the deposits of less frequent high-energy density current events, which transported coarser-grained sediments from shallower settings to deeper settings. Paleocurrent data are sparse but suggest westerly depositional flows, similar to the rest of the overlying Nanaimo Group, suggesting that the significant local topography which influenced Comox deposition had largely been "smoothed-out" during Haslam time (Ward and Stanley, 1982).

As the lowest unit of the Nanaimo Group dominated by fine-grained facies, combined with its general large thickness and blanket-like distribution, the Haslam Formation is considered to represent an important potential regional aquitard (-aquiclude?) zone, which could provide a regional-scale seal to the significant potential aquifers of the underlying Comox Formation. At the same time, certain lower parts of the Haslam where there are numerous thin sandstone beds, and dense fracturing, might provide localized aquifer potential nested within this overall sealing unit. The extensive fracturing observed in outcrop may affect the localized sealing quality of this unit in certain locations, but the regional seal quality should be significant.

Figure 9. Haslam Fm marine mudstone with thin siltstone interbeds, aquitard seal to Lower Bedrock Aquifer System, Erskine Point, Saltspring Island.

Extension Formation (Potential Regional Aquifer Zone)

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

Only five outcrops of Extension Formation were examined in this study, most in the Nanaimo-Saltspring area, and from the lower part of the unit. These strata comprise the typical facies of the Extension, dominated by scour-based, fining-upward beds 1-3 m thick, of clast-supported pebble to cobble conglomerate and a matrix of pebbly coarse-grained sandstone (Figure 10). Clasts are subrounded to subangular, and sorting ranges from good to fair to poor. Large sandstone rip-ups, wood fragments and carbonized tree trunks are commonly present at bed bases. Thin interbeds of medium- to coarse-grained sandstone and pedogenic sandy siltstone are present in some outcrops, but most sections display thick successions of thick coarse-grained beds with almost no intervening fine-grained deposits. In laterally-extensive outcrops, beds are observed to be lenticular on a large (tens of metres) scale, with lenses interleaved and laterally overlapping.

Figure 10. Extension Fm porous and permeable conglomerate (alluvial and braided fluvial), Medial Bedrock Aquifer System, Erskine Point, Saltspring Island.

The Extension Formation has generally been interpreted to include high-energy deposition in deeper marine submarine canyon and fan facies in northern areas, and shallow marine to coastal to braided fluvial depositional environments in the Nanaimo area where coal is present (Mustard, 1994). Paleocurrent indicators suggest predominantly westward flow, with considerable scatter (Mustard, 1994).

The Extension Formation is the second, and overall the coarsest, of the coarse-grained units of the Nanaimo Group, present in outcrop in the central parts of the basin and in the subsurface at depth beneath central and eastern parts of the basin. It is considered here to present considerable aquifer potential. Due to its wide distribution, significant thickness, general coarse-grain size, geographic consistency, potential for significant porosity and permeability, and potential regional seal over large areas of the basin (by the overlying Pender Formation), these strata may represent the second-most important potential bedrock aquifer zone, after the Comox Formation. At surface, these coarse-grained rocks appear to be well-cemented, but at subsurface depth, their porosity, permeability and aquifer quality are currently unknown. Due to the apparent surface-related cementation, these rocks may, or may not, harbour significant potential for major surface infiltration recharge, depending on the presence of extensive fault-related fracturing.

Pender Formation (Potential Regional Aquifer/Aquitard Zone?)

The Pender Formation represents a succession 100-200 m thick of siltstone and mudstone with common interbeds of fine-grained sandstone (equivalent to the Cranberry and Newcastle formations of Clapp, 1914, and the Ganges Formation of Clapp and Cooke, 1917). Fine-grained facies may be dark grey, organic-rich and laminated, but are more typically bioturbated. Thin, interbedded sandstones are generally sharp-based, laminated and rippled and display partial Bouma turbidite sequences. On a formation scale, there is a thinning- and fining-upward trend from the underlying Extension, followed by a general thickening- and coarsening-upward trend into the conformably overlying Protection Formation. A few thin coal seams are present in the finer-grained strata in the Nanaimo area. Cathyl-Bickford (1993) and Mustard (1994) described a basal Cranberry member (Cranberry Formation of Clapp, 1914) of 50-200 m of fine to coarse sandstone with minor siltstone and coal, and an upper Newcastle Member (Newcastle Formation of Clapp, 1914) of about 100 m of dark grey, carbonaceous mudstone with thin sandstones and thick coal seams of high volatile, bituminous A rank (Muller and Jeletzky, 1970).

Only three outcrops of the poorly-exposed Pender Formation rocks were examined in this study, located in the Nanaimo-Saltspring area and all at the uppermost coarsening-upward transition to the Protection Formation. These Newcastle Member strata consist of interbedded dark grey bioturbated siltstone, fine- to medium-grained sandstone with hummocky cross stratification and ripples, and thin carbonaceous mudstone. They can be interpreted as nearshore and shoreline-related facies.

Regionally, the Pender Formation has been interpreted to represent low-energy deposition in relatively deep marine shelf and slope environments of deposition in most areas, but shallow to marginal marine, coastal and fluvial floodplain deposits occur in the Nanaimo area where coal is present (Mustard, 1994). The few sections in this study all reflect this latter depositional setting. Paleocurrent data are very sparse.

As the second lowest unit dominated by fine-grained facies, and its significant thickness and wide distribution, the Pender Formation may represent a potential regional aquitard zone, which could provide a regional-scale seal to the potential aquifers of the underlying Extension and Comox formations. This is especially true where the upper Newcastle Member of thick mudstone is present. However, the sandstone-dominated portions of the basal Cranberry Member may actually provide further potential aquifers. Thus, the Pender Formation presents an interesting mixture of potential aquifers and aquitards, and may not provide a tight regional seal zone everywhere. However, due to its limited surface exposure, the aquifer/aquitard characteristics of the Pender in the subsurface are currently poorly known.

Protection Formation (Potential Regional Aquifer Zone)

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

Twelve outcrops of the well-exposed Protection Formation were measured and described for this study, primarily in the Nanaimo-Parksville area. Beds range 1-5 m thick, are typically fining-upward, with scoured bases and lags of siltstone rip-ups or pebbles. Uncommonly, thick beds of clast- to matrix-supported pebble conglomerate are present. Typically, the formation exposes thick successions of stacked sandstone beds with few intervening finer-grained deposits (Figure 11). The sandstones are characteristically medium- to coarse-grained, well sorted, with horizontal to low angle lamination, lesser trough cross bedding and minor ripple cross lamination. A distinctive characteristic is the common presence of convolute lamination resulting from syn-sedimentary soft-sediment deformation and water escape structures. This deformation suggests very rapid deposition of large volumes of well sorted, uniform sand. Uncommon fine-grained beds include thin sandy siltstone to fine-grained sandstone, sometimes with carbonaceous partings or thin coal seams. When bioturbation is discernible, the burrows tend to be isolated vertical burrows, suggesting high energy, relatively shallow deposition. Overall, the Protection Formation presents a thick, extensive and very uniform horizon of significant aquifer potential.

Figure 11. Protection Fm porous and permeable medium- to coarse-grained sandstone (shallow marine to shoreline), Medial Bedrock Aquifer System, City of Nanaimo Parking Lot.

The Protection Formation has been interpreted to represent high-energy deposition in relatively deep marine shelf to submarine fan facies in most areas, but shallow marine shelf and coastal depositional environments occur in the Nanaimo area where most of this study's outcrops occur (Mustard, 1994). Paleocurrent indicators suggest predominantly westward flow (Mustard, 1994).

The Protection Formation is the third of the coarse-grained units of the Nanaimo Group, present in outcrop in the central to eastern parts of the basin and in the subsurface only beneath eastern parts of the basin (not present in western parts of the study area). These thick bedded, well sorted, coarser-grained sandstones, with almost no intervening fine-grained beds likely display significant lateral continuity and should provide good aquifer conduits, provided the porosity and permeability are not occluded by cements in subsurface settings. The Protection Formation is considered here to present significant secondary aquifer potential due to its wide distribution over central and eastern parts of the basin, and the potential regional seal provided by the overlying Cedar District Formation in the eastern part of the basin. The Protection Formation sandstones may allow surface infiltration recharge in the areas where they outcrop, especially where poorly-cemented or fractured. Fractures are observed in several outcrops.

Cedar District Formation (Potential Regional Aquitard Zone)

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

Strata of the Cedar District Formation were described at 11 outcrops in eastern portions of the study area, primarily on Saltspring and Denman Islands. The unit is dominated by thick successions of grey to dark grey bioturbated silty mudstone with sideritic concretions occurring as isolated features or as thin continuous horizons (Figure 12). Where significant interbedded sandstones are present, there are conspicuous 2-10 m thickening- and coarsening-upward sequences. At the top of the Cedar District, where it passes gradationally upward into the overlying De Courcy Formation, well sorted fine- to medium-grained sandstones with horizontal lamination, up to 1 m thick, are much more prevalent.

The Cedar District Formation has been interpreted to represent low-energy deposition below wave base in relatively deep marine, relatively distal shelf/slope and lower to middle submarine fan environments of deposition in most areas (Rahmani, 1968; Mustard, 1994). Where sandstones are present, they indicate less frequent, higher-energy density current events which transported coarser sediment from shallower water settings. Paleocurrent data are sparse and suggest predominantly westward and northwestward flow (Mustard, 1994).

As a middle unit of the Nanaimo Group dominated by fine-grained facies, the Cedar District Formation is considered to represent a potential regional aquitard (-aquiclude?) zone, which could provide a regional-scale seal to the potential aquifers of the underlying Protection, Extension and Comox formations. Overall porosity and permeability should be low, but some outcrops include significant content of sandstone beds which might have better transmissivity. In addition, many outcrops display fracturing, and further study is required to evaluate how this might alter the seal potential in some areas. Conversely, where thin but extensive concretion horizons are present, these may increase the seal potential.

Figure 12. Cedar District Fm marine mudstone with thin siltstone interbeds, aquitard seal to Medial Bedrock Aquifer System, Vesuvius Bay, Saltspring Island.

De Courcy Formation (Potential Local Aquifer Zone)

The De Courcy Formation is the uppermost coarse-grained unit within the study area and is about 300 m thick, thickening southward. It is typically represented by stacked/amalgamated, thick bedded, uniform, greenish grey, medium- to coarse-grained arkosic sandstone and lesser, matrix-supported pebble conglomerate. Sandstones have erosional bases, may appear to be massive, or may be laminated. Soft sediment deformation/convolute lamination and sandstone dykes are common, as are concretions and cross beds, and the rocks are commonly silica-cemented at surface (Clapp, 1914; Clapp and Cooke, 1917). Concretions commonly erode out, leaving round holes and honeycomb galleries (Clapp and

Cooke, 1917). Coarse beds are separated by darker-coloured minor fine-grained sandstone to siltstone beds. There is generally a coarsening- and thickening-upward trend from the underlying Cedar District, and a thinning- and fining-upward trend into the overlying Northumberland Formation.

Eleven outcrops, plus a 118 metre-long core, of the well-exposed De Courcy Formation were measured and described for this study, primarily in the Nanaimo-Parksville area. Detailed descriptions of the facies present in the core were provided by Hamblin and McCartney (2014). Sandstones occur in buff-coloured thick fining-upward beds, 1-5 m thick, with scoured bases of coarse-grained sandstone to granulestone, well sorted, with lags of sandstone rip-up clasts or pebbles, horizontal to low angle lamination, some large-scale trough cross bedding and minor ripple cross lamination (Figure 13). A distinctive characteristic is the common presence of convolute lamination resulting from syn-sedimentary soft-sediment deformation and water escape structures. In some locations, notably on Saltspring Island, thick beds of fining-upward pebble conglomerate make up a significant portion of the section. Outcrops of the De Courcy Formation tend to display thick successions of stacked coarse-grained beds with few finer-grained interbeds, but in places thin finer beds include grey to dark grey bioturbated siltstone interbedded with silty fine-grained sandstone. In the measured core, coarser-grained facies represent about 65 % of the De Courcy strata, whereas finer-grained facies occupy about 35%, demonstrating that within this regional aquifer zone, there is vertical stratigraphic alternation of individual, laterally-extensive potential aquifer horizons and potential aquitard horizons (Hamblin and McCartney, 2014).

Figure 13. De Courcy Fm porous and permeable coarse-grained sandstone with soft-sediment deformation (submarine fan), Upper Bedrock Aquifer System, Coffin Point near Ladysmith.

Due to the acquisition of the 118 m core, this is the sole unit of the Nanaimo Group where we have some subsurface data regarding aquifer quality (Zhai and Grasby, 2015; Hamblin and McCartney, 2014). There, thick bedded coarse-grained sandstones (~65% of the core) have porosity ranging 2.0 to 10.2%, averaging 6.8%, and permeability ranging 2.8 to 105.0 mD, averaging 24.4 mD (Figure 14). Most porosity is secondary after dissolution of feldspar and volcanic rock fragments. These laterally-extensive units of thick, porous and permeable sandstone, up to 6 m thick, likely represent significant aquifer horizons within the De Courcy Formation. Intervening finer-grained facies (~35% of the core) have porosity ranging 4.0 to 9.7%, averaging 7.4%, and overall permeability ranging 1.8 to 40.0 mD, averaging 12.7 mD. These laterally-extensive units of interbedded siltstone and sandstone may represent significant aquitard horizons within that same formation. The rock characteristics of the De Courcy formation, as revealed by this core, may provide analogies for the deeper, uncored potential aquifer zones of the Comox, Extension and Protection formations.

Figure 14. De Courcy Fm porous and permeable coarse grained sandstone (submarine fan) from subsurface core, Upper Bedrock Aquifer System, near Cedar.

The De Courcy Formation has been interpreted to include high-energy deposition in deeper marine submarine canyon and fan facies deposited on a generally northwestward-sloping margin. These thick bedded, well sorted, coarser-grained sandstones, with few intervening fine-grained beds likely display significant lateral continuity and should provide good aquifer conduits, provided the porosity and permeability are not occluded by cements in subsurface settings. Paleocurrent indicators suggest predominantly westward and northwestward flow (Mustard, 1994).

The De Courcy Formation is the fourth and uppermost of the coarse-grained units of the Nanaimo Group within the study area. It is present in outcrop only in the easternmost part of the study area (Cedar/Ladysmith area, southeast of Nanaimo) and in the shallow subsurface only beneath this same eastern part of the basin. It is considered here to present good aquifer potential, but perhaps only in this local area. Due to its localized distribution at or near the surface, and lack of a potential regional seal over large areas of the basin (only in the Kulleet Bay area of the study area, southeast of Nanaimo, is it overlain by the Northumberland Formation), these strata represent a localized, potential bedrock aquifer of secondary importance within this study area. Likewise, the potential for surface infiltration recharge may be good, but only in this limited area, and only if poorly-cemented and/or fractured. Fractures do, in fact, appear in the core and in several outcrops in this area.

Despite its reduced potential due to its localized distribution, the most important aspect of the De Courcy Formation is that, due to the sedimentological and stratigraphic details observable in the core, it provides a much-needed window onto the subsurface aquifer characteristics and qualities of analogous Nanaimo Group bedrock aquifer zones. This core displays much more positive aquifer characteristics than are apparent in heavily-cemented surface outcrops, and this is potentially true for all potential aquifer zones of the Nanaimo Group.

Northumberland Formation (Potential Local Aquitard Zone)

The Northumberland Formation represents the highest/youngest unit in the study area, present only in a small area around Kulleet Bay at the eastern shoreline margin of the area, southeast of Nanaimo. It includes up to about 200 m (only about 50-100 m in the study area) of recessive, dark grey bioturbated mudstone and siltstone with thin interbeds of sharp-based, very fine- to fine-grained sandstone. The formation fines upward from the underlying De Courcy Formation. Syn-sedimentary slump structures and sandstone dykes are present (Clapp and Cooke, 1917), and there is a slight coarsening-upward trend through the upper part of the formation as it grades upward into the overlying Geoffrey Formation, which is not exposed in the study area. Only one section measured in this study, located on Saltspring Island, was previously mapped as Northumberland Formation. There, 25 m of greenish grey bioturbated silty mudstone with a few sideritic concretions and several pale grey bentonitic volcanic ash beds make up the section (Figure 15). Several bundles of thin, dolomitic siltstone beds with sharp bases and rippled tops are present, but comprise less than 5% of the section.

Figure 15. Northumberland Fm marine mudstone (deep slope) with natural fractures, aquitard seal to Upper Bedrock Aquifer System, St. Mary Lake roadcut, Saltspring Island.

The Northumberland Formation has been interpreted to represent low-energy deposition in relatively deep marine slope and submarine fan environments, with deposition on a northwestward-sloping margin (Mustard, 1994). Paleocurrent data are very sparse. The few sharp-based siltstone beds with partial Bouma sequences are interpreted to represent infrequent density current deposits in this distal setting.

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

REGIONAL BEDROCK AQUIFER SYSTEMS

The above observations, detailing the characteristics of the many alternating, formational-scale aquifer and aquitard units of the Nanaimo Group suggest that this information can be conceptually organized into fewer more practical divisions. The obvious presence of the three thick major aquitard zones (Haslam, Cedar District, Northumberland formations) can be interpreted to hydraulically isolate the coarser-grained units beneath them (Comox, Extension/Pender/Protection, De Courcy formations, respectively) which harbour greater aquifer potential. Therefore, a first attempt at organizing these data for future research is presented here. (Figures 16 and 17).

Lower Bedrock Aquifer System

Within the study area, the combination of a) the extensive regional unconformity with major topography and extremely variable coarse-grained lithologies at the top of the metamorphosed volcanic basement, b) the Comox Formation coarse grained, porous and permeable sandstones which fill irregularities in the unconformity surface, and c) extensive faulting and fracturing, together constitute a major regionally-extensive Potential Bedrock Aquifer Zone 1, up to 200 m thick. This composite zone outcrops in the west and south and is present in the subsurface over most of the study area, although in some portions of the study area, this system may lie too deep for economical exploitation. Within the Comox Formation, the lower, coarser-grained fluvial/alluvial facies may contain laterally-discontinuous individual aquifer bodies, whereas the upper Comox shoreline-related facies may provide more laterally-continuous individual aquifer bodies. Extensive fracturing should enhance the aquifer permeability and conductivity of these rocks. They are overlain by the thick mudstone-dominated Haslam Formation which constitutes a major regionally-extensive Regional Potential Bedrock Aquitard Zone, up to 200 m thick, which has the potential to seal the underlying Bedrock Aquifer Zone over large areas. This bedrock system is here regarded as having the best regional and local groundwater potential of the rocks of the Nanaimo Group. In addition, it may represent a significant zone of surface infiltration recharge in western parts of the field area where it outcrops at somewhat higher elevations.

Medial Bedrock Aquifer System

Within the study area, the combination of a) the Extension Formation coarse-grained porous and permeable conglomerates and sandstones, and b) the Pender Formation fine-grained, porous and permeable sandstones plus mudstones, siltstones and coals, and c) the Protection Formation coarse-grained porous and permeable sandstones together constitute a major regionally-extensive Potential Bedrock Aquifer Zone 2, up to 600 m thick. This composite zone outcrops and is present in the shallow subsurface over most of the eastern and northern parts of the study area. Individual aquifer bodies may be thick and laterally-extensive, but could be quite variable. These rocks are overlain by the thick mudstone-dominated Cedar District Formation which constitutes a major regionally-extensive Regional Potential Aquitard Zone, up to 300 m thick, which has the potential to seal the underlying Aquifer Zone over large areas. This bedrock system is here regarded as having significant regional and local groundwater potential. Fracturing, where present, could significantly enhance the aquifer permeability and conductivity of these rocks. In addition, it may represent a zone of surface infiltration where it outcrops.

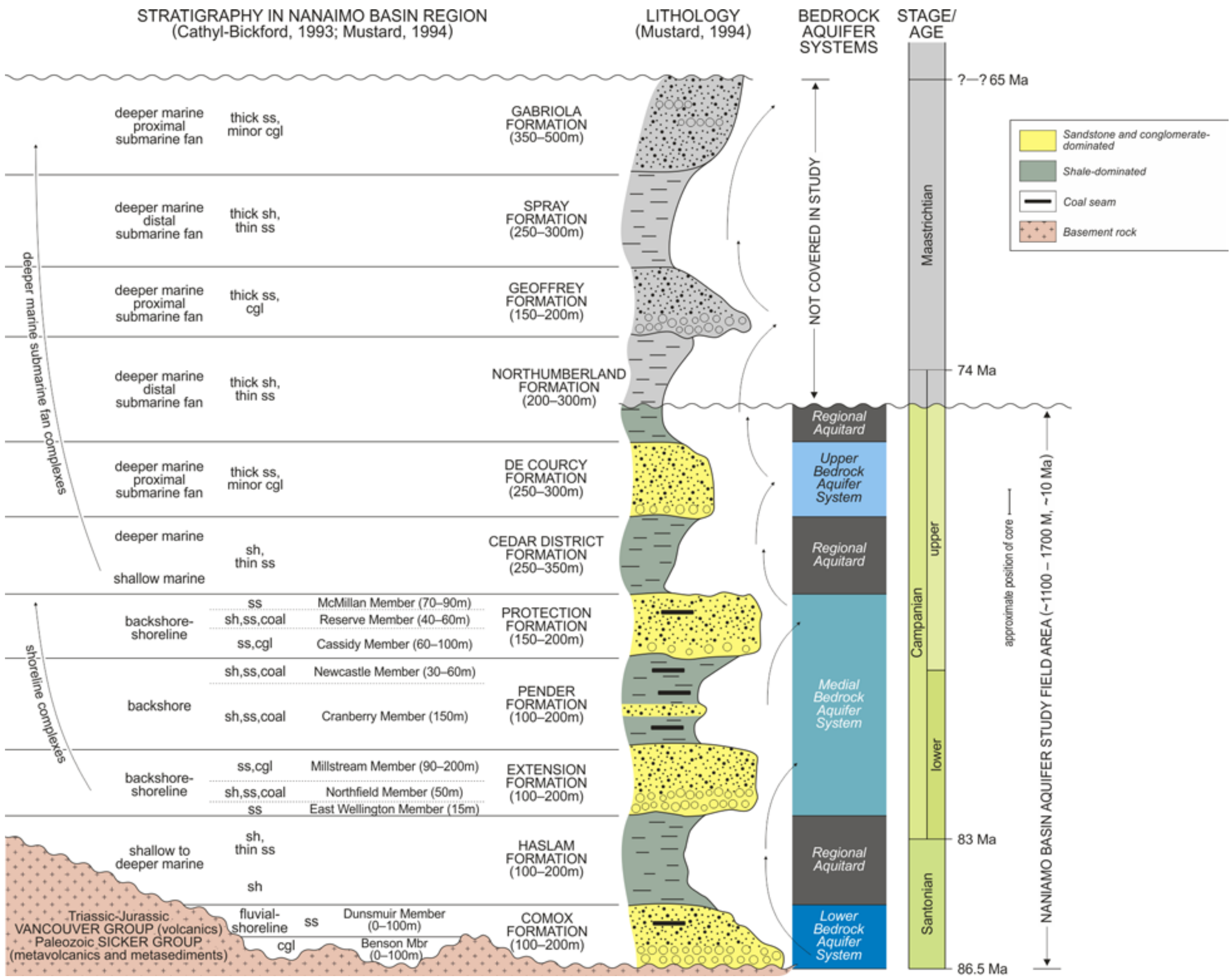

Figure 16. Simplified stratigraphy, illustrating alternating coarse-grained (aquifer) and fine-grained (aquitard) units and interpreted Bedrock Aquifer Systems (simplified from Muller and Jeletzky, 1970; Cathyl-Bickford, 1993; Mustard, 1994). Click here or on figure for full-size version.

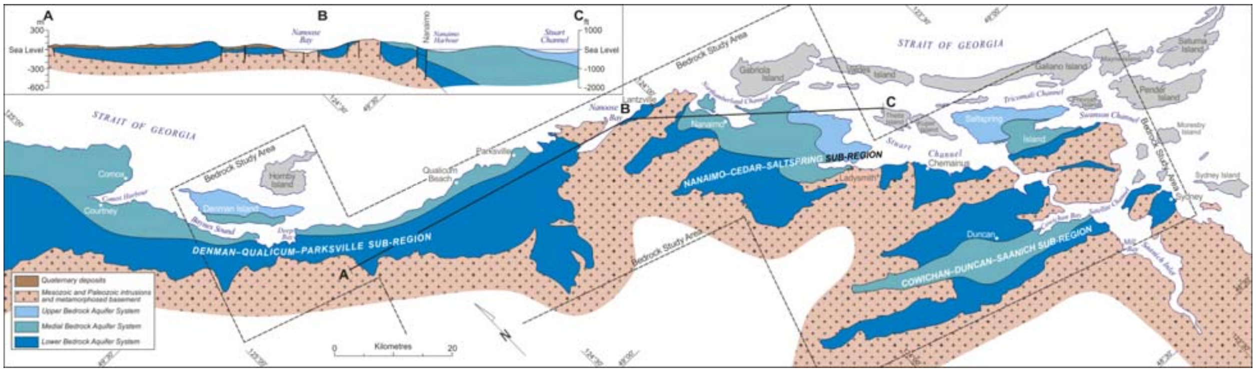

Figure 17. Simplified distribution of interpreted Bedrock Aquifer Systems, Nanaimo Group, eastern Vancouver Island. Click here or on figure for full-size version.

Upper Bedrock Aquifer System

Within the study area, the De Courcy Formation coarse-grained porous and permeable sandstones constitute a near-surface Local Potential Bedrock Aquifer Zone 3, up to 300 m thick, but typically much less in the study area. This is overlain by the modestly thick mudstone-dominated Northumberland Formation which may constitute a locally-developed Local Potential Aquitard Zone over a specific area. Because this bedrock system is present only in the easternmost part of the study area at surface, and is sealed over only a small portion of the study area, it is deemed to have significant local potential, but is less important regionally. However, unlike the other Bedrock Aquifer Systems, in this case we know of the presence of significant subsurface secondary porosity and permeability, due to data recorded from a cored well. Thus, this rock unit provides an important scientific analogy with which to estimate the aquifer quality and characteristics of those units for which there is currently no comparable subsurface data.

FUTURE RESEARCH DIRECTIONS

To properly evaluate the significant bedrock aquifer potential of the Nanaimo Group outlined in this report, a great deal more research, of more detailed nature, is required. Detailed field mapping of the outcrop belts of zones of interest, particularly incorporating data from the numerous shallow water wells, and more detailed stratigraphic/sedimentologic studies within regional aquifer zones would reveal geometries and distributions and limits of individual aquifer horizons. Mineralogic and geochemical studies could enhance understanding of aquifer quality. Acquisition of much more and deeper subsurface data would be paramount in evaluation. Incorporation of detailed fracture studies in specific localities would be crucial to properly evaluating potential.

One interesting aspect of the Nanaimo Bedrock Aquifer Systems is that they could be considered as analogous to bedrock “unconventional gas reservoirs” in the world of petroleum systems. They display similar characteristics, such as modest subsurface porosities and permeabilities, but large rock volumes and therefore large storage capacities, perhaps yielding relatively long-lived, but low-flow resources. In addition, fracturing, either the considerable existing natural fracture systems, or mechanically-induced fracturing, might significantly enhance the production of these bedrock groundwater resources. Likewise, perhaps future production strategies might incorporate modern oilfield techniques such as directional drilling along steeply-dipping fracture zones within mapped aquifer systems, or even oriented horizontal drilling in well-defined preferred aquifer zones.

These groundwater resources can be envisioned and treated in similar ways to near-frontier hydrocarbon resource plays. As with all such endeavours, more detailed regional geological mapping and sampling is required to elucidate thickness, depth, quality and structural complexities of potential aquifers. Further targeted exploratory drilling, coring geophysical logging and possibly localized shallow seismic studies would provide excellent information on depth, geometry and fracture patterns in assessment of these resources.

CONCLUSIONS

The basic geology of the Upper Cretaceous Nanaimo Group suggests that the coarser-grained formations in the Nanaimo Basin may present significant zones of aquifer potential for new groundwater resources, whereas the intertonguing finer-grained formations could provide zones of potential aquitard seals, a situation which might provide good prospects for stacked multiple groundwater targets, provided subsurface porosity and permeability are adequate. These groundwater targets are mutually nested within several scales, or orders, of geographic and stratigraphic magnitude.

The full Nanaimo Group sedimentary rock succession, residing between impervious basement rock below and unconsolidated Quaternary deposits above represent a First Order package. Within this, the three Regional Bedrock Aquifer Systems defined here, separated by Regional Aquitard horizons, represent Second Order packages with specific mappable distributions in three dimensions. At a Third Order scale, the four potential aquifer formations (Comox, Extension, Protection, De Courcy) also have specific mappable distributions within the study area and within the Aquifer Systems, and are isolated by the intervening potential aquitard formations. However, at a smaller-scale within these formations, there are Fourth Order packages of individual aquifer bodies with specific geometries and distributions related to their original depositional environments, diagenetic effects and structural complications such as folding and natural fracturing.

The subsurface diagenetic processes that most of these rocks have undergone, and therefore the aquifer characteristics and quality, are essentially unknown at this time. However, the Comox, Extension, Protection and De Courcy formations may harbour significant groundwater aquifer potential. To properly evaluate this potential, the detailed internal stratigraphy, sedimentology, geometries, aquifer characteristics, presence of internal permeability barriers, and presence of subsurface fracturing of these units must be further studied and will determine their ultimate characters. The intervening finer-grained units, the Haslam, Pender, Cedar District and Northumberland formations, may be important as sealing aquitard zones, and therefore also warrant further study. In addition, fracturing, both local and regional, may influence or alter the rock characteristics and potential of both aquifer and aquitard horizons, and must also be studied in more detail. As a preliminary conclusion, these rocks can be divided into 3 Regional Bedrock Aquifer Systems: a) the Lower System, of the underlying regional unconformity and the coarse-grained facies of the Comox Formation, present at depth beneath the entire study area, b) the Medial System encompassing the Extension Formation conglomerates, Pender Formation sandstones and siltstones and the Protection Formation sandstones, present over most of the eastern part of the study area, and c) the Upper System of De Courcy formation sandstones, present in only one localized area in the eastern part of the region.

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LIST OF FIGURES

LIST OF APPENDICES

1. Nanaimo Group Measured Section Outcrop and Core Locations (arranged in stratigraphic order).
2. Nanaimo Group Detailed Measured Sections.

APPENDIX I – Nanaimo Group Measured Section Outcrop and Core Locations (arranged in stratigraphic order)

2010 – 2013 Nanaimo Group Measured Sections (arranged in stratigraphic order, from base to top) (62 sections: 61 outcrops + 1 core) (2480 m total).

Basement - Comox Formation transition

1. Entwhistle Drive Shoreline end of Entwhistle Drive, off Hammond Bay Road, North Nanaimo, Basement - Comox Formation, 15.5 m. Nanaimo sheet, 92G/14, NTS 278546. GPS: 10U 0427858 5454580, N 49° 14' 22.7" / W 123° 59' 27.6".

2. South Ruckle Park, Saltspring Island dangerous tidal flat and cliff exposures along S shore of Beaver Point peninsula, from Grandma's beach cove to campground, Basement – Comox Formation, 37.3 m. Mayne Island sheet, 92 B / 14, NTS 725016. GPS: 10 U 0472435 5401676, N 48° 46' 03.0" / W 123° 22' 30.4" at base to 10 U 0472689 5401603, N 48° 46' 00.7" / W 123° 22' 18.0" at top.

3. Horsewell Bluff II coastal exposure immediately SW of end of Stephenson Point Rd beach access stairway, Basement – Comox Formation, 11.2 m. Nanaimo sheet, 92G/4, NTS 314514. GPS: 10 U 0431421 5451417, N 49° 12' 42.2" / W 123° 56' 29.8".

4. Nanaimo Parkway/Jingle Pot Road ("Malaspina Roadcut") large roadcut on S side of Hwy., 0.5 km SE of Jingle Pot Rd/3rd St intersection, Basement – Comox Formation, 43.0 m. Nanaimo sheet, 92G/4, NTS 286462. GPS: 10 U 0428603 5446293, N 49° 09' 55.0" / W 123° 58' 45.8".

5. Armstrong Point coastal and tidal flat exposure NW along shore from access stairway at end of Allbay Rd, Basement – Comox Formation, 20.0 m. Sidney sheet, 92B/11, NTS 708906. GPS: 10 U 0470754 5390527, N 48° 40' 01.6" / W 123° 23' 49.9".

6. Towner Road Shoreline tidal flat and bank exposure west of Towner Road beach access, south of Deep Cove and 4 km west of Sidney, Basement – Comox Formation, 55.8 m. Sidney sheet 92B/11, NTS 648907. GPS: 10 U 0464760 5390702, N 48° 40' 06.1" / W123° 28' 43.0" at base to 10U 0464767 5390782, N 48° 40' 08.7" / W 123° 28' 42.7" at top.

Comox Formation

7. Moses Point NW tip of Saanich Peninsula, 8 km NW of Sidney, Comox Formation, 39.0 m. Sidney sheet, 92B/11, NTS 643931. GPS: 10U 0464300 5393061, N 49° 41' 22.5" / W 123° 29' 06.3".

8. Pacific Biological Station Stephenson Point Road, Departure Bay, 5 km N of Nanaimo city centre, Comox Formation, 8.0 m. Nanaimo sheet, 92G/14, NTS 305513. GPS: 10U 0430491 5451261, N 49° 12' 36.6" / W 123° 57' 15.8".

9. Horsewell Bluff end of Stephenson Point Road, Departure Bay, 5 km N of Nanaimo city centre, Comox Formation, 10.2 m. Nanaimo sheet 92G/14, NTS 315516. GPS: 10U 0431508 5451611, N 49° 12' 48.6" / W 123° 56' 25.6".

10. Blunden Point end of Sebastien Road, south shoreline of Nanoose Harbour, 1 km NW of Lantzville, Comox Formation, 8.8 m. Parksville sheet 92F/8, NTS 212566. GPS: 10U 0421091 5456578, N 49° 15' 24.8" / W 124° 05' 04.0".

11. Englishman River Falls (Upper Falls) small cliff area across from Upper Falls, Comox Formation, 6.0 m. Nanaimo Lakes sheet, 92F/1, 018553. GPS: 10U 0401875 5455307, N 49° 14' 36.2" / W 124° 20' 53.5".

12. Hwy. 19 & Miracle Beach Interchange roadcut at intersection of Hwy. 19 and Hamm Road to Miracle Beach Provincial Park, Comox Formation, 7.5 m. Oyster River sheet, 92F/14, NTS 423222. GPS: 10 U 0392513 5522029, N 49° 49' 48.0" / W 125° 11' 23.5".

13. Hwy. 17, Schwarz Bay Roadcut large roadcut on NW side of Hwy. 1 km W of Ferry Terminal immediately W of Lands End Rd., Comox Formation, 94.7 m. Sidney sheet, 92B/11, NTS 692922. GPS: 10 U 0469320 5392105, N 48° 40' 52.4" / W 123° 25' 10.6" at base to 10 U 0469470 5392264, N 48° 40' 57.7" / W 123° 24' 53.1" at top.
14. Norris Road Shoreline long tidal flat and cliff exposure from foot of Norris Road beach access stairway to headland, south of Deep Cove and 4 km west of Sidney, Comox Formation, 129.9 m. Sidney sheet 92B/11, NTS 646909. GPS: 10 U 0464758 5390017, N 48° 40' 13.2" / W 123° 25' 43.2" at base to 10 U 0464483 5391148, N 48° 40' 20.5" / W123° 28' 56.7" at top.
15. Cromar Road Shoreline tidal platform exposure at bottom of access stairway at intersection of Madrona Road and Cromar Road, south of Deep Cove and 4 km west of Sidney, Comox Formation, 25.2 m. Sidney sheet 92B/11, NTS 644915. GPS: 10 U 0464477 5391432, N48° 40'29.8" / W 123° 28' 59.1" at base to 10 U 0464301 5391468, N 48° 40' 30.9" / W 123° 29' 01.7" at top.
16. Kingfisher Lane Shoreline much-faulted shoreline section off Land's End Road, immediately west of West Saanich Road, 4 km NW of Sidney, Comox Formation, 61.0 m. Sidney sheet, 92B/11, NTS 660938. GPS: 10 U 0466098 5393830, N 48° 41' 42.7" / W 123° 27' 38.6" at base to 10 U 0465819 5393861, N 48° 41' 48.6" / W 123° 27' 52.1" at top.
17. Hwy. 19 & Auld's Road roadcut exposure along Hwy. 19 on SW corner of intersection, in north Nanaimo, 2 km N of Brannen Lake, Comox Formation, 24.1 m. Nanaimo Lakes sheet 92F/1, NTS 234537. GPS: 10 U 0423429 5453789, N 49° 13' 55.6" / W 124° 03' 06.5" at base to 10 U 0423424 5453499, N 49° 13' 46.0" / W 124° 03' 06.3" at top.

Comox Formation – Haslam Formation transition

18. Englishman River Falls (Lower Falls) exposure at Lower Falls and northward along river, Comox Formation – Haslam Formation, 45.0 m. Nanaimo Lakes sheet, 92 F / 1, NTS 019557. GPS: 10 U 0401835 5455831, N 49° 14' 50.6" / W 124° 20' 55.8"at base to 10 U 0401918 5456086, N 49° 15' 02.4" / W 124° 20' 48.3" at top.
19. Beddes Beach, Saltspring Island tidal flat and cliff exposures SE along shore from Beddes Beach public access to Cusheon Creek, SE shore of Island, Comox Formation – Haslam Formation, 173.0 m. Mayne Island sheet, 92B/14, NTS 688063. GPS: 10 U 0468973 5406026, at base, N 48° 48' 23.1" / W 123° 25' 21.1" at base to 10 U 0468743 5406353, N 48° 48' 33.8" / W 123° 25' 32.5" at top.
20. Bryden Bay Beach tidal flat exposure to S and to E of access with long covered interval between, Comox Formation – Haslam Formation, 139.8 m. Sidney sheet, 92B/11, NTS 710904. GPS: 10 U 0469014 5391319, N 48° 40' 27.1" / W 123° 24' 36.1".

Haslam Formation

21. Marie Canyon Cowichan River Provincial Park, Marie Canyon access, off Riverbottom Rd, 16 km W of Duncan, Haslam Formation, 95.1 m. Duncan sheet 92B/13, NTS 329029. GPS: 10U 0432917 5402961, N 48° 46' 39.5" / W 123° 55' 31.0".
22. Chemainus Kin Beach Park Boat Launch tidal flat exposures on NW shoreline of Chemainus Harbour, from Kin Beach Park at foot of Maple St SE toward Hospital, Haslam Formation, 36.3 m. Duncan sheet, 92B/13, NTS 476197. GPS: 10 U 0447456 5419778, N 48° 55' 43.4" / W 123° 43' 02.4" at base to 10 U 0447614 5419680, N 48° 55' 40.1" / W 123° 45' 54.7" at top.
23. Seabreeze Road Shoreline tidal platform exposure at bottom of access stairway near Land's End Road, 4 km NW of Sidney, Haslam Formation, 42.0 m. Sidney sheet 92B/11, NTS 670941. GPS: 10 U 0464996 5394065, N48° 41' 55.4" / W 123° 26' 54.7" at base to 10 U 0467152 5394138, N 48° 41' 57.9" / W 123° 26' 47.1" at top.
24. Hwy. 19 & Jingle Pot Road roadcut exposure along Hwy. 19 NW of Jingle Pot Road/Mostar Road intersection, easily accessed from Biggs Road, in north Nanaimo, 1 km SE of Brannen Lake, Haslam Formation, 10.3 m. Nanaimo Lakes sheet 92F/1, NTS 243511. GPS: 10 U 0424214 5451061, N 49° 12' 27.6" / W 124° 02' 25.7".

Haslam Formation – Extension Formation transition

25. Erskine Point, Saltspring Island unnamed bay 500 m east of Erskine Point, west shore of Saltspring Island, Haslam Formation - Extension Formation, 78.0 m. Duncan sheet, 92B/13, NTS 587112 to 587116. GPS: 10U 0458693 5411184, N 48° 51' 08.1" / W 123° 33' 47.2" at base to 10U 0458775 5411523, N 48° 51' 19.1" / W 123° 33' 43.1" at top.

26. Trent River beneath Hwy. 19 bridge, 6 km SW of Royston and 7 km SW of Courtney, on both sides of river, Haslam Formation – Extension Formation - Pender Formation, 23.0 m. Comox sheet, 92F/10, NTS 566961. GPS: 10 U 0356730 5495958, N 49° 35’ 57.1” / W 124° 58’ 58.0” at base.

27. Hwy. 19 & Harewood Road roadcut exposure on NE side of Hwy. 19, NW of Harewood Mines Road, 3 km SW of downtown Nanaimo, Haslam Formation – Extension Formation, 40.5 m. Nanaimo sheet 92G/4, NTS 294440. GPS: 10 U 0429263 5444058, N 49° 06’ 42.5” / W 123° 58’ 13.2” at base to 10 U 0429375 5443890, N 49° 06’ 37.6” / W 123° 58’ 06.0” at top.

Extension Formation

28. Nanaimo River Canyon off Nanaimo River Rd, 3 km W of airport and Highway #1, 10 km S of Nanaimo, Extension Formation, 18.0 m. Nanaimo sheet, 92G/14, NTS 328359. GPS: 10U 0432780 5435936, N 49° 04’ 21.4” / W 123° 55’ 13.3”.

29. McKeowen Way roadcut exposure along abandoned road beside Highway 19, off Cranberry/Extension Road, village of Starks, 5 km S of Nanaimo, Extension Formation, 7.7 m. Nanaimo sheet 92G/4, NTS 323418. GPS: 10 U 0432317 5441846, N 49° 07’ 32.6” / W 123° 55’ 40.2”.

Pender Formation – Protection Formation transition

30. Newcastle Island, Eastern Shore entire northeastern/eastern shore of Island, Pender Formation - Protection Formation, 100.2 m. Nanaimo sheet, 92G/14, NTS 322501 to 327485. GPS: 10U 0432197 5450045, N 49° 11’ 57.4” / W 123° 53’ 50.9” at base to 10U 0432724 5448500, N 49° 11’ 10.8” / W 123° 55’ 23.7” at top.

31. Grace Point, Ganges, Saltspring Island section composed of tidal flat, cliff and parking lot exposures, behind Grace Point Shopping Centre and in Mouat’s parking lot, downtown Ganges, Pender Formation – Protection Formation, 37.2 m. Mayne Island sheet, 92 B / 14, NTS 637112. GPS: 10 U 0463491 5411245, N 48° 51’ 11.2” / W 123° 29’ 51.7” at top, across from Mouat’s.

32. Trans-Canada Hwy. & Hwy. 19 Ramp large roadcut exposure on E side of TC Hwy., 1 km S of Cedar Road intersection, 5 km S of downtown Nanaimo, Pender Formation – Protection Formation, 23.9 m. Nanaimo sheet 92G/4, 334410. GPS: 10 U 0433386 5441154, N 49° 07’ 10.5” / W 123° 54’ 46.6” at base to 10 U 0433449 5441050, N 49° 07’ 07.2” / W 123° 54’ 43.3” at top.

Protection Formation

33. City of Nanaimo Public Parking Lot corner of Victoria and Cavan streets, immediately S of downtown, just off Highway #1, Protection Formation, 14.1 m. Nanaimo sheet, 92G/14, NTS 318458. GPS: 10U 0431816 5445902, N 49° 09’ 43.7” / W 123° 56’ 07.0”.

34. Wall Beach Headland shore of headland NE of Wall Beach in Northwest Bay, 7.5 km E of Parksville, Protection Formation, 5.0 m. Parksville sheet 92F/8, NTS 115618. GPS: 10U 0411511 5461888, N 49° 18’ 12.0” / W 124° 13’ 02.1”.

35. Madrona Point N tip of Madrona Point, 5 km E of Parksville city centre, 5 km NW of Nanoose Bay, Protection Formation, 20.3 m. Parksville sheet 92F/8, NTS 097631. GPS: 10U 0409669 5462970, N 49° 18’ 46.0” / W 124° 14’ 34.2”.

36. Beachcomber Regional Park NW tip of Cottam Point, in Northwest Bay, 7 km E of Parksville city centre, 5 km N of Nanoose Bay, Protection Formation, 6.0 m. Parksville sheet 92F/8, NTS 117630. GPS: 10U 0411683 5462969, N 49° 18’ 47.0” / W 124° 12’ 54.4”.

37. Cottam Point N tip of Cottam Point, facing Mistaken Island, 7 km E of Parksville city centre, 5 km N of Nanoose Bay, Protection Formation, 11.0 m. Parksville sheet 92F/8, NTS 117632. GPS: 10U 0411728 5463161, N 49° 18’ 53.0” / W 124° 12’ 52.3”.

38. Cedar Road & Trans-Canada Hwy. Interchange roadcut immediately E of highway, N side of Cedar Road. Protection Formation, 16.0 m. Nanaimo sheet, 92G/4, NTS 334417. GPS: 10 U 0433322 5441721, N 49° 07’ 29.0” / W 123° 54’ 50.1”.

39. Nanaimo River Canyon II beneath Trans-Canada Hwy. river channel cliff face 10 km SE of City of Nanaimo and 2 km N of airport, generally inaccessible and only measured approximately, Protection Formation, 18.0 m. Nanaimo sheet 92G/4, NTS 356357. GPS: 10 U 0435667 5435690, N 49° 04’ 14.3” / W 123° 52’ 50.7”.

40. Duke Point Hwy. 19 at Trans-Canada Hwy. 1 roadcut exposure on N side of Duke Point Hwy. immediately E of TC Hwy., 6 km SE of Nanaimo, Protection Formation, 20.9 m. Nanaimo sheet 92G/4, NTS 344404. GPS : 10 U 0434448 5440259, N 49° 06' 42.1" / W 123° 53' 53.7" at base to 10 U 0434668 5440367, N 49° 06' 45.5" / W 123° 53' 42.8" at top.

Protection Formation – Cedar District Formation transition

41. Vesuvius Bay Shoreline, Saltspring Island shoreline of Bay from southern point to ferry dock, west shore of Saltspring Island, Protection Formation - Cedar District Formation, 214.3 m. Duncan sheet, 92B/13, NTS 580140 to 581143. GPS: 10U 0458030 5414031, N 48° 52' 40.1" / W 123° 34' 20.7" at base to 10U 0458111 5414340, N 48° 52' 50.3" / W 123° 34' 16.8" at top.

Cedar District Formation

42. Barnes Road Shoreline end of Barnes Road, along Stuart Channel shore, opposite Round Island, 4 km E of Cedar, Cedar District Formation, 82.2 m. Nanaimo sheet, 92G/14, NTS 413410. GPS: 10U 0441278 5441198, N 49° 07' 15.0" / W 123° 48' 17.4" (base) to 10U 0441278 5440952, N 49° 07' 06.9" / W 123° 48' 17.1" (Barnes Road) to 10U 0441254 5440546, N 49° 06' 53.9" / W 123° 48' 18.1" (Nelson Road boat ramp) (top).

43. Highway 19 & Buckley Bay Ferry Interchange along road toward Denman Island ferry terminal, 100 m E of Highway 19, Cedar District Formation, 21.9 m. Comox sheet 92F/10, 661873. GPS: 10 U 0365878 5487369, N 49° 31' 26.8" / W 124° 51' 11.9".

44. Ship Peninsula tidal platform exposure on east side of southern Peninsula, only exposed at low tide, Cedar District Formation, 11.2 m. Horne Lake sheet, 92F/7, NTS 702841. GPS: 10 U 0370277 5484110, N 49° 29' 44.7" / W 124° 47' 29.3" at base.

45. Denman Ferry Dock Shoreline, Denman Island coastal tidal platform section about 0.5 km NW of Denman Island ferry dock, west shore of Island, Cedar District Formation, 12.0 m. Comox sheet, 92F/10, NTS 676888. GPS: 10 U 0367620 548880, N 49° 32' 18.0" / W 124° 49' 50.0".

46. Ganges Harbour Shoreline, Saltspring Island tidal flat and cliff exposure on NE shoreline of Ganges Harbour, behind Moby's Pub, below Hastings House Hotel, Cedar District Formation, 24.5 m. Mayne Island sheet, 92 B / 14, NTS 635118. GPS: 10 U 0463358 5411863, N 48° 51' 31.1" / W 123° 29' 58.4".

47. Fernwood Shoreline, Saltspring Island tidal flat and cliff exposure, NE shoreline of Island, immediately SE of Fernwood, Cedar District Formation, 10.3 m. Duncan sheet, 92 B / 13, NTS 612181. GPS: 10 U 046123 5418105, N 48° 54' 52.8" / W 123° 31' 50.2".

48. Hudson Point Shoreline tidal platform exposure from beach access off North Beach Road, 1 km NW of Fernwood, Saltspring Island, Cedar District Formation, 25.7 m. Duncan sheet 92B/13 598186. GPS: 10 U 0459003 5418660, N 48° 55' 10.5" / W 123° 36' 49.9" at base to 10 U 0459808 5418697, N 48° 55' 11.2" / W 123° 32' 55.1" at top.

49. North Beach Road Shoreline tidal platform exposure from beach access path on North Beach Road toward north, 2 km NW of Fernwood, Saltspring Island, Cedar District Formation, 15.5 m. Duncan sheet 92B/13, 592194. GPS : 10 U 0459157 5419351, N 48° 55' 32.6" / W 123° 33' 27.3" at base to 10 U 0459220 5419333, N 48° 55' 32.0" / W 123°33' 24.4" at top.

Cedar District Formation – De Courcy Formation transition

50. Denman Escarpment, Denman Island small roadcut escarpment adjacent to Denman Rd, E of ferry dock, Cedar District Formation – De Courcy Formation., 17.5 m. Comox sheet, 92F/10, NTS 693887. GPS: 10 U 0369290 5488740, N 49° 32' 15.1" / W 124° 48' 21.6".

51. Gladstone Way, Denman Island coastal section westward on NW shore of Island, Cedar District Formation – De Courcy Formation, 48.4 m. Comox sheet, 92F/10, NTS 671942. GPS: 10 U 0367061 5494118, N 49° 35' 05.9" / W 124° 50' 21.2" at base to 10 U 0367113 5494627, N 49° 35' 22.6" / W 124° 50' 19.2" at top.

52. Southey Point, Saltspring Island tidal flat exposures from Southey Bay westward around tip of Point, northern tip of Saltspring Island, Cedar District Formation – De Courcy Formation, 31.5 m. Duncan sheet, 92B/13, NTS 563213. GPS: 10 U 0456299 5421240, N 48° 56' 33.5" / W 123° 35' 48.5" at base to 10 U 0456215 5421039, N 48° 56' 26.6" / W 123° 35' 52.5" at top.

De Courcy Formation

53. Blue Heron Park along Stuart Channel shoreline, off Yellow Point Rd, 8.5 km E of Nanaimo Airport, De Courcy Formation, 2.0 m. Nanaimo sheet, 92G/14, NTS 448327. GPS: 10U 0444732 5432706, N 49° 02' 41.3" / W 123° 45' 22.6".

54. Robert's Memorial Provincial Park along Stuart Channel shoreline, off Yellow Point Rd, 7.5 km E of Nanaimo Airport, De Courcy Formation, 4.0 m. Nanaimo sheet, 92G/14, NTS 438347. GPS: 10U 0443752 5434732, N 49° 03' 46.3" / W 123° 46' 12.0".

55. De Courcy Road Shoreline end of De Courcy Rd, along Stuart Channel, N of Robert's Memorial Provincial Park, 8 km SE of Cedar, De Courcy Formation, 10.2 m. Nanaimo sheet, 92G/14, NTS 426364. GPS: 10U 0442493 5436452, N 49° 04' 57.8" / W 123° 47' 18.1".

56. Duke Point Barge Terminal partway up Duke Point peninsula at 870 Jackson Rd, 5 km SE of Nanaimo, De Courcy Formation, 40.2 m. Nanaimo sheet, 92G/14, NTS 362435. GPS: 10U 0436164 5443504, N 49° 08' 27.2" / W 123° 52' 30.7".

57. Coffin Point southern tip of Coffin Point, east of Evening Cove, 4 km E of Ladysmith, De Courcy Formation, 105.7 m. Duncan sheet, 92B/13, NTS 443263. GPS: 10U 0444012 5426310, N 48° 59' 14.2" / W 123° 45' 54.9".

58. Nanaimo Observation Well #390 Corehole (OW-11-01), NW corner of Holden Corso and Lofthouse Roads near village of Cedar, De Courcy Formation, 118.26 m (388 ft). Nanaimo sheet 92G/14, 399398. GPS: 10 U 0439917 5439794, N 49° 06' 29.1" / W 123° 49' 23.6".

59. Bill Mee Park, Denman Island coastal exposure on SE shore of Denman Island, SE of Hornby Island Ferry Dock, De Courcy Formation, 24.1 m. Horne Lake sheet, 92F/7, NTS 775833. GPS: 10 U 0377328 5483167, N 49° 29' 19.4" / W 124° 41' 37.8" at base to 10 U 0376685 5483436, N 49° 29' 27.7" / W 124° 42' 10.0" at top.

60. Whalebone Point, Denman Island coastal tidal platform and cliff NW along shoreline from cove, along E shore of Island, De Courcy Formation, 31.4 m. Comox sheet 92F/10, NTS 747853 to 743858. GPS: 10 U 0374660 5484938, N 49° 30' 14.8" / W 124° 43' 52.5" at base to 10 U 0374197 5485793, N 49° 30' 42.1" / W 124° 44' 16.4"at top.

61. Lindsey Road large roadcut along escarpment 1.5 km NE of village of Cedar, De Courcy Formation, 38.5 m. Nanaimo sheet, 92G/4, NTS 385416. GPS: 10 U 0438080 5441583, N 49° 07' 29.6" / W 123° 50' 55.1".

Northumberland Formation

62. St. Mary Lake Roadcut, Saltspring Island roadcut on St. Mary Lake Road, across from small swimmers parking spot, E shore of Lake, Northumberland Formation, 24.4 m. Duncan sheet, 92B/13, NTS 607159. GPS: 10 U 0460721 5416094, N 48° 53' 47.2" / W 123° 32' 09.6" at base to 10 U 0460723 5416052, N 48° 53' 46.2" / W 123° 32' 09.2" at top.

APPENDIX II – Nanaimo Group Detailed Measured Sections

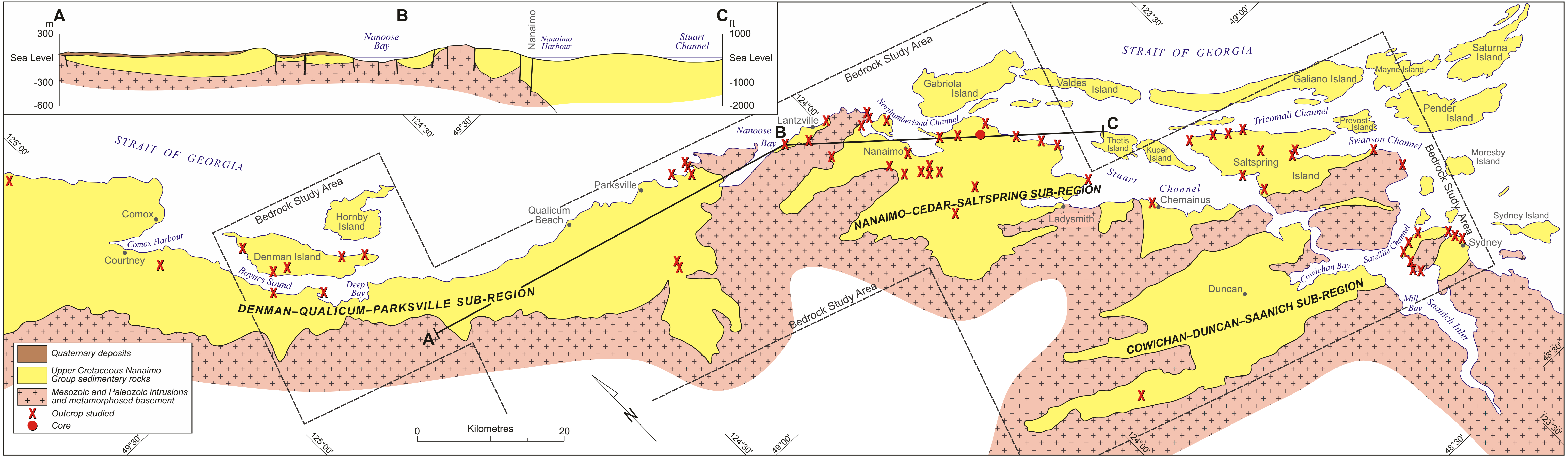


Figure 1. Outcrop and core locations, Nanaimo Lowland Bedrock Aquifer Study field area (geology simplified from Muller and Jeletzky, 1970).

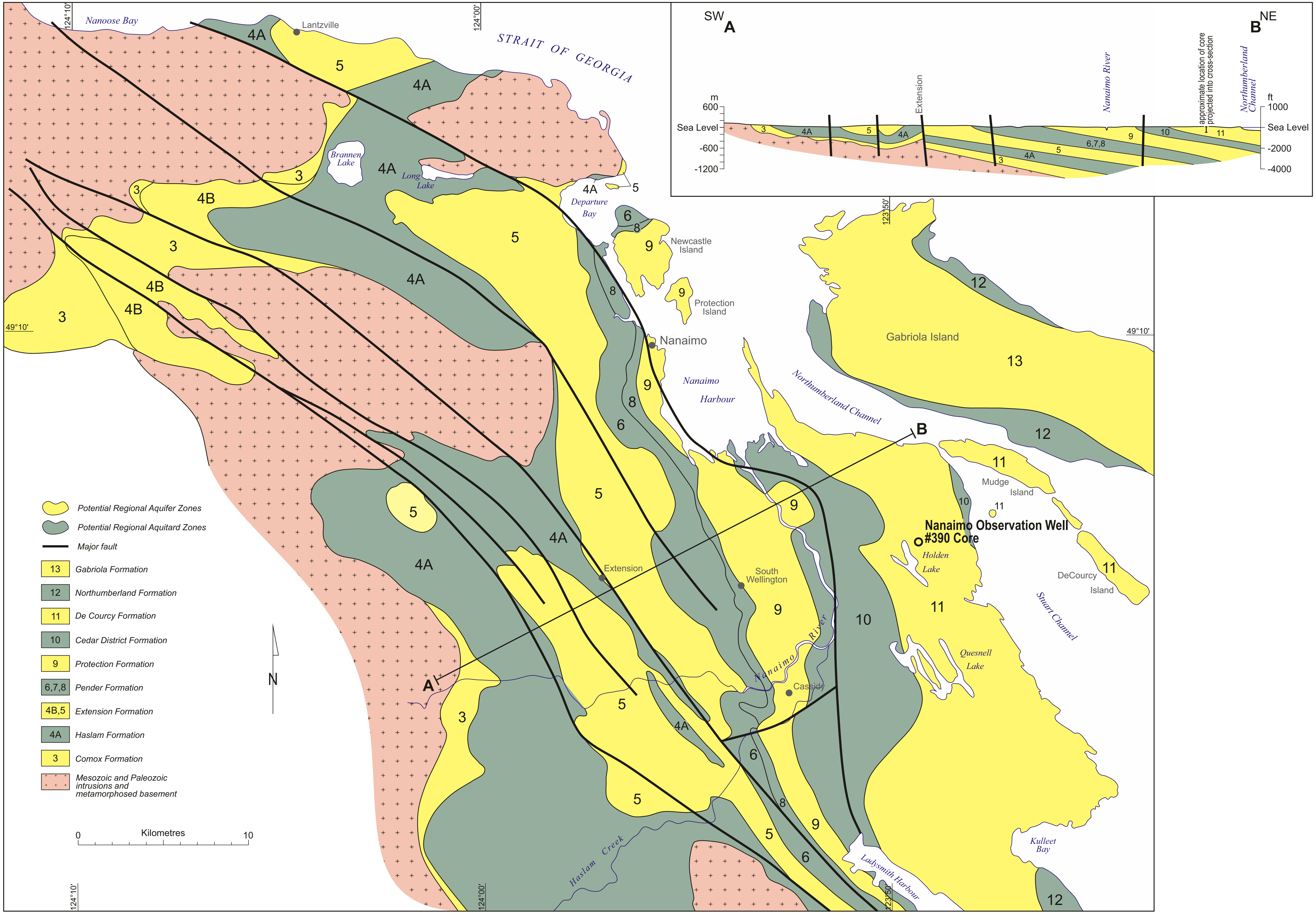


Figure 2. Geology of Nanaimo sub-region, with location of studied core, illustrating monoclinal eastward-dipping ramp structure and alternating coarse- and fine-grained units (geology simplified from Clapp, 1914; Buckham, 1947; Muller and Jeletzky, 1970).

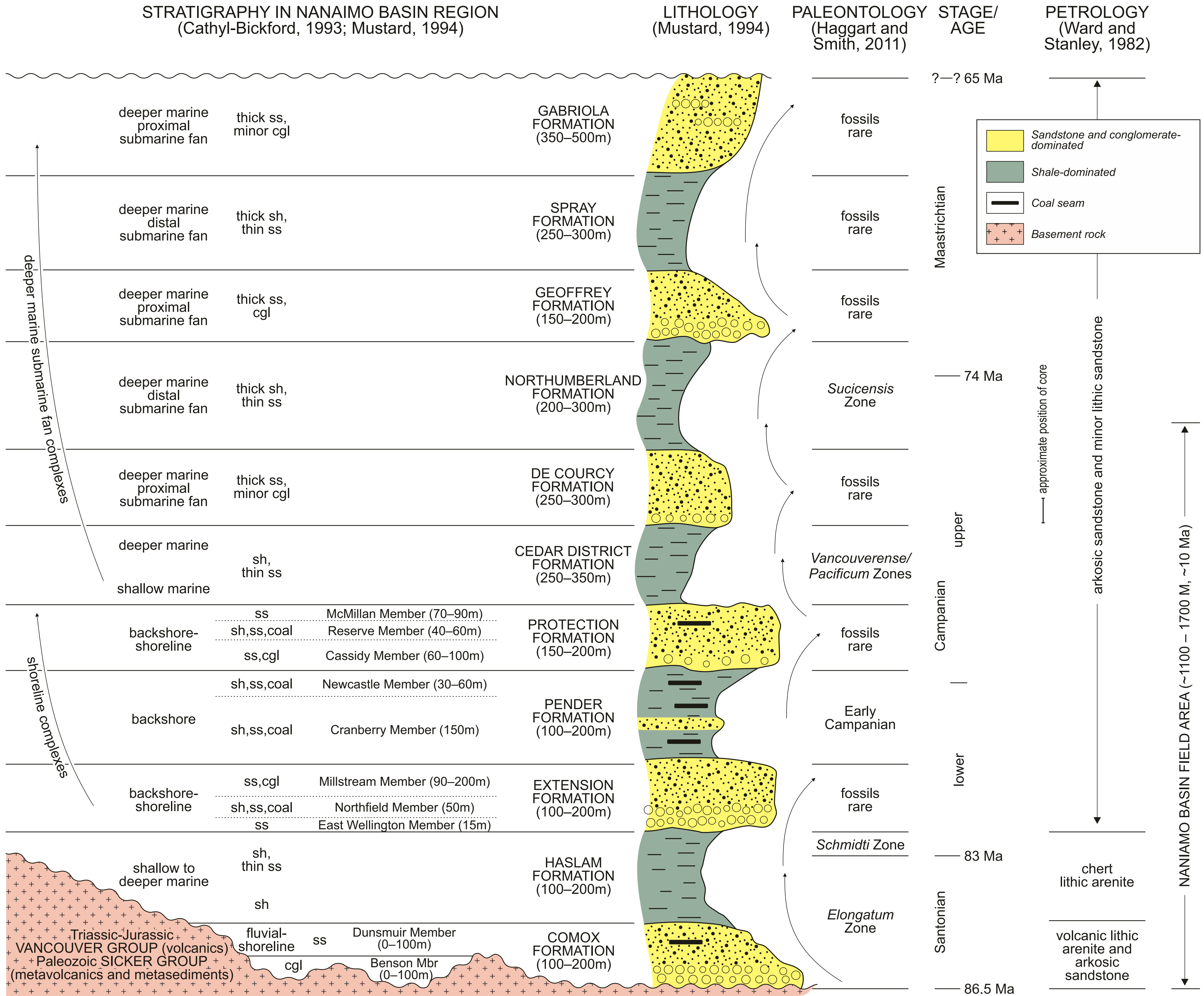


Figure 3. Simplified stratigraphy of the Upper Cretaceous Nanaimo Group of eastern Vancouver Island (simplified from Muller and Jeletzky, 1970; Cathyl-Bickford, 1993; Mustard, 1994).

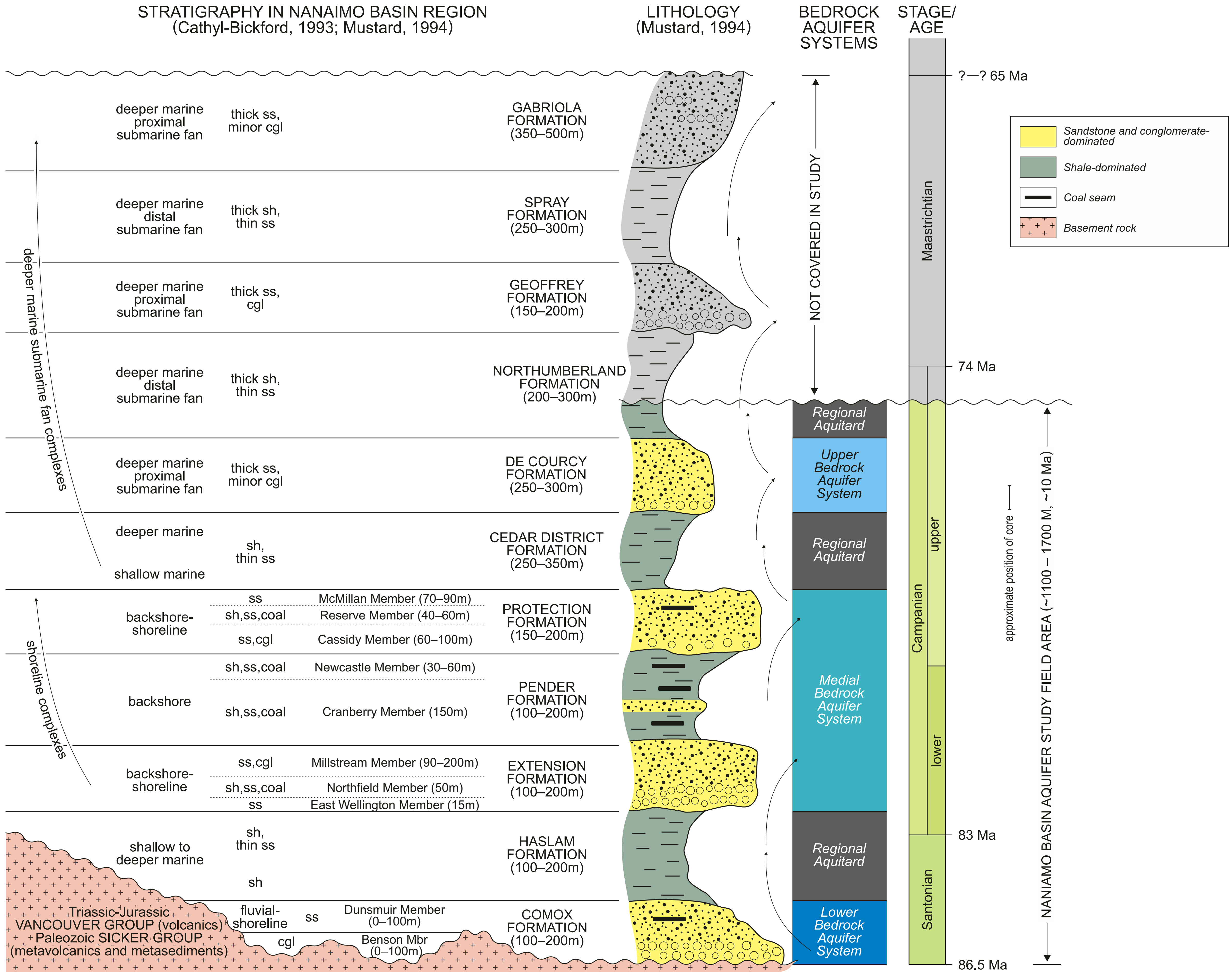


Figure 16. Simplified stratigraphy, illustrating alternating coarse-grained (aquifer) and fine-grained (aquitard) units and interpreted Bedrock Aquifer Systems (simplified from Muller and Jeletzky, 1970; Cathyl-Bickford, 1993; Mustard, 1994).

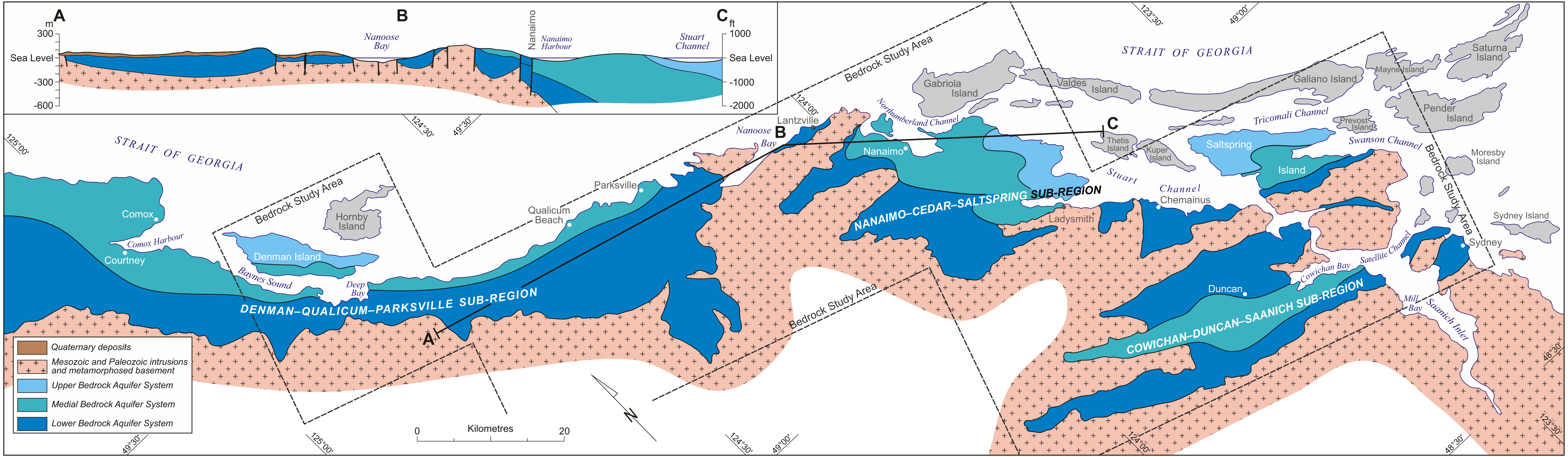
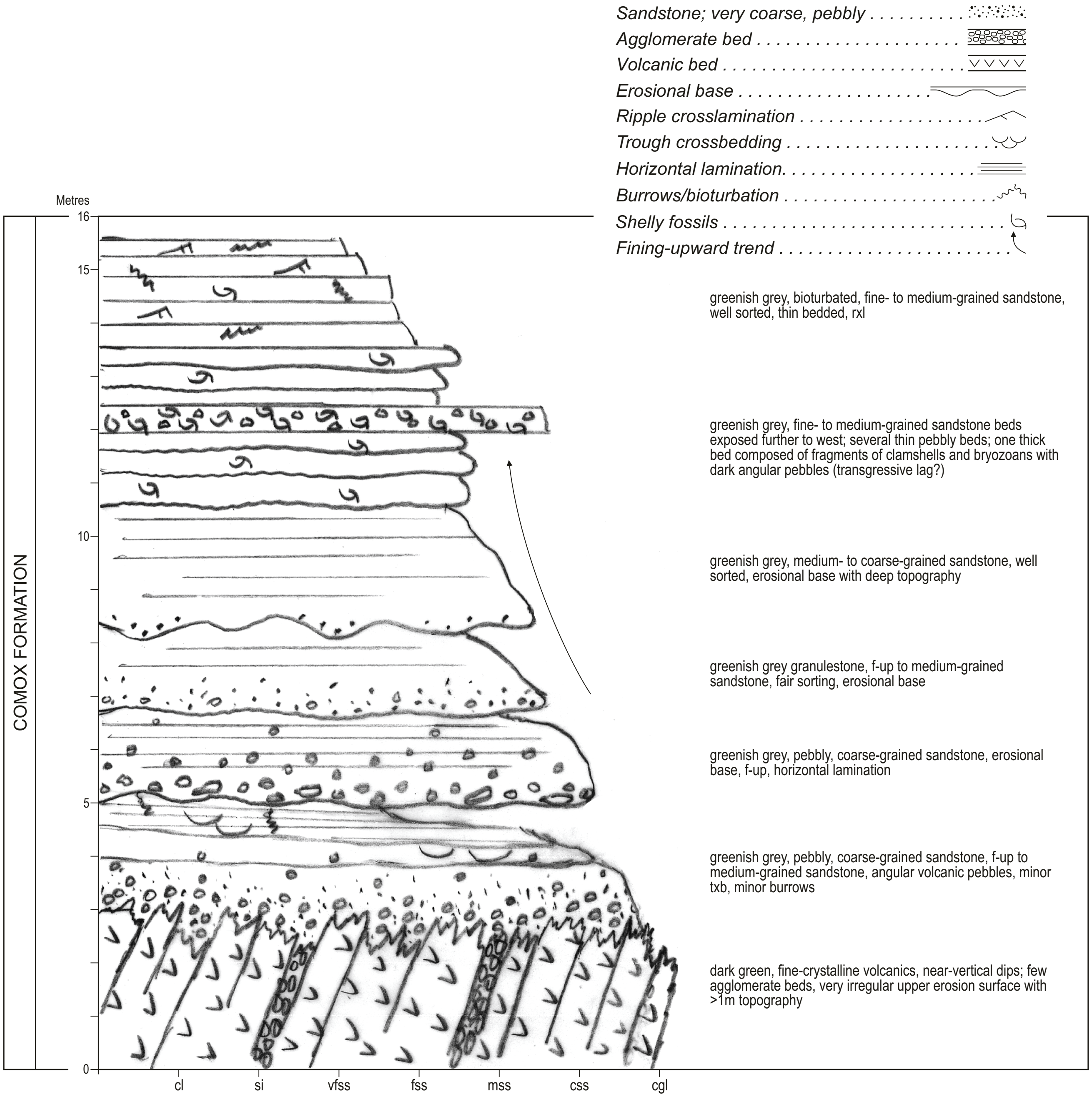
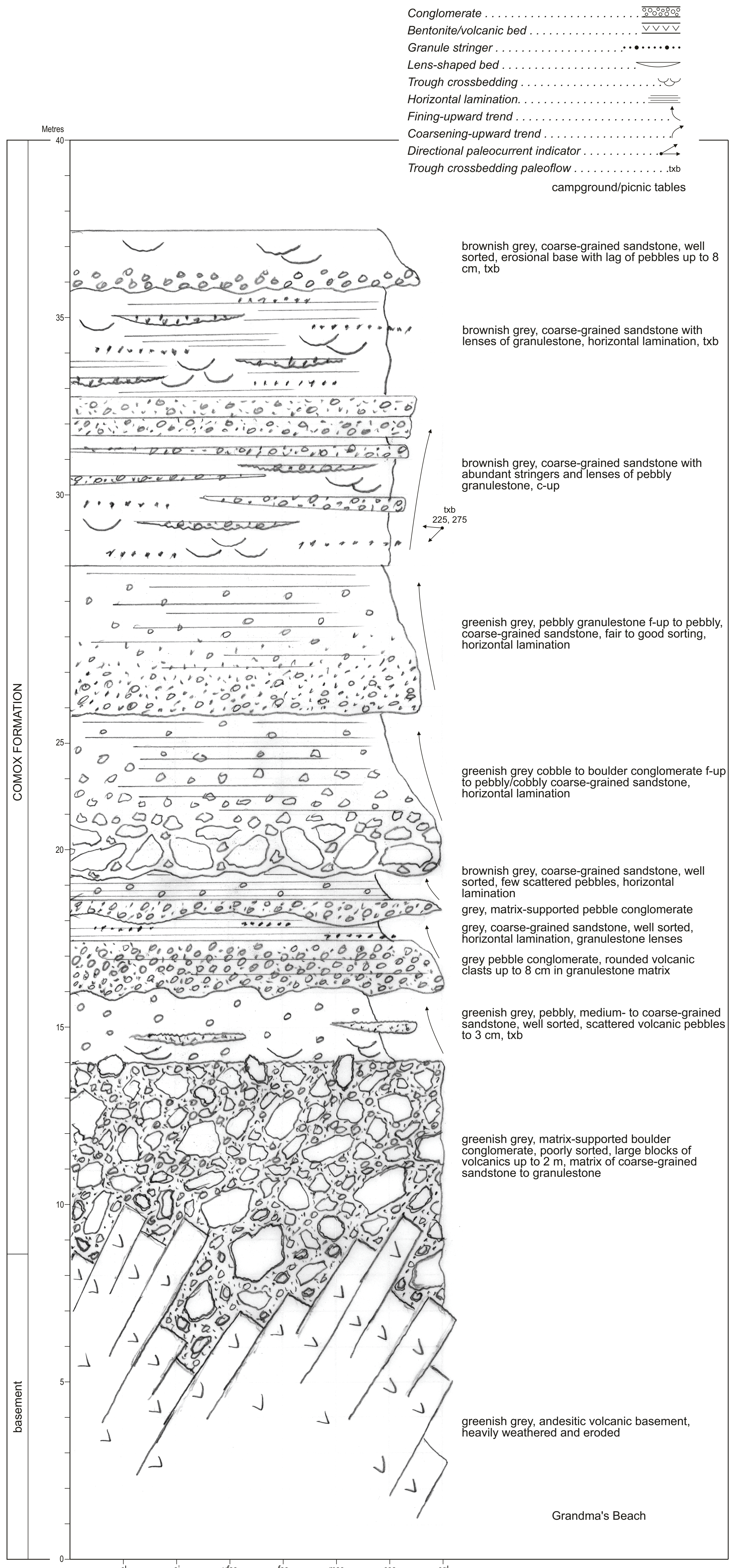


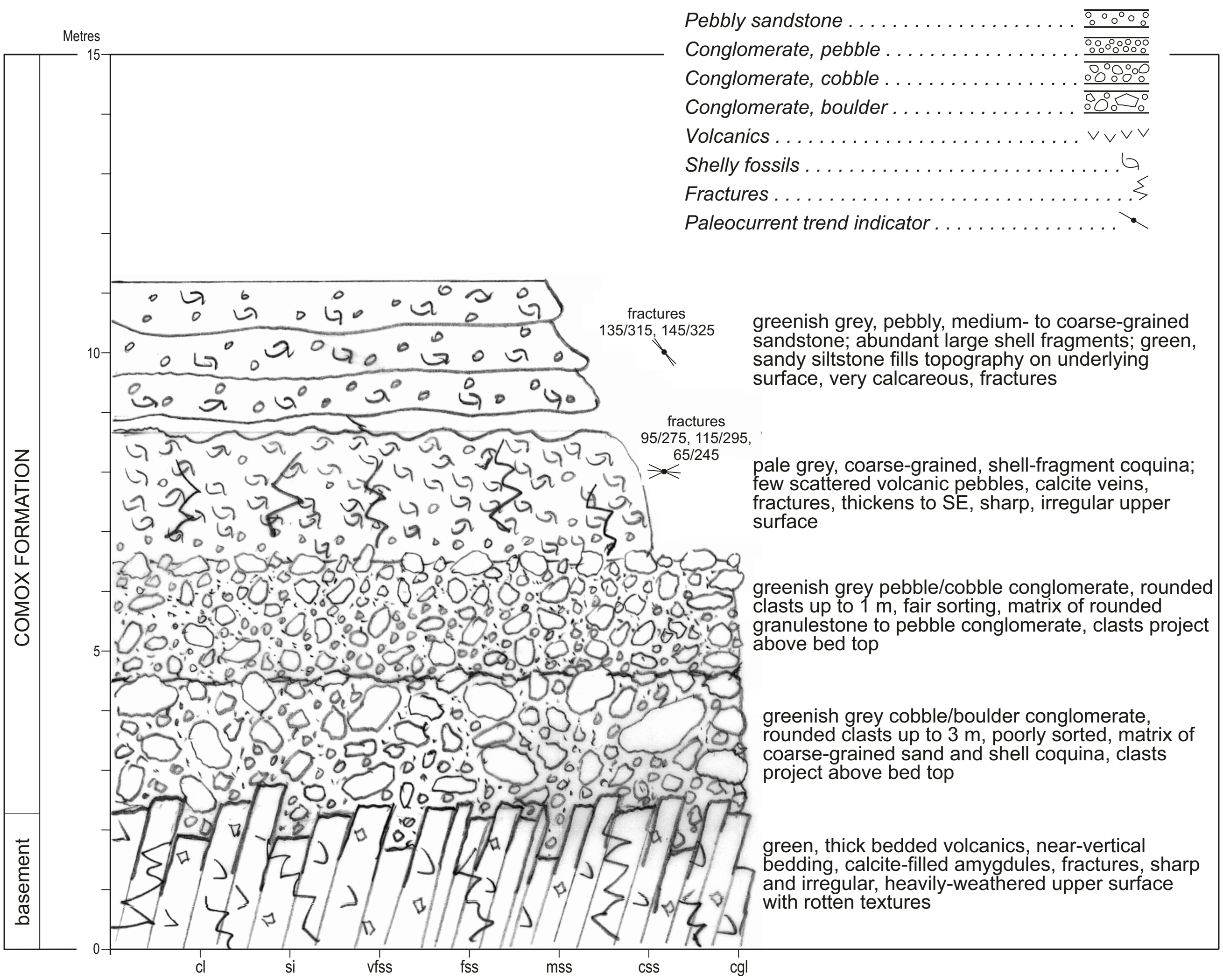
Figure 17. Simplified distribution of interpreted Bedrock Aquifer Systems, Nanaimo Group, eastern Vancouver Island.



Appendix Figure 1
Entwhistle Drive Shoreline
end of Entwhistle Drive, off Hammond Bay Road, North Nanaimo
Comox Formation
NTS Map 92G/14 (Nanaimo)
49° 14' 22.7"N, 123° 59' 27.6"W; UTM Zone 10: 0427858E, 5454580N

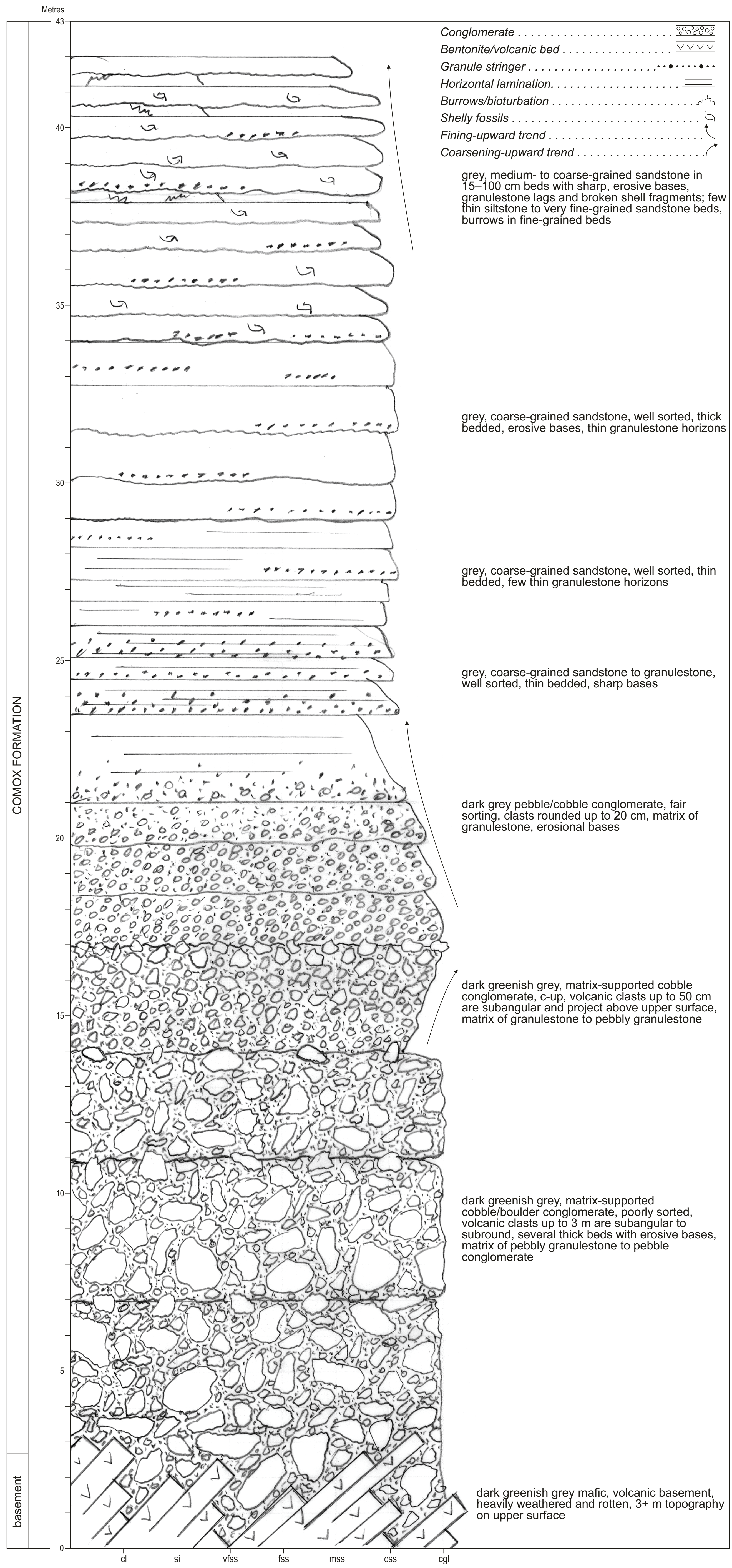


Appendix Figure 2
South Ruckle Park, Saltspring Island
dangerous tidal flat and cliff exposures along S shore of Beaver Point peninsula, from Grandma's Beach cove to campground
volcanic basement – Comox Formation
NTS Map 92B/14 (Mayne Island) 725016
48° 46' 03.0" N, 123° 22' 30.4" W; UTM Zone 10: 0472435E, 5401676N at base;
48° 46' 00.7" N, 123° 22' 18.0" W; UTM Zone 10: 0472689E, 5401603,N at top

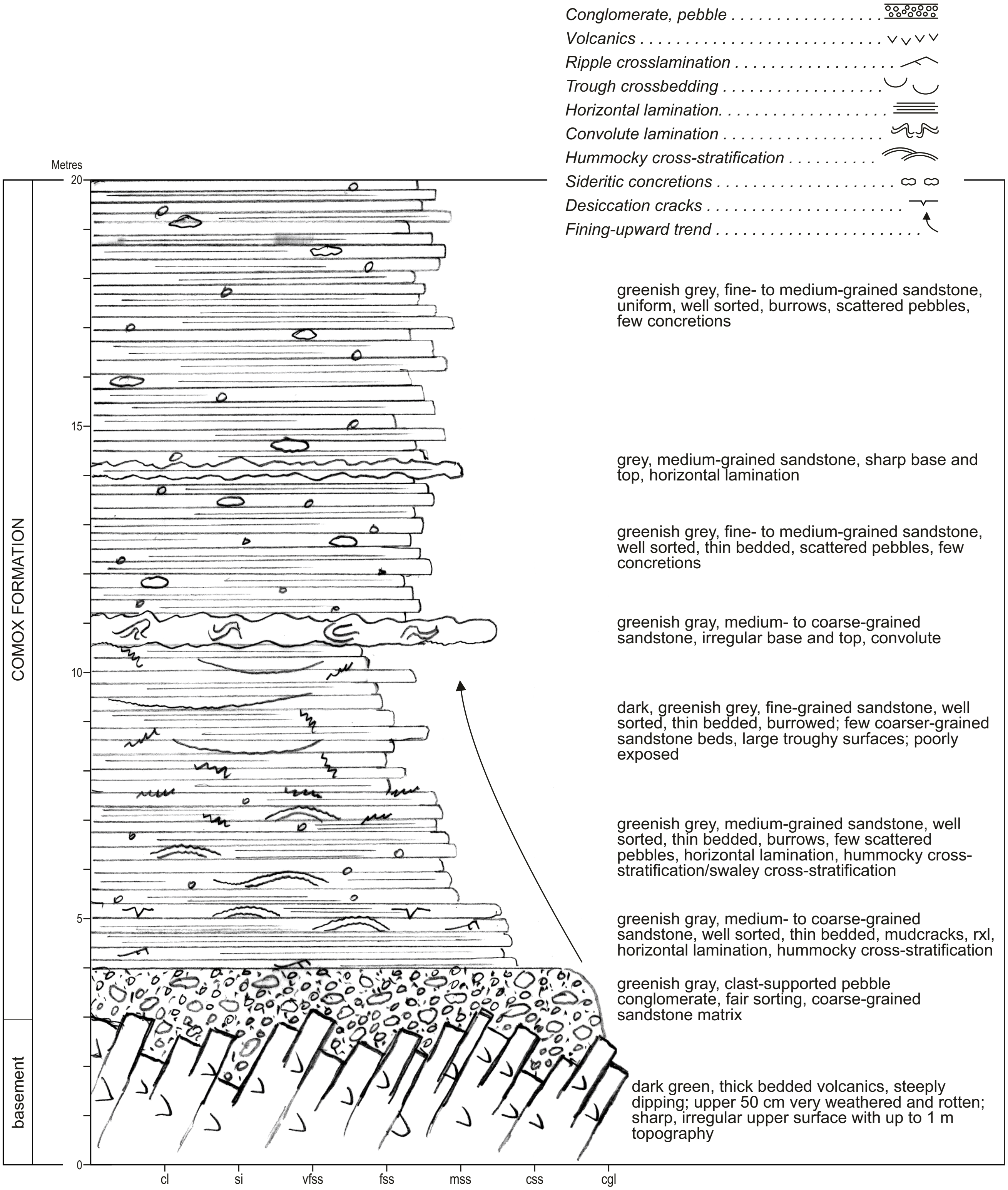


Appendix Figure 3
Horsewell Bluff II

coastal exposure immediately SW of end of Stephenson Point Road beach access stairway
basement – Comox Formation
NTS Map 92G/4 (Nanaimo) 314514
49° 12' 42.2" N, 123° 56' 29.8" W; UTM Zone 10: 0431421E, 5451417N

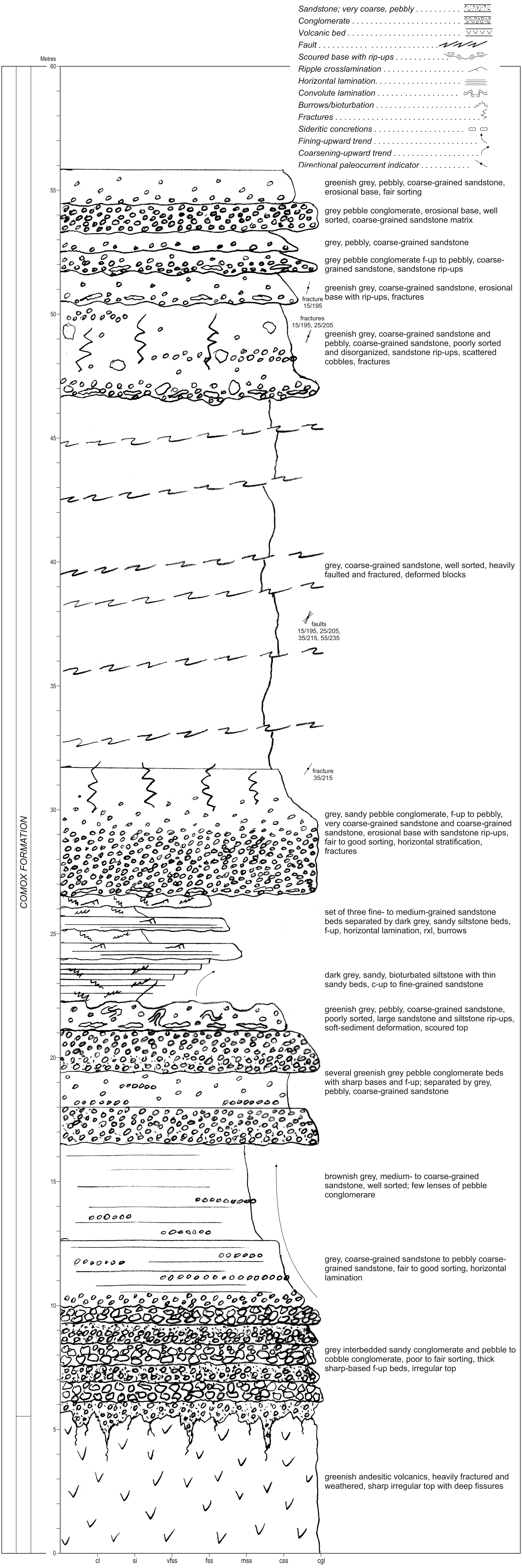


Appendix Figure 4
Nanaimo Parkway/Jingle Pot Road ("Malaspina Roadcut")
large roadcut on S side of highway, 0.5 km SE of Jinglepot Road/3rd Street intersection in Nanaimo
basement – Comox Formation
NTS Map 92G/4 (Nanaimo) 286462
49° 09' 55.0" N, 123° 58' 45.8" W; UTM Zone 10: 0428603E, 5446293N



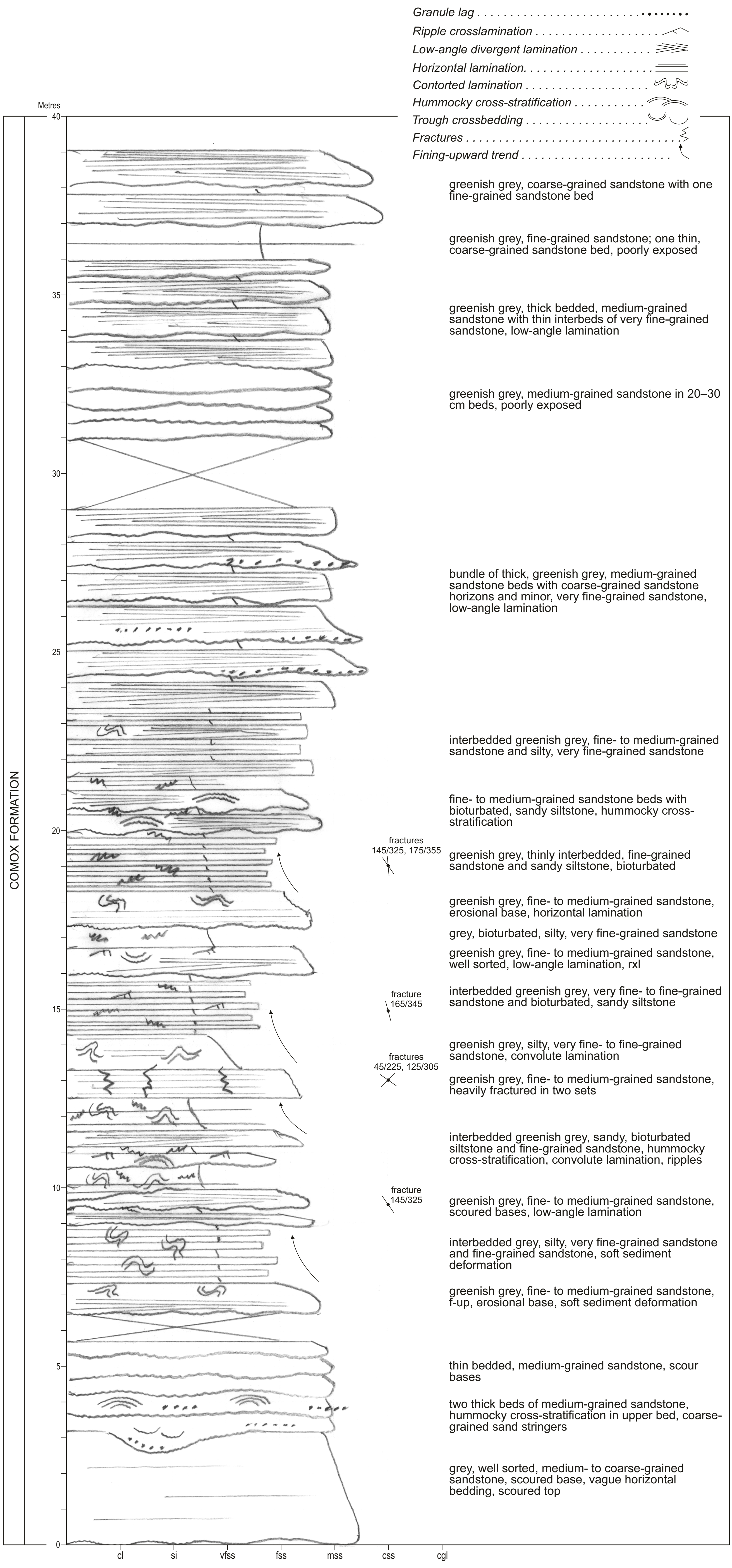
Appendix Figure 5
Armstrong Point

coastal and tidal flat exposure NW along shore from access stairway at end of Allbay Road
basement – Comox Formation
NTS Map 92B/11 (Sidney) 708906
48° 40' 01.6" N, 123° 23' 49.9" W; UTM Zone 10: 0470754E, 5390527N



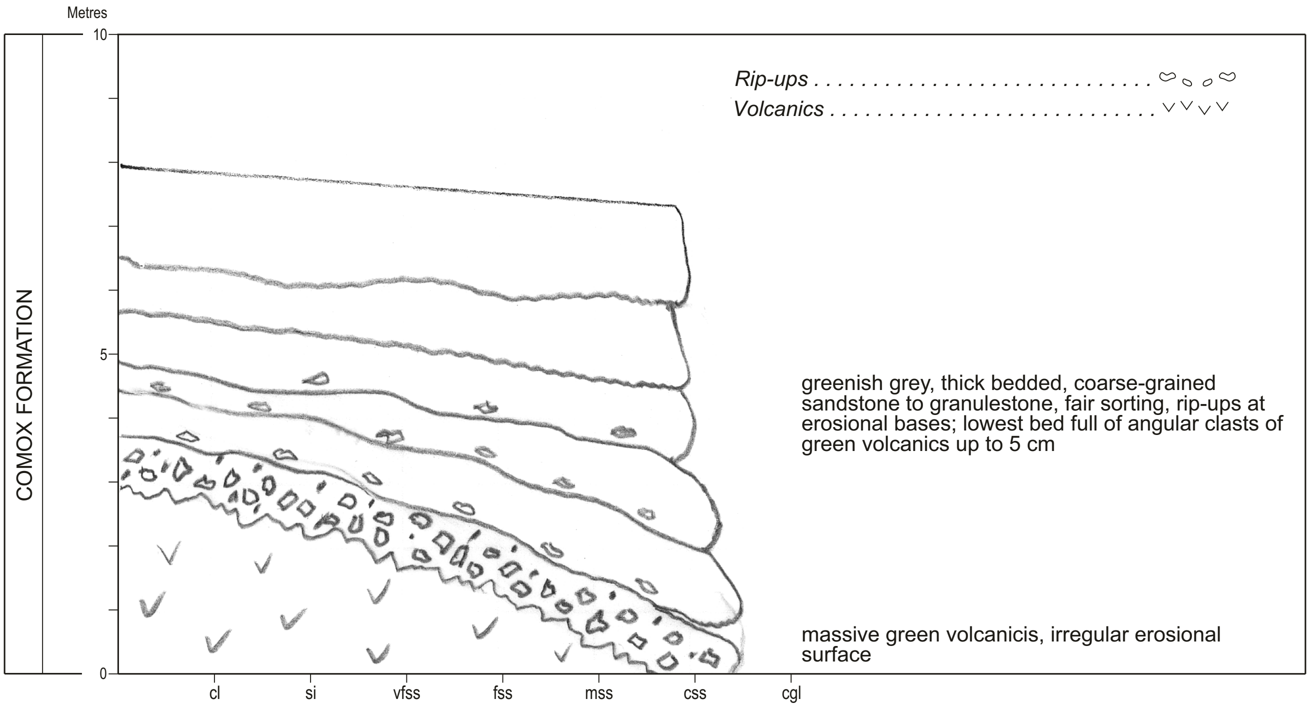
Appendix Figure 6
Towner Road Shoreline

tidal flat and bank exposure W of Towner Road beach access,
S of Deep Cove and 4 km W of Sidney
Basement–Comox Formation
NTS Map 92B/11 (Sidney) 648907
48° 40' 06.1"N, 123° 28' 43.0"W UTM Zone 10: 0464760E, 5390702N (base) to
48° 40' 08.7"N, 123° 28' 42.7"W UTM Zone 10: 0464767E, 5390782N (top)



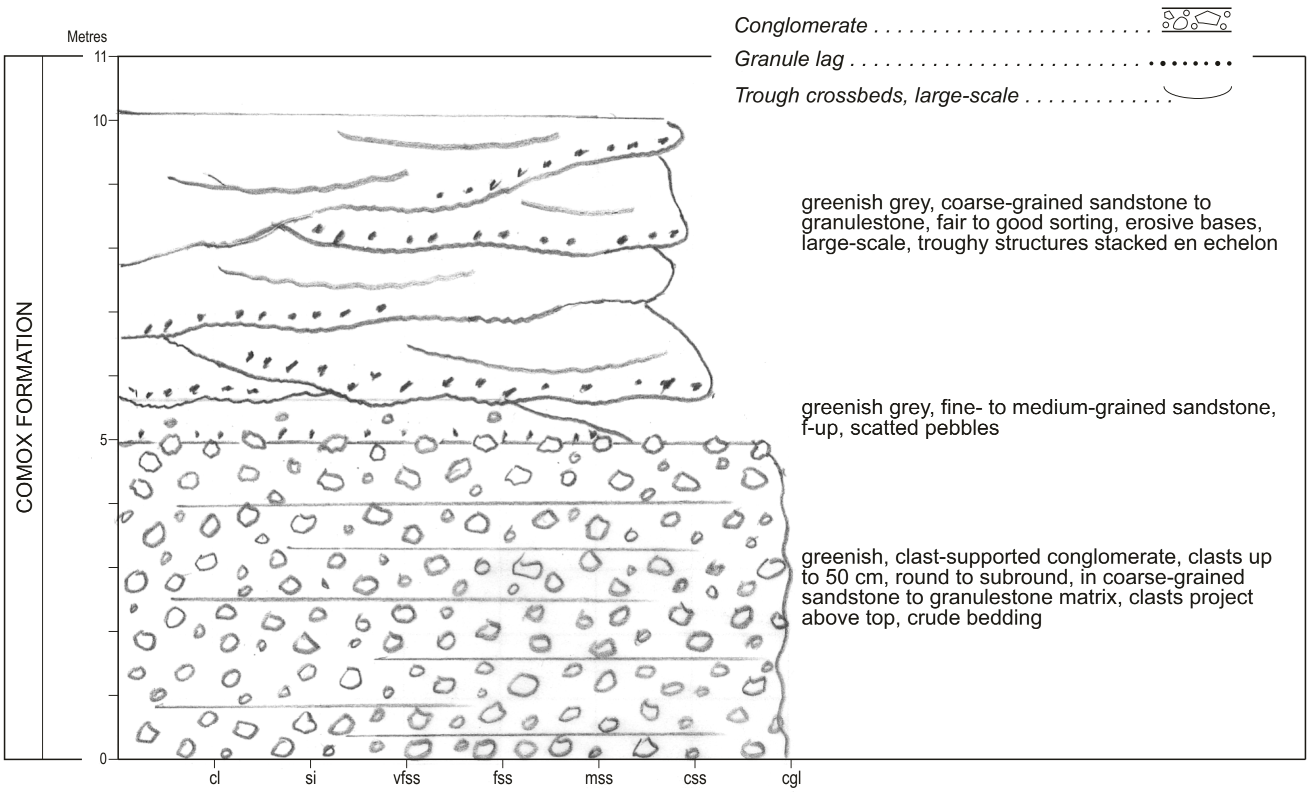
Appendix Figure 7
Moses Point

NW tip of Saanich Peninsula, 8 km NW of Sidney
Comox Formation
NTS Map 92B/11 (Sidney)
49° 41' 22.5"N, 123° 29' 06.3"W; UTM Zone 10: 0464300E, 5393061N

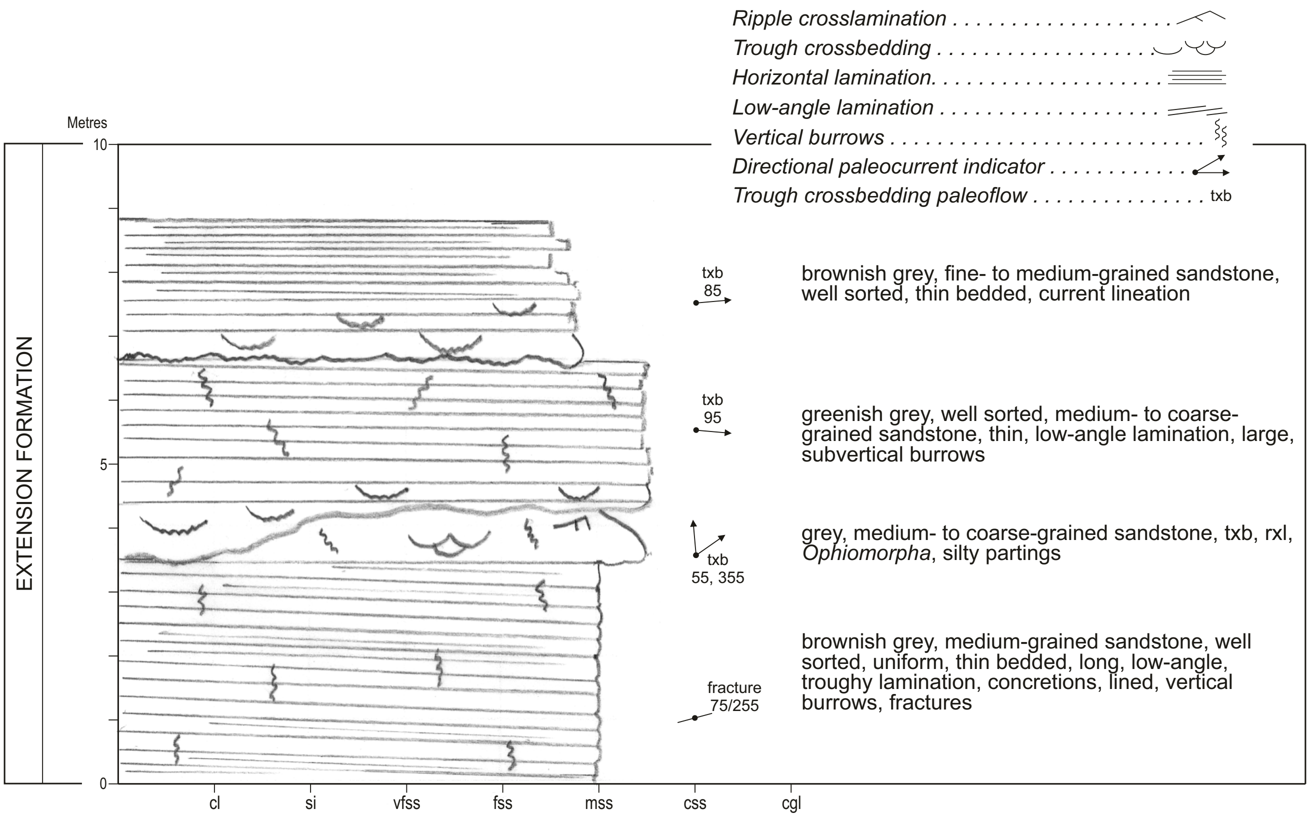


Appendix Figure 8
Pacific Biological Station

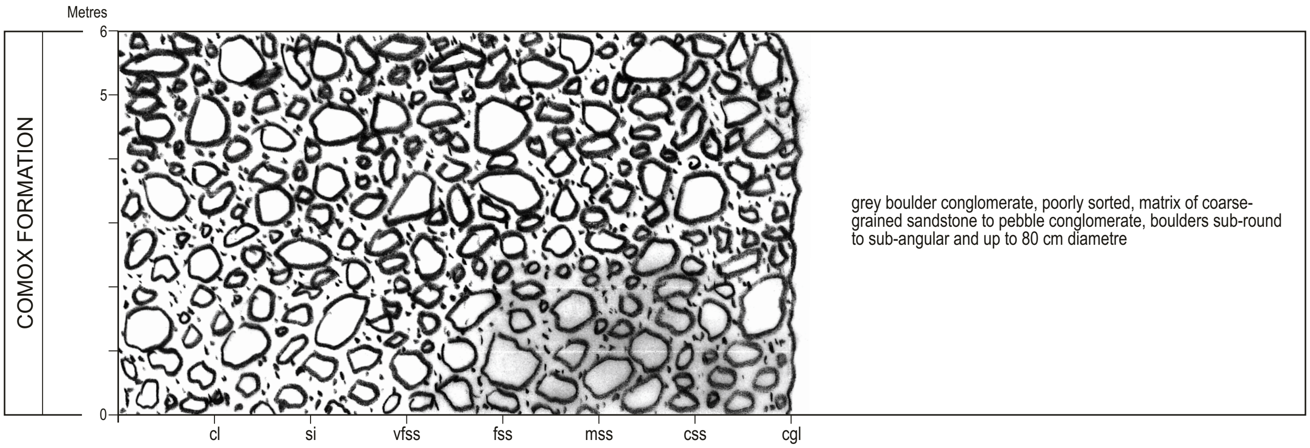
Stephenson Point Road, Departure Bay, 5 km N of Nanaimo city centre
Comox Formation
NTS Map 92G/14 (Nanaimo)
49° 12' 36.6"N, 123° 57' 15.8"W; UTM Zone 10: 0430491E, 5451261N



Appendix Figure 9
Horsewell Bluff
end of Stephenson Point Road, Departure Bay, 5 km N of Nanaimo city centre
Comox Formation
NTS Map 92G/14 (Nanaimo)
48° 12' 48.6"N, 123° 56' 25.6"W; UTM Zone 10: 0431508E, 5451611N



Appendix Figure 10
Blunden Point
end of Sebastien Road, south shoreline of Nanoose Harbour, 1 km NW of Lantzville
Extension Formation
NTS Map 92F/8 (Parksville)
49° 15' 24.8"N, 124° 05' 04.0"W; UTM Zone 10: 0421091E, 5456578N



Appendix Figure 11

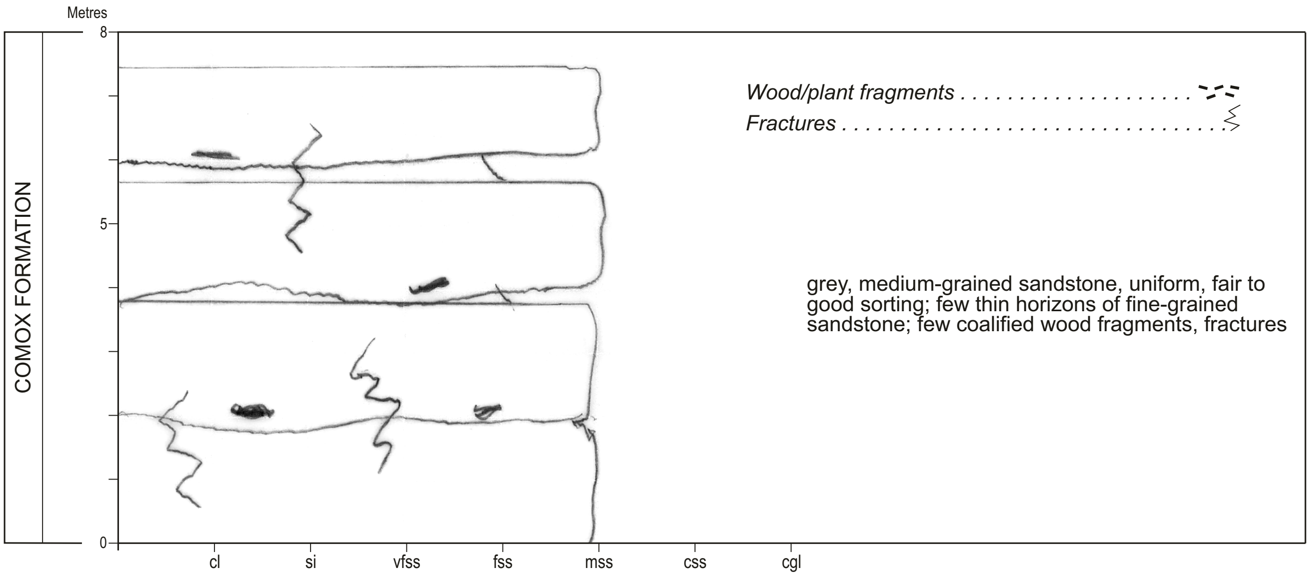
Englishman River Falls (Upper Falls)

small cliff area across from Upper Falls

Comox Formation

NTS Map 92F/1 (Nanaimo Lakes)

49° 14' 36.2"N, 124° 20' 53.3"W; UTM Zone 10: 0401875E, 5455307N

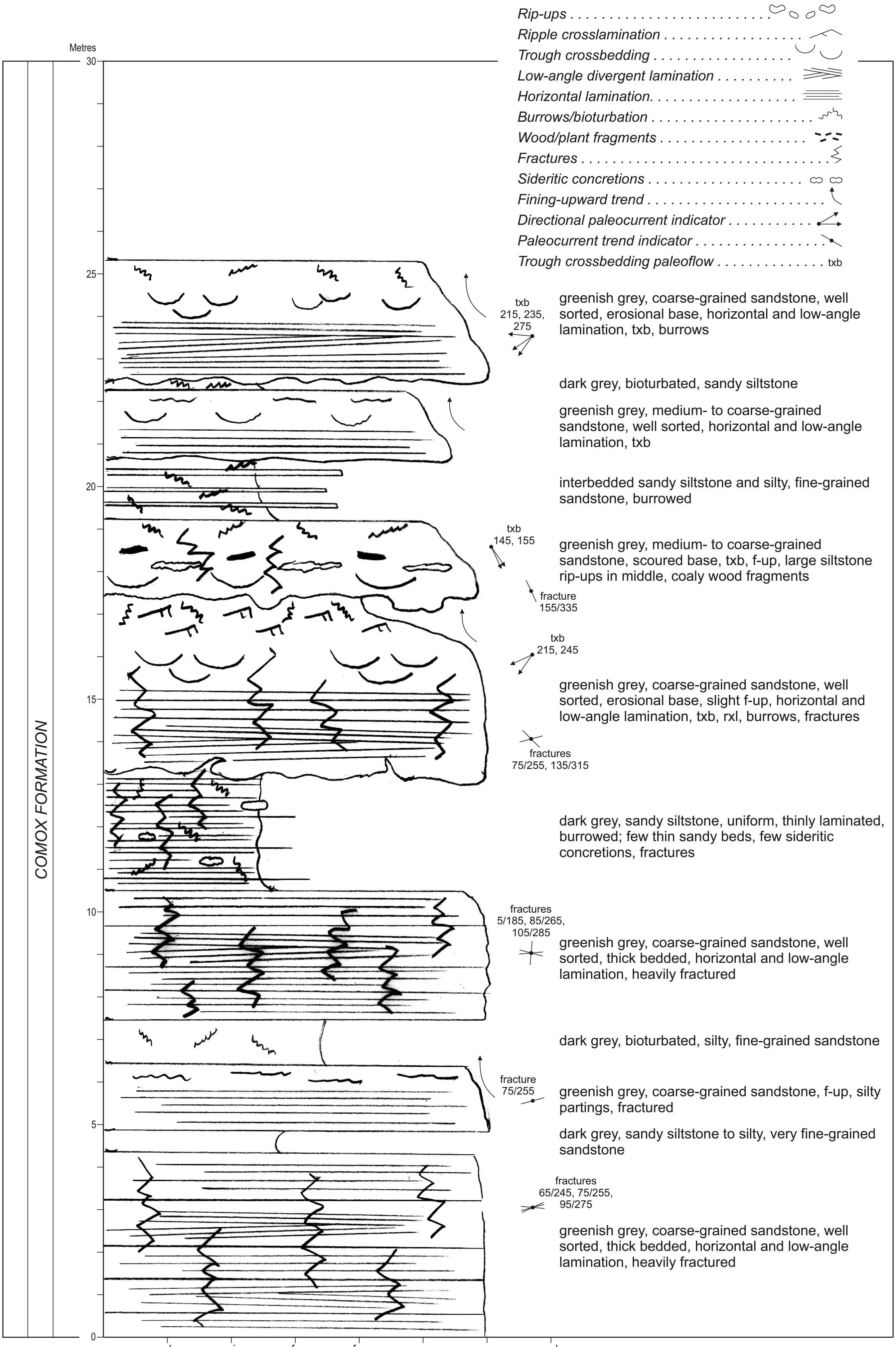


Appendix Figure 12
Highway 19 & Miracle Beach Interchange
roadcut at intersection of Highway 19 and Hamm Road to Miracle Beach Provincial Park
Comox Formation
NTS Map 92F/14 (Oyster River) 423222
49° 49' 48.0" N, 125° 11' 23.5" W; UTM Zone 10: 0392513E, 5522029N

Appendix Figure 13
Highway 17, Schwarz Bay Roadcut
large roadcut on NW side of highway 1 km W of Ferry Terminal immediately W of Lands End Road
Comox Formation
NTS Map 92B/11 (Sidney) 692922
48° 40' 52.4" N, 123° 25' 10.6" W; UTM Zone 10: 0469320E, 5392105N at base;
48° 40' 57.7" N, 123° 24' 51.3" W; UTM Zone 10: 0469470E, 5392264N at top

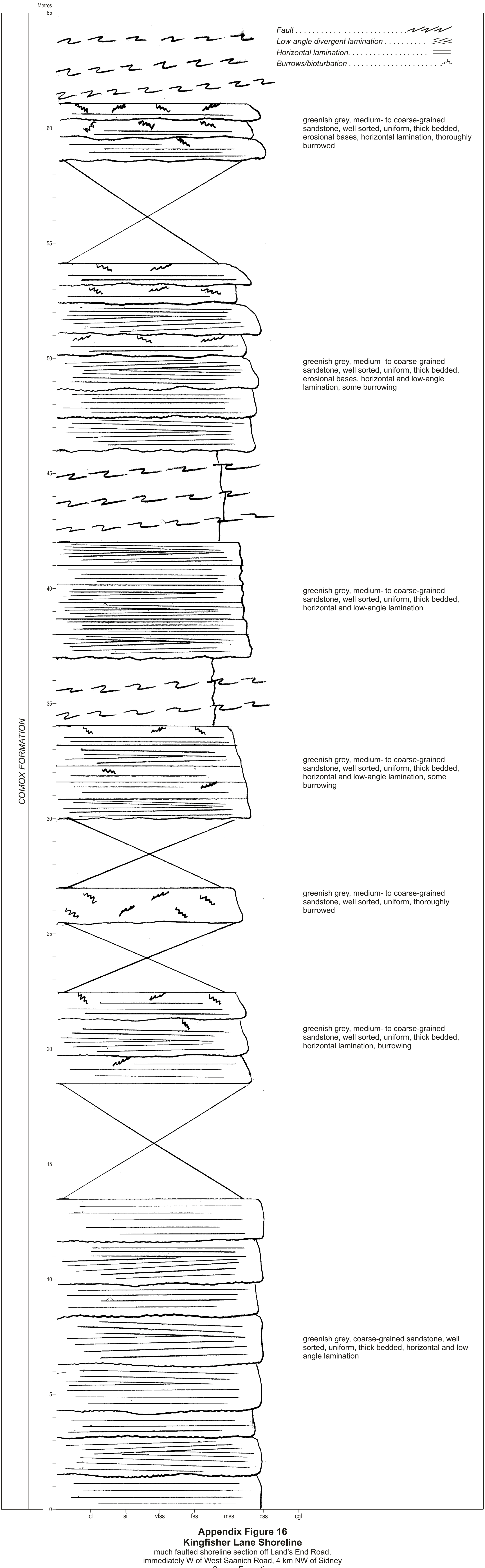
Appendix Figure 14
Norris Road Shoreline

long tidal flat and cliff exposure from foot of Norris Road beach access stairway to headland, S of Deep Cove and 4 km W of Sidney
Comox Formation
NTS Map 92B/11 (Sidney) 646909
48° 40' 13.2"N, 123° 25' 43.2"W; UTM Zone 10: 0464758E, 5390017N (base) to
48° 40' 20.5"N, 123° 28' 56.7"W; UTM Zone 10: 0464483E, 5391148N (top)

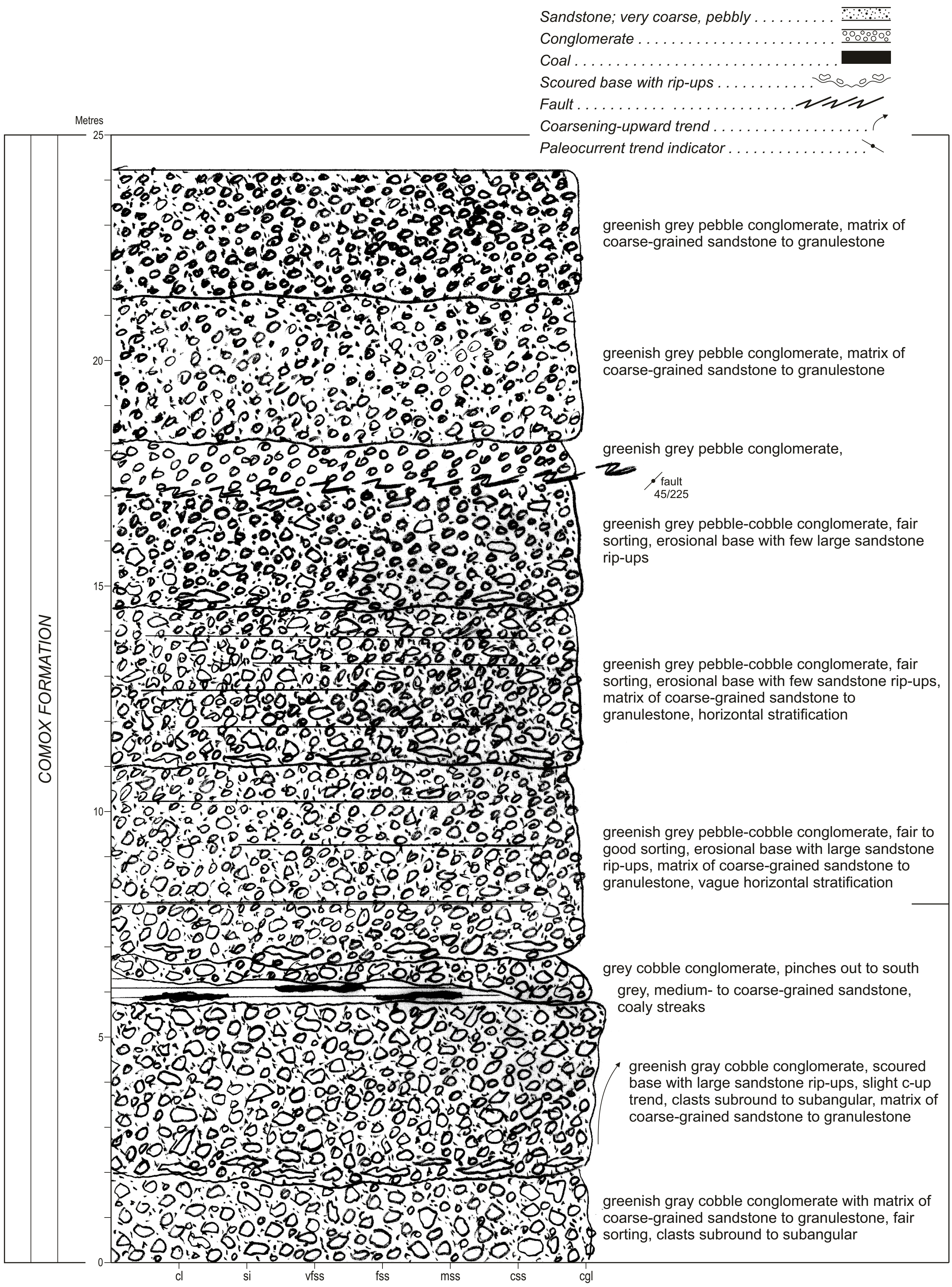


Appendix Figure 15
Cromar Road Shoreline

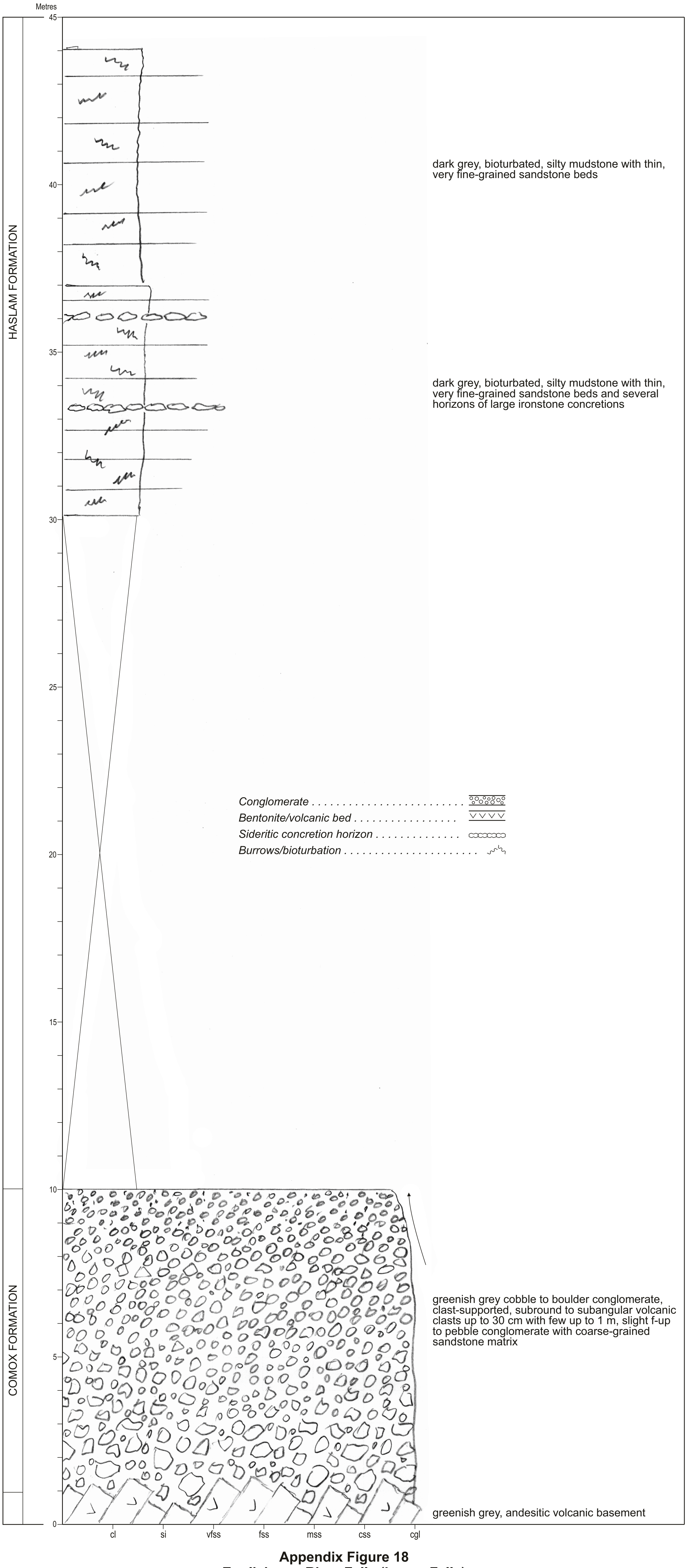
tidal platform exposure at bottom of access stairway at intersection of Madrona Road and Cromar Road, S of Deep Cove and 4 km W of Sidney
Comox Formation
NTS Map 92B/11 (Sidney) 644915
48° 40' 29.8"N, 123° 28' 59.1"W; UTM Zone 10: 0464477E, 5391432N (base) to
48° 40' 30.9"N, 123° 29' 01.7"W; UTM Zone 10: 0464301E, 5391468N (top)



Appendix Figure 16
Kingfisher Lane Shoreline
much faulted shoreline section off Land's End Road,
immediately W of West Saanich Road, 4 km NW of Sidney
Comox Formation
NTS Map 92B/11 (Nanaimo) 660938
48° 41' 42.7"N, 123° 27' 38.6"W UTM Zone 10: 0466098E, 5393830N (base) to
49° 41' 48.6"N, 123° 27' 52.1"W UTM Zone 10: 0465819E, 5393861N (top)

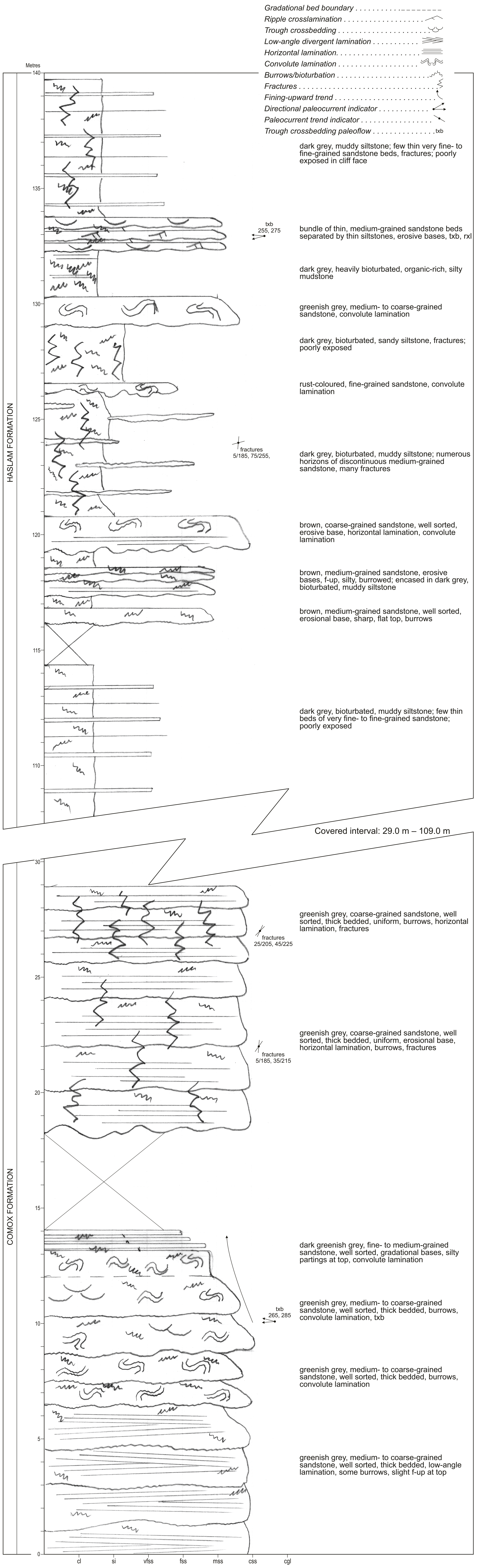


Appendix Figure 17
Highway 19 and Auld's Road
roadcut exposure along Highway 19 on SW corner of intersection, in north Nanaimo, 2 km N of Brannen Lake
Comox Formation
NTS Map 92F/01 (Nanaimo Lakes) 234537
49° 13' 55.6"N, 124° 03' 06.5"W; UTM Zone 10: 0423429E, 5453789N (base) to
49° 13' 46.0"N, 124° 03' 06.3"W; UTM Zone 10: 0423424E, 5453499N (top)



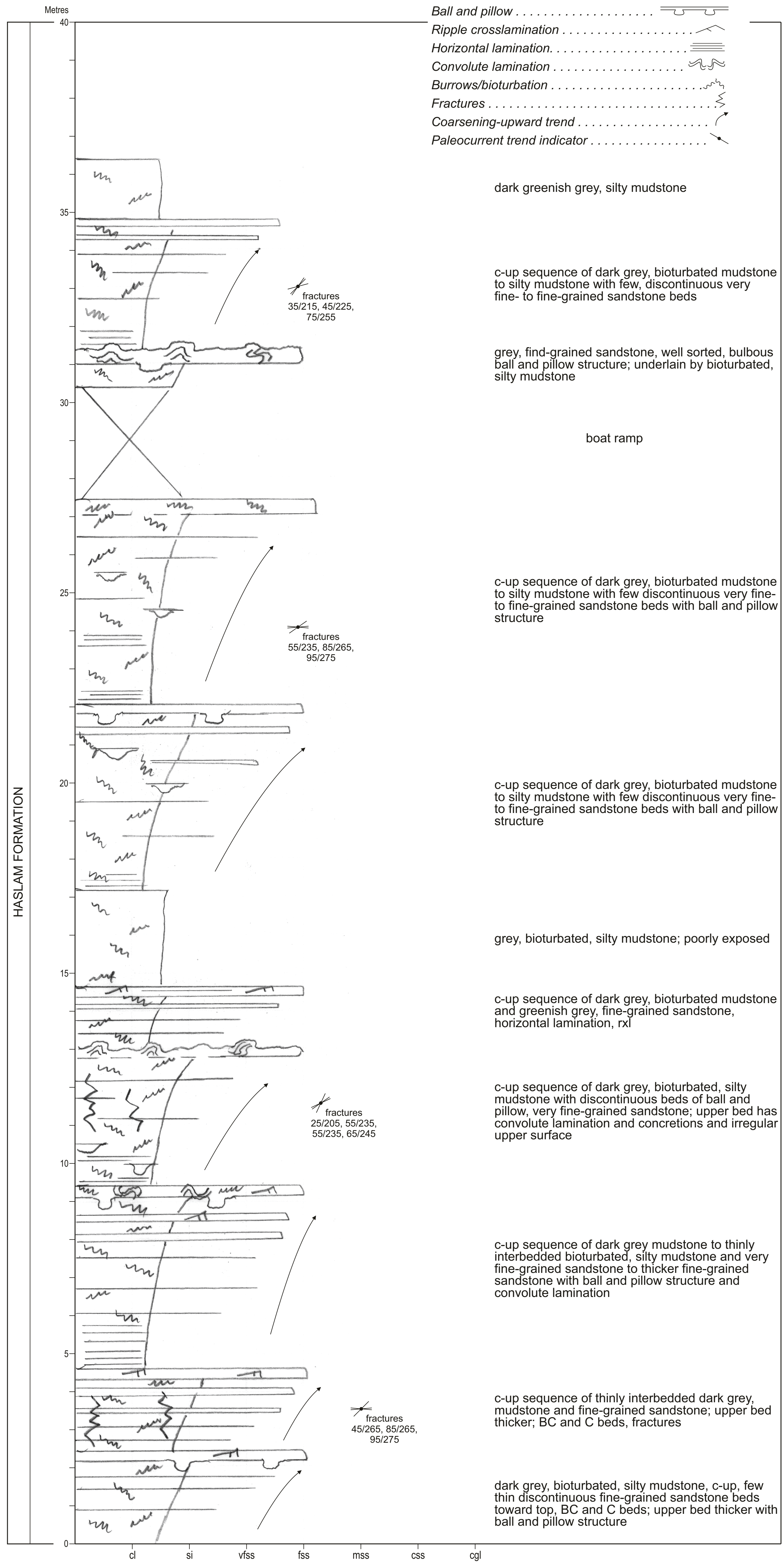
Appendix Figure 18
Englishman River Falls (Lower Falls)
exposure at Lower Falls and northward along river
Comox – Haslam formations
NTS Map 92F/1 (Nanaimo Lakes) 019557
49° 14' 50.6" N, 124° 20' 55.8" W; UTM Zone 10: 0401835E, 5455831N at base;
49° 15' 02.4" N, 124° 20' 48.3" W; UTM Zone 10: 0401918E, 5456086N at top

Appendix Figure 19
Beddes Beach, Saltspring Island
tidal flat and cliff exposures SE along shore from Beddes Beach
public access to Cusheon Creek, SE shore of island
Comox – Haslam formations
NTS Map 92B/14 (Mayne Island) 688063
48° 48' 23.1"N, 123° 25' 21.1"W; UTM Zone 10: 0468973E, 5406026N at base
48° 48' 33.8"N, 123° 25' 32.5"W; UTM Zone 10: 0468743E, 5406353N at top



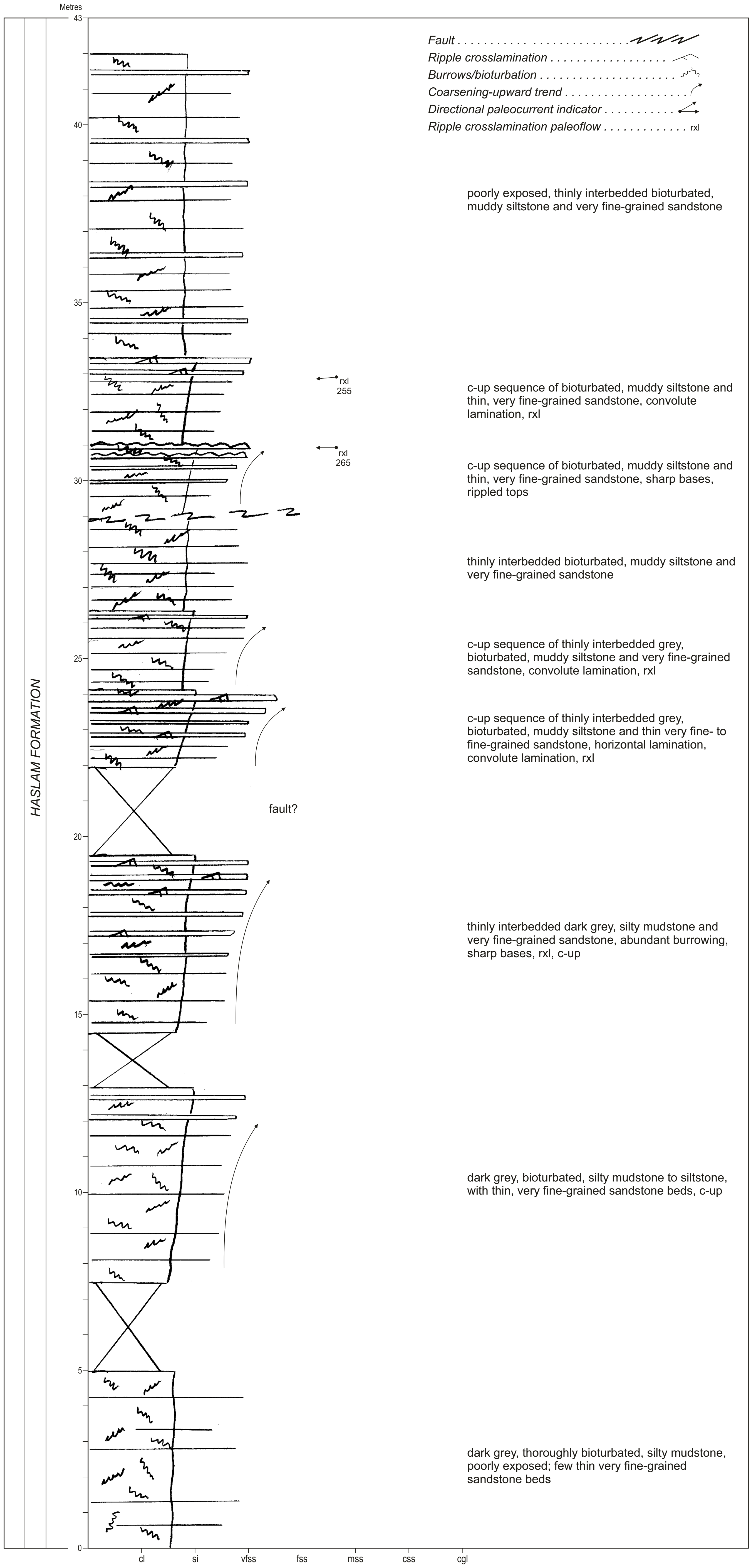
Appendix Figure 20
Bryden Bay Beach
tidal flat exposure to S and to E of access with long covered interval between
Comox – Haslam formations
NTS Map 92B/11 (Sidney) 710904
48° 40' 27.1" N, 123° 24' 36.1" W; UTM Zone 10: 0469014E, 5391319N

Appendix Figure 21
Marie Canyon
Cowichan River Provincial Park, Marie Canyon access, off Riverbottom Road, 16 km W of Duncan
Haslam Formation
NTS Map 92B/13 (Duncan)
48° 46' 39.5"N, 123° 55' 31.0"W; UTM Zone 10: 0432117E, 5402961N



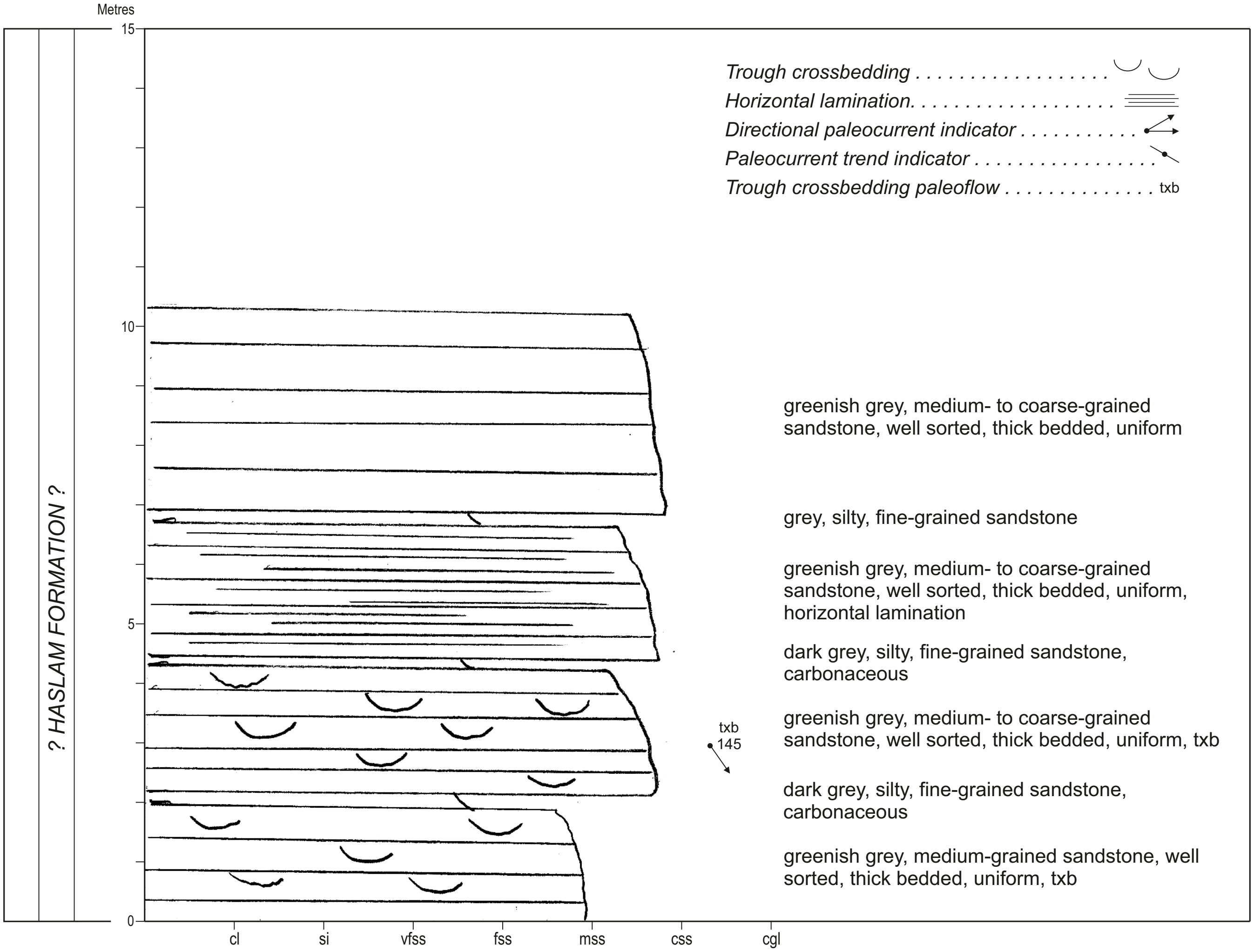
Appendix Figure 22
Chemainus Kin Beach Park Boat Launch

tidal flat exposures on NW shoreline of Chemainus Harbour, from Kin Beach at foot of Maple Street SE toward hospital
Haslam Formation
NTS Map 92B/13 (Duncan) 476197
48° 55' 43.4" N, 123° 43' 02.4" W; UTM Zone 10: 0447456E, 5419778N at base;
48° 55' 40.1" N, 123° 45' 54.7" W; UTM Zone 10: 0447614E, 5419680N at top



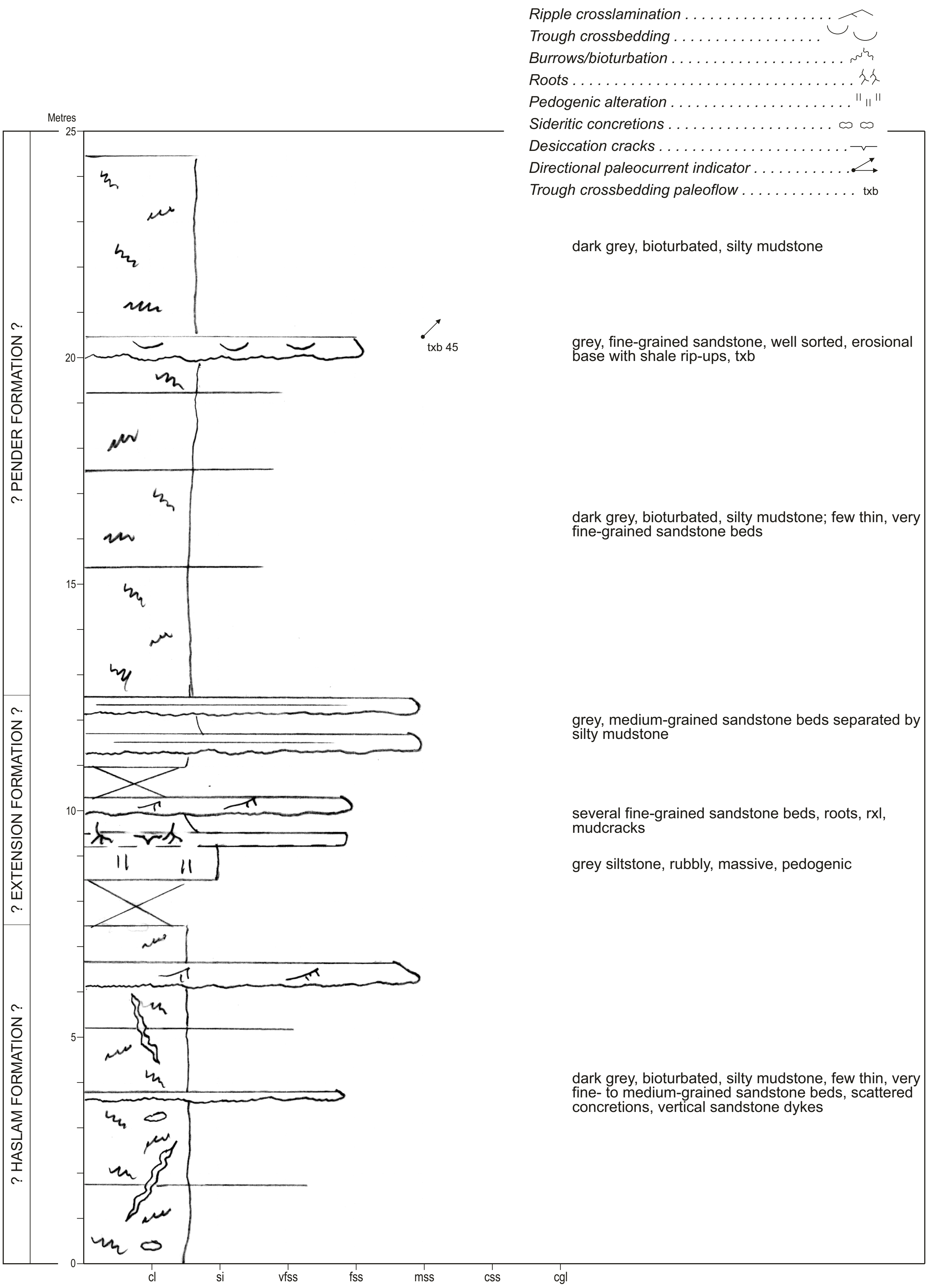
Appendix Figure 23
Seabreeze Road Shoreline

tidal platform exposure at bottom of access stairway near Land's End Road,
4 km NW of Sidney
Haslam Formation
NTS Map 92B/11 (Sidney) 670941
48° 41' 55.4"N, 123° 26' 54.7"W UTM Zone 10: 0464996E, 5394065N (base) to
48° 41' 57.9"N, 123° 26' 47.1"W UTM Zone 10: 0467152E, 5394138N (top)



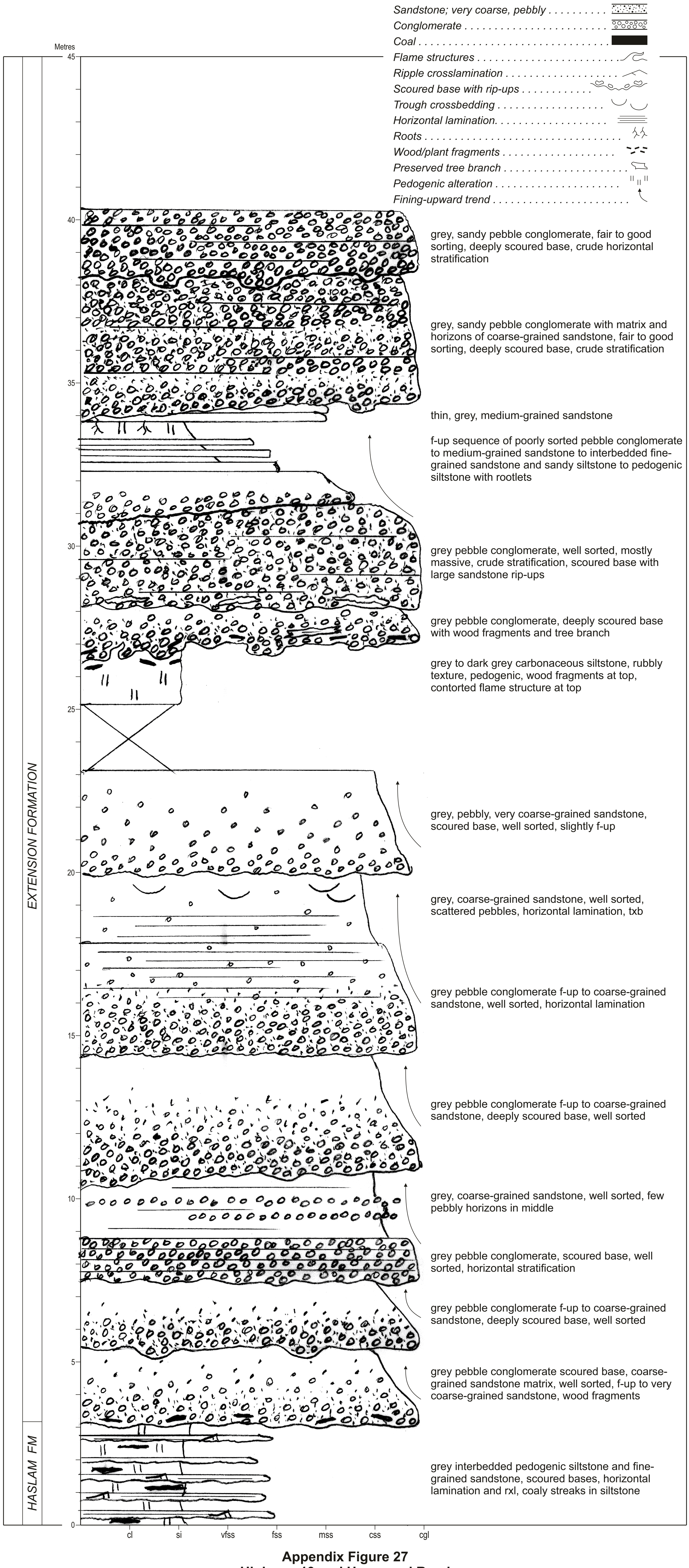
Appendix Figure 24
Highway 19 and Jingle Pot Road
roadcut exposure along Highway 19 NW of Jingle Pot Road/Mostar Road intersection,
accessed from Biggs Road, in north Nanaimo, 1 km SE of Brannen Lake
Haslam Formation
NTS Map 92F/01 (Nanaimo Lakes) 243511
49° 12' 27.6"N, 124° 02' 25.7"W; UTM Zone 10: 0424214E, 5451061N

Appendix Figure 25
Erskine Point, Saltspring Island
unnamed bay 500 m east of Erskine Point, west shore of Saltspring Island
Haslam Formation/Extension Formation
NTS Map 92B/13 (Duncan)
base of section: 48° 51' 08.1"N, 123° 33' 47.2"W; UTM Zone 10: 0458693E, 5411184N
top of section: 48° 51' 19.1"N, 123° 33' 43.1"W; UTM Zone 10: 0458775E, 5411523N

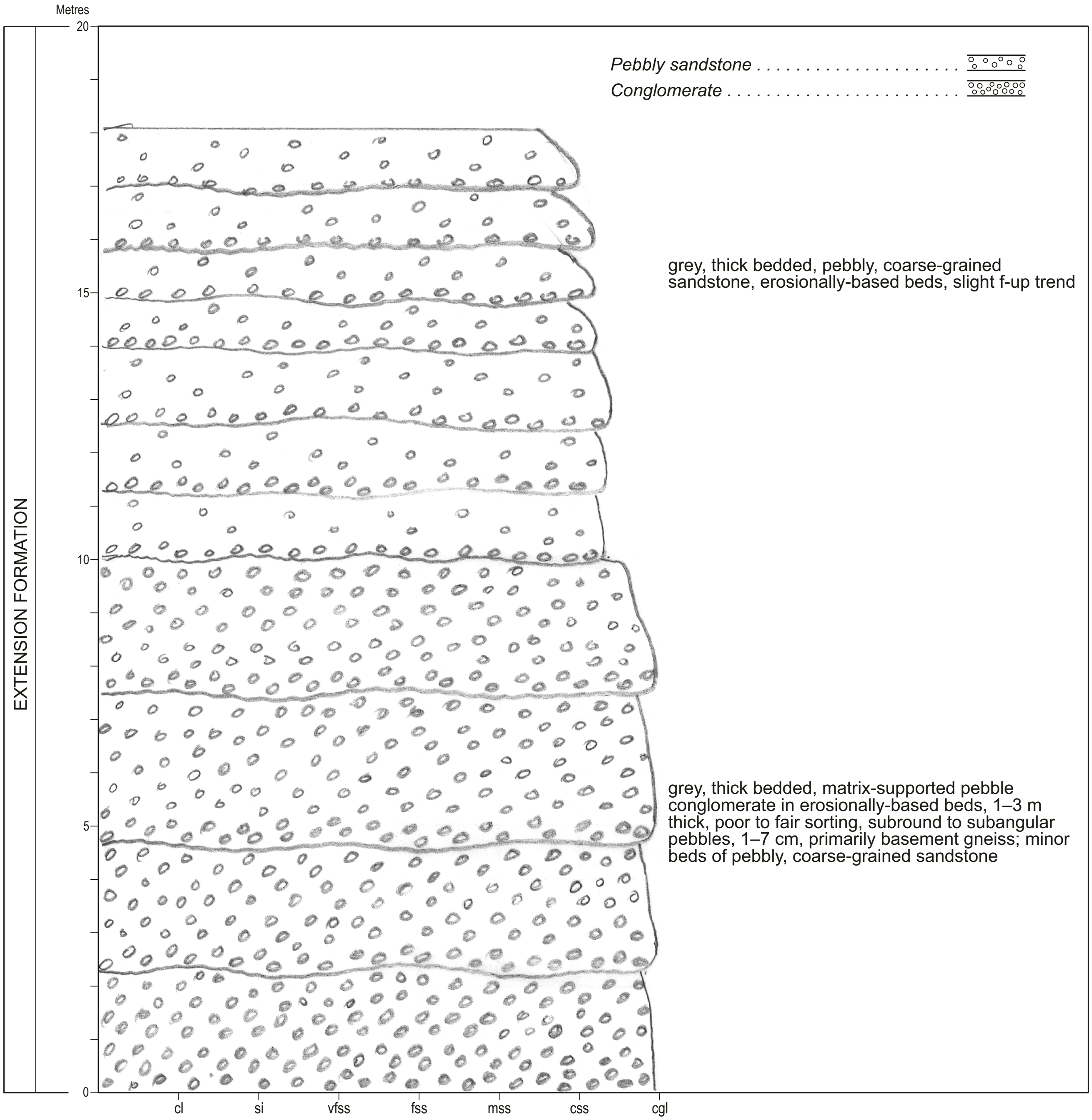


Appendix Figure 26
Trent River

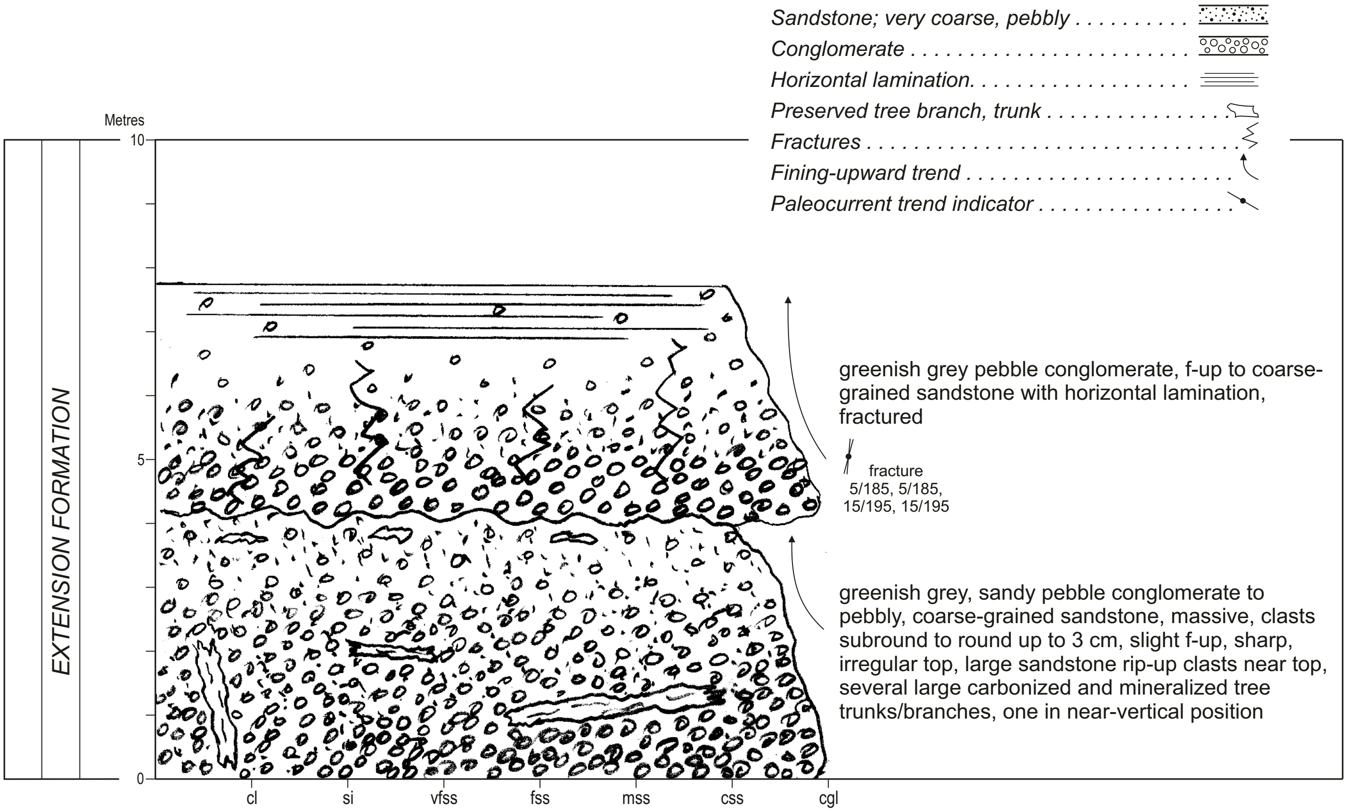
beneath Highway 19 bridge, 6 km SW of Royston and 7 km SW of Courtney, on both sides of river
?Haslam/?Extension/?Pender formations
NTS Map 92F/10 (Comox) 565961
49° 35' 57.1" N, 124° 58' 58.0" W; UTM Zone 10: 0356730E, 5495958N at base



Appendix Figure 27
Highway 19 and Harewood Road
roadcut exposure on NE side of Highway 19,
NW of Harewood Mines Road, 3 km SW of downtown Nanaimo
Haslam–Extension formations
NTS Map 92G/04 (Nanaimo) 294440
49° 06' 42.5"N, 123° 58' 13.2"W UTM Zone 10: 0429263E, 5444058N (base) to
49° 06' 37.6"N, 123° 58' 06.0"W UTM Zone 10: 0429375E, 5443890N (top)



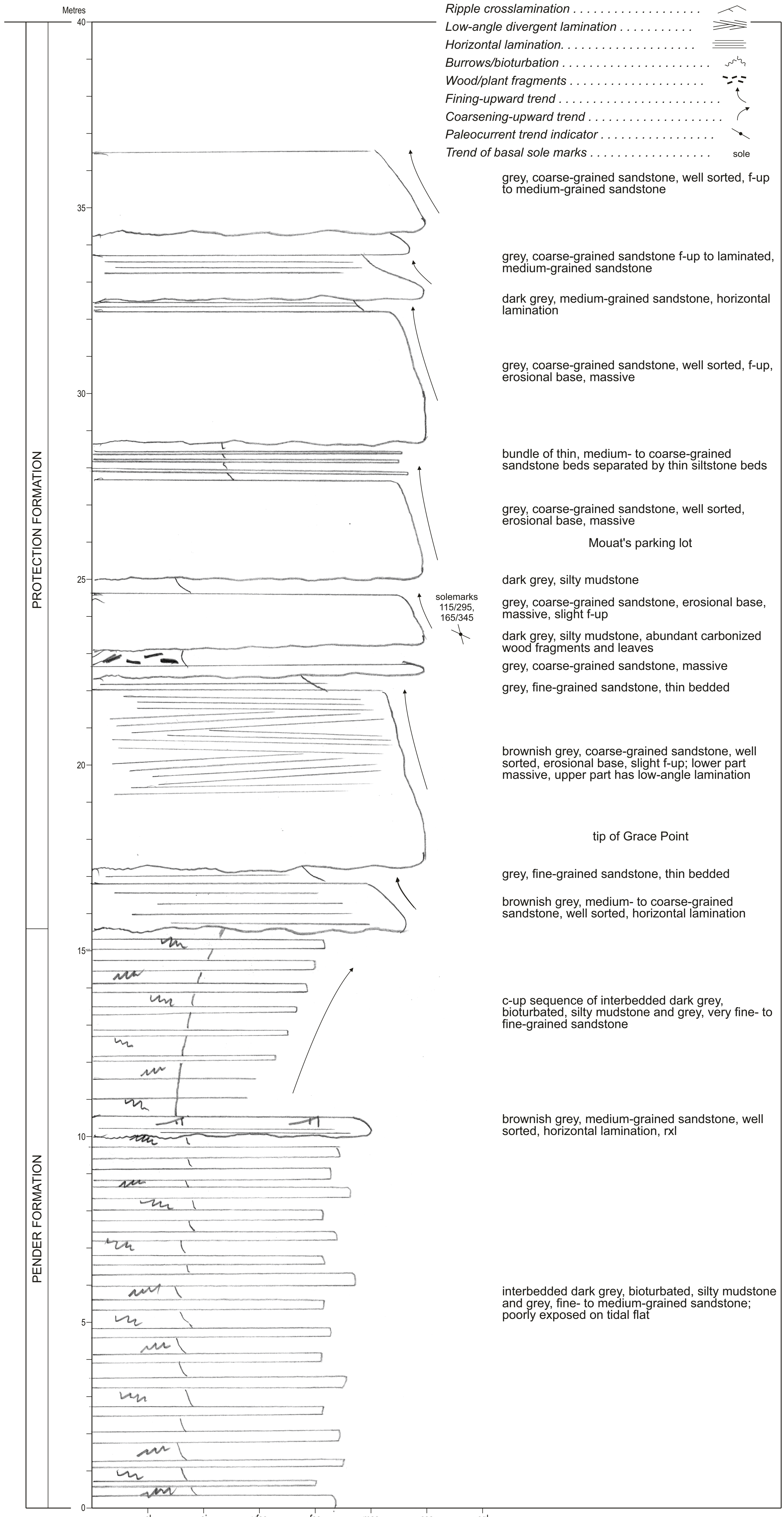
Appendix Figure 28
Nanaimo River Canyon
off Nanaimo River Road, 3 km W of airport and Highway 1, 10 km S of Nanaimo
Extension Formation
NTS Map 92G/14 (Nanaimo)
49° 04' 21.4"N, 123° 55' 13.3"W; UTM Zone 10: 0432780E, 5435936N



Appendix Figure 29
McKeowen Way

roadcut exposure along abandoned road beside Highway 19,
off Cranberry/Extension Road, village of Starks, 5 km S of Nanaimo
Extension Formation
NTS Map 92G/04 (Nanaimo) 323418
49° 07' 32.6"N, 123° 55' 40.2"W; UTM Zone 10: 0432317E, 5441846N

Appendix Figure 30
Newcastle Island, Eastern Shore
entire northeastern/eastern shore of island
Pender Formation/Protection Formation
NTS Map 92G/14 (Nanaimo)
base of section: 49° 11' 57.4"N, 123° 53' 50.9"W; UTM Zone 10: 0432197E, 5450045N
top of section: 49° 11' 10.8"N, 123° 55' 23.7"W; UTM Zone 10: 0432724E, 5448500N (top)



Appendix Figure 31

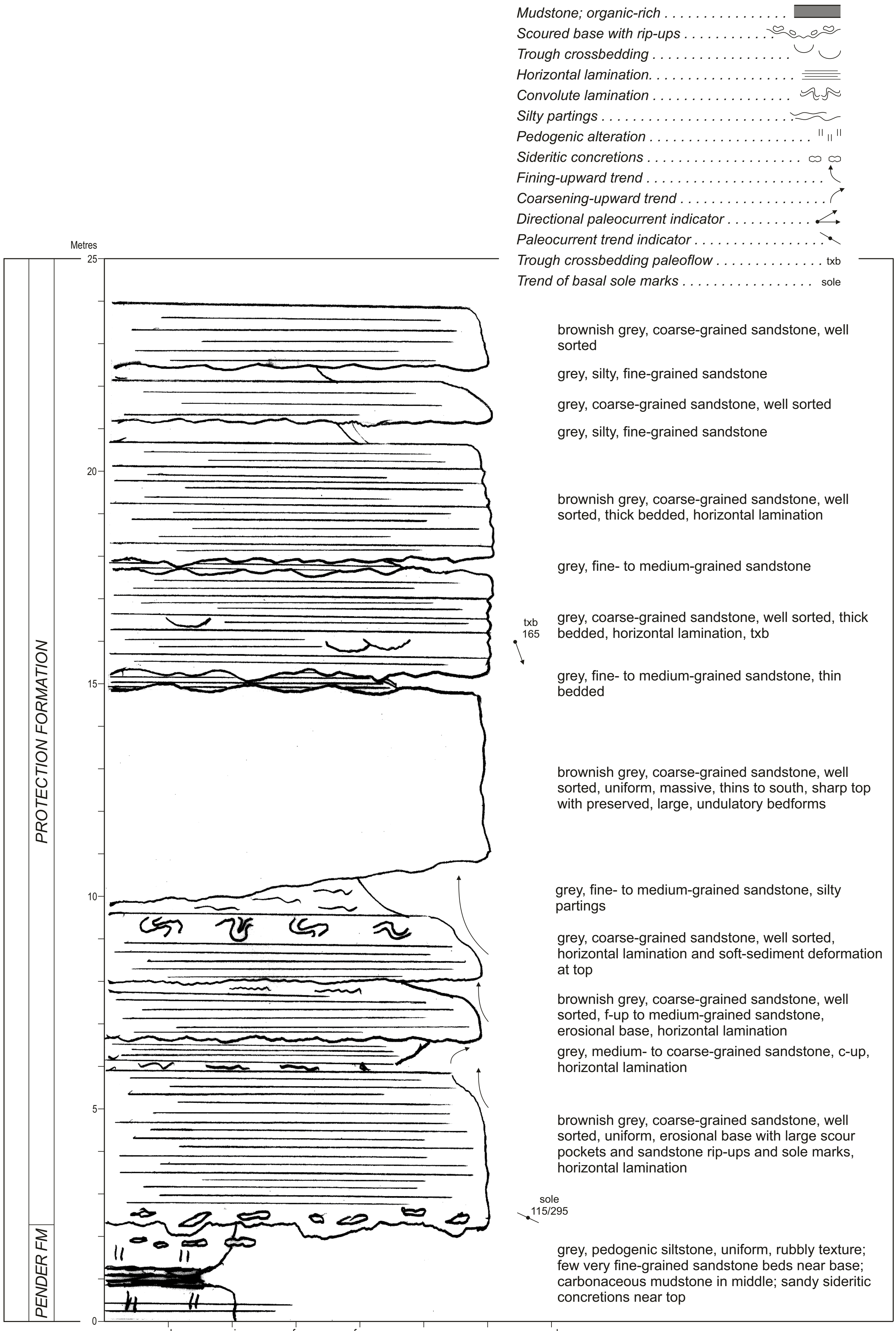
Grace Point, Ganges, Saltspring Island

tidal flat, cliff and parking lot exposures, behind Grace Point shopping centre and in Mouat's parking lot, downtown Ganges

Pender – Protection formations

NTS Map 92B/14 (Mayne Island) 637112

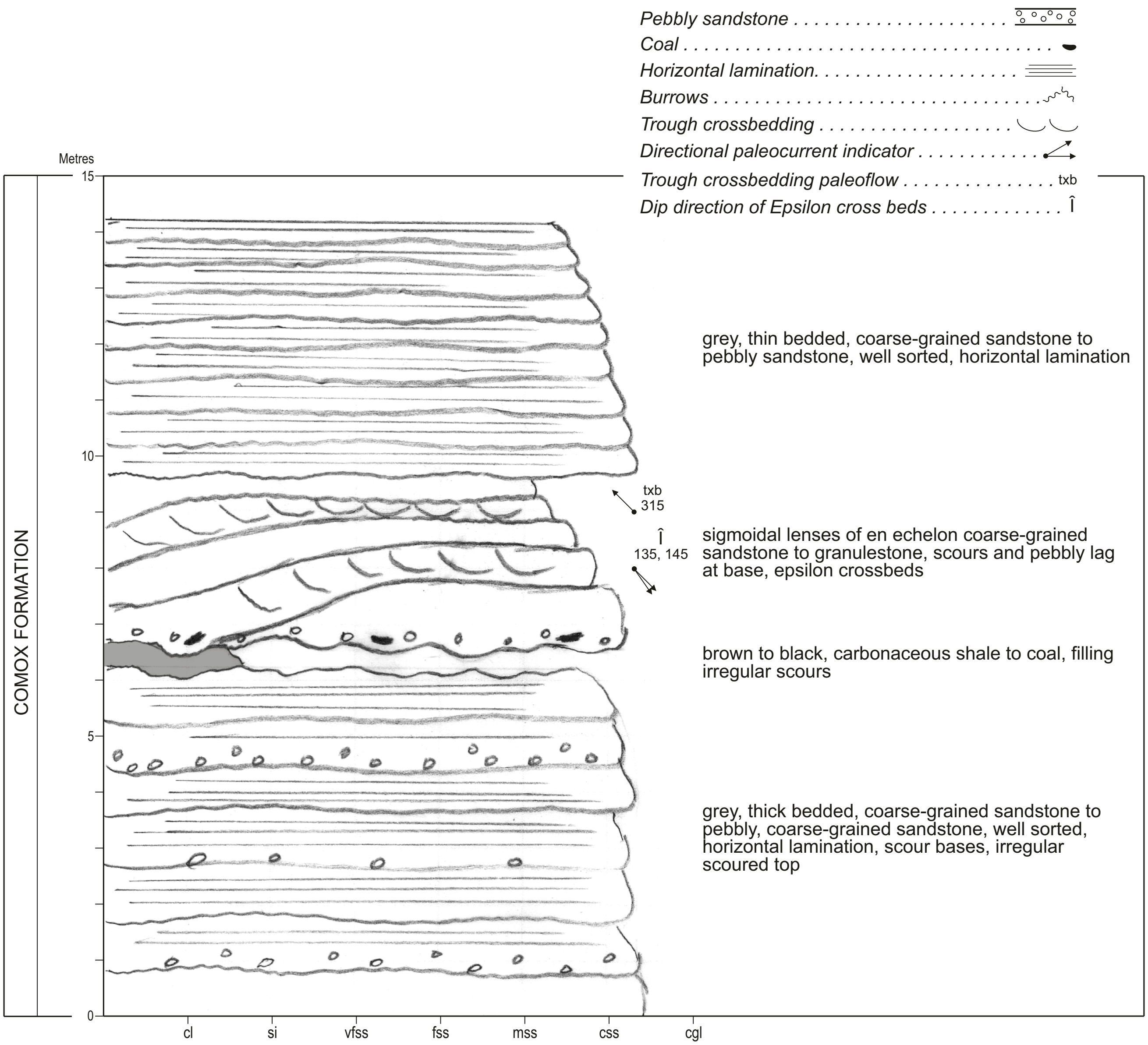
48° 51' 11.2" N, 123° 29' 51.7" W; UTM Zone 10: 0463491E, 5411245N at top (across from Mouat's)



Appendix Figure 32

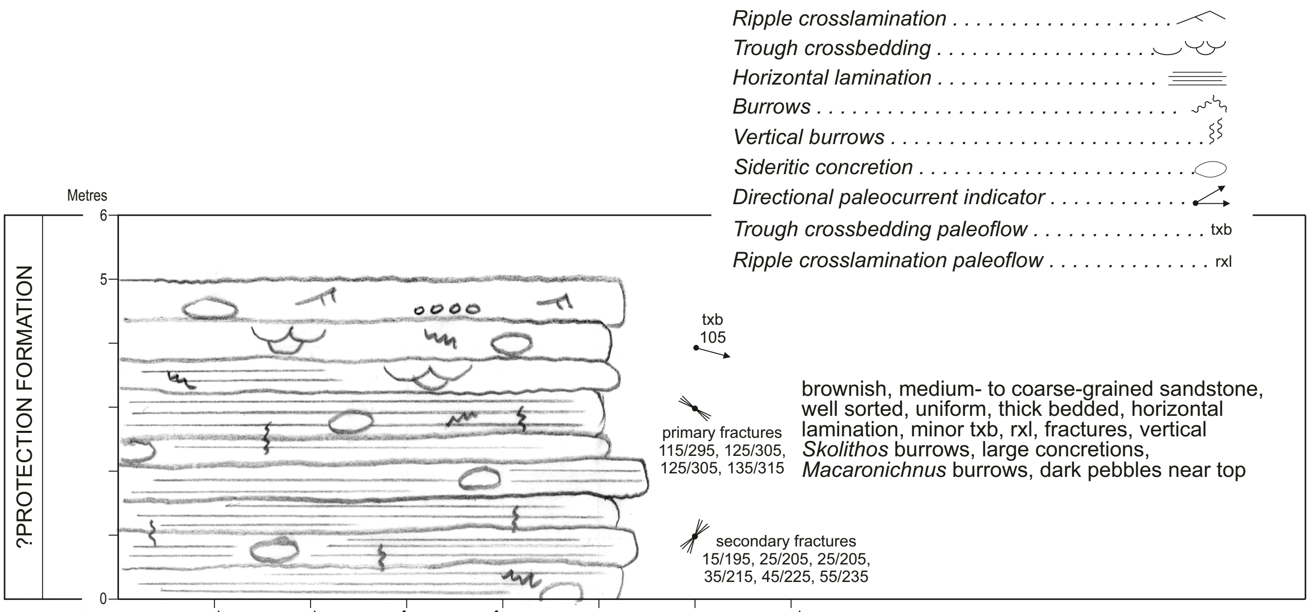
Trans–Canada Highway and Highway 19 Ramp

large roadcut exposure on E side of Trans Canada Highway,
1 km S of Cedar Road intersection, 5 km S of downtown Nanaimo
Pender–Protection formations
NTS Map 92G/04 (Nanaimo) 334410
49° 07' 10.5"N, 123° 54' 46.6"W; UTM Zone 10: 0433386E, 5441154N (base) to
49° 07' 07.2"N, 123° 54' 43.3"W; UTM Zone 10: 0433449E, 5441050N (top)



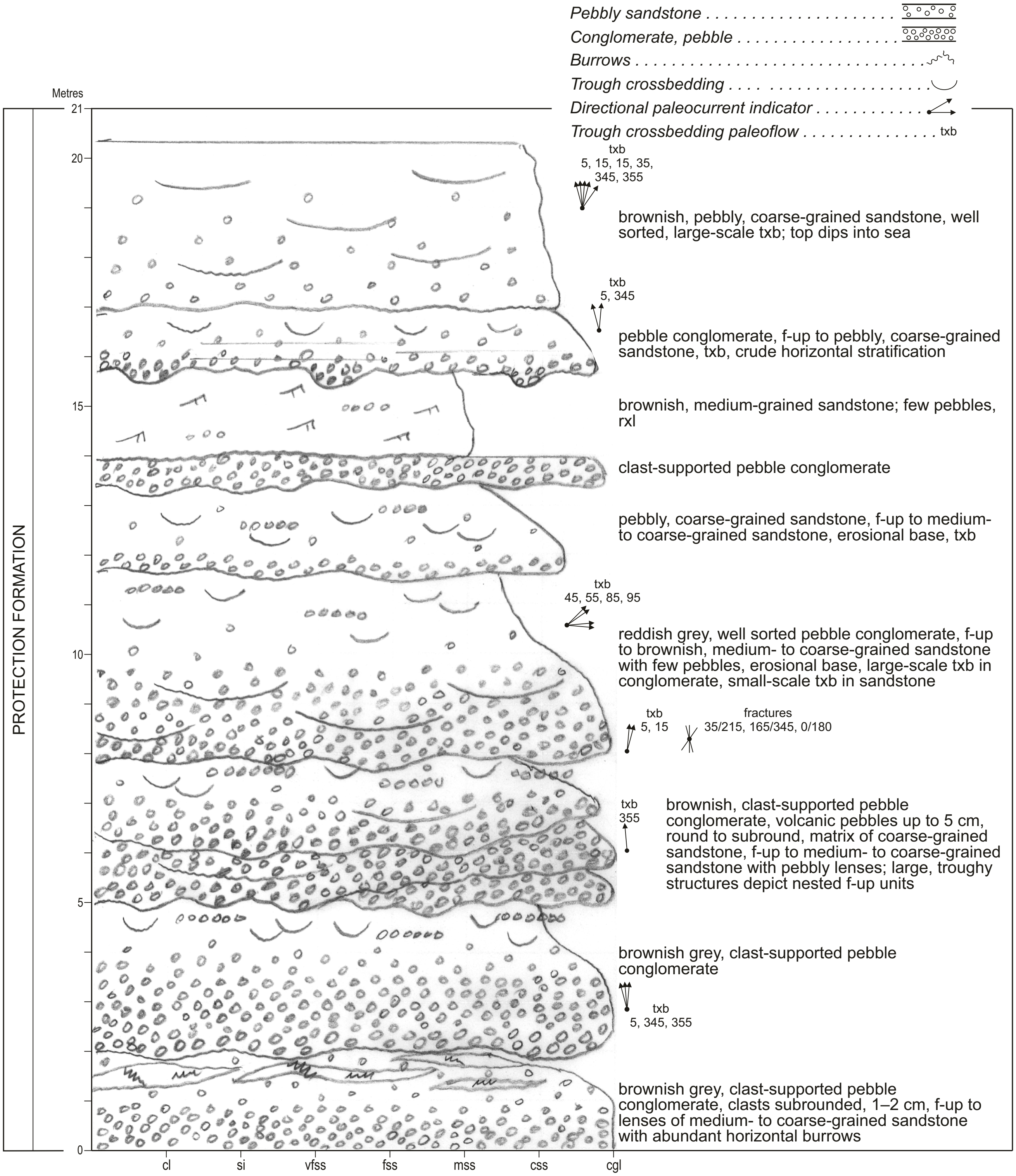
Appendix Figure 33
City of Nanaimo Public Parking Lot

corner of Victoria and Cavan streets, immediately S of downtown, just off Highway 1
Comox Formation
NTS Map 92G/14 (Nanaimo)
49° 09' 43.7"N, 123° 56' 07.0"W; UTM Zone 10: 0431816E, 5445902N



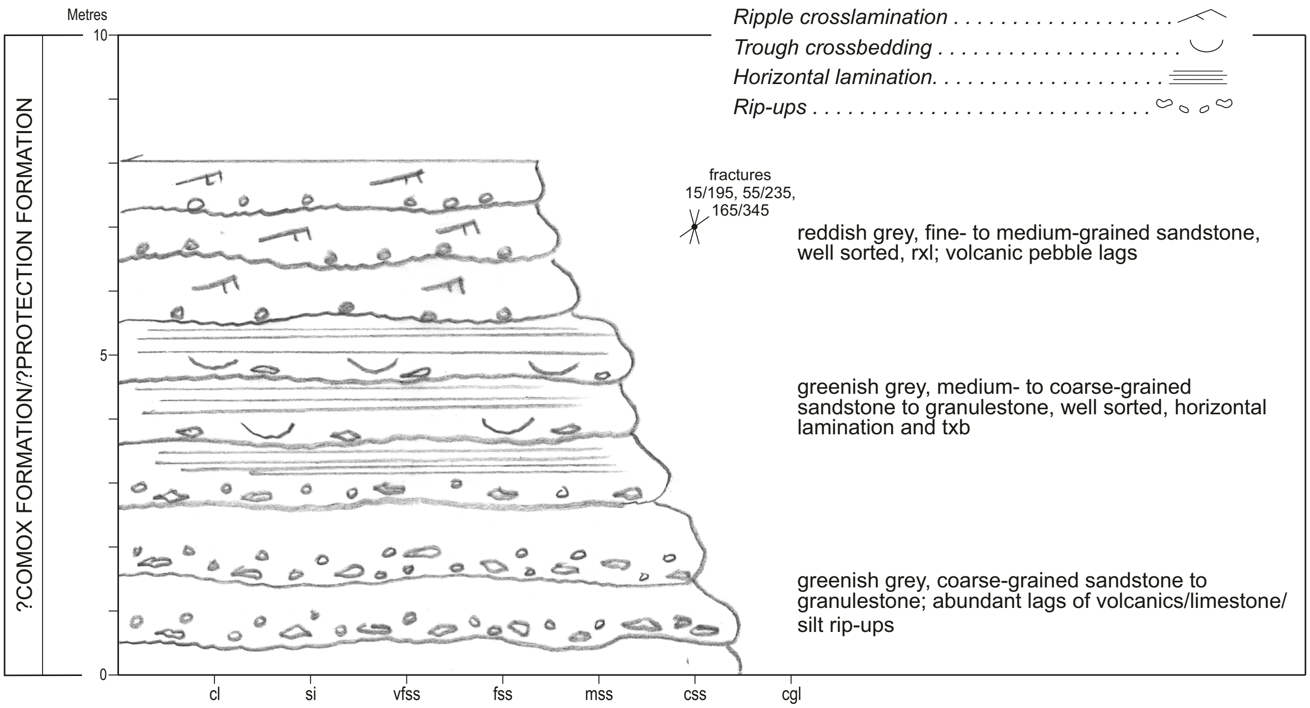
Appendix Figure 34
Wall Beach Headland

headland NE of Wall Beach in Northwest Bay, 7.5 km E of Parksville
?Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 12.0"N, 124° 13' 02.1"W; UTM Zone 10: 0411511E, 5461888N



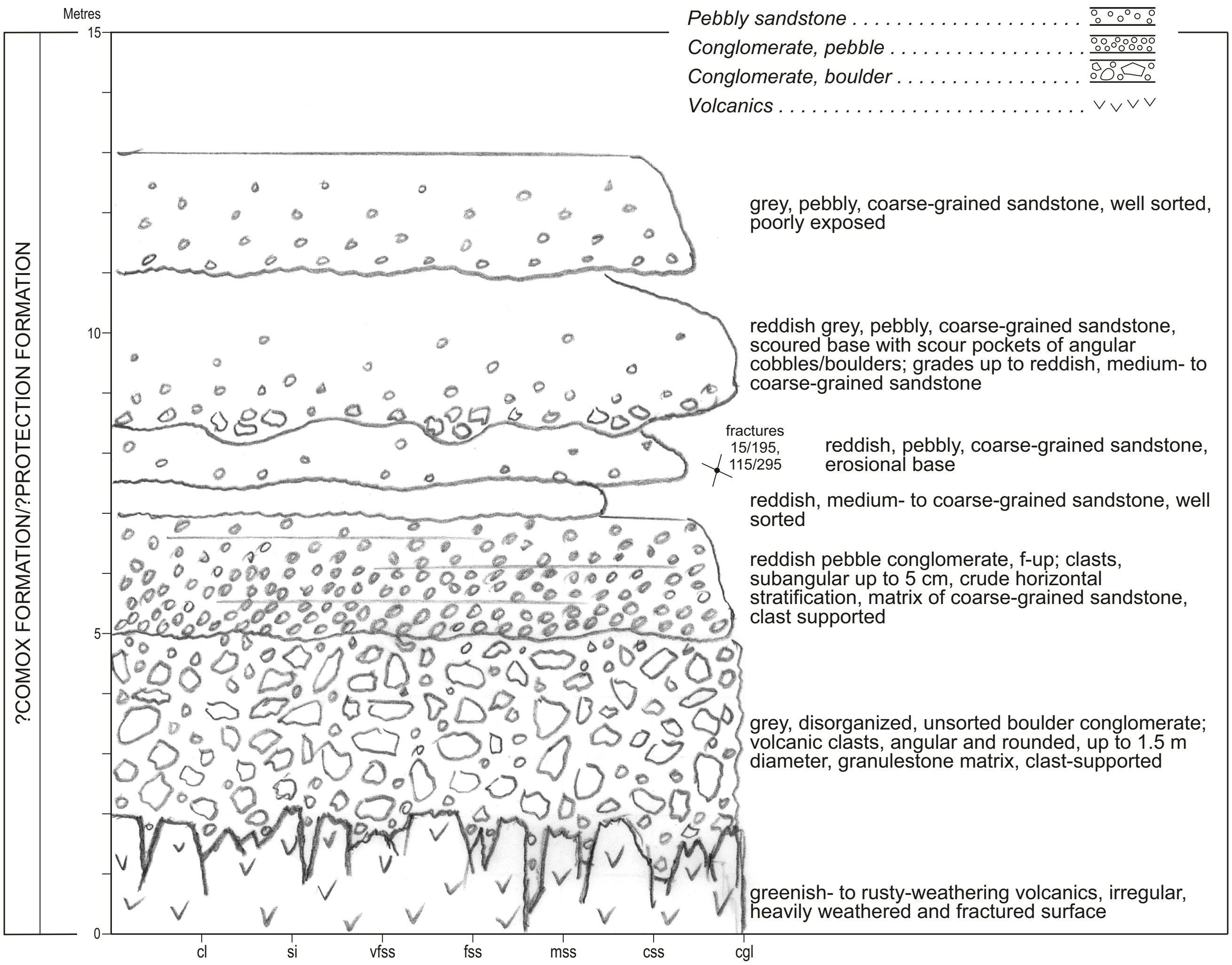
Appendix Figure 35
Madrona Point

N tip of Madrona Point, 5 km E of Parksville city centre, 5 km NW of Nanoose Bay
Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 46.0"N, 124° 14' 34.2"W; UTM Zone 10: 0409669E, 5462970N



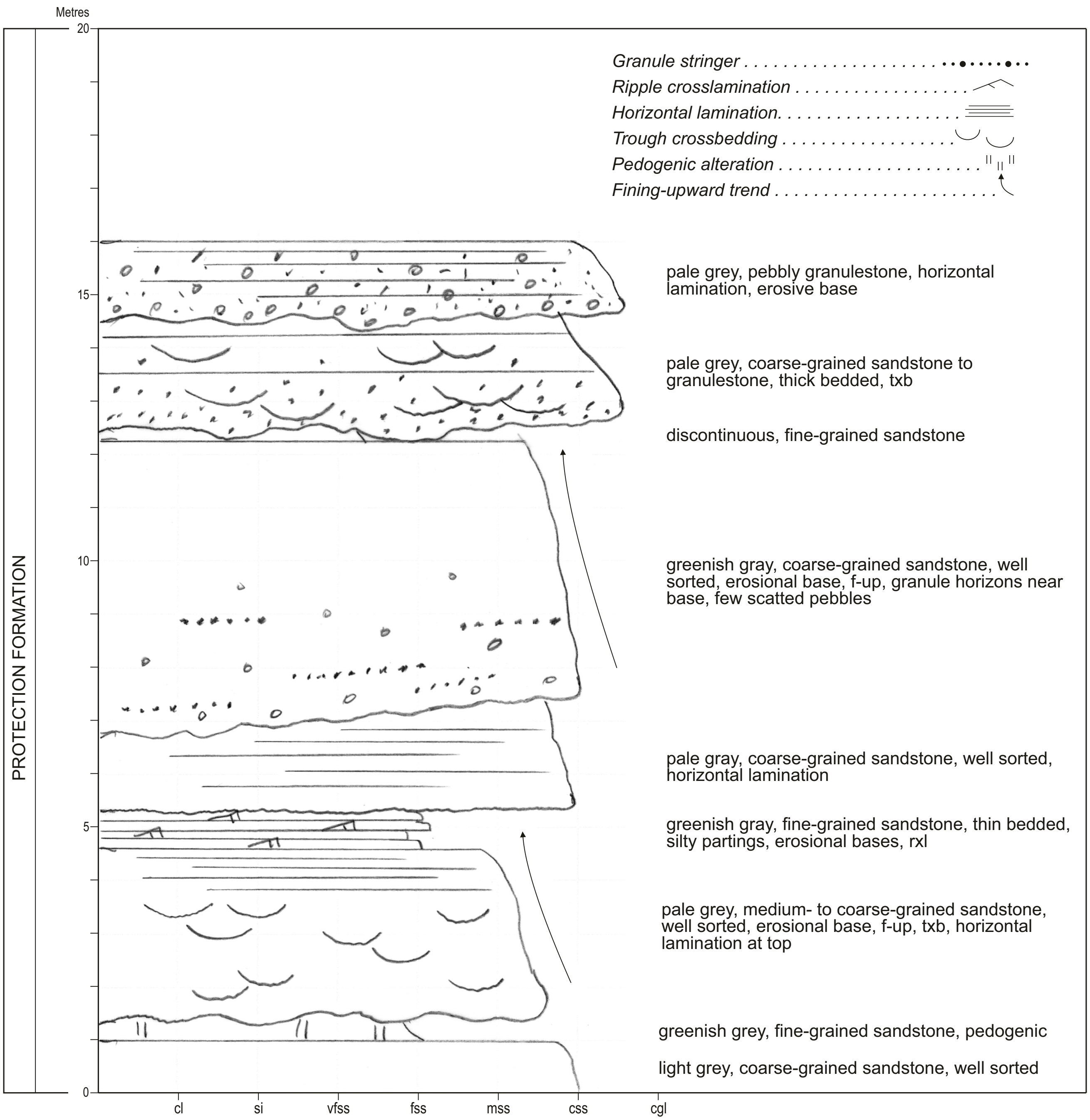
Appendix Figure 36
Beachcomber Regional Park

NW tip of Cottam Point, in Northwest Bay, 7 km E of Parksville city centre, 5 km N of Nanoose Bay
?Comox Formation/?Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 47.0"N, 124° 12' 54.4"W; UTM Zone 10: 0411683E, 5462969N



Appendix Figure 37
Cottam Point

N tip of Cottam Point, facing Mistaken Island, 7 km E of Parksville city centre, 5 km N of Nanoose Bay
?Comox Formation/?Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 53.0"N, 124° 12' 52.3"W; UTM Zone 10: 0411728E, 5463161N



Appendix Figure 38

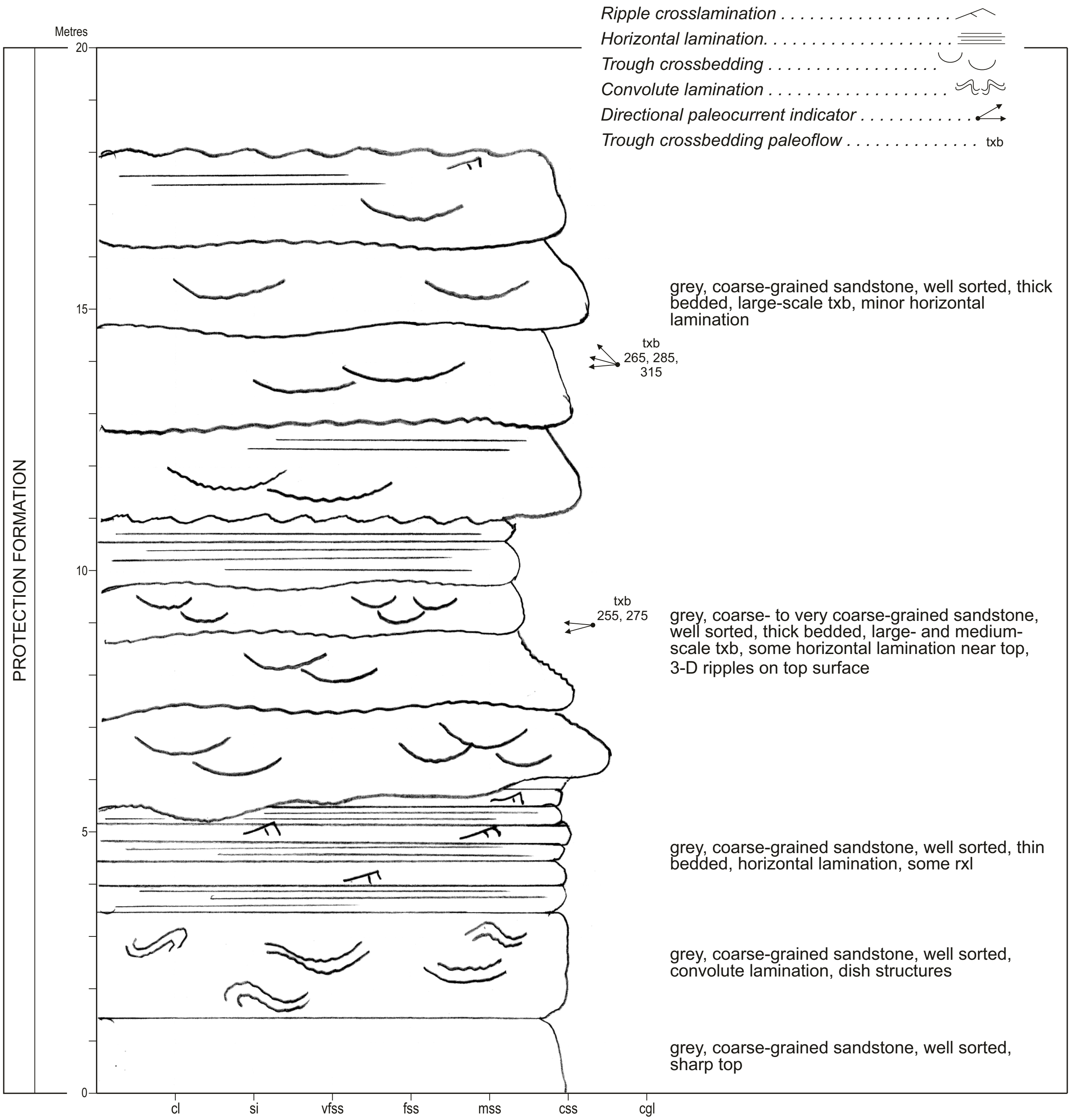
Cedar Road & Trans–Canada Highway Interchange

roadcut immediately E of highway, N side of Cedar Road

Protection Formation

NTS Map 92G/4 (Nanaimo) 334417

49° 07' 29.0" N, 123° 54' 50.1" W; UTM Zone 10: 433322E, 5441721N



Appendix Figure 39

Nanaimo River Canyon II beneath Trans-Canada Highway

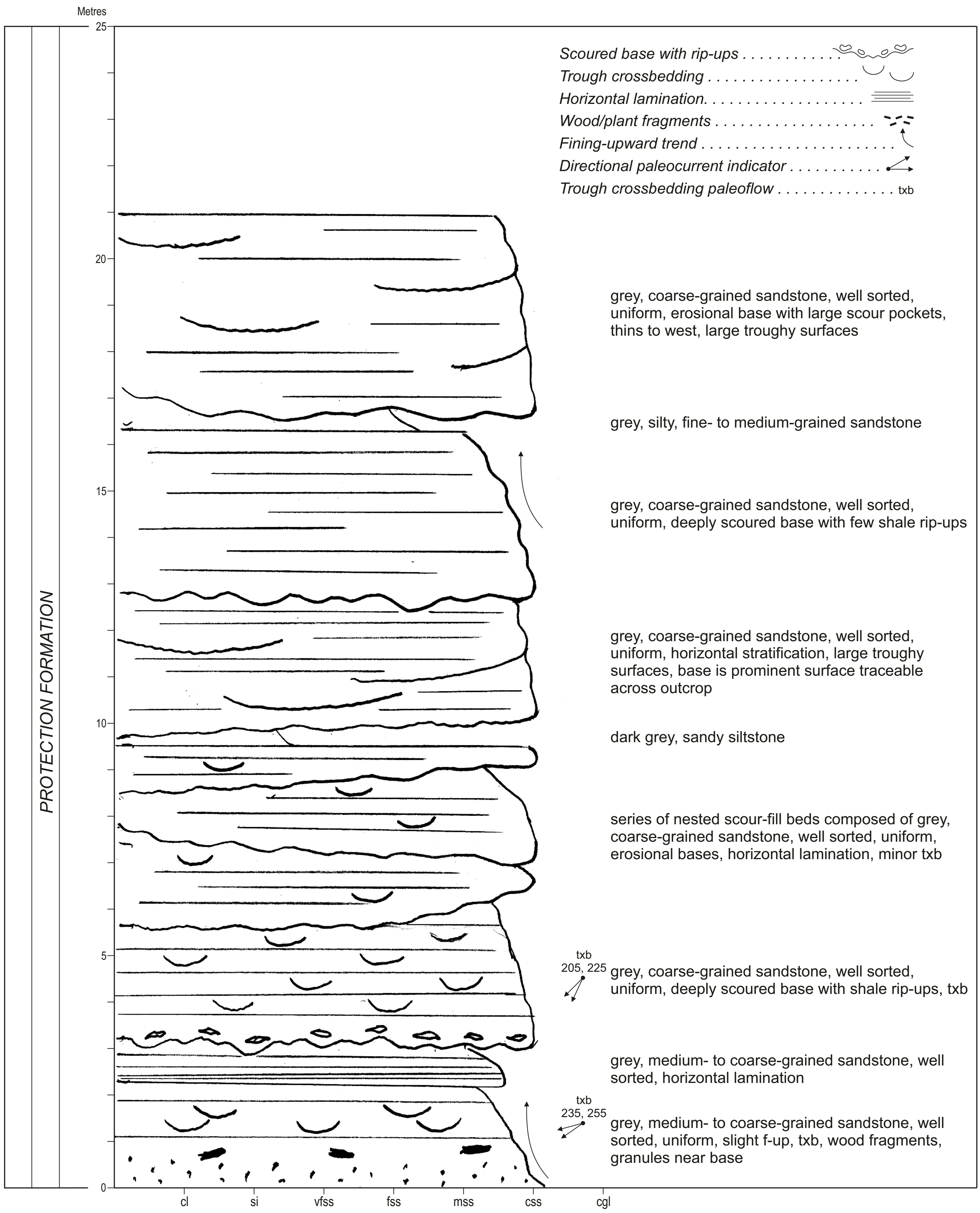
river channel cliff face 10 km SE of City of Nanaimo and 2 km N of airport

(generally inaccessible and only measured approximately)

Protection Formation

NTS Map 92G/4 (Nanaimo) 356357

49° 04' 14.3" N, 123° 52' 50.7" W; UTM Zone 10: 0435667E, 5435690N



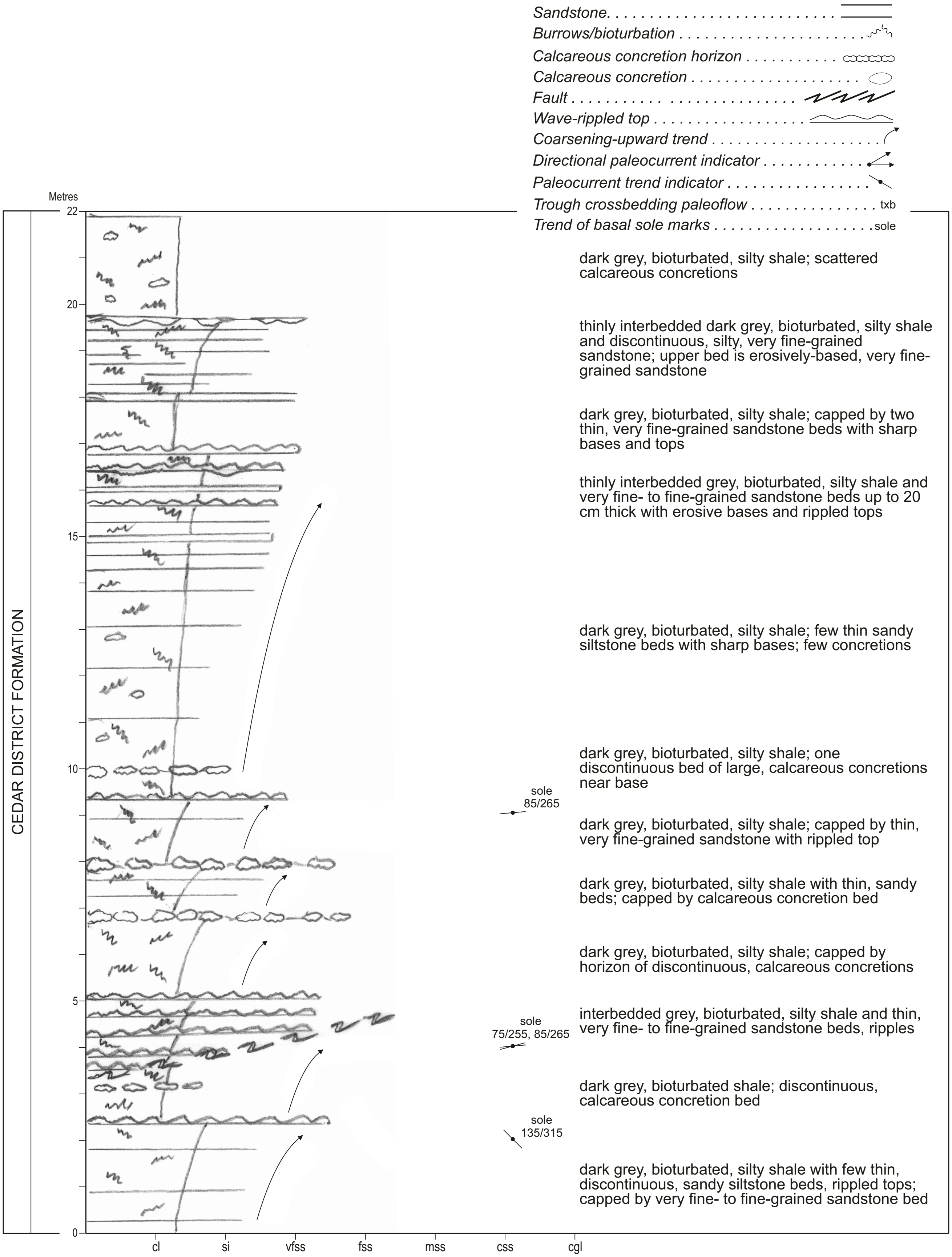
Appendix Figure 40

Duke Point Highway 19 at Trans–Canada Highway 1

roadcut exposure on N side of Duke Point Highway,
immediately E of Trans Canada Highway, 6 km SE of Nanaimo
Protection Formation
NTS Map 92G/04 (Nanaimo) 344404
49° 06' 42.1"N, 123° 53' 53.7"W; UTM Zone 10: 0434448E, 5440259N (base) to
49° 06' 45.5"N, 123° 53' 42.8"W; UTM Zone 10: 0434668E, 5440367N (top)

Appendix Figure 41
Vesuvius Bay Shoreline, Saltspring Island
shoreline of bay from southern point to ferry dock, west shore of Saltspring Island
Protection Formation/Cedar District Formation/De Courcy Formation
NTS Map 92B/13 (Duncan)
base of section: 48° 52' 40.1"N, 123° 34' 20.7"W; UTM Zone 10: 0458030 E, 5414031N
top of section: 48° 52' 50.3"N, 123° 34' 16.8"W; UTM Zone 10: 0458111 E, 5414340N

Appendix Figure 42
Barnes Road Shoreline
end of Barnes Road, along Stuart Channel shore, opposite Round Island, 4 km E of Cedar
Cedar District Formation
NTS Map 92G/14 (Nanaimo)
49° 07' 15.0"N, 123° 48' 17.4"W UTM Zone 10: 0441278E, 5441198N (base) to
49° 07' 06.9"N, 123° 48' 17.1"W UTM Zone 10: 0441278E, 5440952N (Barnes Road) to
49° 06' 53.9"N, 123° 48' 18.1"W UTM Zone 10: 0441254E, 5440546N (Murdoch Road boat ramp)



Appendix Figure 43

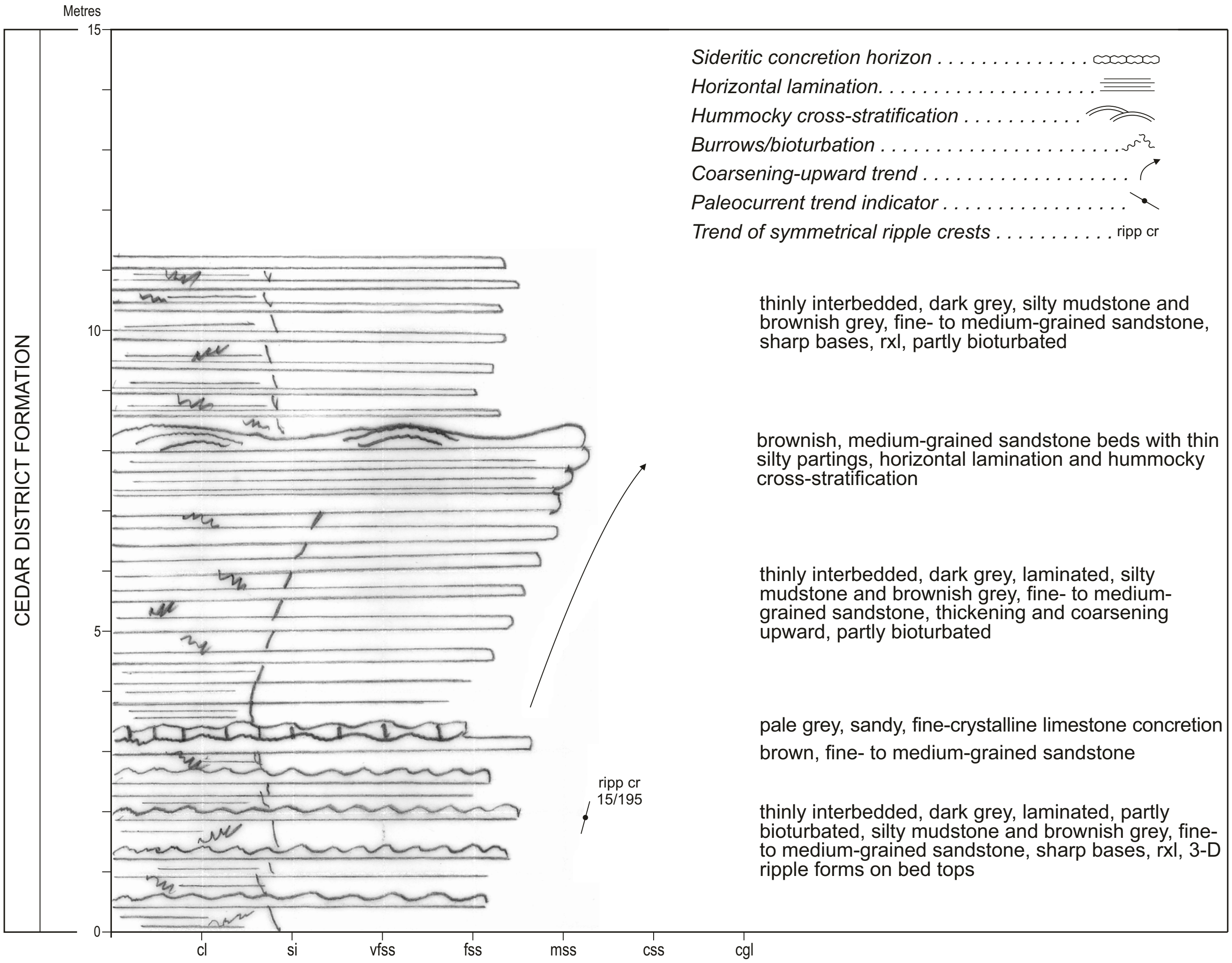
Highway 19 & Buckley Bay Ferry Interchange

along road toward Denman Island ferry terminal, 100 m E of Highway 19

Cedar District Formation

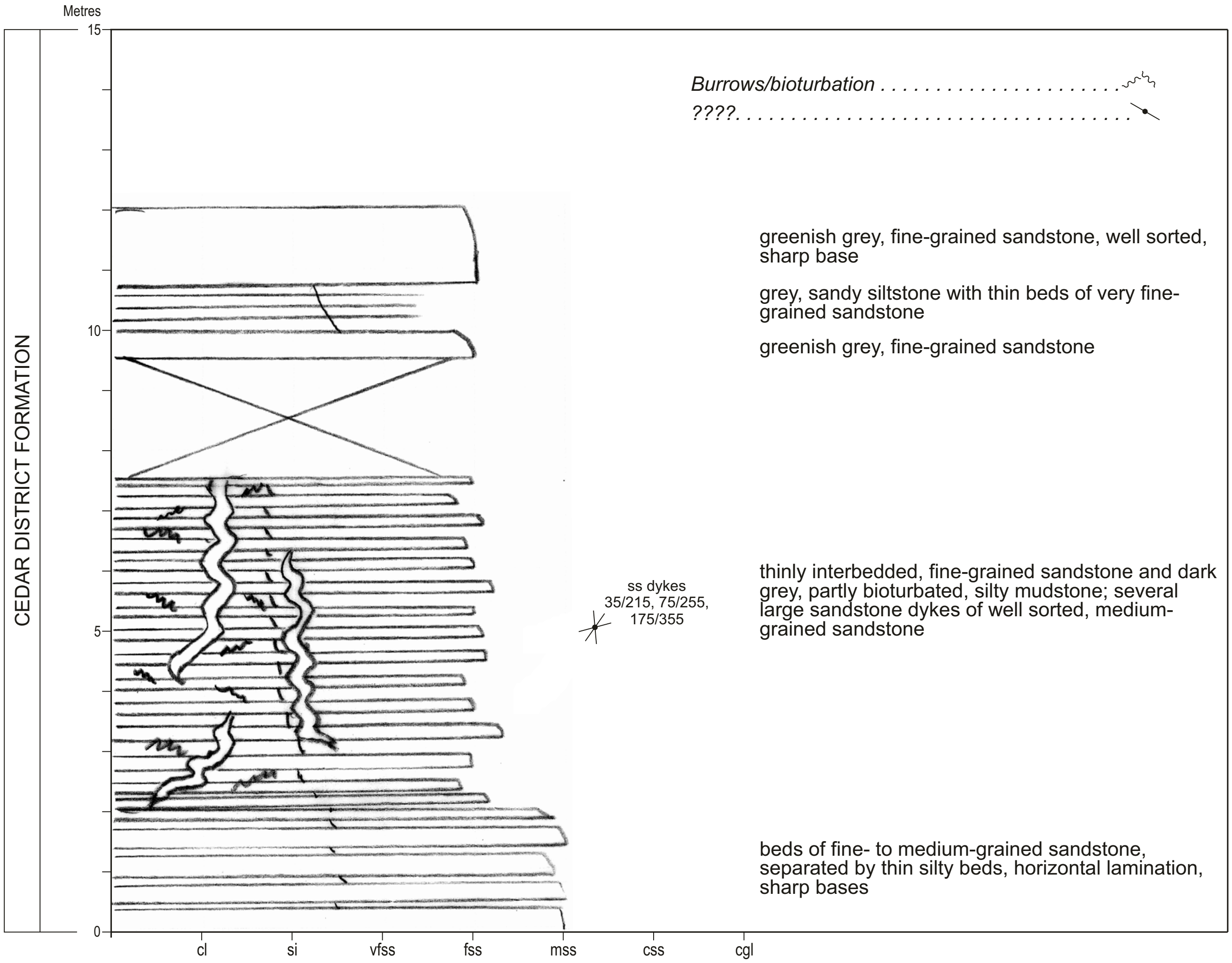
NTS Map 92F/10 (Comox)

49° 31' 26.8"N, 124° 51' 11.9"W; UTM Zone 10: 0365878E, 5487369N



Appendix Figure 44
Ship Peninsula

tidal platform exposure on east side of southern peninsula, well-exposed only at low tide
Cedar District Formation
NTS Map 92F/7 (Horne Lake) 702841
49° 29' 44.7" N, 124° 47' 29.3 W"; UTM Zone 10: 0370277E, 5484110N at base



Appendix Figure 45

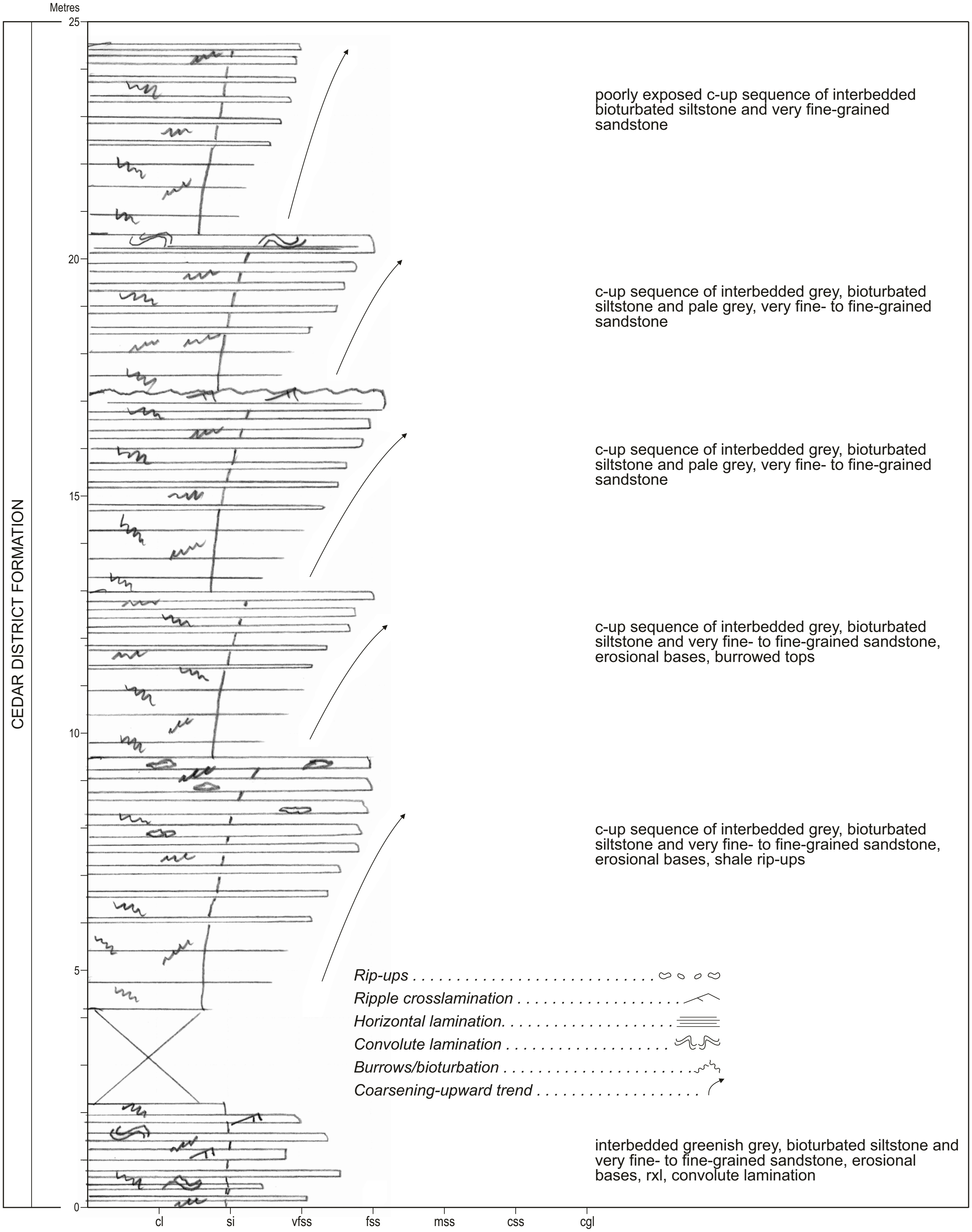
Denman Ferry Dock Shoreline, Denman Island

coastal tidal platform section about 0.5 km NW of Denman Island ferry dock, west shore of island

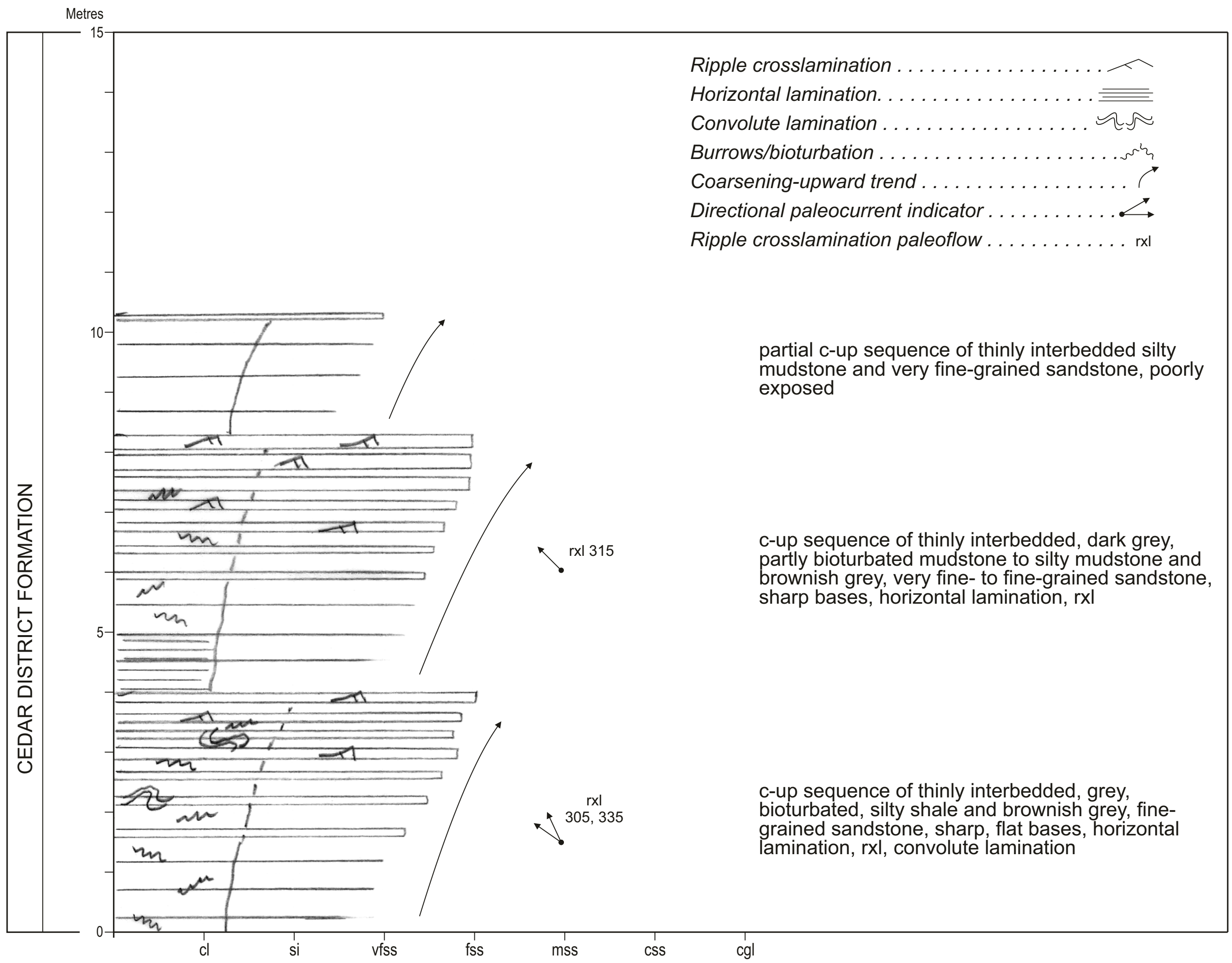
Cedar District Formation

NTS Map 92F/10 (Comox) 676888

49° 32' 18.0" N, 124° 49' 50.0" W; UTM Zone 10: 0367620E, 548880N

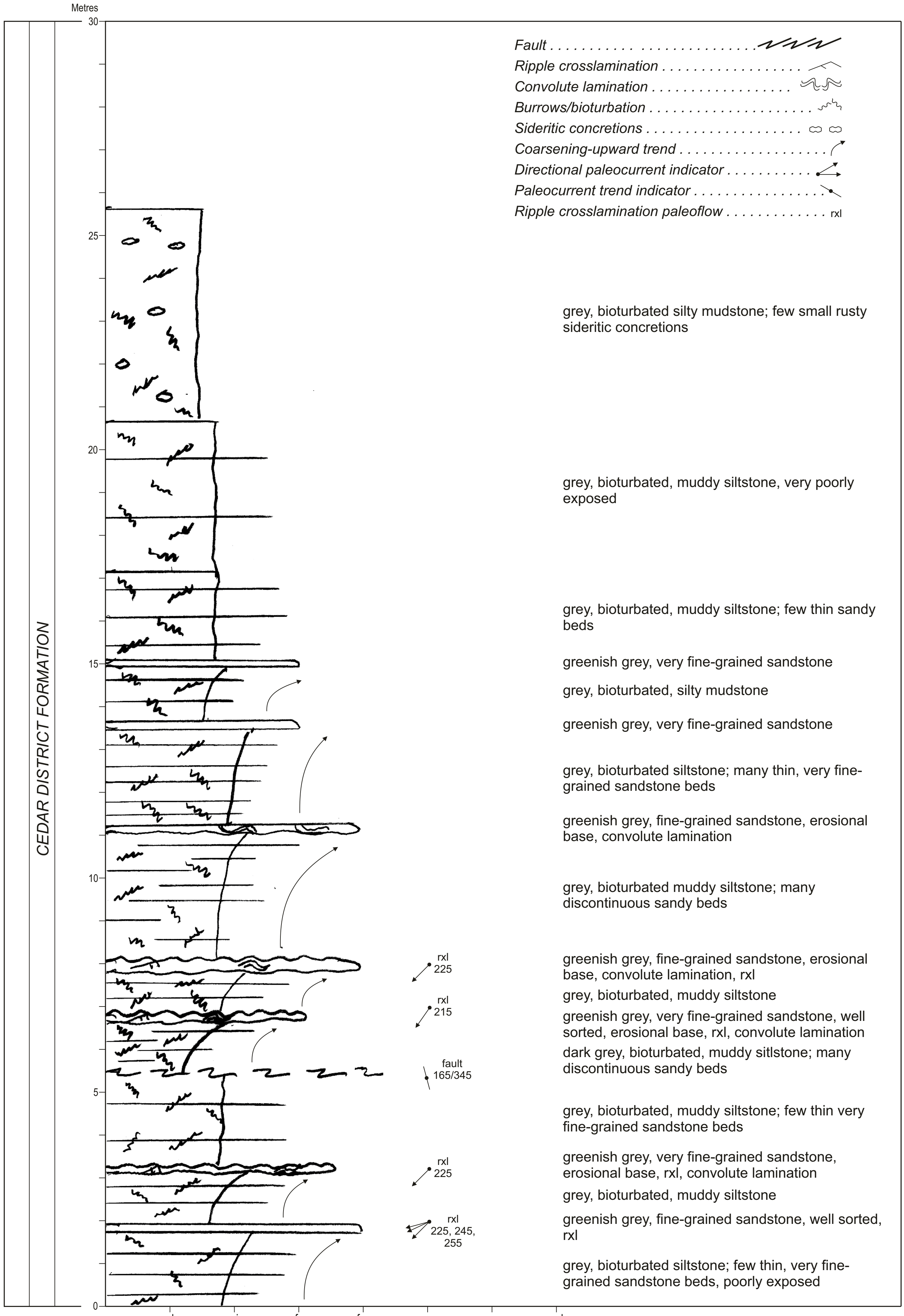


Appendix Figure 46
Ganges Harbour Shoreline, Saltspring Island
tidal flat and cliff exposure on NE shoreline of Ganges Harbour,
behind Moby's Pub, below Hastings House Hotel
Cedar District Formation
NTS Map 92B/14 (Mayne Island) 635118
48° 51' 31.1" N, 123° 29' 58.4" W; UTM Zone 10: 0463358 E, 5411863N at base



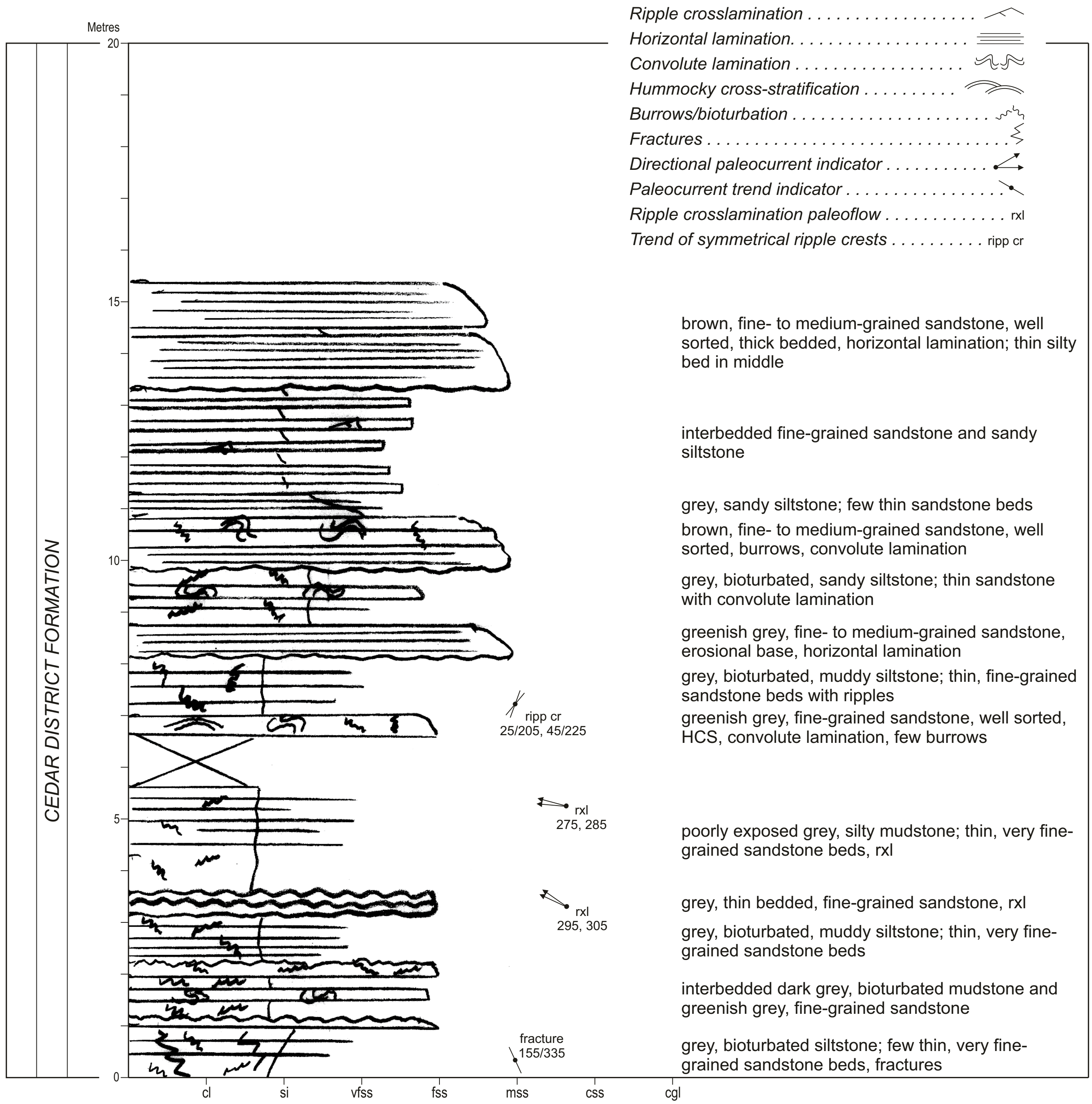
Appendix Figure 47
Fernwood Shoreline, Saltspring Island

tidal flat and cliff exposure, NE shoreline of island, immediately SE of Fernwood
Cedar District Formation
NTS Map 92B/13 (Duncan) 612181
48° 54' 52.8" N, 123° 31' 50.2" W; UTM Zone 10: 046123E, 5418105N at base



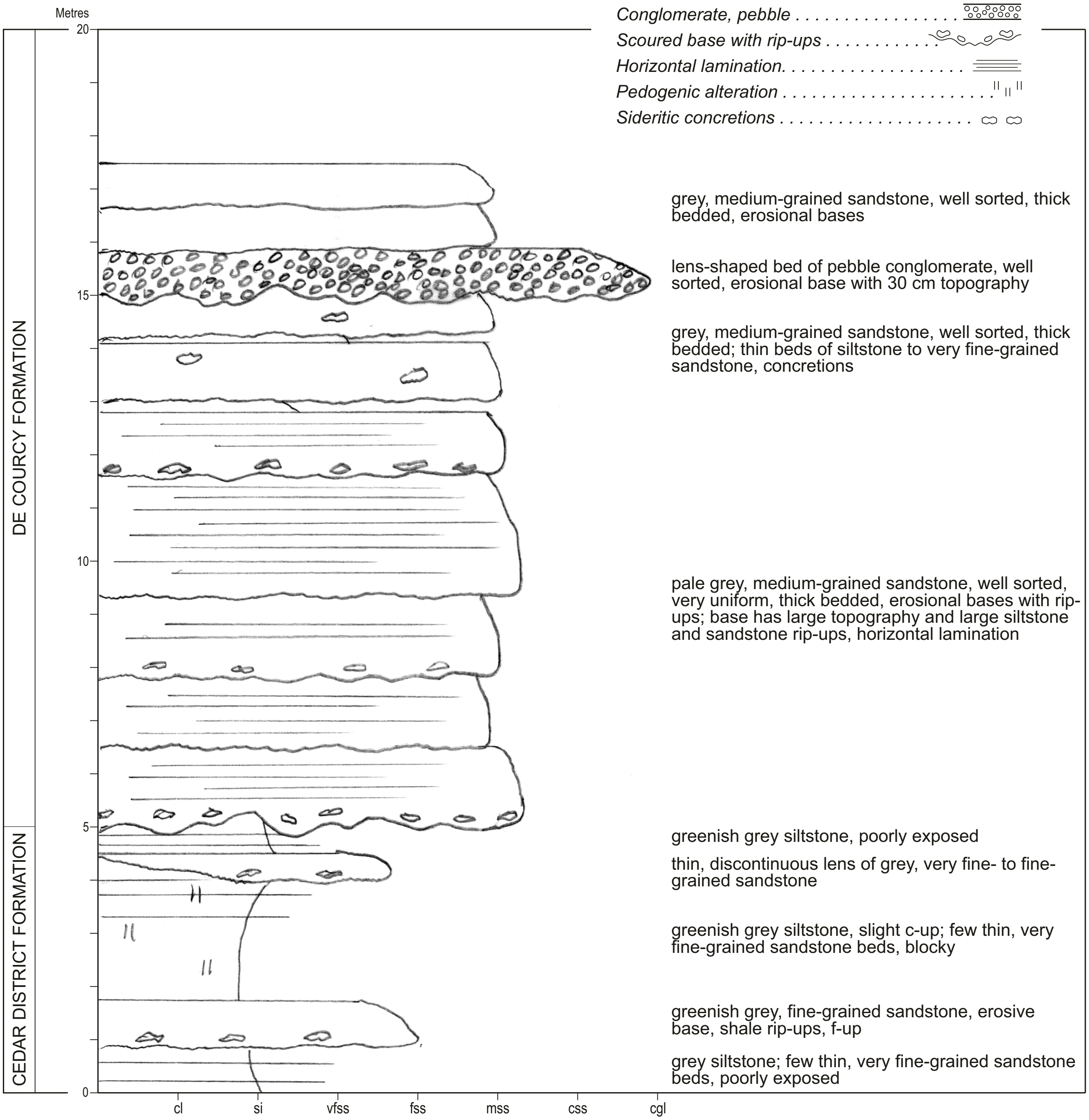
Appendix Figure 48
Hudson Point Shoreline

tidal platform exposure from beach access off North Beach Road,
1 km NW of Fernwood, Saltspring Island
Cedar District Formation
NTS Map 92B/13 (Duncan) 598186
48° 55' 10.5"N, 123° 36' 49.9"W; UTM Zone 10: 0459803E, 5418660N (base) to
48° 55' 11.2"N, 123° 32' 55.1"W; UTM Zone 10: 0459808E, 5418697 (top)

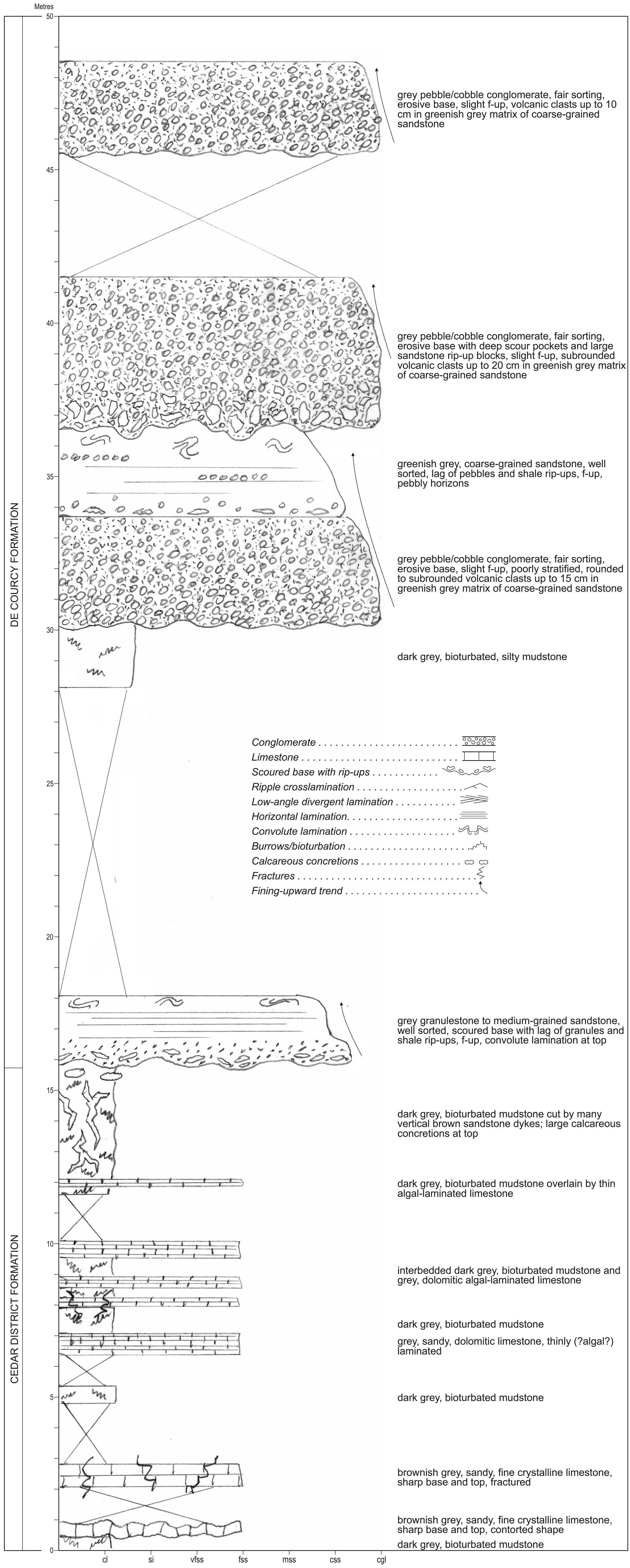


Appendix Figure 49
North Beach Road Shoreline

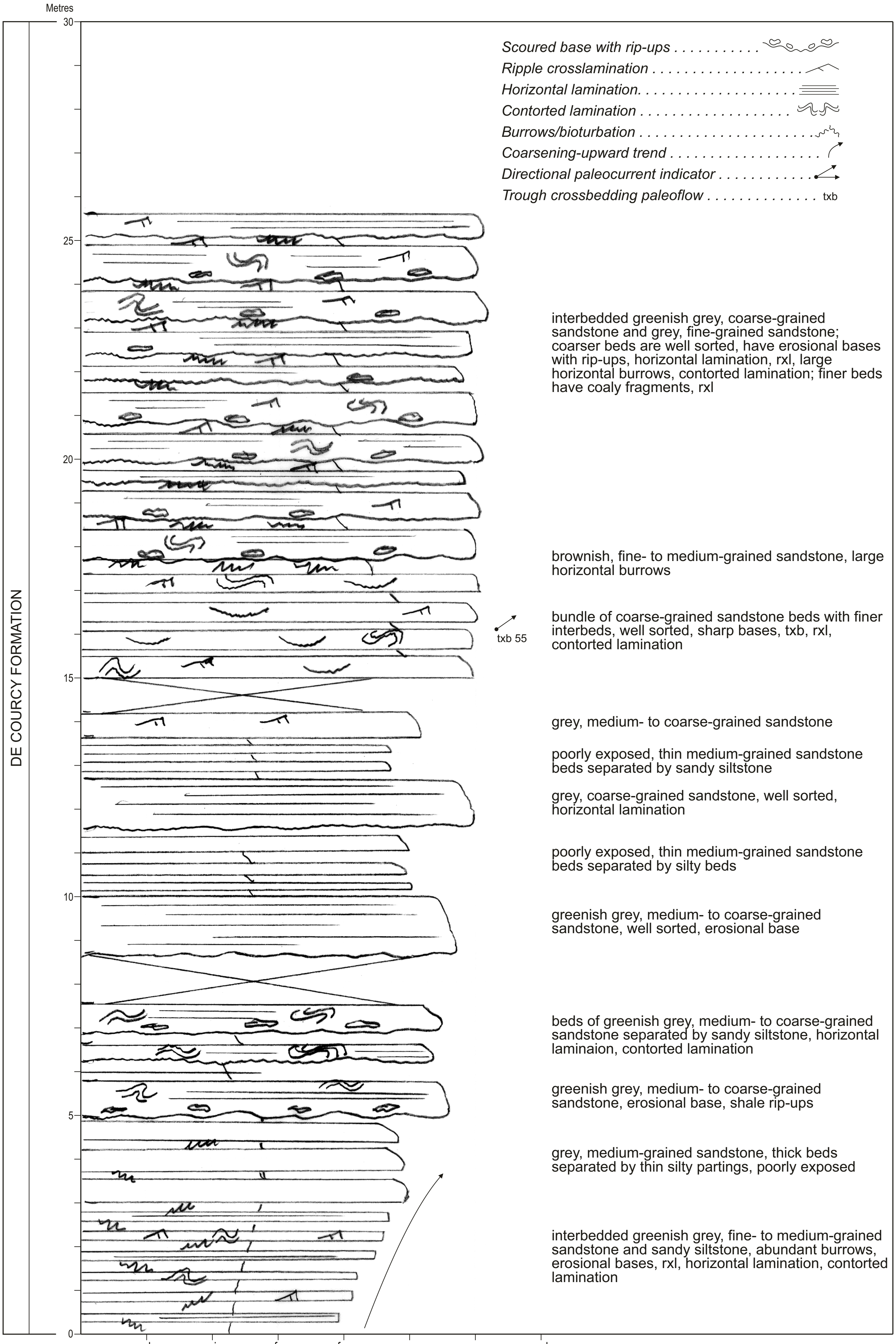
tidal platform exposure from beach access path on North Beach Road toward north,
2 km NW of Fernwood, Saltspring Island
Cedar District Formation
NTS Map 92B/13 (Duncan) 592194
48° 55' 32.6"N, 123° 33' 27.3"W; UTM Zone 10: 0459157E, 5419351N (base) to
48° 55' 32.0"N, 123° 33' 24.4"W; UTM Zone 10: 0459220E, 5419333N (top)



Appendix Figure 50
Denman Escarpment, Denman Island
small roadcut escarpment adjacent to Denman Road, E of ferry dock
Cedar District – De Courcy formations
NTS Map 92F/10 (Comox) 693887
49° 32' 15.1" N, 124° 48' 21.6" W; UTM Zone 10: 0369290E, 5488740N

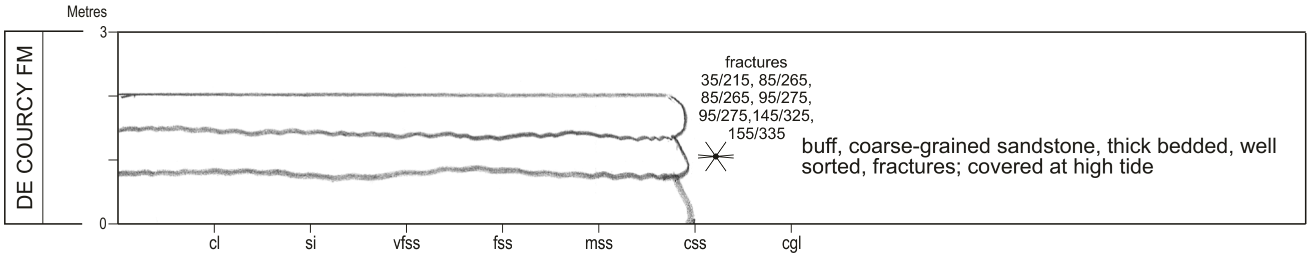


Appendix Figure 51
Gladstone Way, Denman Island
coastal section westward on NW shore of island
Cedar District – De Courcy formations
NTS Map 92F/10 (Comox) 671942
49° 35' 05.9" N, 124° 50' 21.2" W; UTM Zone 10: 0367061E, 5494118N at base
to 49° 35' 22.6" N, 124° 50' 19.2" W; UTM Zone 10: 0367113E, 5494627N at top

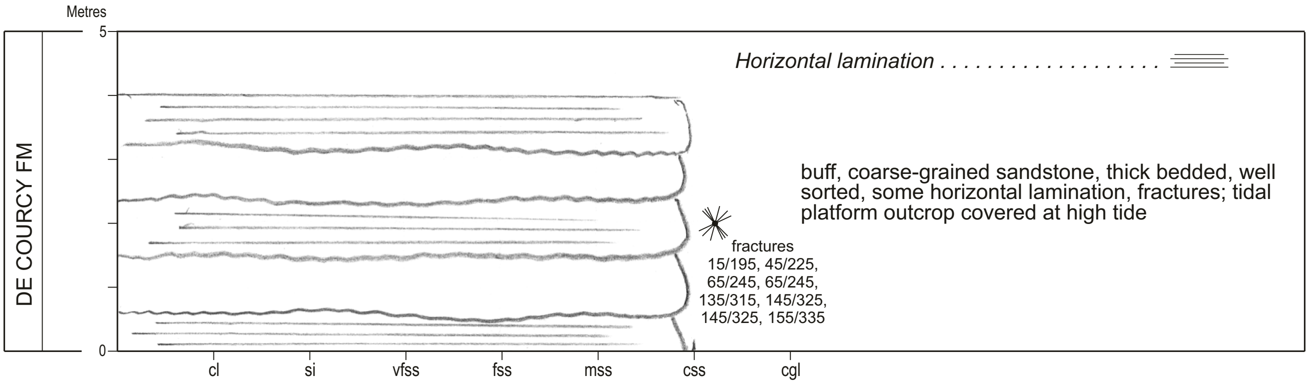


Appendix Figure 52
Southey Point, Saltspring Island

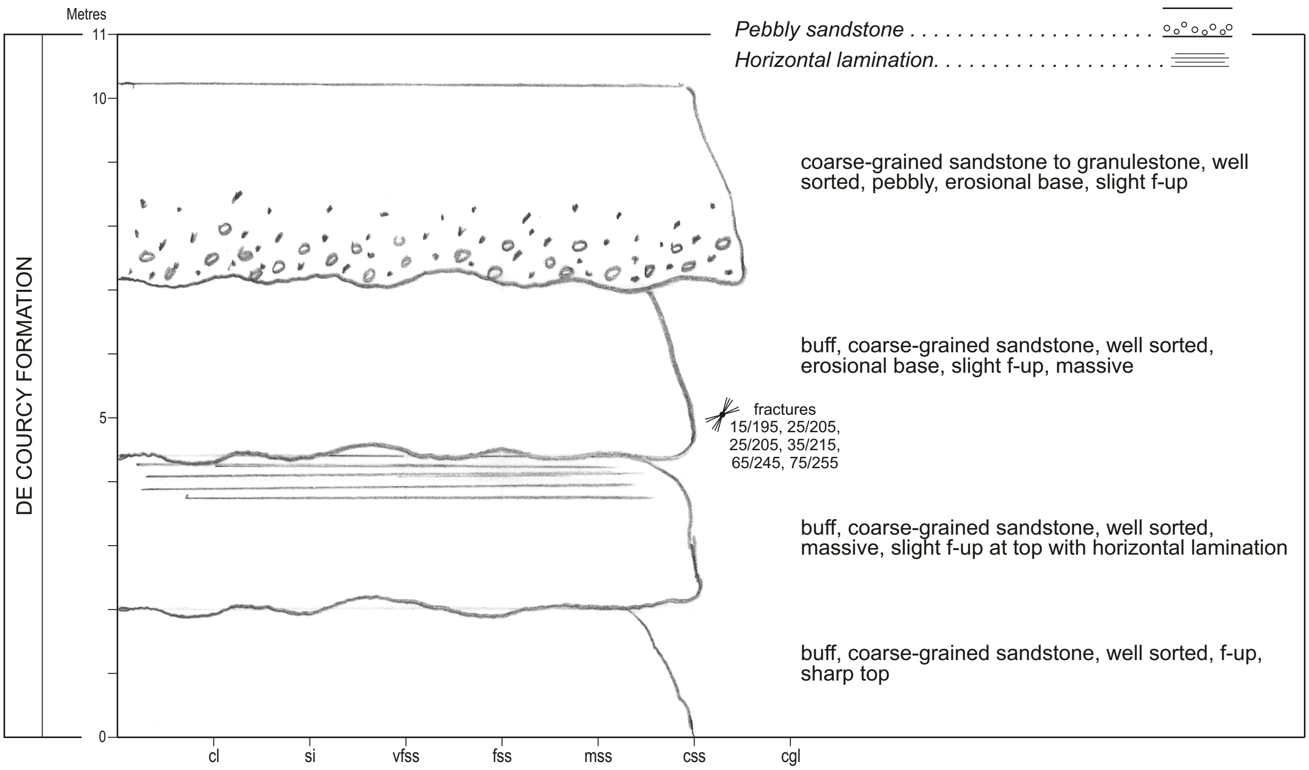
tidal flat exposures from Southey Bay westward around tip of point, northern tip of Saltspring Island
Cedar District – De Courcy formations
NTS Map 92B/13 (Duncan) 563213
48° 56' 33.5" N, 123° 35' 48.5" W; UTM Zone 10: 0456299E, 5421240N at base;
48° 56' 26.6" N, 123° 35' 52.5" W; UTM Zone 10: 0456215E, 5421039N at top



Appendix Figure 53
Blue Heron Park
along Stuart Channel shoreline, off Yellow Point Road, 8.5 km E of Nanaimo Airport
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 02' 41.3"N, 123° 45' 22.6"W; UTM Zone 10: 0444732E, 5432706N

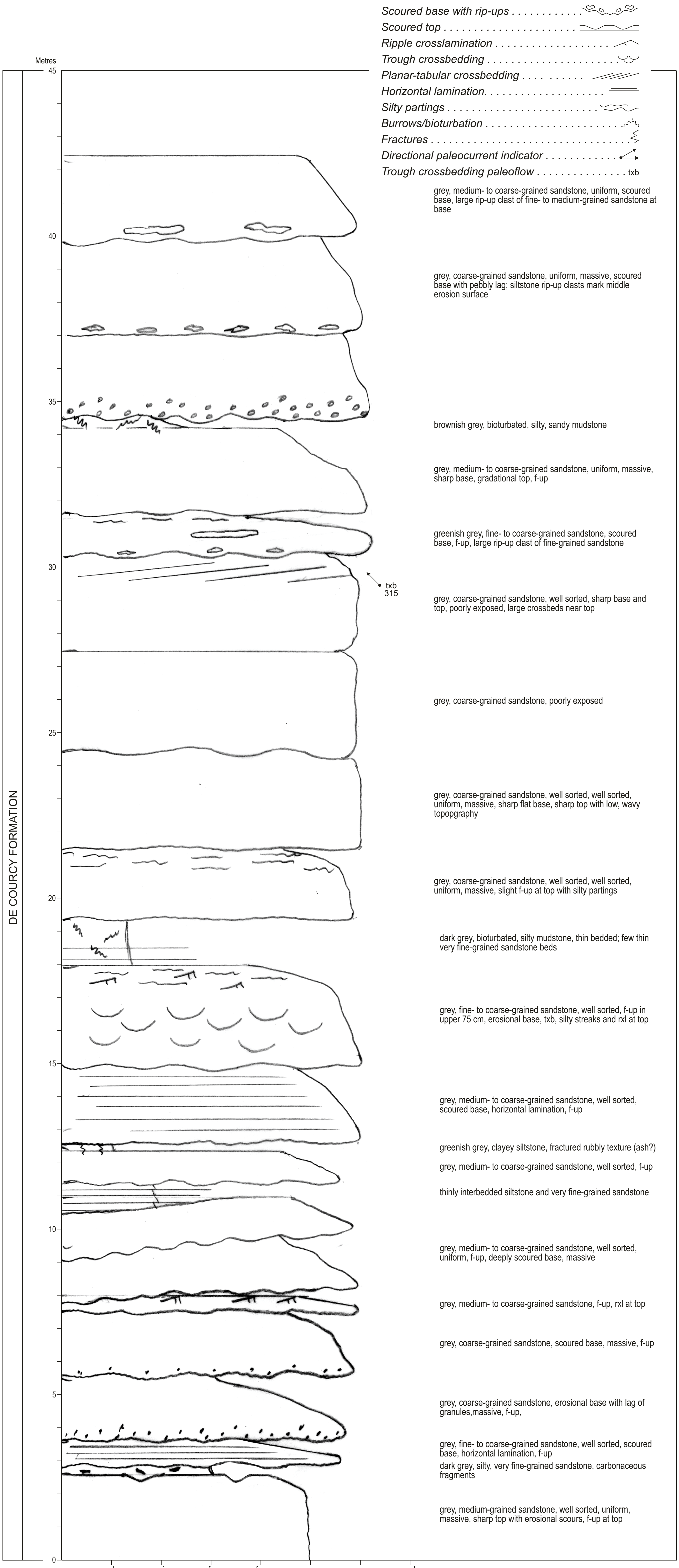


Appendix Figure 54
Robert's Memorial Provincial Park
along Stuart Channel shoreline, off Yellow Point Road, 7.5 km E of Nanaimo Airport
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 03' 46.3"N, 123° 46' 12.0"W; UTM Zone 10: 0443752E, 5434732N



Appendix Figure 55
De Courcy Road Shoreline

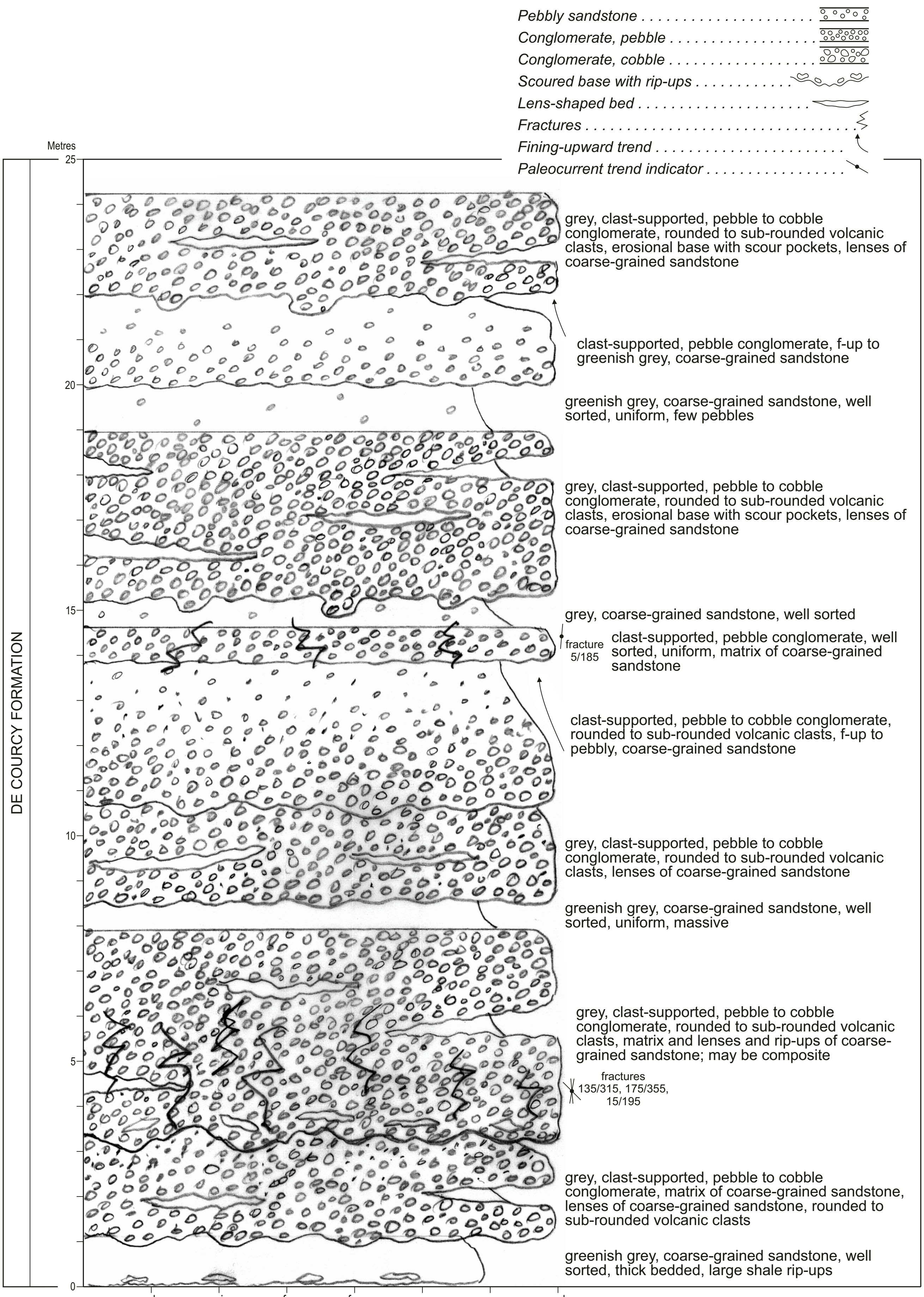
end of De Courcy Road, along Stuart Channel, N of Robert's Memorial Provincial Park, 8 km SE of Cedar
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 04' 57.8"N, 123° 47' 18.1"W; UTM Zone 10: 0442493E, 5436952N



Appendix Figure 56
Duke Point Barge Terminal
partway up Duke Point peninsula at 870 Jackson Road, 5 km southeast of Nanaimo
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 08' 27.2"N, 123° 52' 30.7"W; UTM Zone 10: 0436164E, 5443504N

Appendix Figure 57
Coffin Point
southern tip of Coffin Point, east of Evening Cove, 4 km east of Ladysmith
De Courcy Formation
NTS Map 92B/13 (Duncan)
48° 59' 14.2"N, 123° 45' 54.9"W; UTM Zone 10: 0444012E, 5426310N

Appenidix Figure 58
Nanaimo Observation Well #390 Corehole (OW-11-01)
corner of Holden Corso and Lofthouse roads, Cedar
De Courcy Formation, 112.5 m
NTS Map 92G/14 (Nanaimo)
49° 06' 29.1"N, 123° 49' 23.6"W; UTM Zone 10: 0438917E, 5439794N



Appendix Figure 59

Bill Mee Park, Denman Island

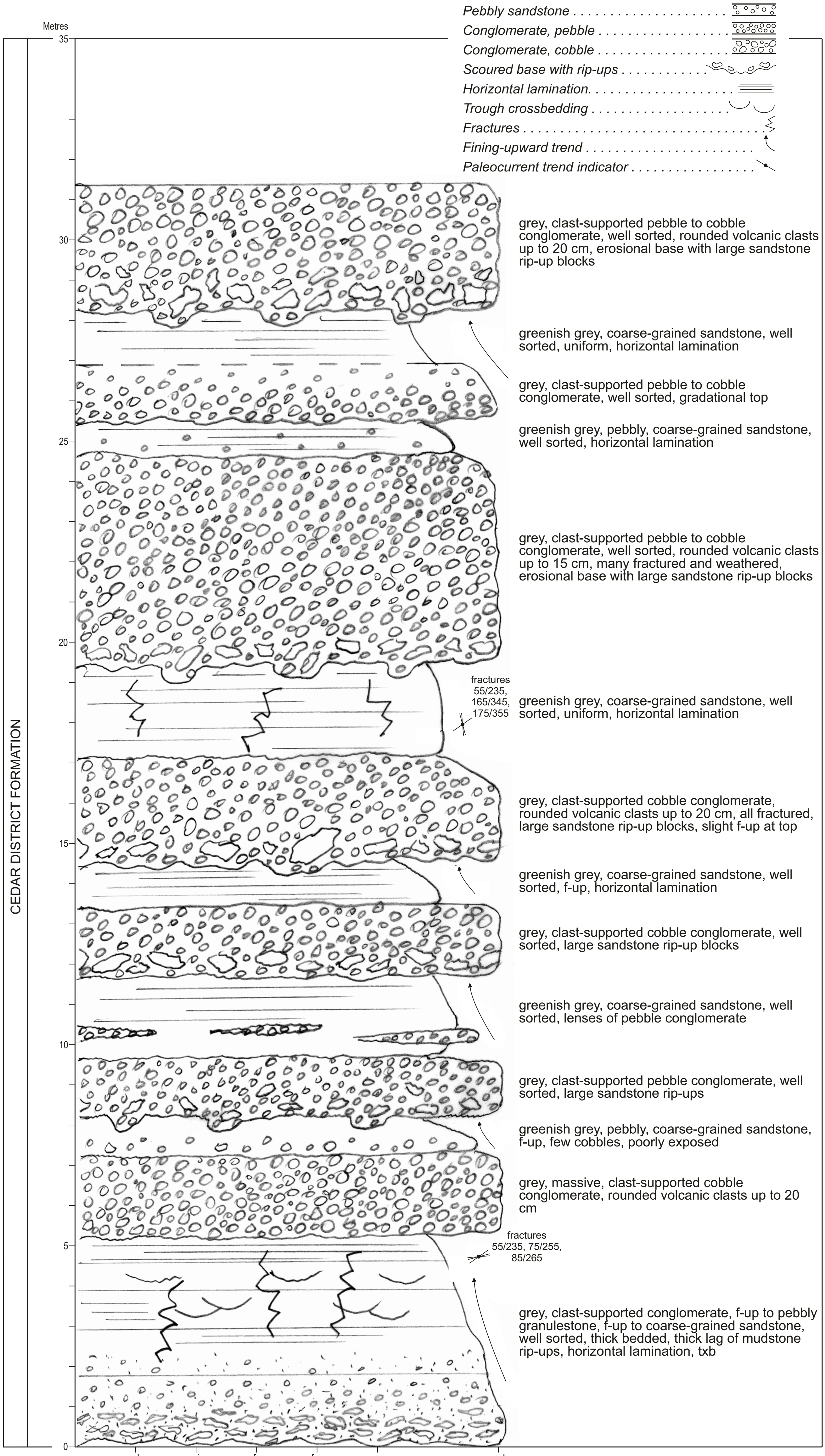
coastal exposure on SE shore of Denman Island, SE of Hornby Island ferry dock

De Courcy Formation

NTS Map 92F/7 (Home Lake) 775833

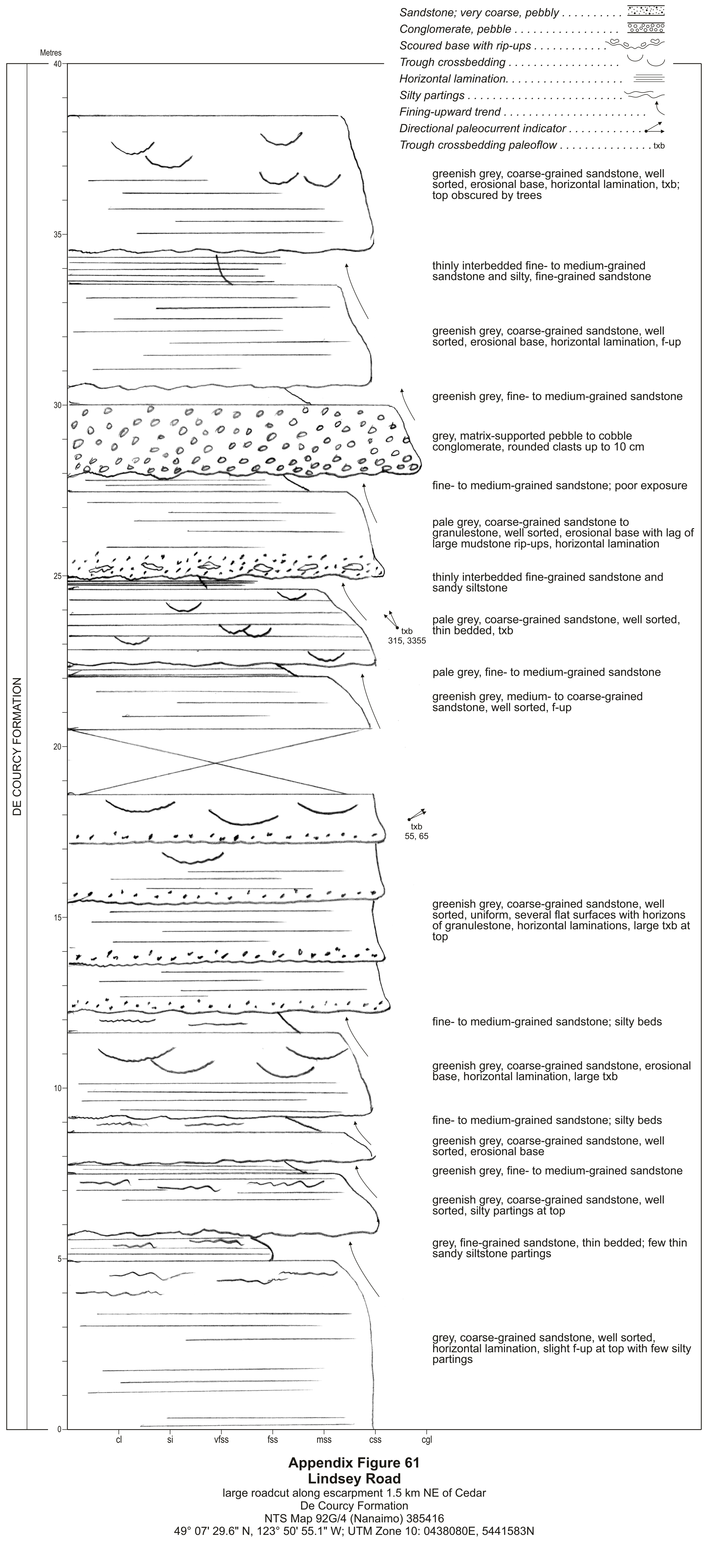
49° 29' 19.4" N, 124° 41' 37.8" W; UTM Zone 10: 0377328E, 5483167N at base;

49° 29' 27.7" N,124° 42' 10.0" W; UTM Zone 10: 0376685E, 5483436N at top

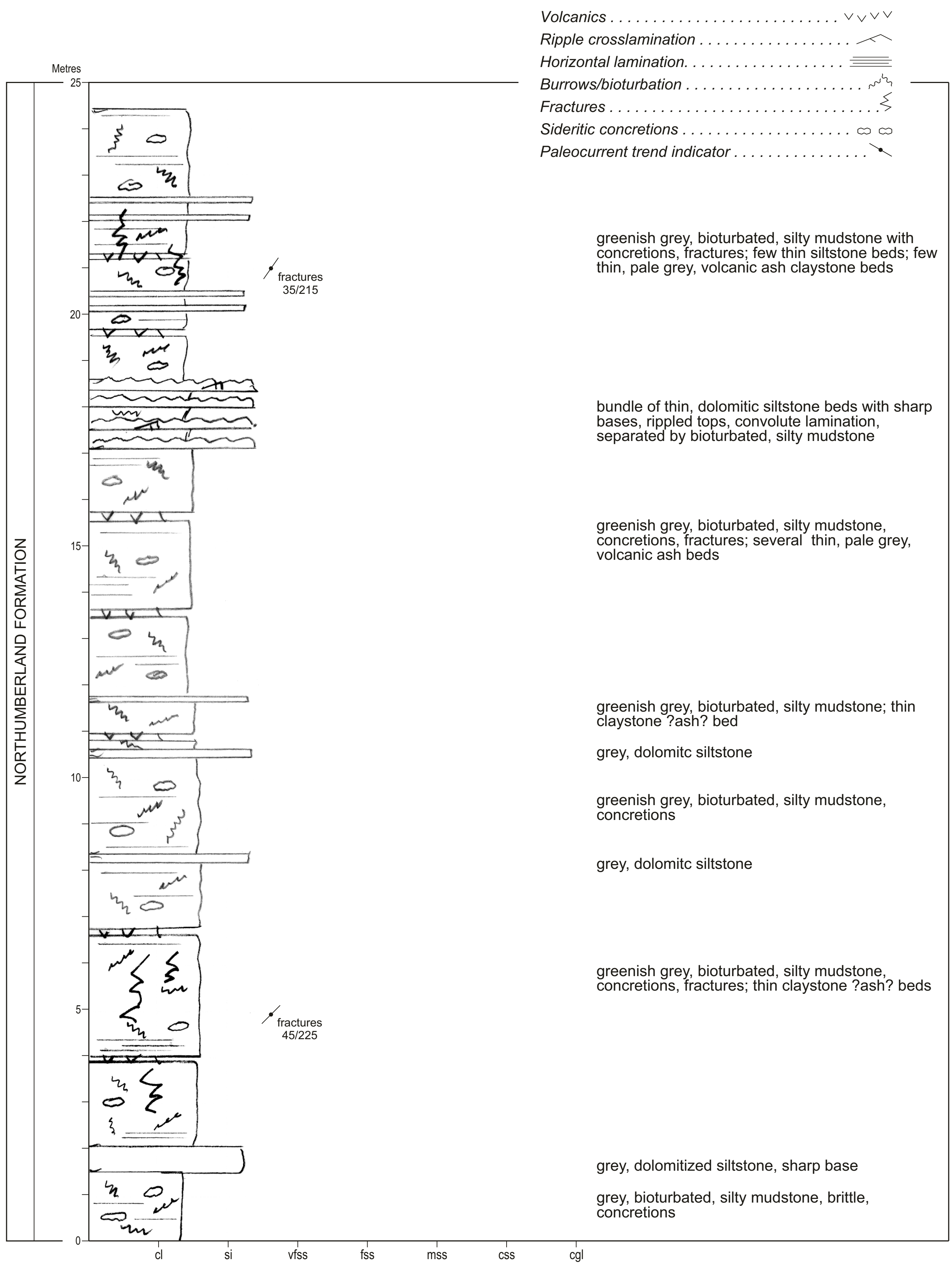


Appendix Figure 60
Whalebone Point, Denman Island

coastal tidal platform and cliff NW along shoreline from cove, along E shore of island
De Courcy Formation
NTS Map 92F/10 (Comox) 745855
49° 30' 14.8" N, 124° 43' 52.5" W; UTM Zone 10: 0374660E, 5484938N at base;
49° 30' 42.1" N, 124° 44' 16.4" W; UTM Zone 10: 0374197E, 5485793N



Appendix Figure 61
Lindsey Road
large roadcut along escarpment 1.5 km NE of Cedar
De Courcy Formation
NTS Map 92G/4 (Nanaimo) 385416
49° 07' 29.6" N, 123° 50' 55.1" W; UTM Zone 10: 0438080E, 5441583N



Appendix Figure 62
St. Mary Lake Roadcut, Saltspring Island
roadcut on St. Mary Lake Road, across from small swimmer's parking spot, E shore of lake
Northumberland Formation
NTS Map 92B/13 (Duncan) 607159
48° 53' 47.2" N, 123° 32' 09.6" W; UTM Zone 10: 0460721E, 5416094N at base;
48° 53' 33.8" N, 123° 32' 09.2" W; UTM Zone 10: 0460723E, 5416052N at top

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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7849

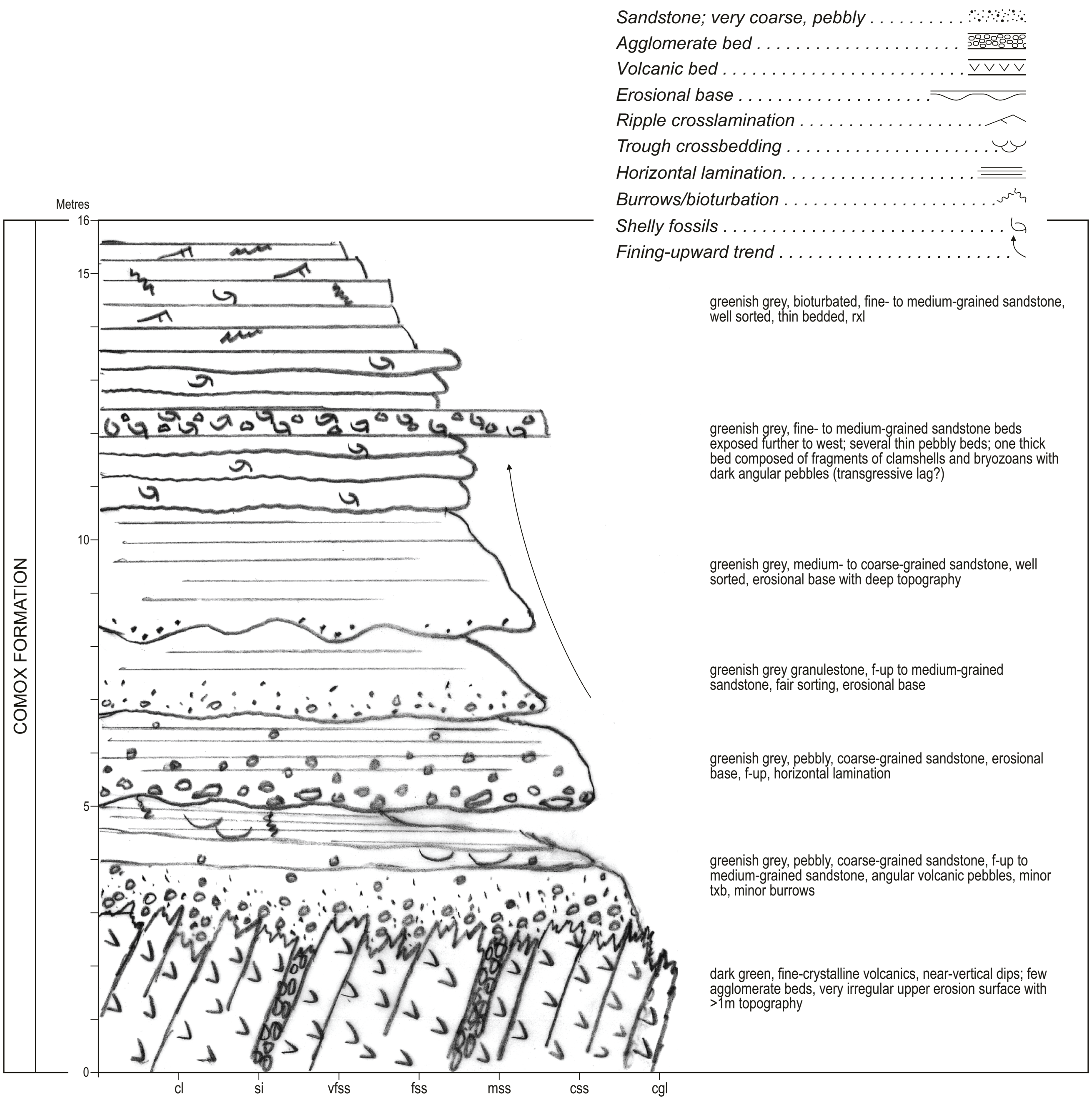
Detailed measured sections, bedrock aquifer/aquitard facies and potential bedrock aquifer systems of the Upper Cretaceous Nanaimo Group, Nanaimo Lowland, eastern Vancouver Island, British Columbia, Canada

APPENDIX II – Nanaimo Group Detailed Measured Sections

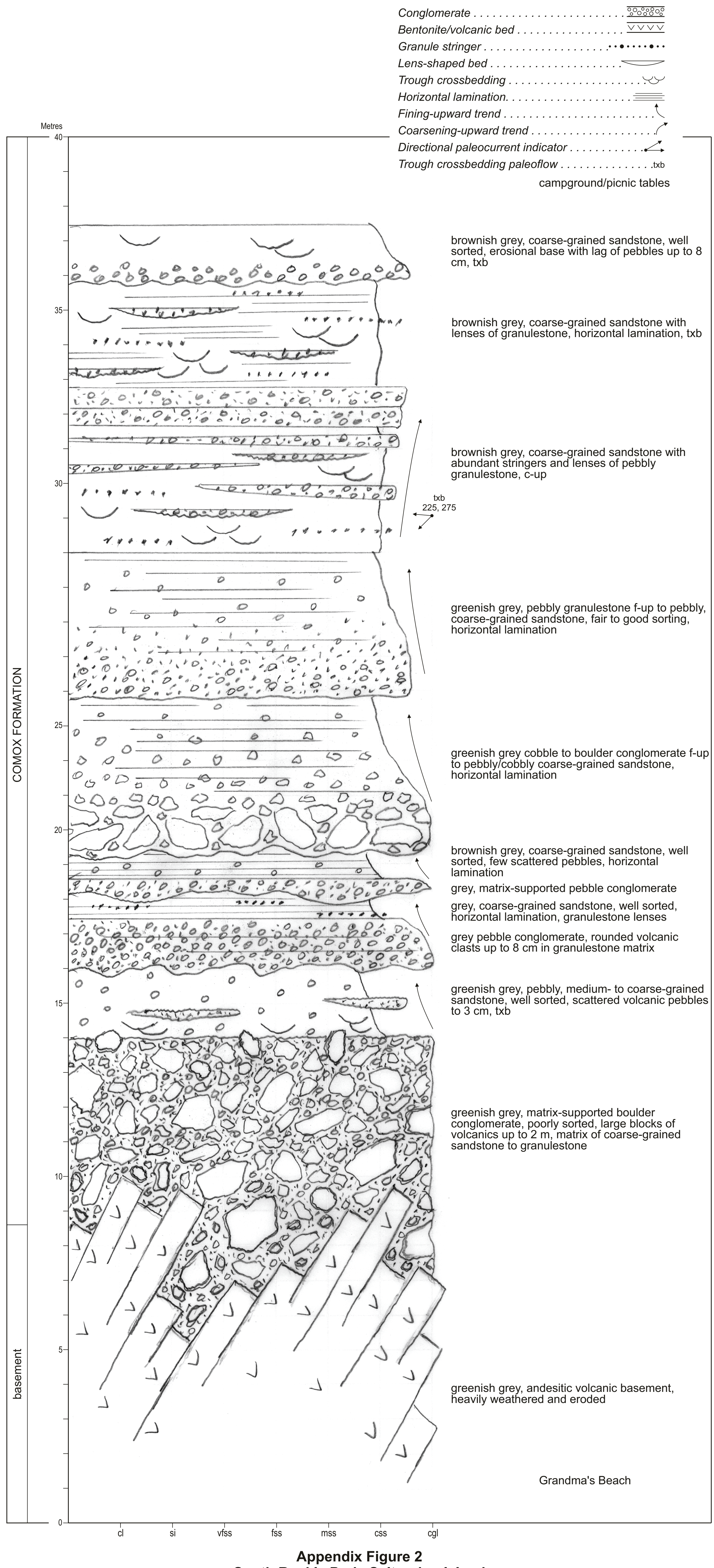
A.P. Hamblin

2015

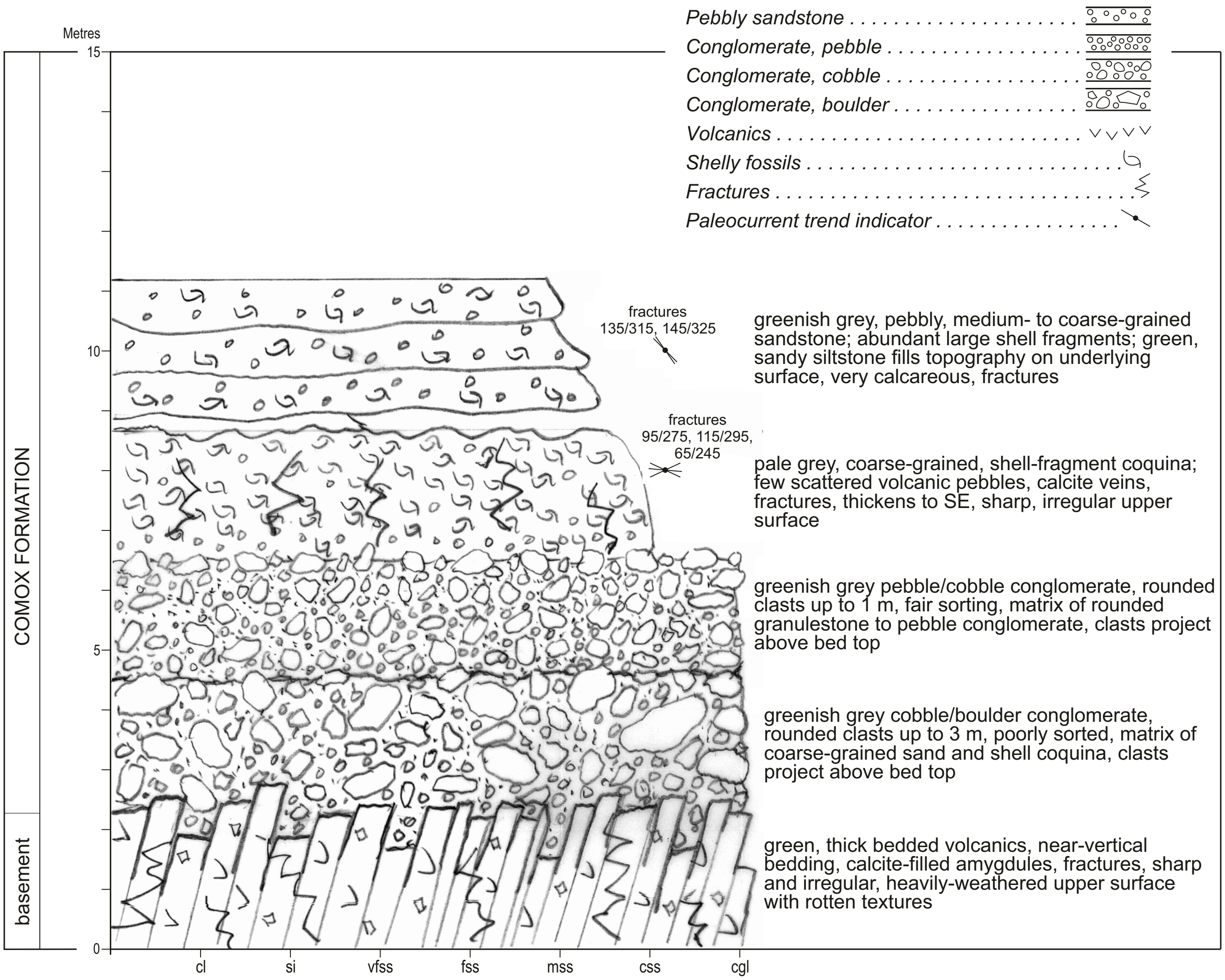
Canada



Appendix Figure 1
Entwhistle Drive Shoreline
end of Entwhistle Drive, off Hammond Bay Road, North Nanaimo
Comox Formation
NTS Map 92G/14 (Nanaimo)
49° 14' 22.7"N, 123° 59' 27.6"W; UTM Zone 10: 0427858E, 5454580N

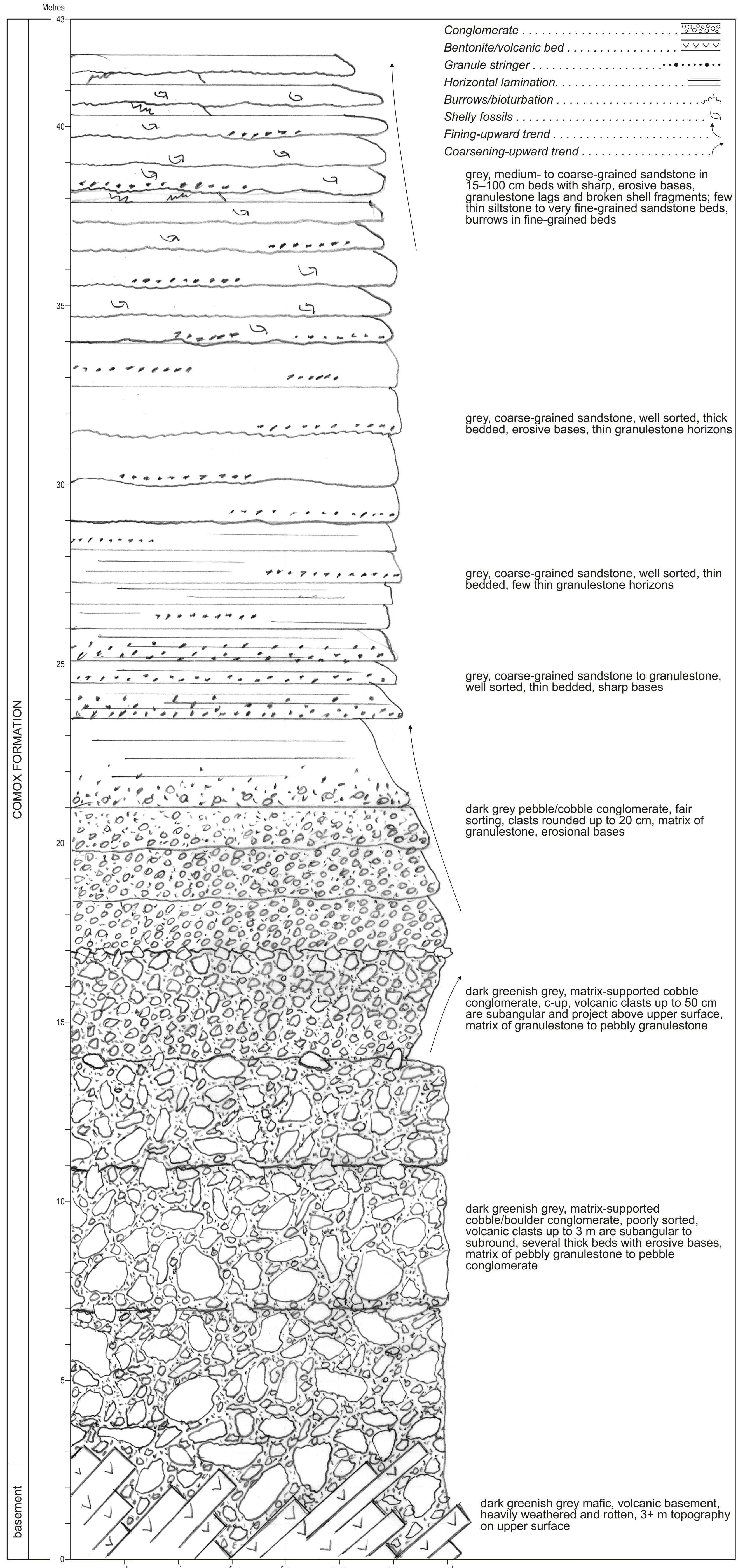


Appendix Figure 2
South Ruckle Park, Saltspring Island
dangerous tidal flat and cliff exposures along S shore of Beaver Point peninsula, from Grandma's Beach cove to campground
volcanic basement – Comox Formation
NTS Map 92B/14 (Mayne Island) 725016
48° 46' 03.0" N, 123° 22' 30.4" W; UTM Zone 10: 0472435E, 5401676N at base;
48° 46' 00.7" N, 123° 22' 18.0" W; UTM Zone 10: 0472689E, 5401603,N at top



Appendix Figure 3
Horsewell Bluff II

coastal exposure immediately SW of end of Stephenson Point Road beach access stairway
basement – Comox Formation
NTS Map 92G/4 (Nanaimo) 314514
49° 12' 42.2" N, 123° 56' 29.8" W; UTM Zone 10: 0431421E, 5451417N



Appendix Figure 4

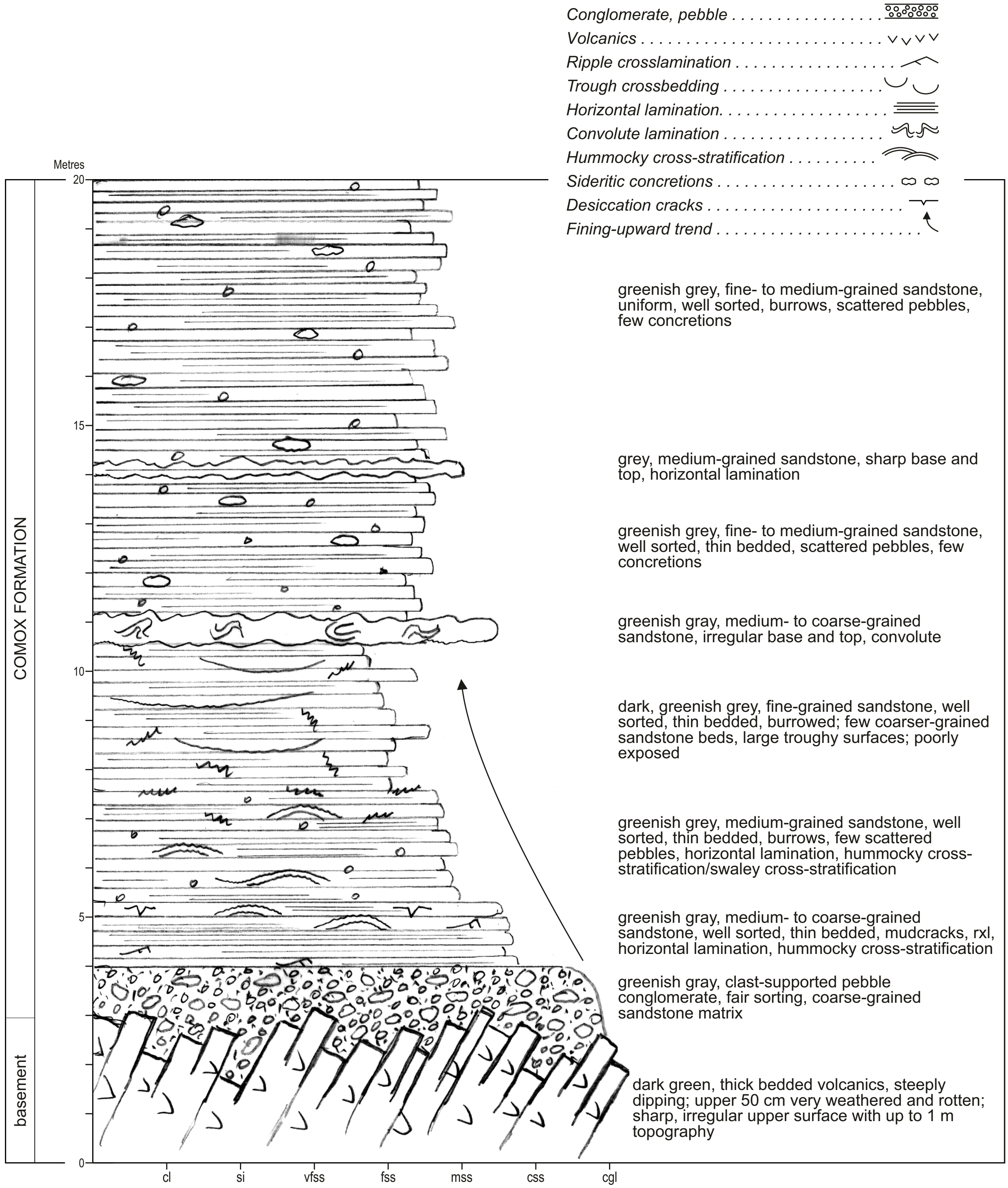
Nanaimo Parkway/Jingle Pot Road ("Malaspina Roadcut")

large roadcut on S side of highway, 0.5 km SE of Jinglepot Road/3rd Street intersection in Nanaimo

basement – Comox Formation

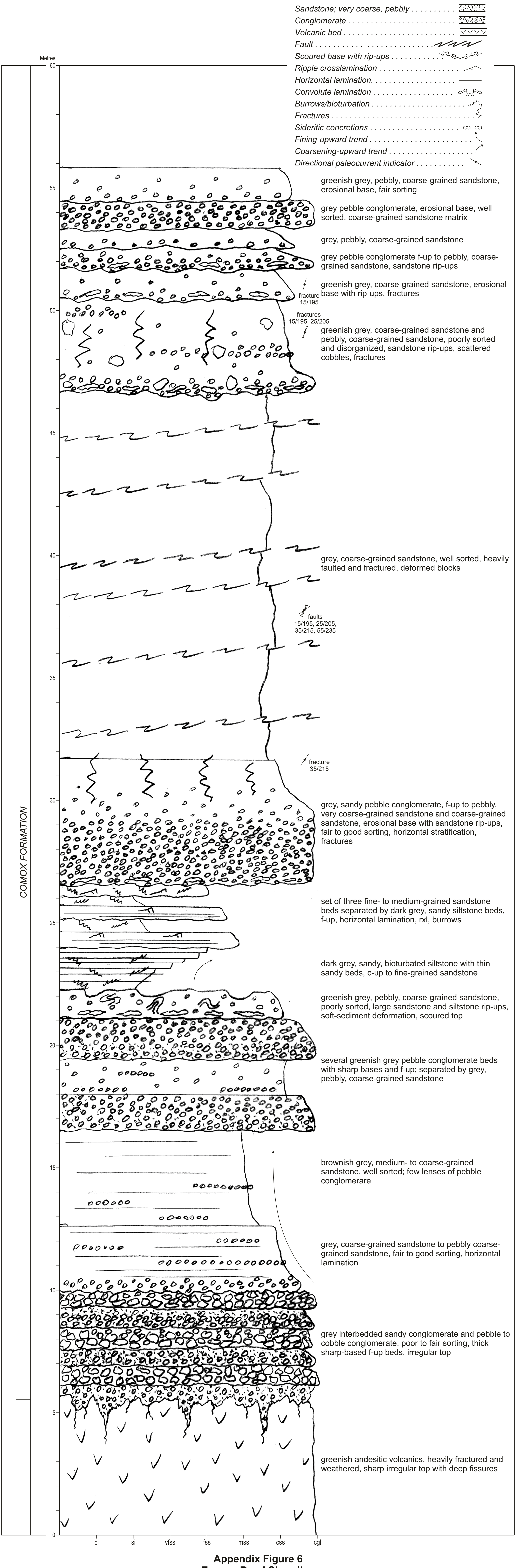
NTS Map 92G/4 (Nanaimo) 286462

49° 09' 55.0" N, 123° 58' 45.8" W; UTM Zone 10: 0428603E, 5446293N



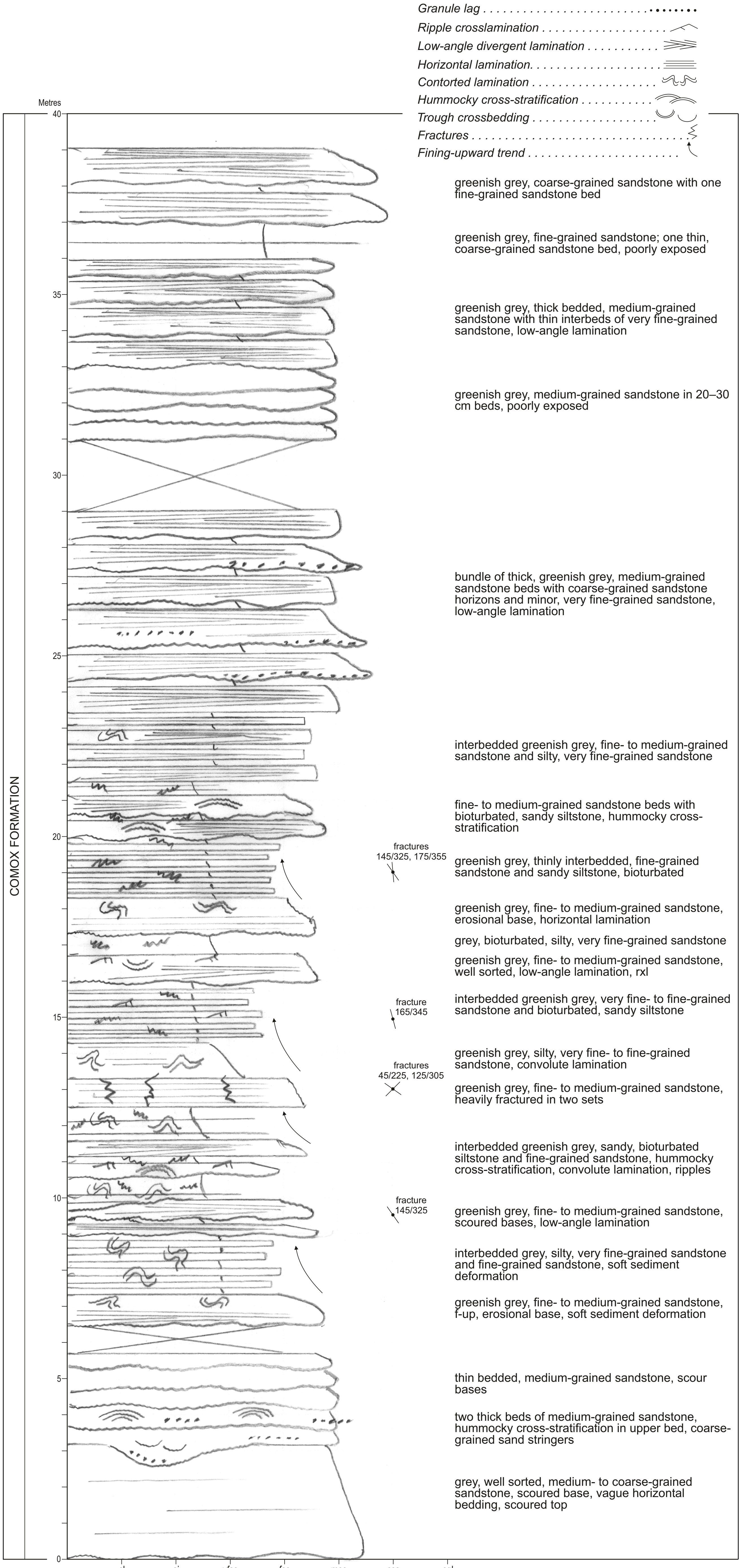
Appendix Figure 5
Armstrong Point

coastal and tidal flat exposure NW along shore from access stairway at end of Allbay Road
basement – Comox Formation
NTS Map 92B/11 (Sidney) 708906
48° 40' 01.6" N, 123° 23' 49.9" W; UTM Zone 10: 0470754E, 5390527N

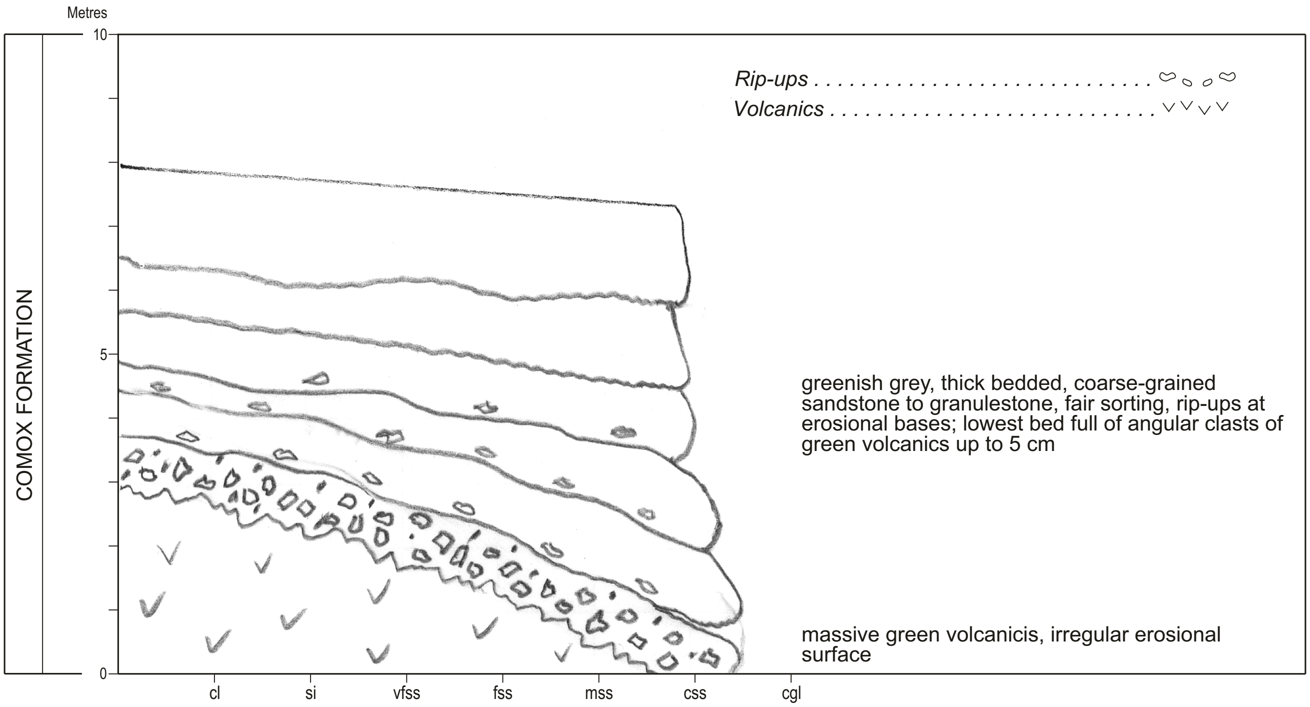


Appendix Figure 6
Towner Road Shoreline

tidal flat and bank exposure W of Towner Road beach access,
S of Deep Cove and 4 km W of Sidney
Basement–Comox Formation
NTS Map 92B/11 (Sidney) 648907
48° 40' 06.1"N, 123° 28' 43.0"W UTM Zone 10: 0464760E, 5390702N (base) to
48° 40' 08.7"N, 123° 28' 42.7"W UTM Zone 10: 0464767E, 5390782N (top)

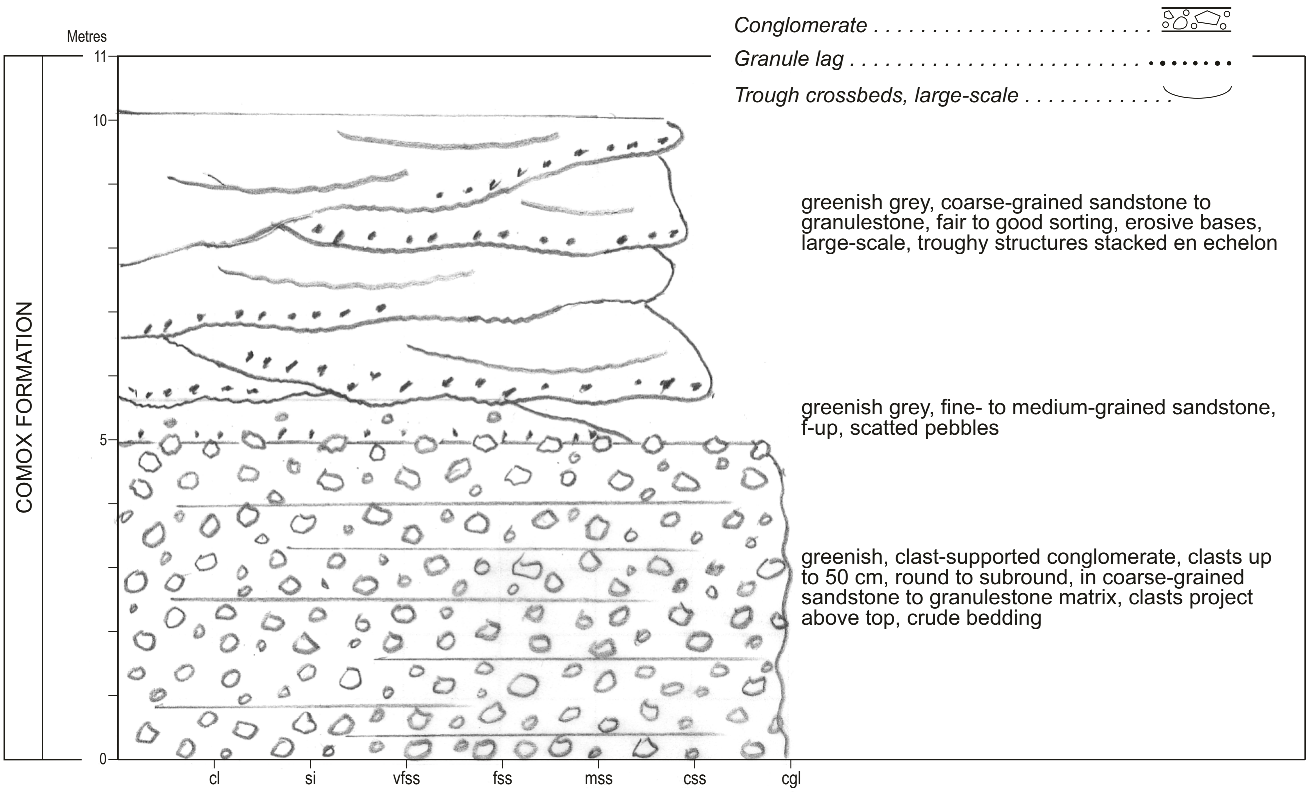


Appendix Figure 7
Moses Point
NW tip of Saanich Peninsula, 8 km NW of Sidney
Comox Formation
NTS Map 92B/11 (Sidney)
49° 41' 22.5"N, 123° 29' 06.3"W; UTM Zone 10: 0464300E, 5393061N



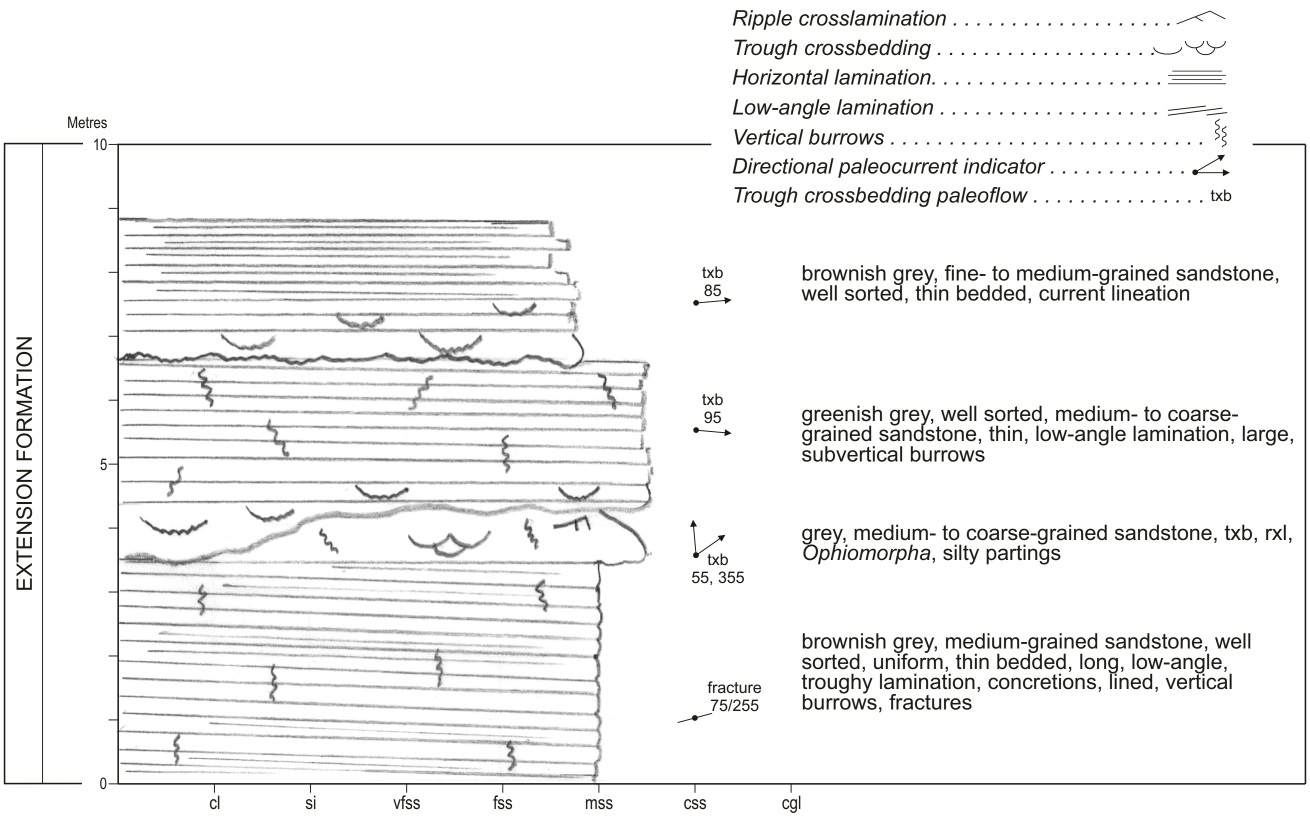
Appendix Figure 8
Pacific Biological Station

Stephenson Point Road, Departure Bay, 5 km N of Nanaimo city centre
Comox Formation
NTS Map 92G/14 (Nanaimo)
49° 12' 36.6"N, 123° 57' 15.8"W; UTM Zone 10: 0430491E, 5451261N



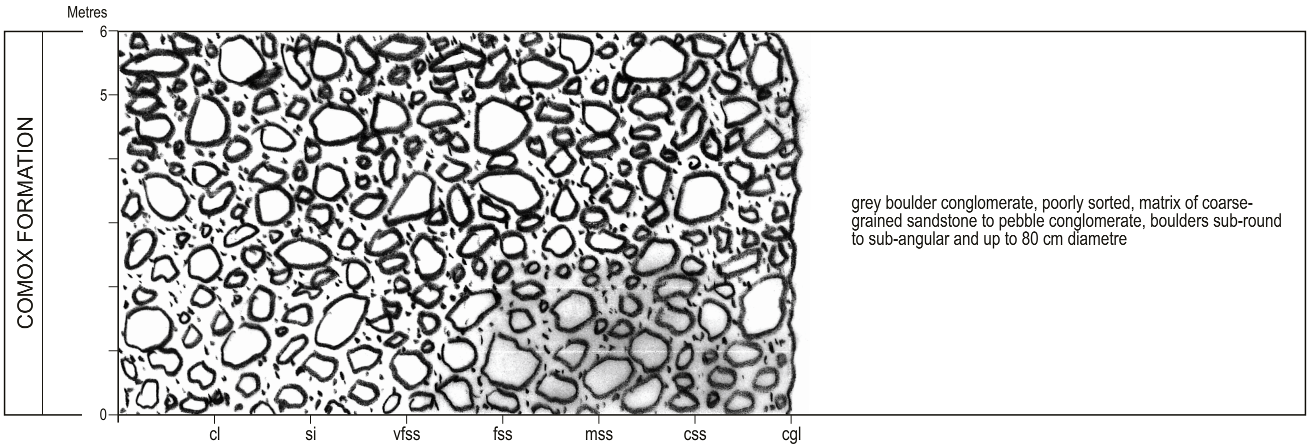
Appendix Figure 9
Horsewell Bluff

end of Stephenson Point Road, Departure Bay, 5 km N of Nanaimo city centre
Comox Formation
NTS Map 92G/14 (Nanaimo)
48° 12' 48.6"N, 123° 56' 25.6"W; UTM Zone 10: 0431508E, 5451611N

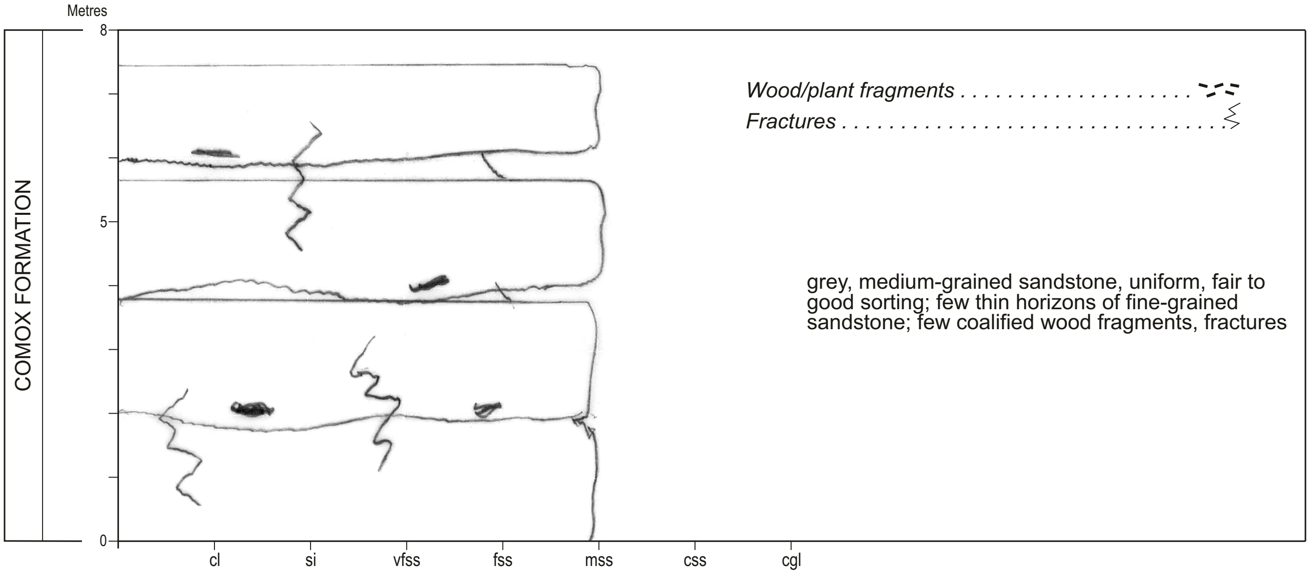


Appendix Figure 10
Blunden Point

end of Sebastien Road, south shoreline of Nanoose Harbour, 1 km NW of Lantzville
Extension Formation
NTS Map 92F/8 (Parksville)
49° 15' 24.8"N, 124° 05' 04.0"W; UTM Zone 10: 0421091E, 5456578N



Appendix Figure 11
Englishman River Falls (Upper Falls)
small cliff area across from Upper Falls
Comox Formation
NTS Map 92F/1 (Nanaimo Lakes)
49° 14' 36.2"N, 124° 20' 53.3"W; UTM Zone 10: 0401875E, 5455307N

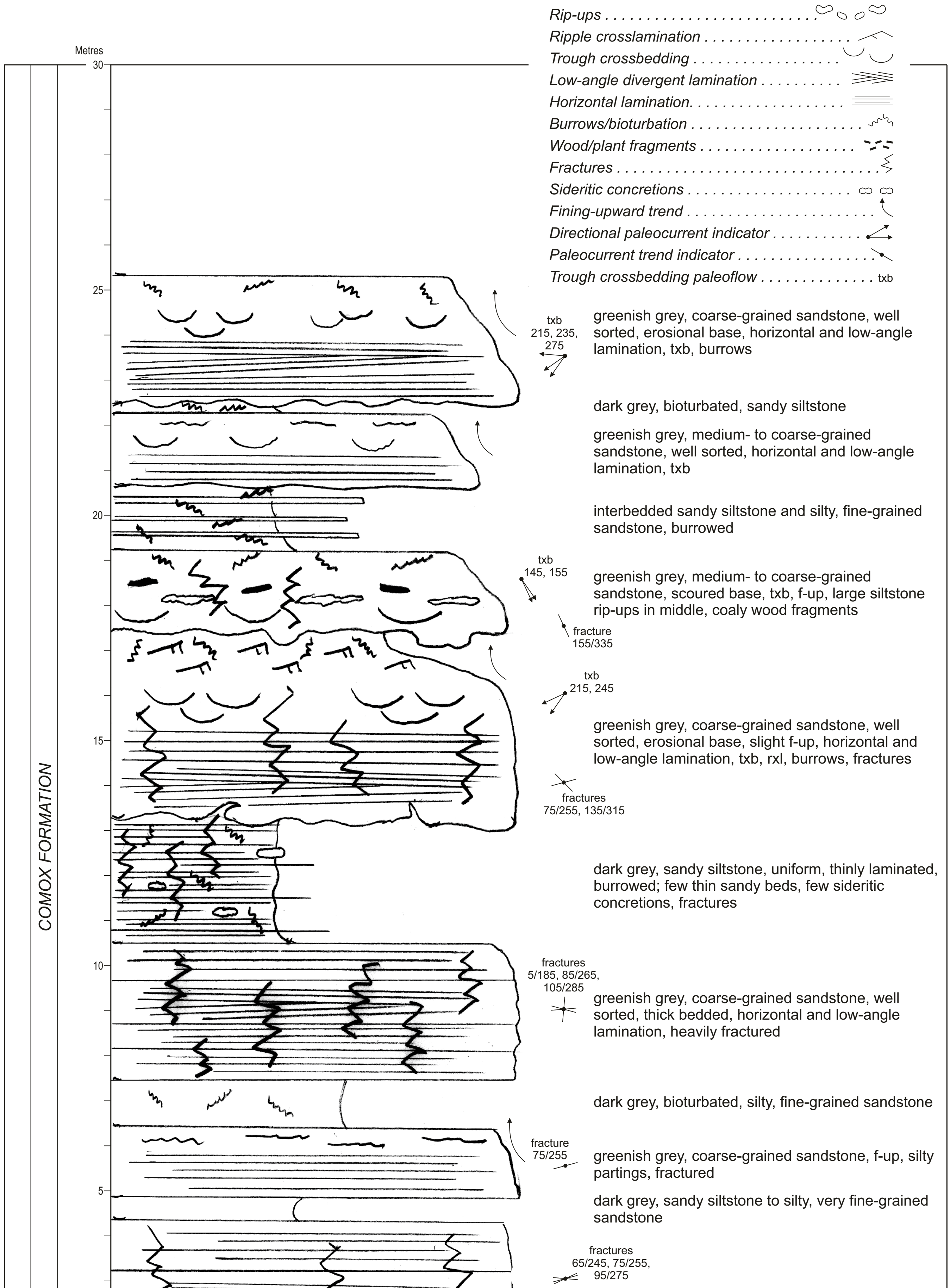


Appendix Figure 12
Highway 19 & Miracle Beach Interchange
roadcut at intersection of Highway 19 and Hamm Road to Miracle Beach Provincial Park
Comox Formation
NTS Map 92F/14 (Oyster River) 423222
49° 49' 48.0" N, 125° 11' 23.5" W; UTM Zone 10: 0392513E, 5522029N

Appendix Figure 13
Highway 17, Schwarz Bay Roadcut

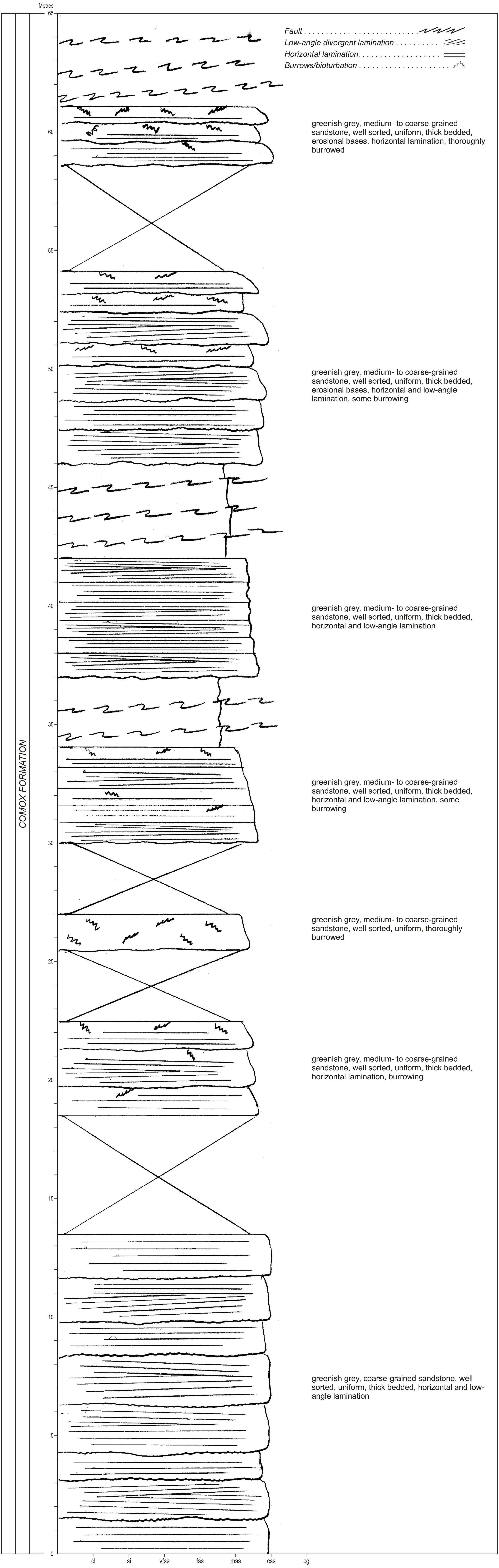
large roadcut on NW side of highway 1 km W of Ferry Terminal immediately W of Lands End Road
Comox Formation
NTS Map 92B/11 (Sidney) 692922
48° 40' 52.4" N, 123° 25' 10.6" W; UTM Zone 10: 0469320E, 5392105N at base;
48° 40' 57.7" N, 123° 24' 51.3" W; UTM Zone 10: 0469470E, 5392264N at top

Appendix Figure 14
Norris Road Shoreline
long tidal flat and cliff exposure from foot of Norris Road beach access stairway to headland, S of Deep Cove and 4 km W of Sidney
Comox Formation
NTS Map 92B/11 (Sidney) 646909
48° 40' 13.2"N, 123° 25' 43.2"W; UTM Zone 10: 0464758E, 5390017N (base) to
48° 40' 20.5"N, 123° 28' 56.7"W; UTM Zone 10: 0464483E, 5391148N (top)

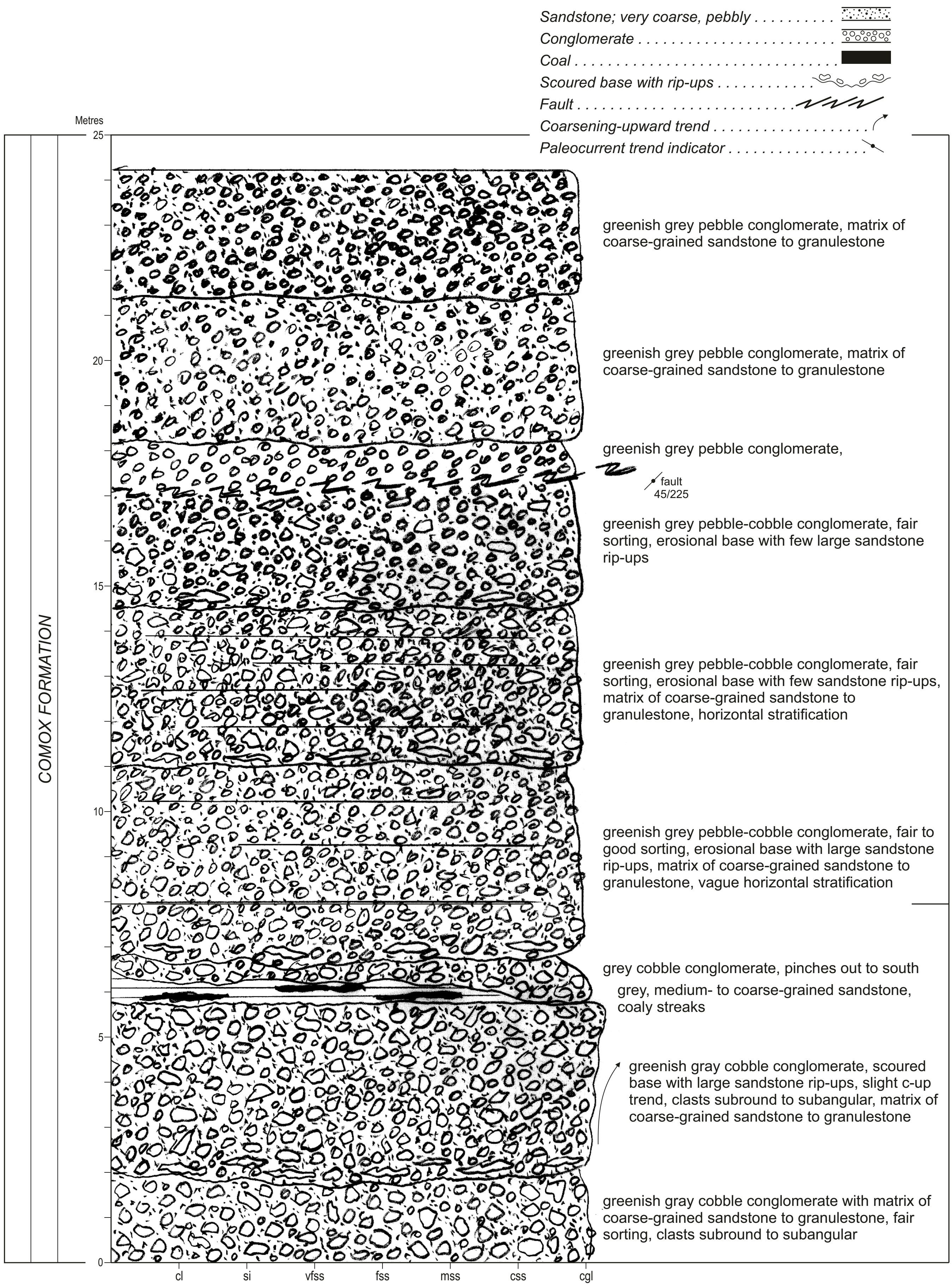


Appendix Figure 15
Cromar Road Shoreline

tidal platform exposure at bottom of access stairway at intersection of Madrona Road and Cromar Road, S of Deep Cove and 4 km W of Sidney
Comox Formation
NTS Map 92B/11 (Sidney) 644915
48° 40' 29.8"N, 123° 28' 59.1"W; UTM Zone 10: 0464477E, 5391432N (base) to
48° 40' 30.9"N, 123° 29' 01.7"W; UTM Zone 10: 0464301E, 5391468N (top)

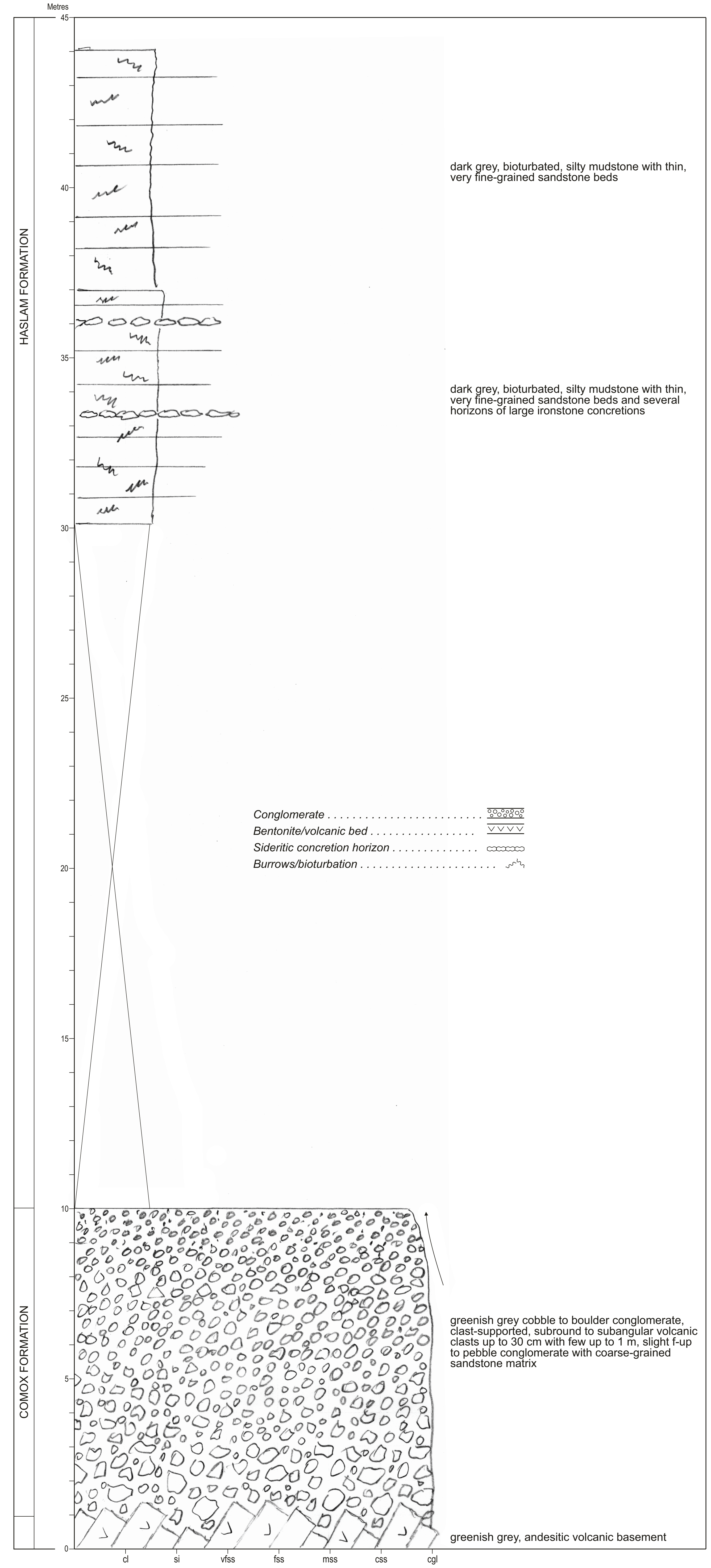


Appendix Figure 16
Kingfisher Lane Shoreline
much faulted shoreline section off Land's End Road,
immediately W of West Saanich Road, 4 km NW of Sidney
Comox Formation
NTS Map 92B/11 (Nanaimo) 660938
48° 41' 42.7"N, 123° 27' 38.6"W UTM Zone 10: 0466098E, 5393830N (base) to
49° 41' 48.6"N, 123° 27' 52.1"W UTM Zone 10: 0465819E, 5393861N (top)



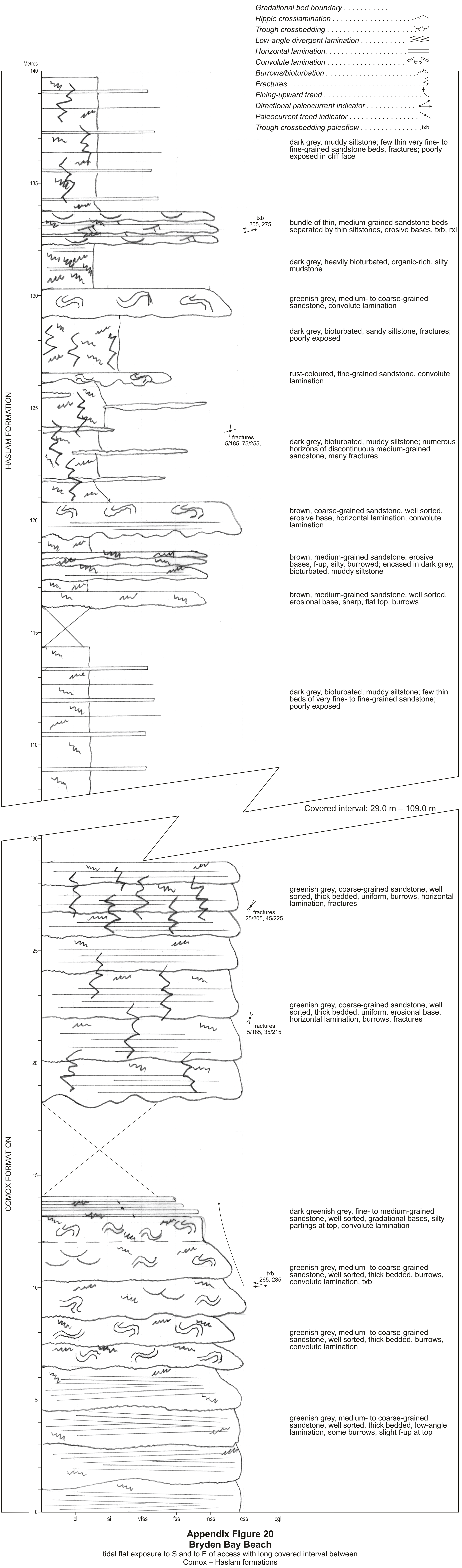
Appendix Figure 17
Highway 19 and Auld's Road

roadcut exposure along Highway 19 on SW corner of intersection,
in north Nanaimo, 2 km N of Brannen Lake
Comox Formation
NTS Map 92F/01 (Nanaimo Lakes) 234537
49° 13' 55.6"N, 124° 03' 06.5"W; UTM Zone 10: 0423429E, 5453789N (base) to
49° 13' 46.0"N, 124° 03' 06.3"W; UTM Zone 10: 0423424E, 5453499N (top)



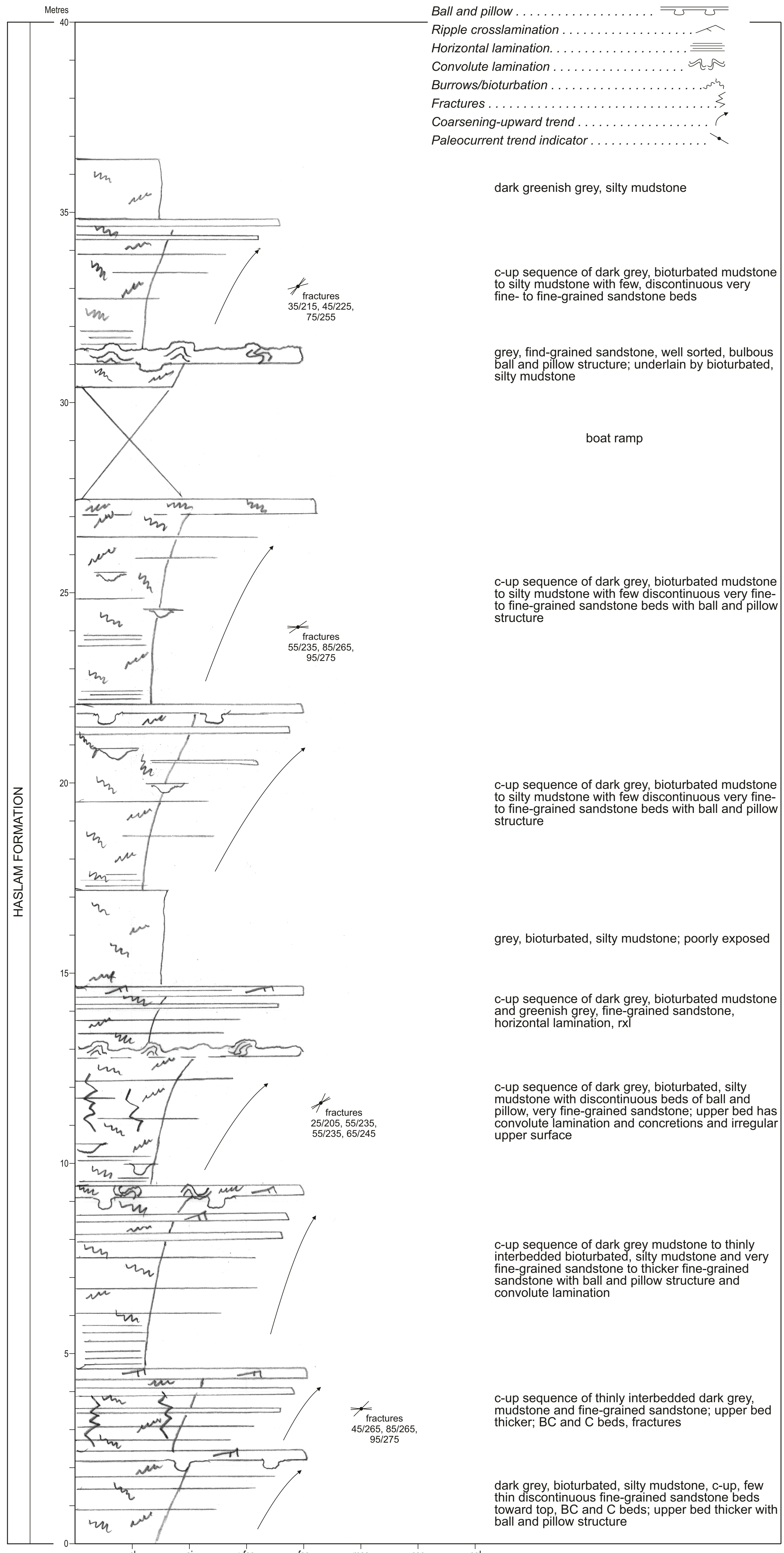
Appendix Figure 18
Englishman River Falls (Lower Falls)
exposure at Lower Falls and northward along river
Comox – Haslam formations
NTS Map 92F/1 (Nanaimo Lakes) 019557
49° 14' 50.6" N, 124° 20' 55.8" W; UTM Zone 10: 0401835E, 5455831N at base;
49° 15' 02.4" N, 124° 20' 48.3" W; UTM Zone 10: 0401918E, 5456086N at top

Appendix Figure 19
Beddes Beach, Saltspring Island
tidal flat and cliff exposures SE along shore from Beddes Beach
public access to Cusheon Creek, SE shore of island
Comox – Haslam formations
NTS Map 92B/14 (Mayne Island) 688063
48° 48' 23.1"N, 123° 25' 21.1"W; UTM Zone 10: 0468973E, 5406026N at base
48° 48' 33.8"N, 123° 25' 32.5"W; UTM Zone 10: 0468743E, 5406353N at top



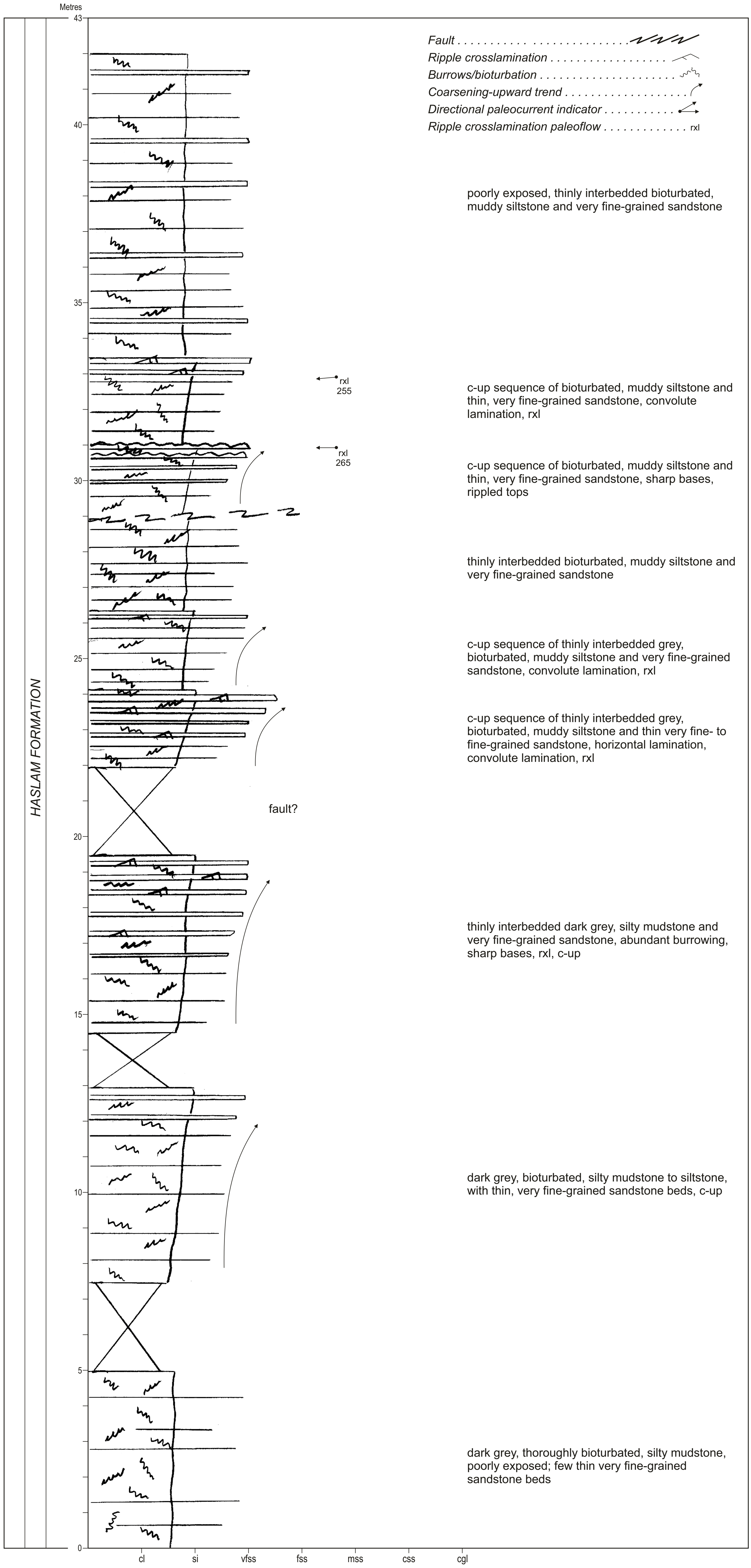
Appendix Figure 20
Bryden Bay Beach
tidal flat exposure to S and to E of access with long covered interval between
Comox – Haslam formations
NTS Map 92B/11 (Sidney) 710904
48° 40' 27.1" N, 123° 24' 36.1" W; UTM Zone 10: 0469014E, 5391319N

Appendix Figure 21
Marie Canyon
Cowichan River Provincial Park, Marie Canyon access, off Riverbottom Road, 16 km W of Duncan
Haslam Formation
NTS Map 92B/13 (Duncan)
48° 46' 39.5"N, 123° 55' 31.0"W; UTM Zone 10: 0432117E, 5402961N



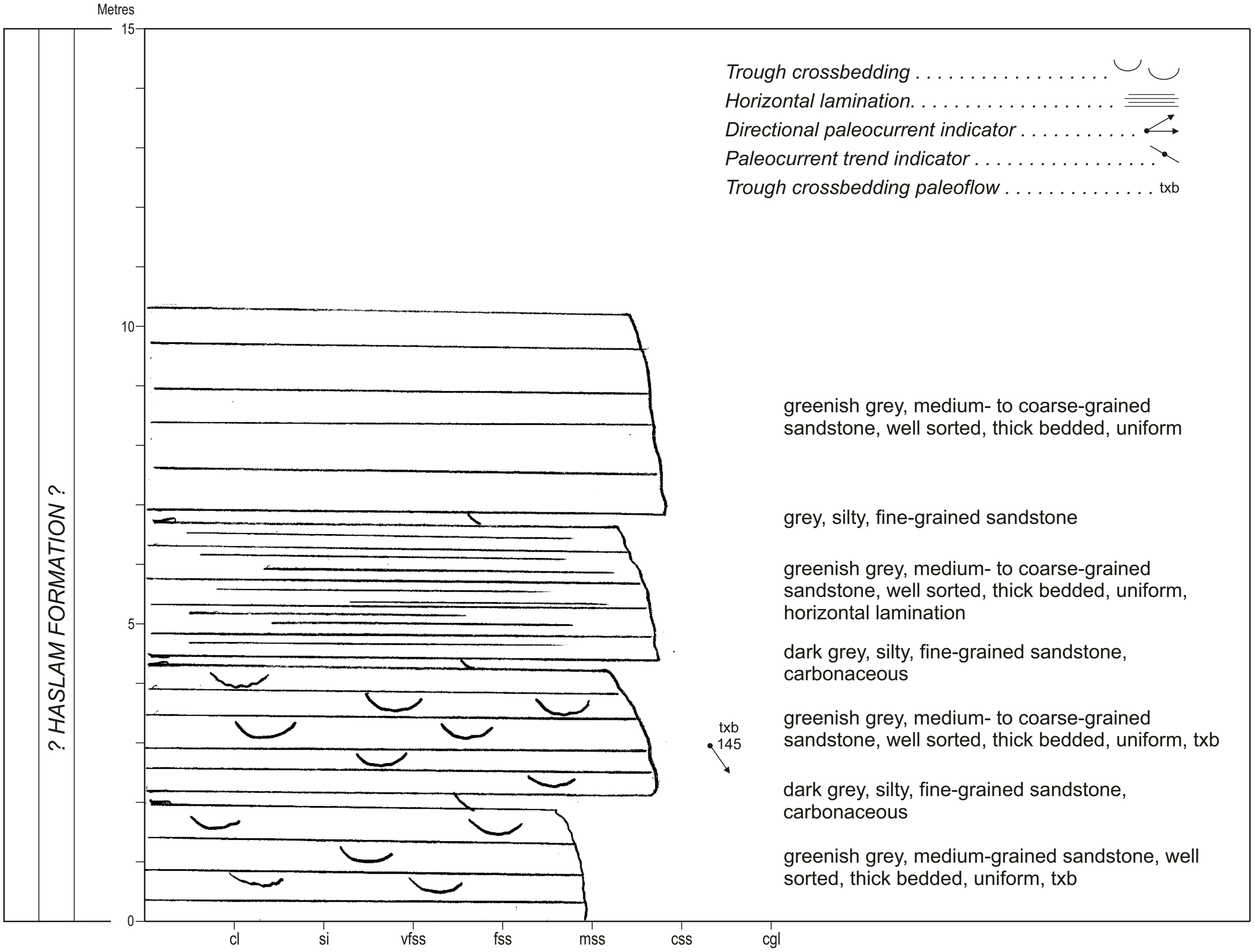
Appendix Figure 22
Chemainus Kin Beach Park Boat Launch

tidal flat exposures on NW shoreline of Chemainus Harbour, from Kin Beach at foot of Maple Street SE toward hospital
Haslam Formation
NTS Map 92B/13 (Duncan) 476197
48° 55' 43.4" N, 123° 43' 02.4" W; UTM Zone 10: 0447456E, 5419778N at base;
48° 55' 40.1" N, 123° 45' 54.7" W; UTM Zone 10: 0447614E, 5419680N at top



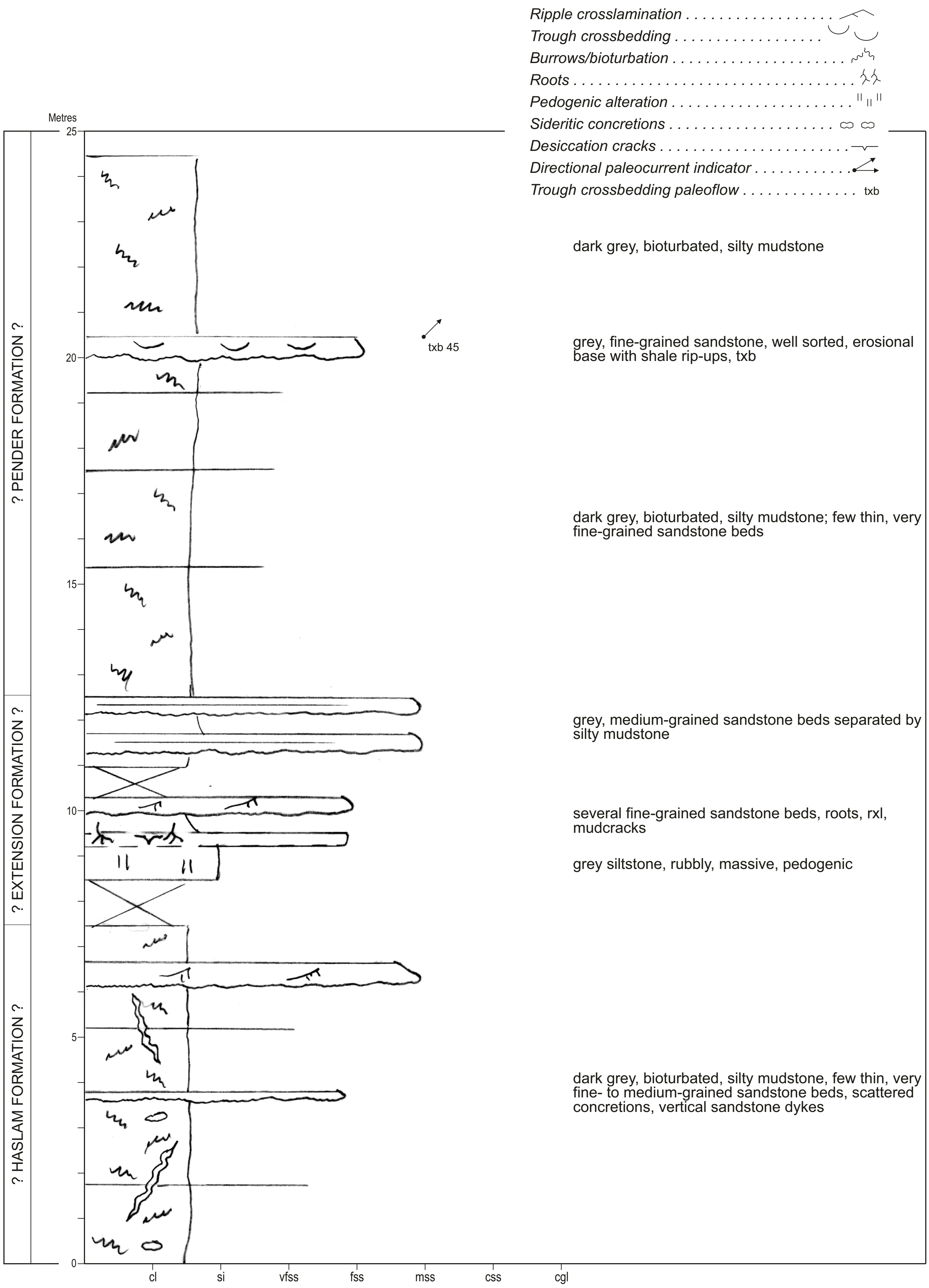
Appendix Figure 23
Seabreeze Road Shoreline

tidal platform exposure at bottom of access stairway near Land's End Road,
4 km NW of Sidney
Haslam Formation
NTS Map 92B/11 (Sidney) 670941
48° 41' 55.4"N, 123° 26' 54.7"W UTM Zone 10: 0464996E, 5394065N (base) to
48° 41' 57.9"N, 123° 26' 47.1"W UTM Zone 10: 0467152E, 5394138N (top)



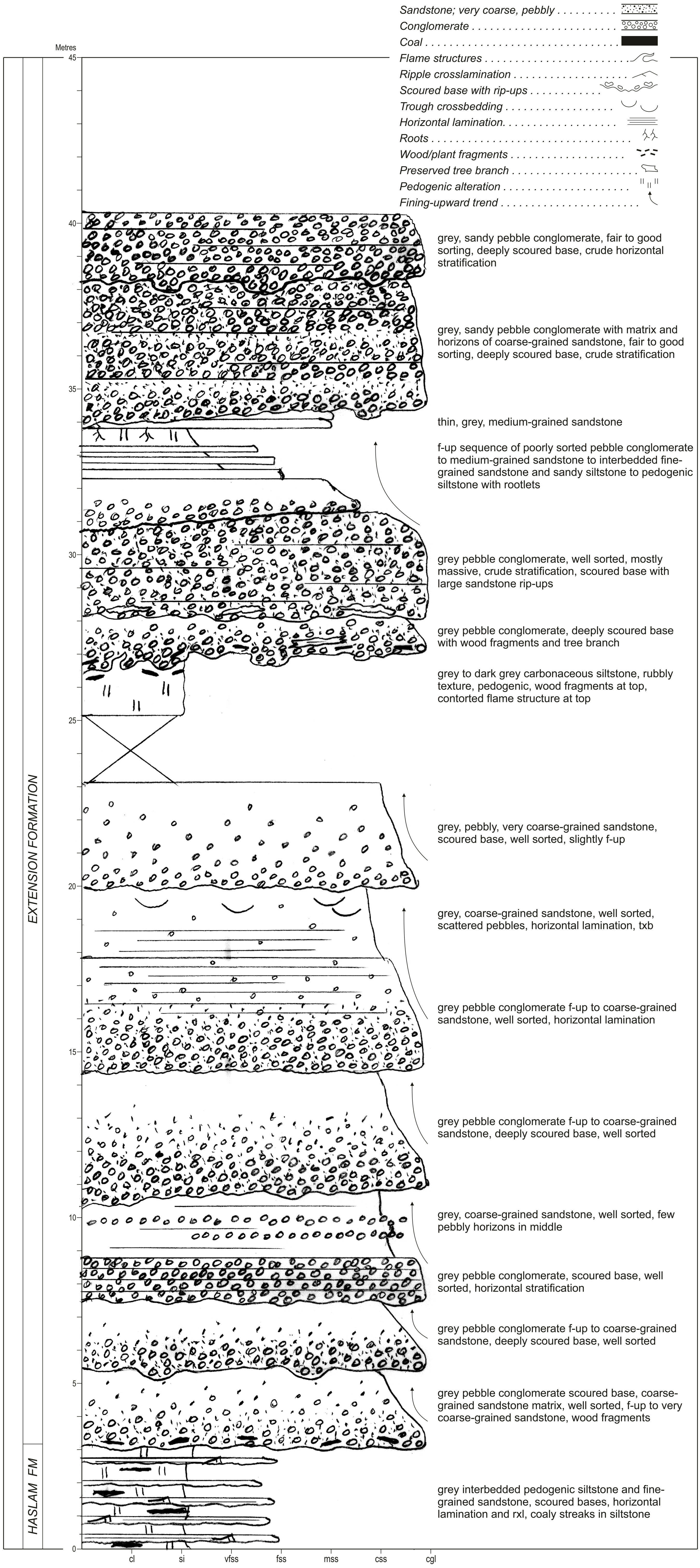
Appendix Figure 24
Highway 19 and Jingle Pot Road
roadcut exposure along Highway 19 NW of Jingle Pot Road/Mostar Road intersection,
accessed from Biggs Road, in north Nanaimo, 1 km SE of Brannen Lake
Haslam Formation
NTS Map 92F/01 (Nanaimo Lakes) 243511
49° 12' 27.6"N, 124° 02' 25.7"W; UTM Zone 10: 0424214E, 5451061N

Appendix Figure 25
Erskine Point, Saltspring Island
unnamed bay 500 m east of Erskine Point, west shore of Saltspring Island
Haslam Formation/Extension Formation
NTS Map 92B/13 (Duncan)
base of section: 48° 51' 08.1"N, 123° 33' 47.2"W; UTM Zone 10: 0458693E, 5411184N
top of section: 48° 51' 19.1"N, 123° 33' 43.1"W; UTM Zone 10: 0458775E, 5411523N

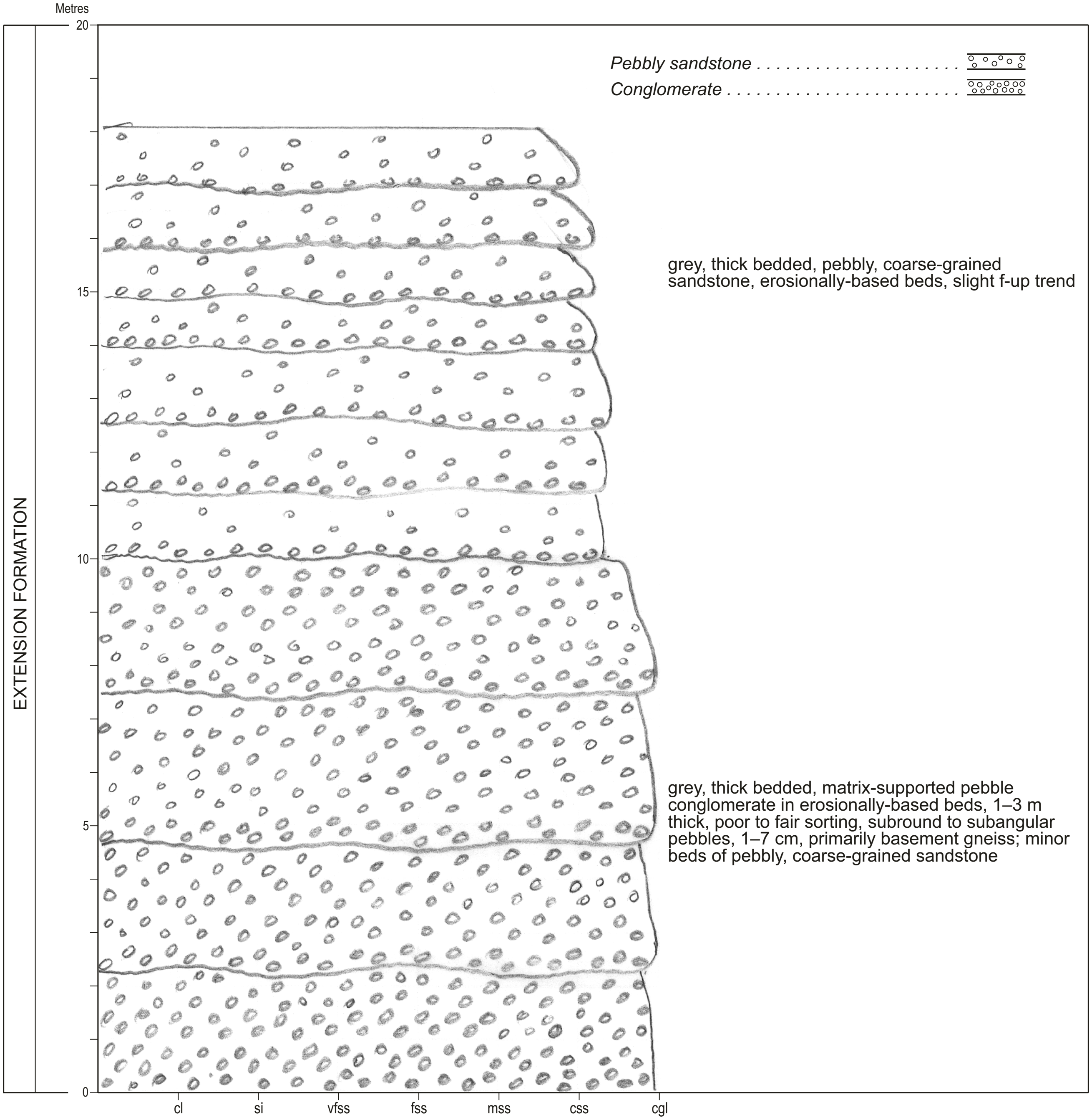


Appendix Figure 26
Trent River

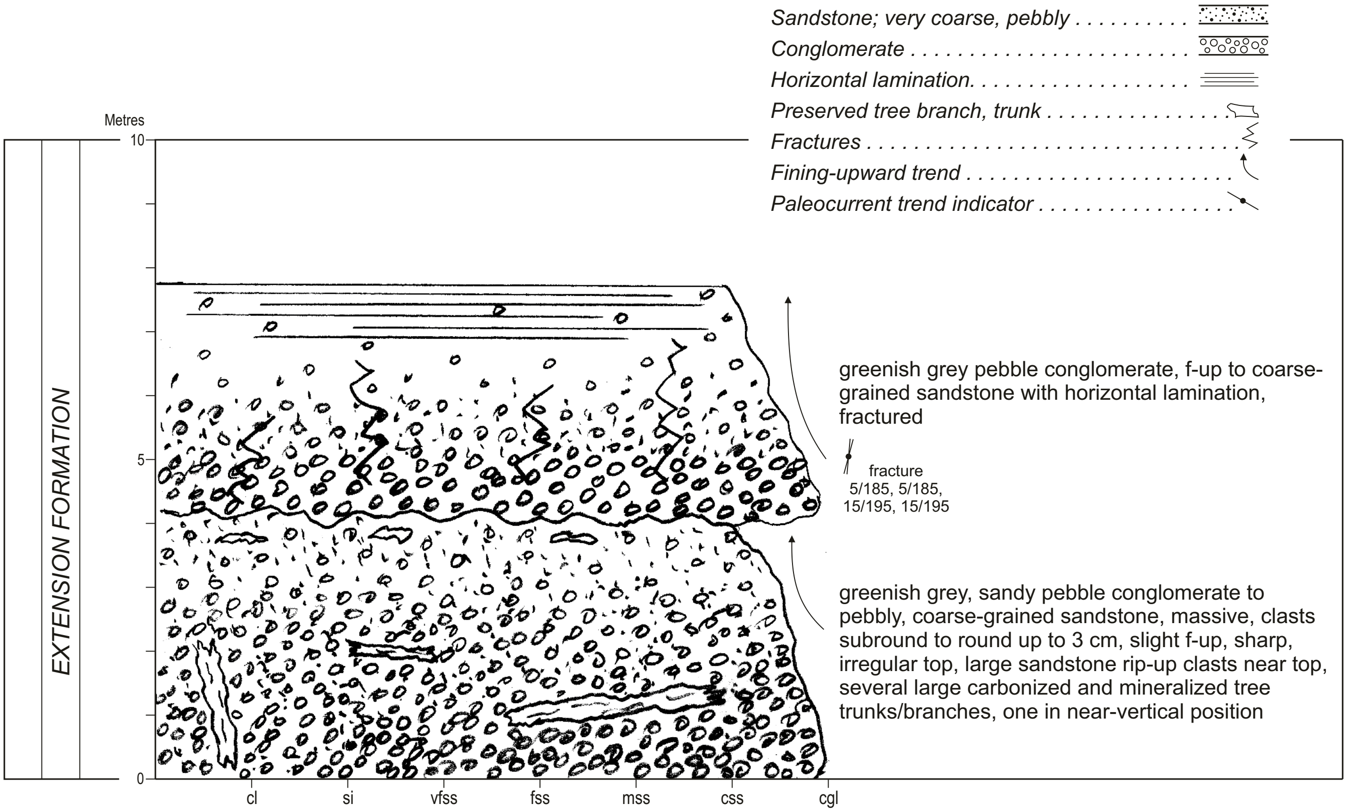
beneath Highway 19 bridge, 6 km SW of Royston and 7 km SW of Courtney, on both sides of river
?Haslam/?Extension/?Pender formations
NTS Map 92F/10 (Comox) 565961
49° 35' 57.1" N, 124° 58' 58.0" W; UTM Zone 10: 0356730E, 5495958N at base



Appendix Figure 27
Highway 19 and Harewood Road
roadcut exposure on NE side of Highway 19,
NW of Harewood Mines Road, 3 km SW of downtown Nanaimo
Haslam–Extension formations
NTS Map 92G/04 (Nanaimo) 294440
49° 06' 42.5"N, 123° 58' 13.2"W UTM Zone 10: 0429263E, 5444058N (base) to
49° 06' 37.6"N, 123° 58' 06.0"W UTM Zone 10: 0429375E, 5443890N (top)



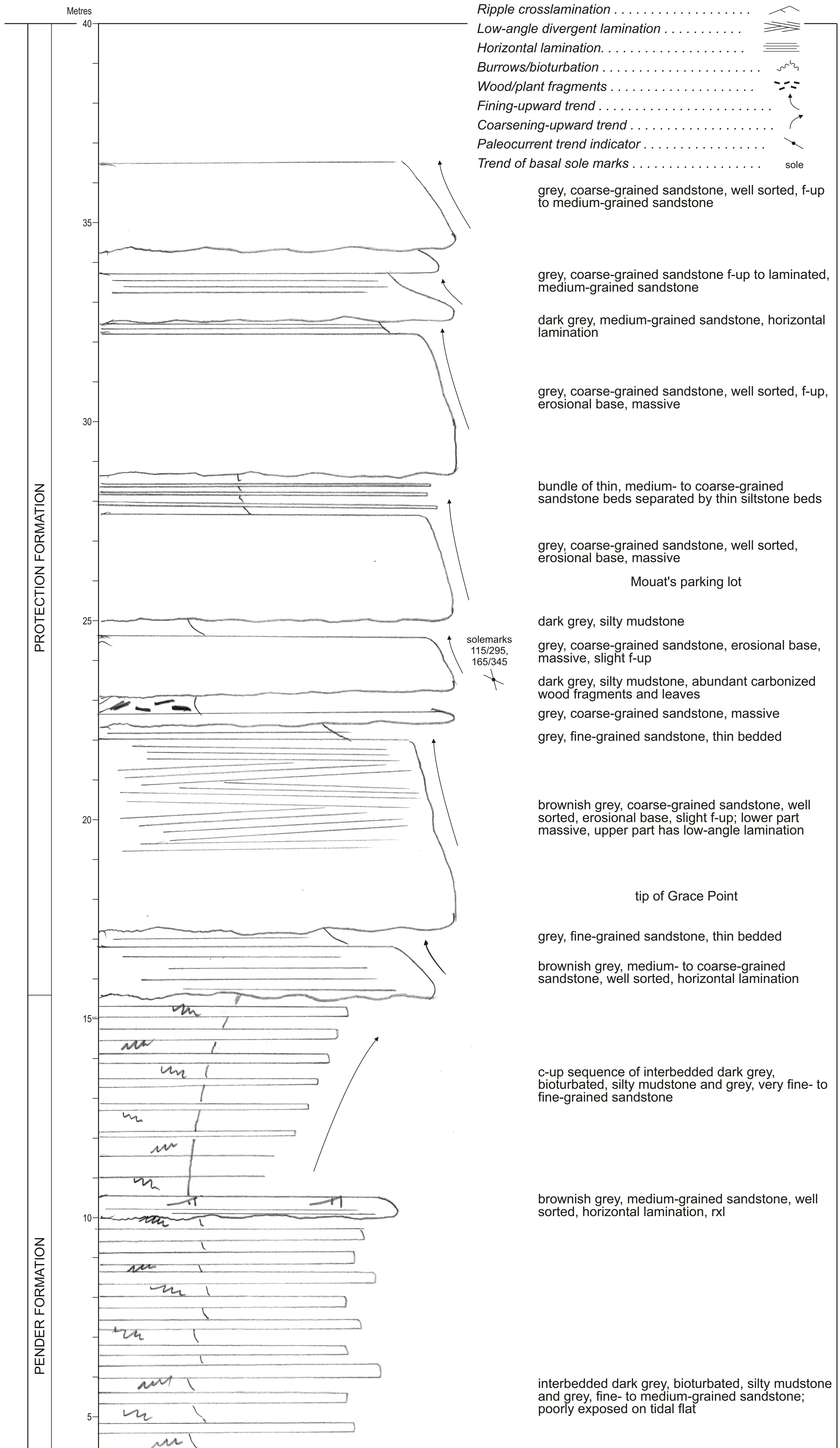
Appendix Figure 28
Nanaimo River Canyon
off Nanaimo River Road, 3 km W of airport and Highway 1, 10 km S of Nanaimo
Extension Formation
NTS Map 92G/14 (Nanaimo)
49° 04' 21.4"N, 123° 55' 13.3"W; UTM Zone 10: 0432780E, 5435936N



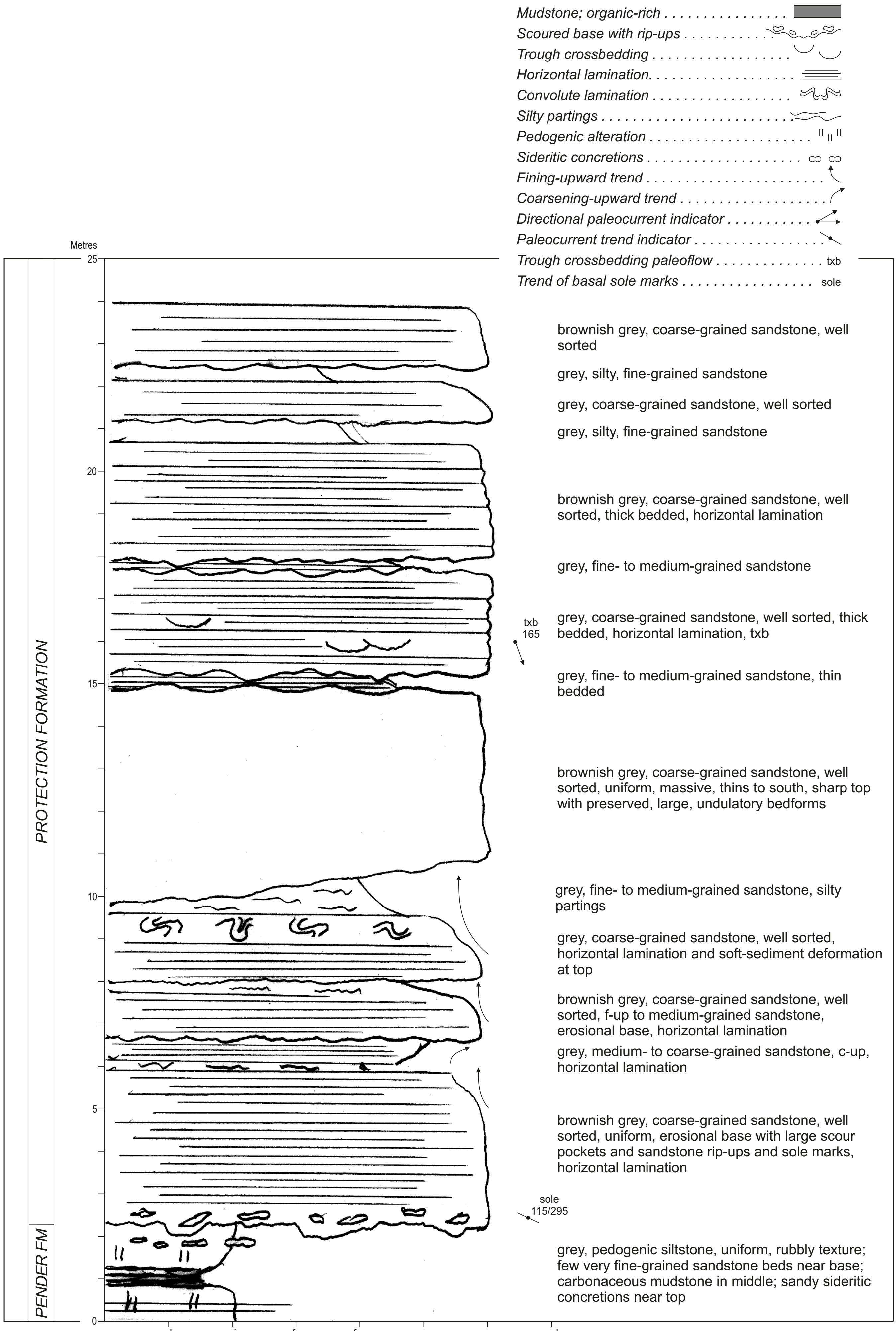
Appendix Figure 29
McKeowen Way

roadcut exposure along abandoned road beside Highway 19,
off Cranberry/Extension Road, village of Starks, 5 km S of Nanaimo
Extension Formation
NTS Map 92G/04 (Nanaimo) 323418
49° 07' 32.6"N, 123° 55' 40.2"W; UTM Zone 10: 0432317E, 5441846N

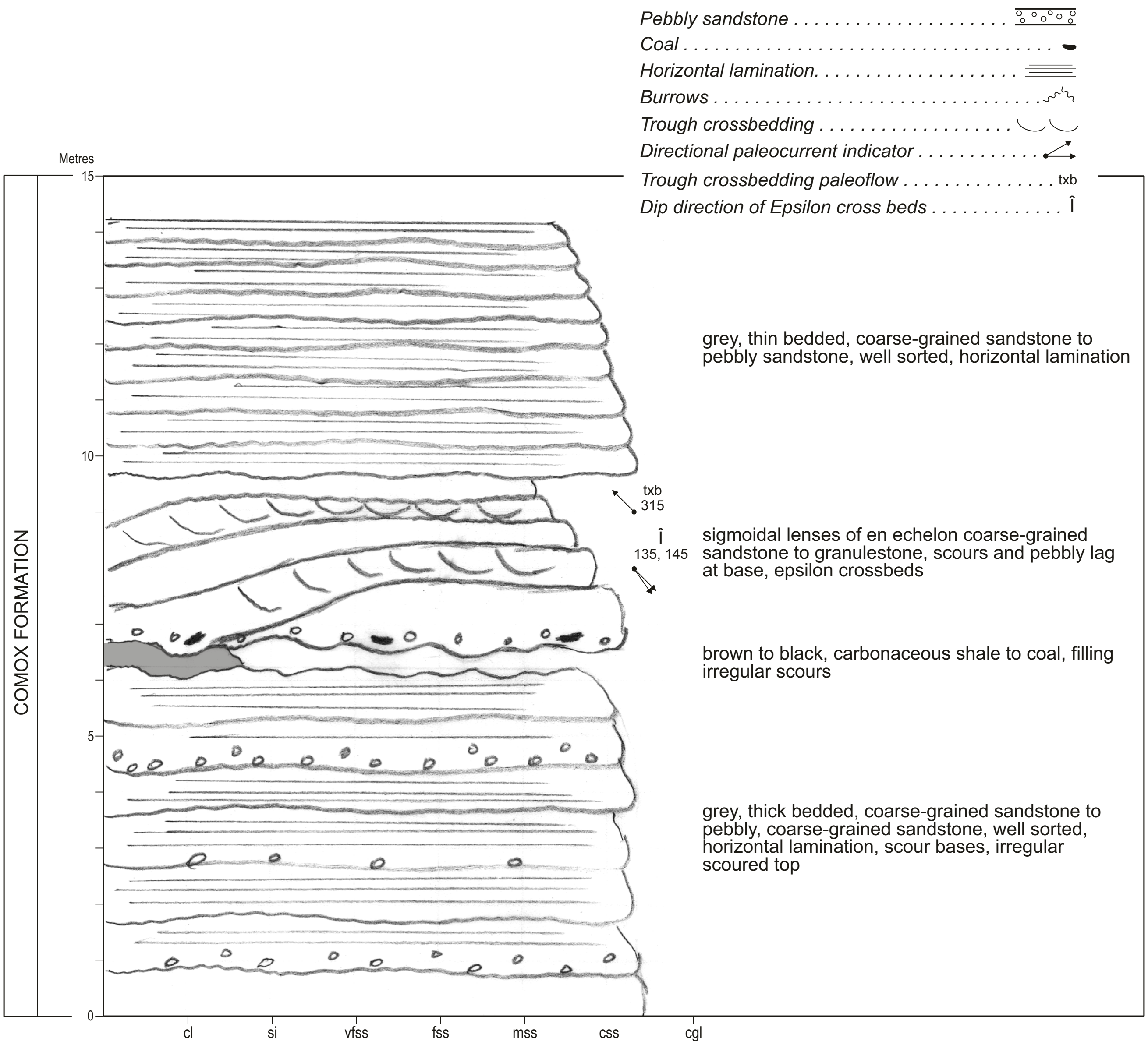
Appendix Figure 30
Newcastle Island, Eastern Shore
entire northeastern/eastern shore of island
Pender Formation/Protection Formation
NTS Map 92G/14 (Nanaimo)
base of section: 49° 11' 57.4"N, 123° 53' 50.9"W; UTM Zone 10: 0432197E, 5450045N
top of section: 49° 11' 10.8"N, 123° 55' 23.7"W; UTM Zone 10: 0432724E, 5448500N (top)



Appendix Figure 31
Grace Point, Ganges, Saltspring Island
tidal flat, cliff and parking lot exposures, behind Grace Point shopping centre and in Mouat's parking lot, downtown Ganges
Pender – Protection formations
NTS Map 92B/14 (Mayne Island) 637112
48° 51' 11.2" N, 123° 29' 51.7" W; UTM Zone 10: 0463491E, 5411245N at top (across from Mouat's)



Appendix Figure 32
Trans–Canada Highway and Highway 19 Ramp
large roadcut exposure on E side of Trans Canada Highway,
1 km S of Cedar Road intersection, 5 km S of downtown Nanaimo
Pender–Protection formations
NTS Map 92G/04 (Nanaimo) 334410
49° 07' 10.5"N, 123° 54' 46.6"W; UTM Zone 10: 0433386E, 5441154N (base) to
49° 07' 07.2"N, 123° 54' 43.3"W; UTM Zone 10: 0433449E, 5441050N (top)



Appendix Figure 33

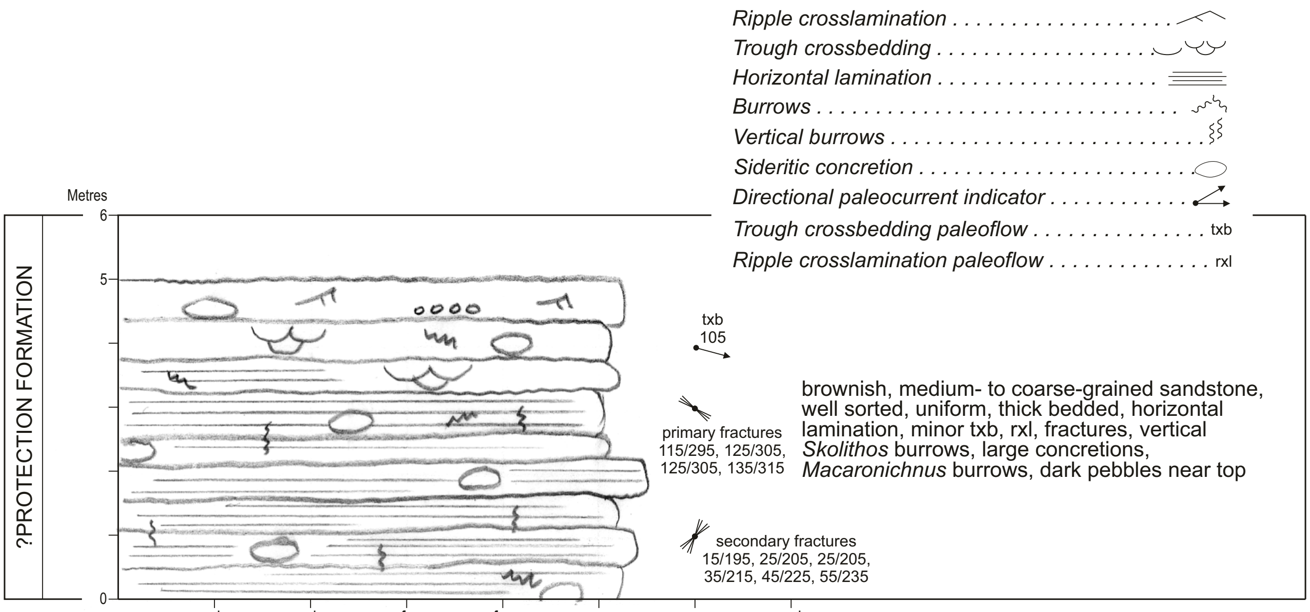
City of Nanaimo Public Parking Lot

corner of Victoria and Cavan streets, immediately S of downtown, just off Highway 1

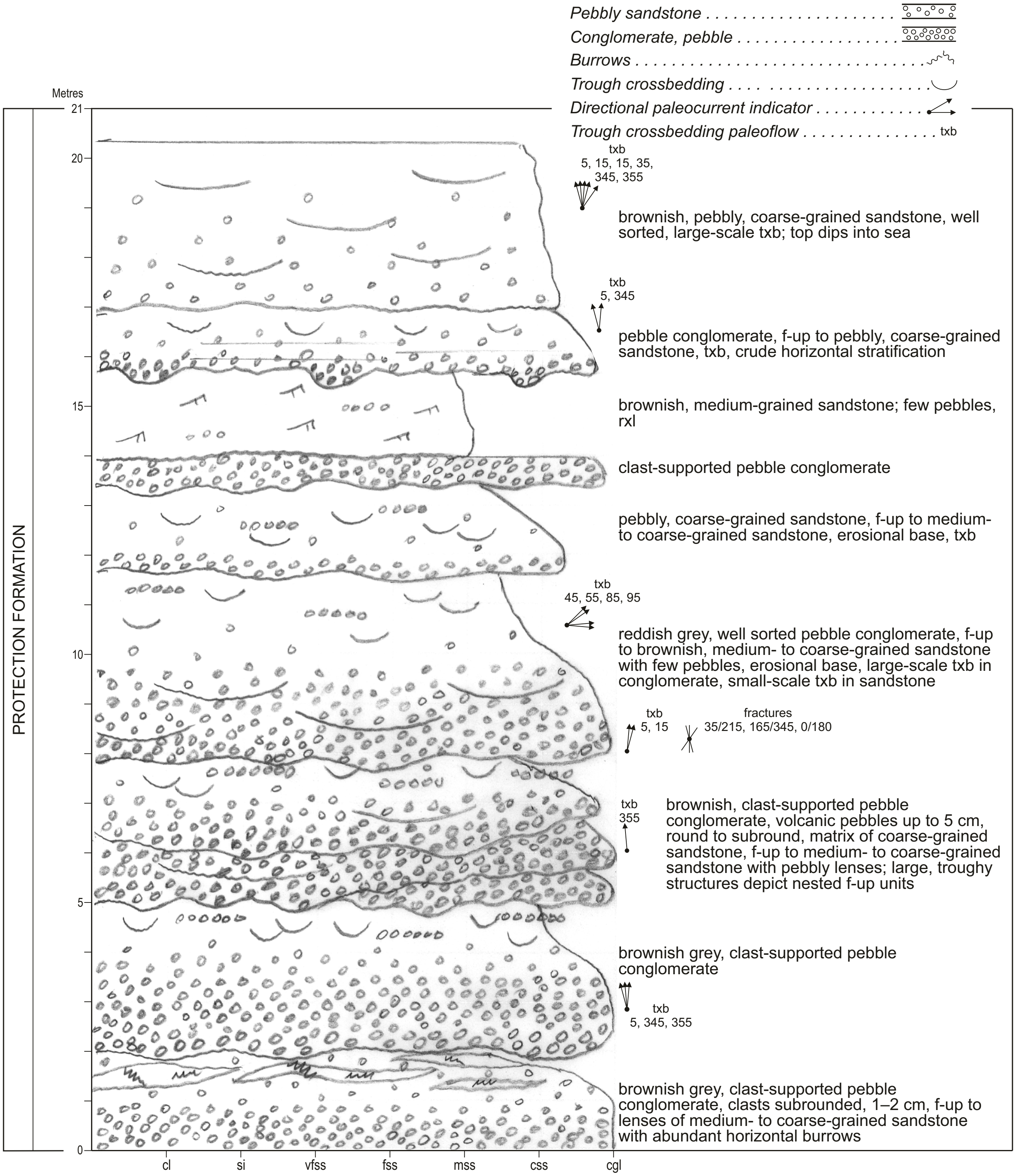
Comox Formation

NTS Map 92G/14 (Nanaimo)

49° 09' 43.7"N, 123° 56' 07.0"W; UTM Zone 10: 0431816E, 5445902N

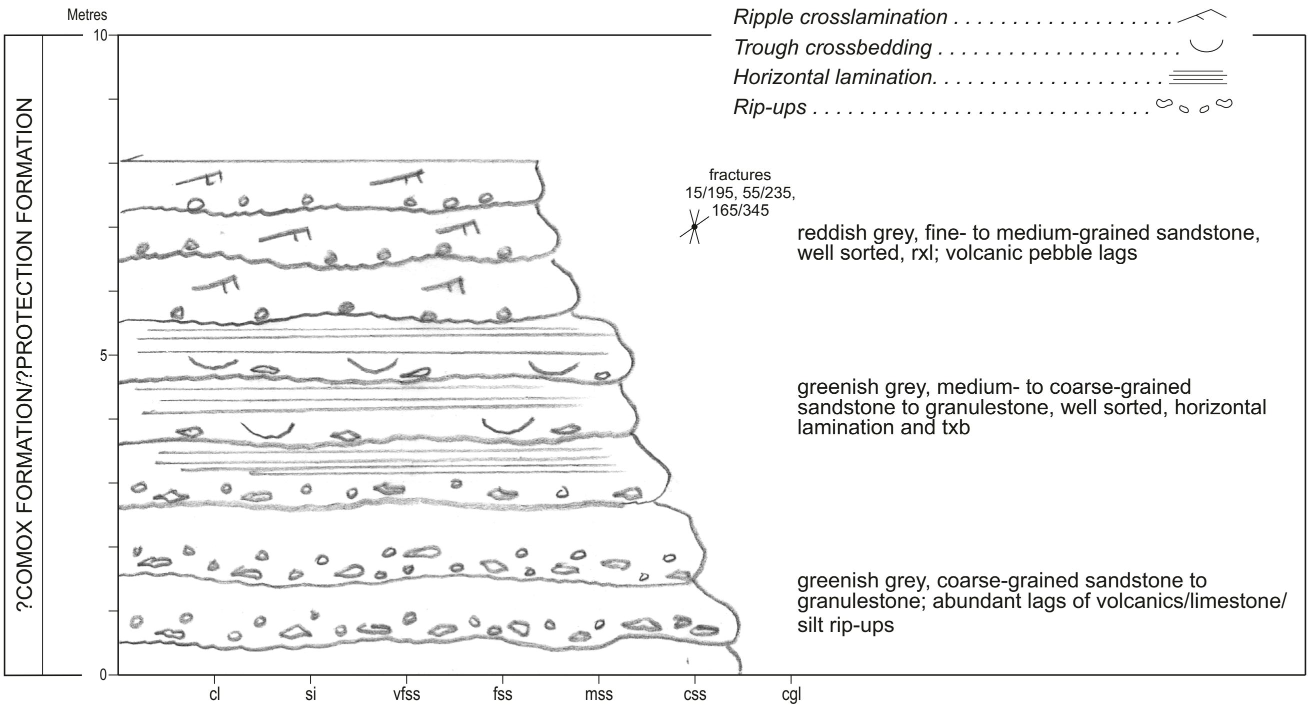


Appendix Figure 34
Wall Beach Headland
headland NE of Wall Beach in Northwest Bay, 7.5 km E of Parksville
?Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 12.0"N, 124° 13' 02.1"W; UTM Zone 10: 0411511E, 5461888N

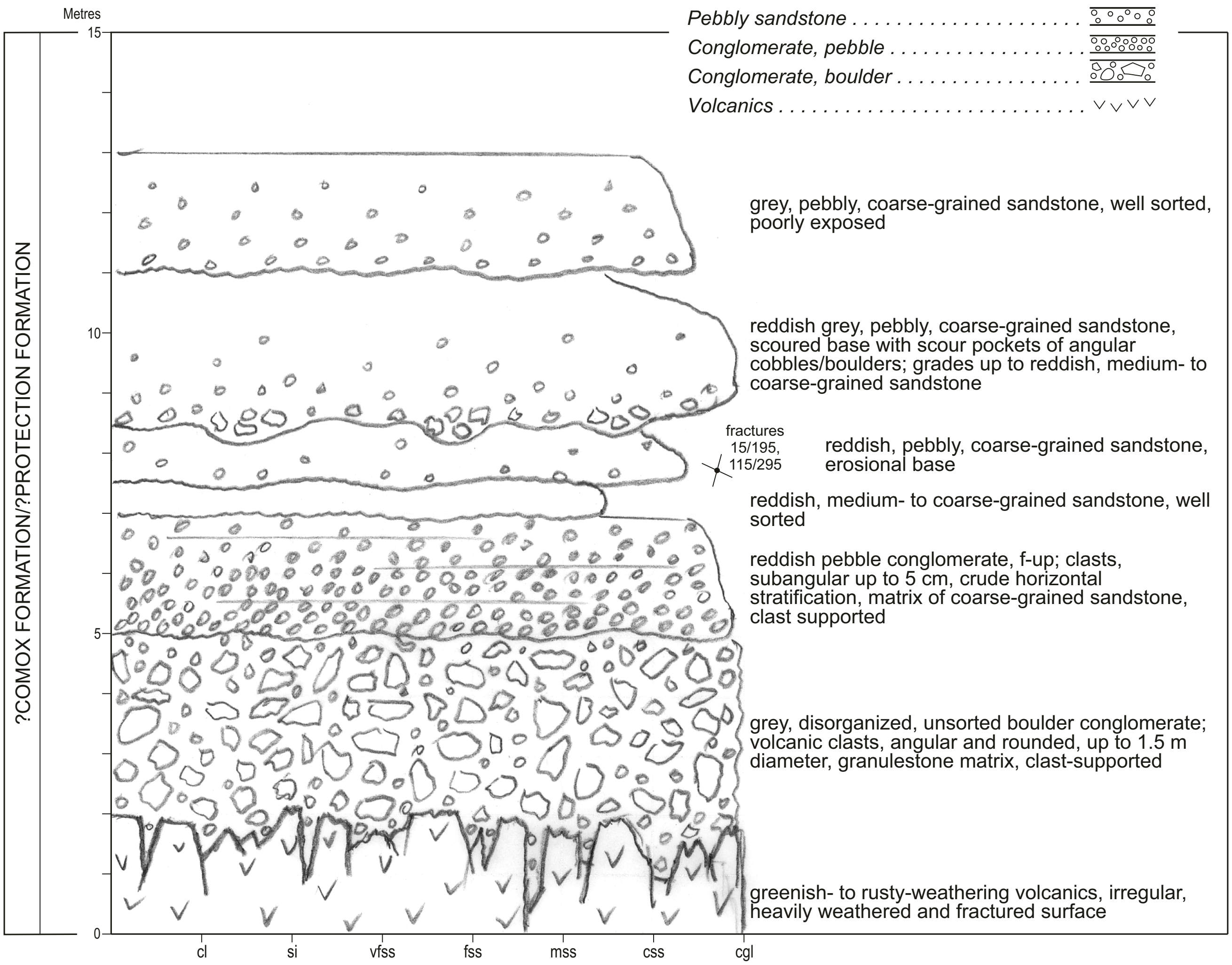


Appendix Figure 35
Madrona Point

N tip of Madrona Point, 5 km E of Parksville city centre, 5 km NW of Nanoose Bay
Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 46.0"N, 124° 14' 34.2"W; UTM Zone 10: 0409669E, 5462970N

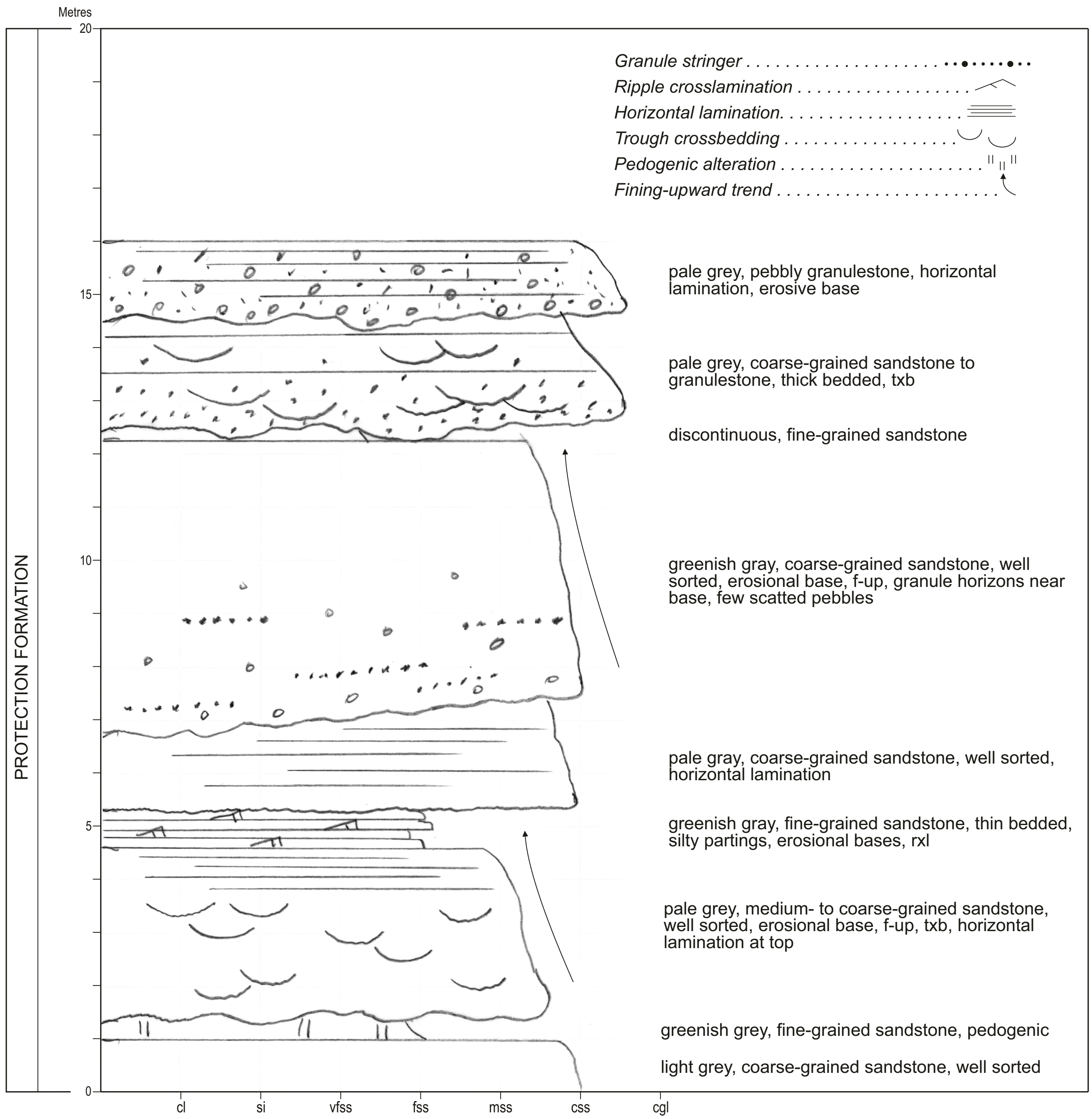


Appendix Figure 36
Beachcomber Regional Park
NW tip of Cottam Point, in Northwest Bay, 7 km E of Parksville city centre, 5 km N of Nanoose Bay
?Comox Formation/?Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 47.0"N, 124° 12' 54.4"W; UTM Zone 10: 0411683E, 5462969N

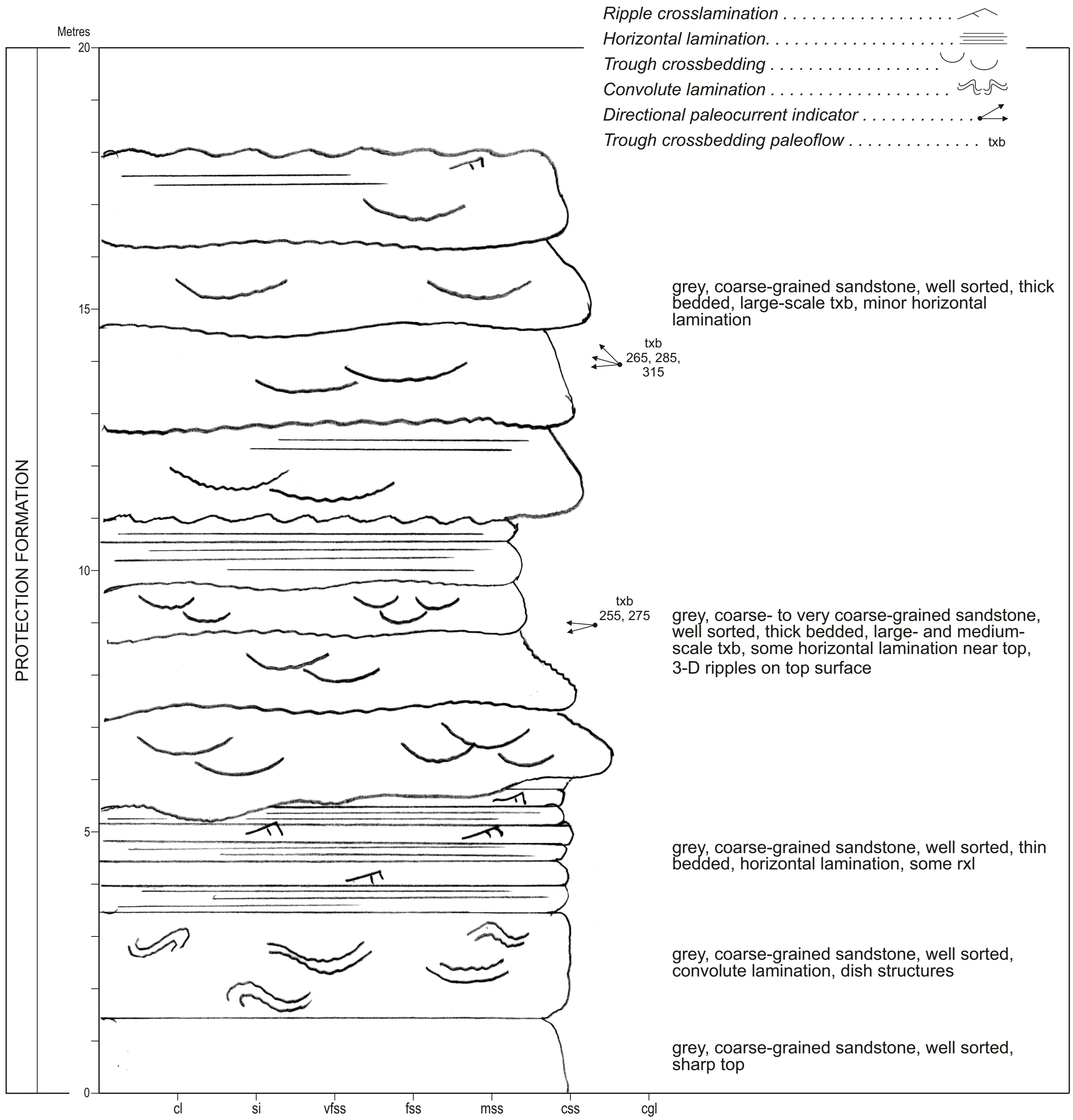


Appendix Figure 37
Cottam Point

N tip of Cottam Point, facing Mistaken Island, 7 km E of Parksville city centre, 5 km N of Nanoose Bay
?Comox Formation/?Protection Formation
NTS Map 92F/8 (Parksville)
49° 18' 53.0"N, 124° 12' 52.3"W; UTM Zone 10: 0411728E, 5463161N



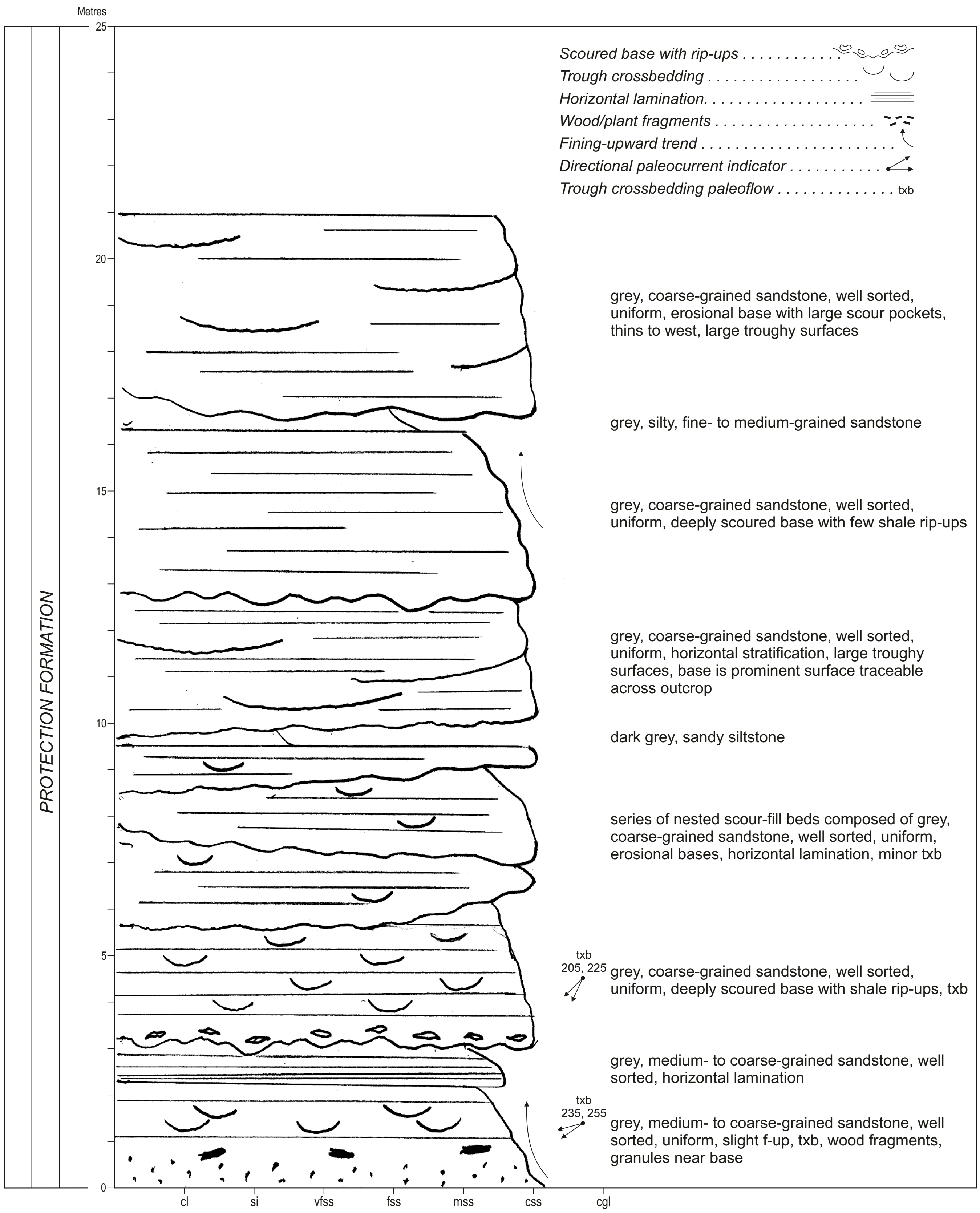
Appendix Figure 38
Cedar Road & Trans–Canada Highway Interchange
roadcut immediately E of highway, N side of Cedar Road
Protection Formation
NTS Map 92G/4 (Nanaimo) 334417
49° 07' 29.0" N, 123° 54' 50.1" W; UTM Zone 10: 433322E, 5441721N



Appendix Figure 39

Nanaimo River Canyon II beneath Trans-Canada Highway

river channel cliff face 10 km SE of City of Nanaimo and 2 km N of airport
(generally inaccessible and only measured approximately)
Protection Formation
NTS Map 92G/4 (Nanaimo) 356357
49° 04' 14.3" N, 123° 52' 50.7" W; UTM Zone 10: 0435667E, 5435690N

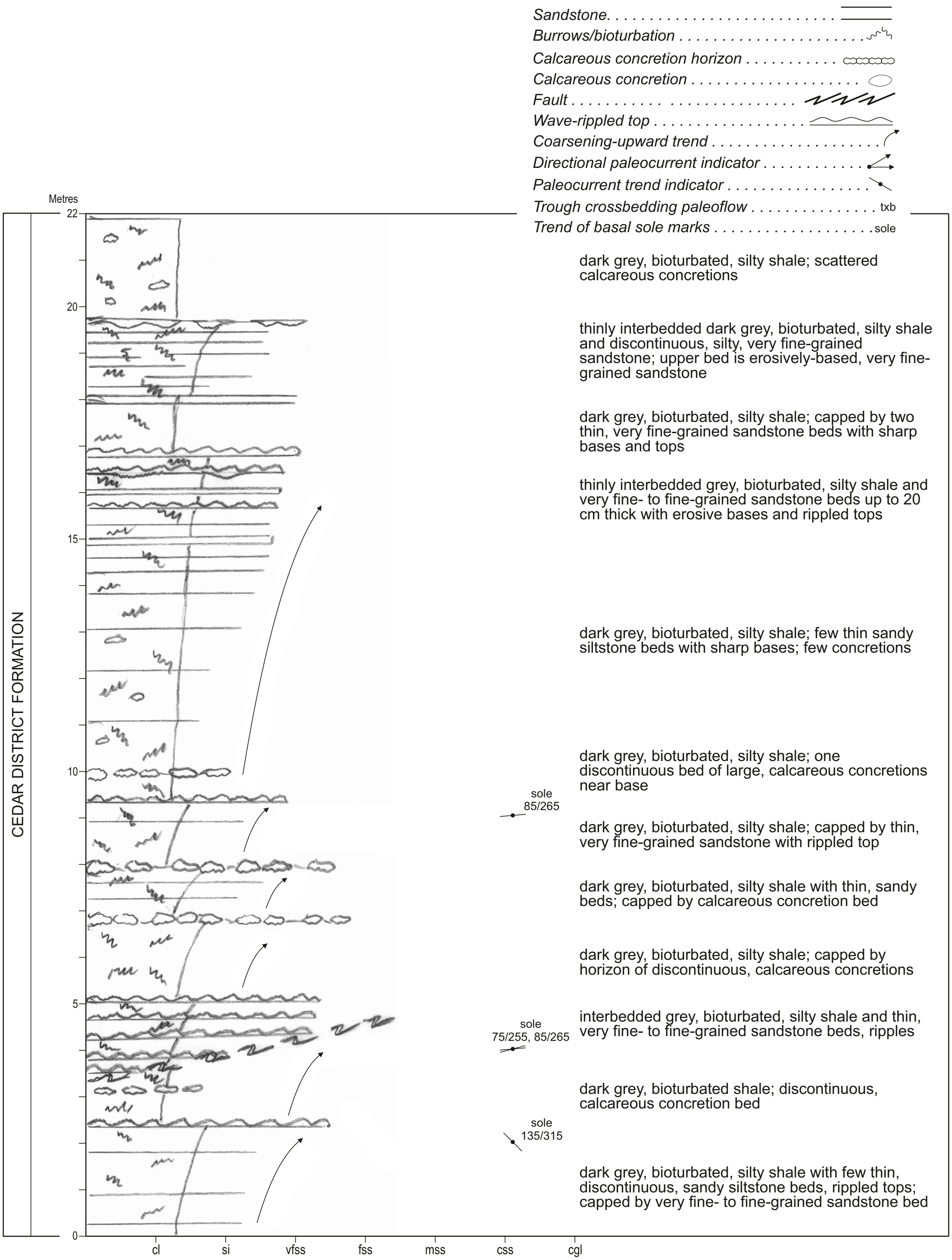


Appendix Figure 40
Duke Point Highway 19 at Trans–Canada Highway 1
roadcut exposure on N side of Duke Point Highway,
immediately E of Trans Canada Highway, 6 km SE of Nanaimo
Protection Formation
NTS Map 92G/04 (Nanaimo) 344404
49° 06' 42.1"N, 123° 53' 53.7"W; UTM Zone 10: 0434448E, 5440259N (base) to
49° 06' 45.5"N, 123° 53' 42.8"W; UTM Zone 10: 0434668E, 5440367N (top)

Appendix Figure 41
Vesuvius Bay Shoreline, Saltspring Island
shoreline of bay from southern point to ferry dock, west shore of Saltspring Island
Protection Formation/Cedar District Formation/De Courcy Formation
NTS Map 92B/13 (Duncan)
base of section: 48° 52' 40.1"N, 123° 34' 20.7"W; UTM Zone 10: 0458030 E, 5414031N
top of section: 48° 52' 50.3"N, 123° 34' 16.8"W; UTM Zone 10: 0458111 E, 5414340N

Appendix Figure 42
Barnes Road Shoreline

end of Barnes Road, along Stuart Channel shore, opposite Round Island, 4 km E of Cedar
Cedar District Formation
NTS Map 92G/14 (Nanaimo)
49° 07' 15.0"N, 123° 48' 17.4"W UTM Zone 10: 0441278E, 5441198N (base) to
49° 07' 06.9"N, 123° 48' 17.1"W UTM Zone 10: 0441278E, 5440952N (Barnes Road) to
49° 06' 53.9"N, 123° 48' 18.1"W UTM Zone 10: 0441254E, 5440546N (Murdoch Road boat ramp)



Appendix Figure 43

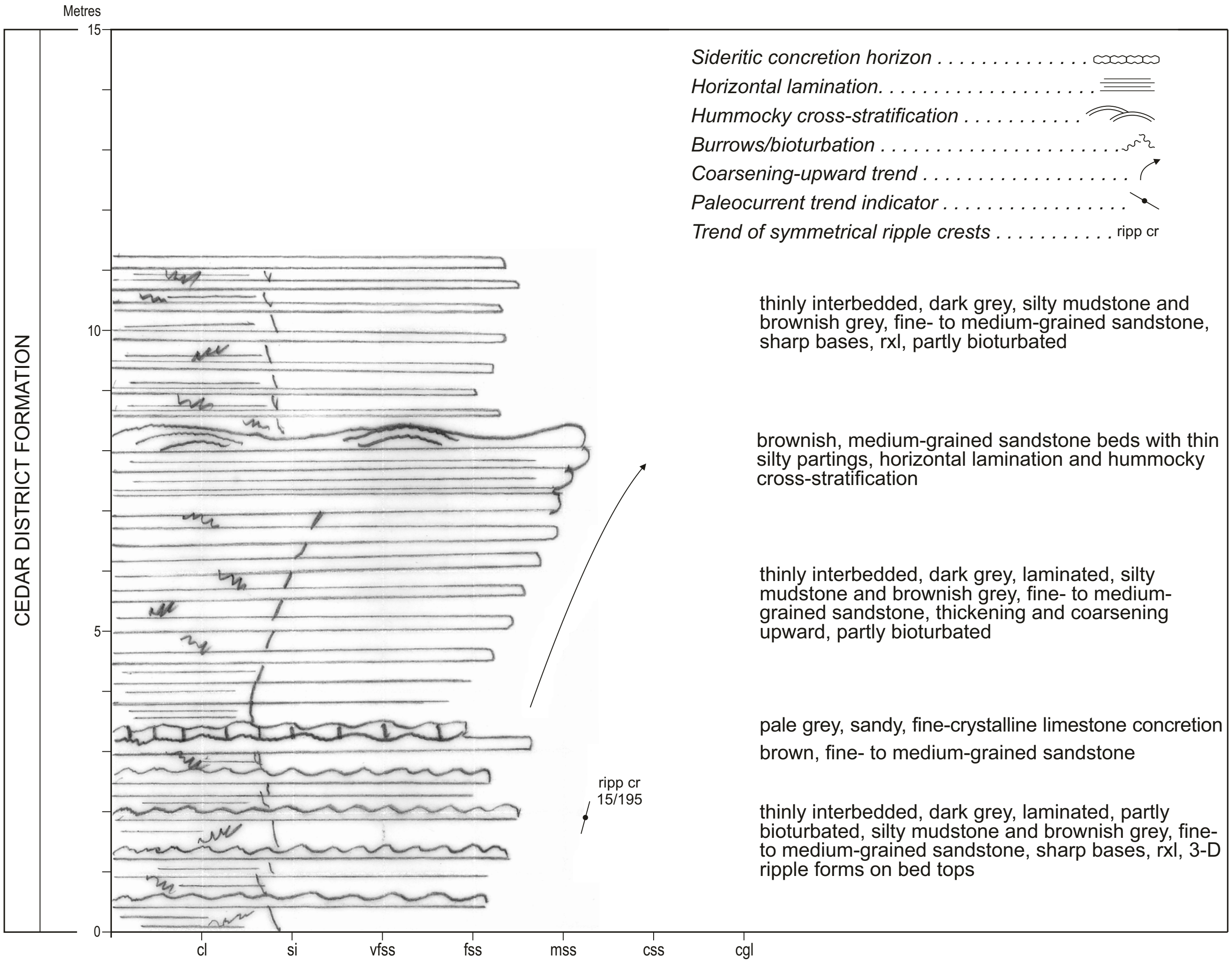
Highway 19 & Buckley Bay Ferry Interchange

along road toward Denman Island ferry terminal, 100 m E of Highway 19

Cedar District Formation

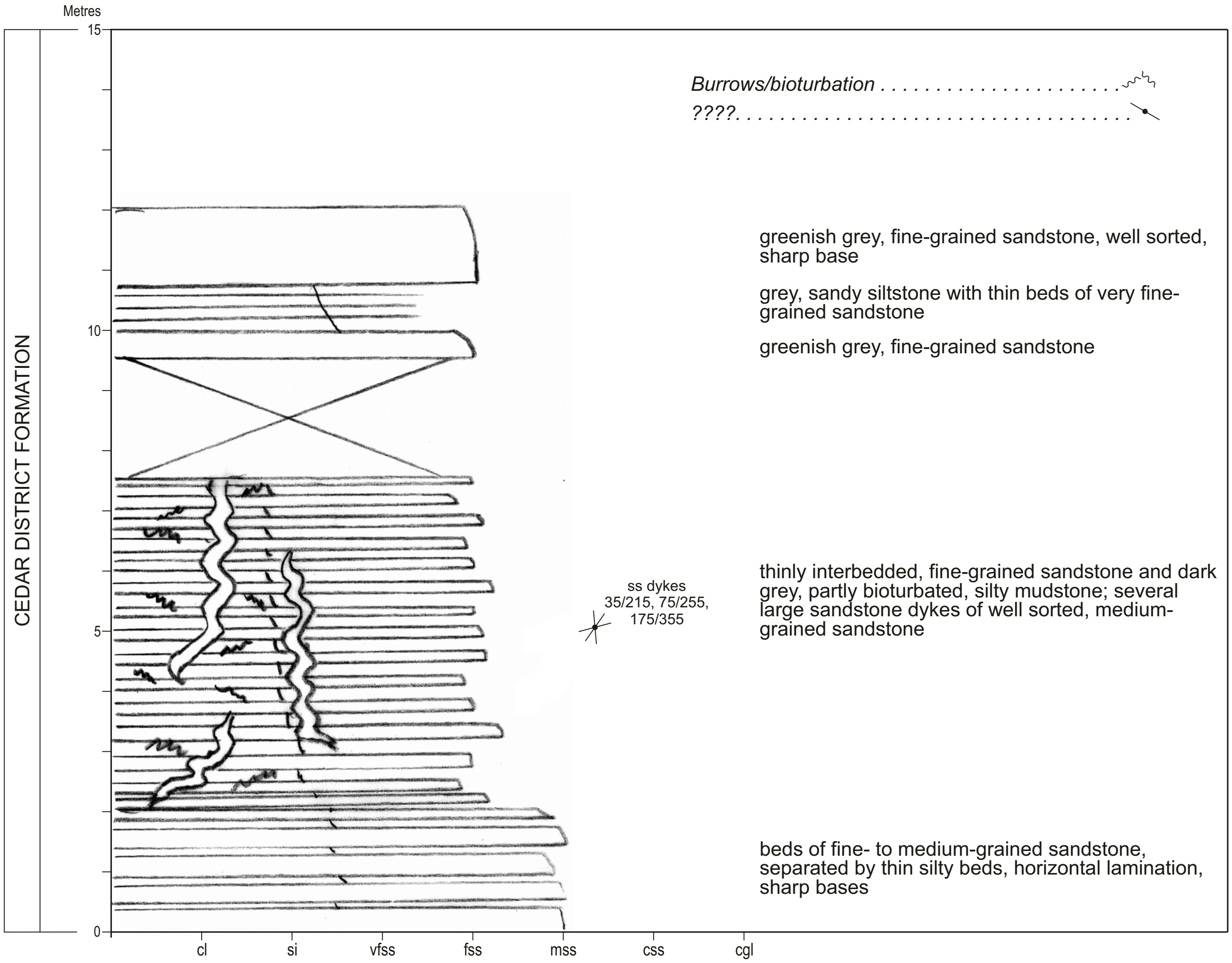
NTS Map 92F/10 (Comox)

49° 31' 26.8"N, 124° 51' 11.9"W; UTM Zone 10: 0365878E, 5487369N



Appendix Figure 44
Ship Peninsula

tidal platform exposure on east side of southern peninsula, well-exposed only at low tide
Cedar District Formation
NTS Map 92F/7 (Horne Lake) 702841
49° 29' 44.7" N, 124° 47' 29.3 W"; UTM Zone 10: 0370277E, 5484110N at base



Appendix Figure 45

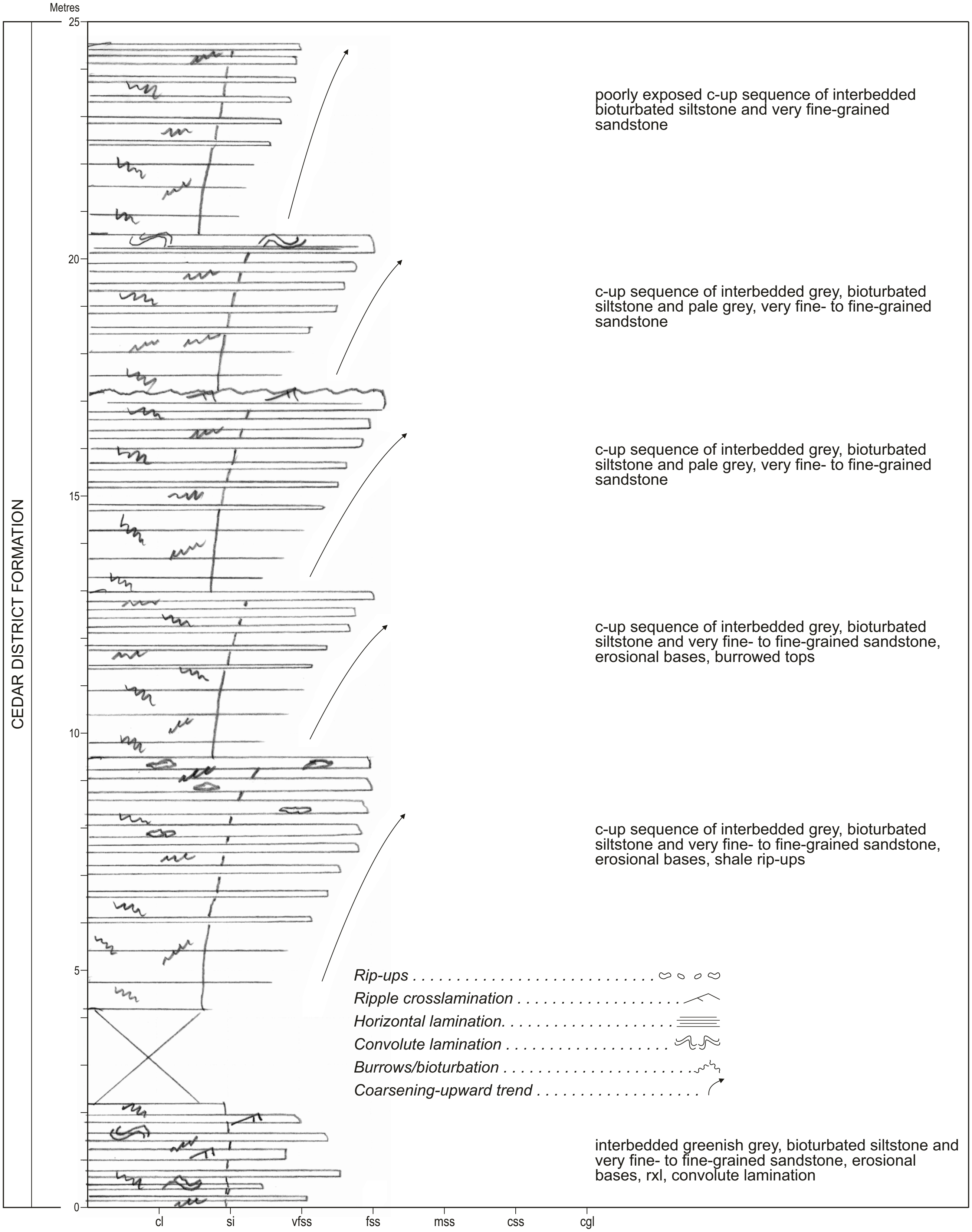
Denman Ferry Dock Shoreline, Denman Island

coastal tidal platform section about 0.5 km NW of Denman Island ferry dock, west shore of island

Cedar District Formation

NTS Map 92F/10 (Comox) 676888

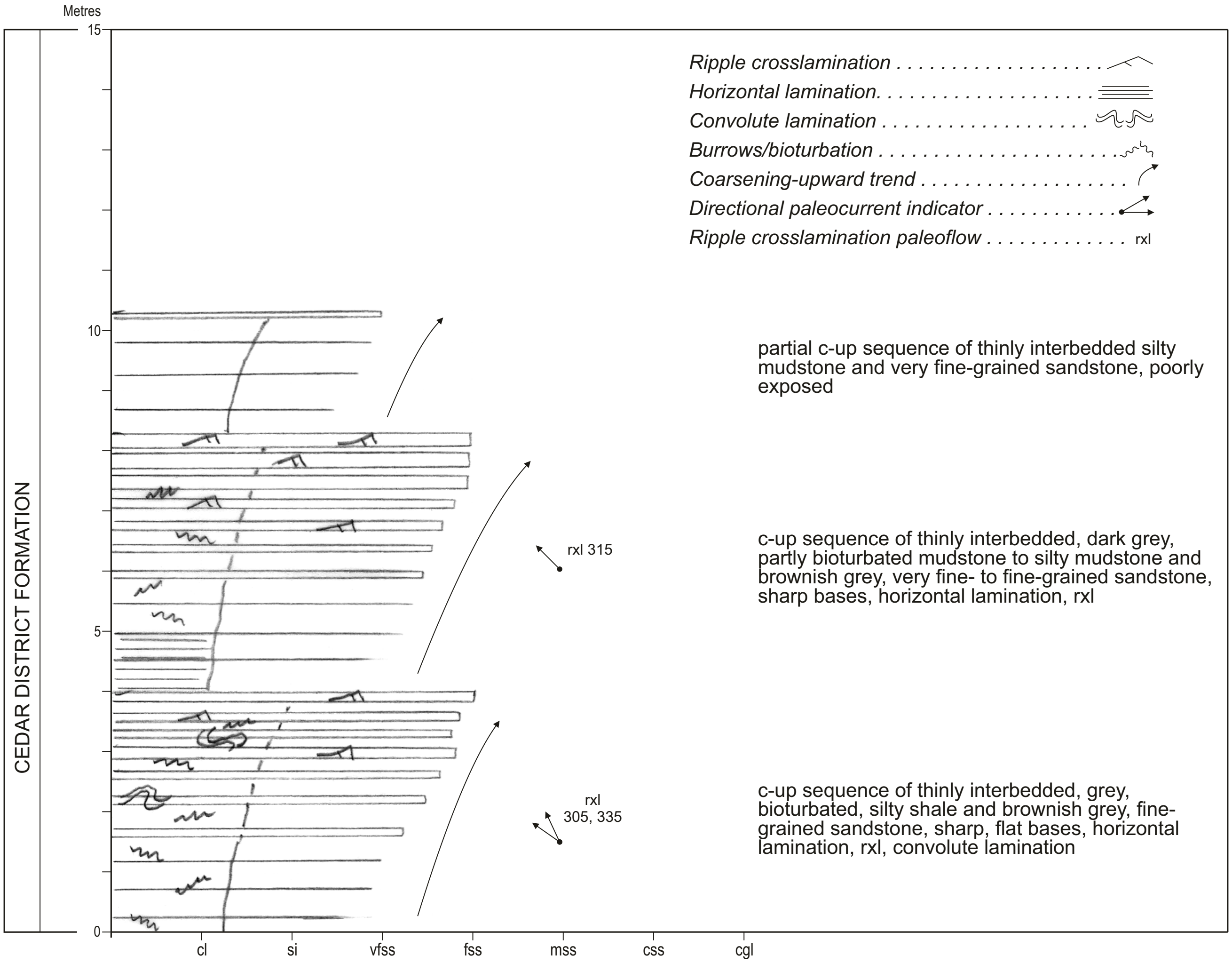
49° 32' 18.0" N, 124° 49' 50.0" W; UTM Zone 10: 0367620E, 548880N



Appendix Figure 46

Ganges Harbour Shoreline, Saltspring Island

tidal flat and cliff exposure on NE shoreline of Ganges Harbour,
behind Moby's Pub, below Hastings House Hotel
Cedar District Formation
NTS Map 92B/14 (Mayne Island) 635118
48° 51' 31.1" N, 123° 29' 58.4" W; UTM Zone 10: 0463358 E, 5411863N at base



Appendix Figure 47

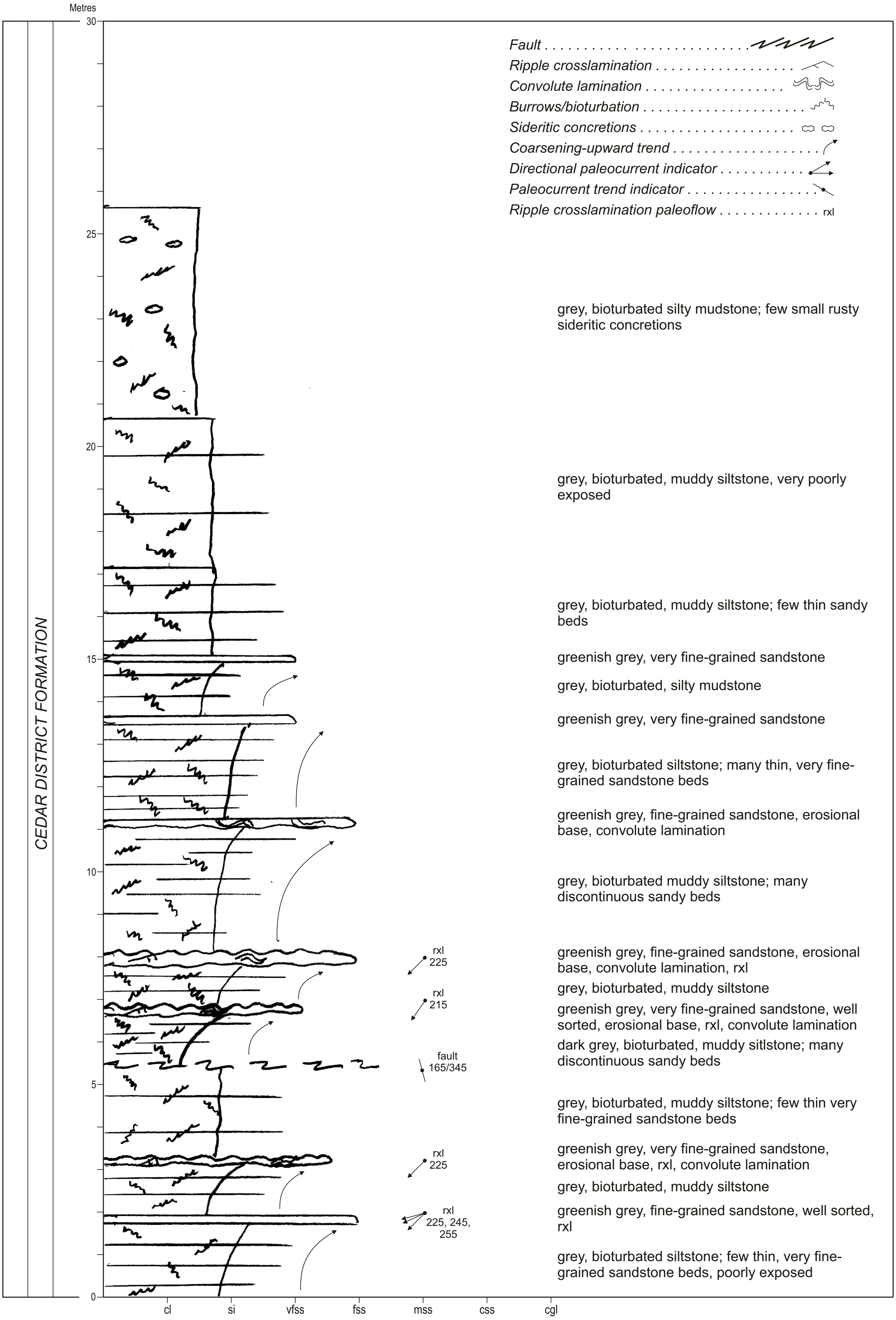
Fernwood Shoreline, Saltspring Island

tidal flat and cliff exposure, NE shoreline of island, immediately SE of Fernwood

Cedar District Formation

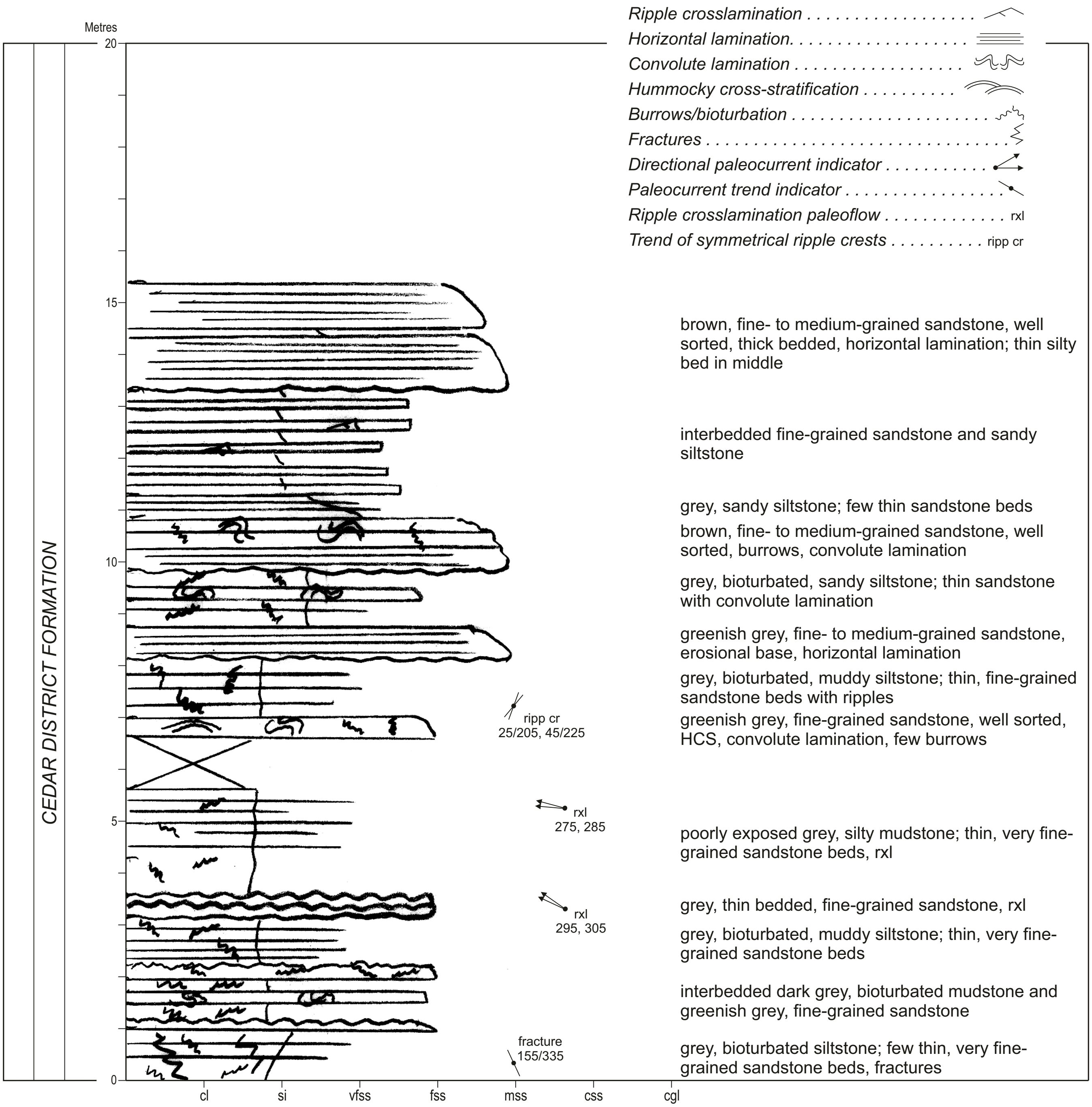
NTS Map 92B/13 (Duncan) 612181

48° 54' 52.8" N, 123° 31' 50.2" W; UTM Zone 10: 046123E, 5418105N at base



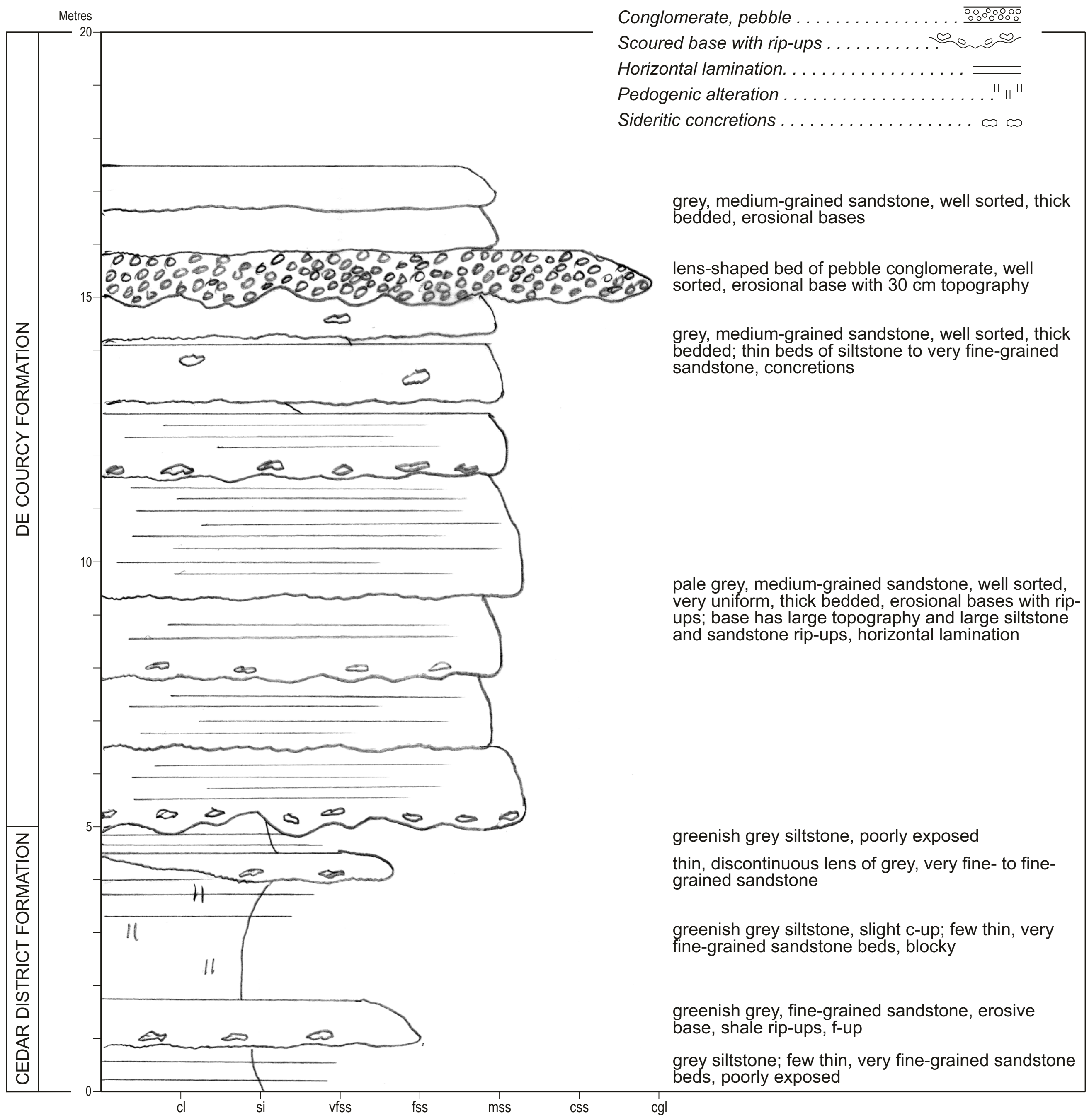
Appendix Figure 48
Hudson Point Shoreline

tidal platform exposure from beach access off North Beach Road,
1 km NW of Fernwood, Saltspring Island
Cedar District Formation
NTS Map 92B/13 (Duncan) 598186
48° 55' 10.5"N, 123° 36' 49.9"W; UTM Zone 10: 0459803E, 5418660N (base) to
48° 55' 11.2"N, 123° 32' 55.1"W; UTM Zone 10: 0459808E, 5418697 (top)



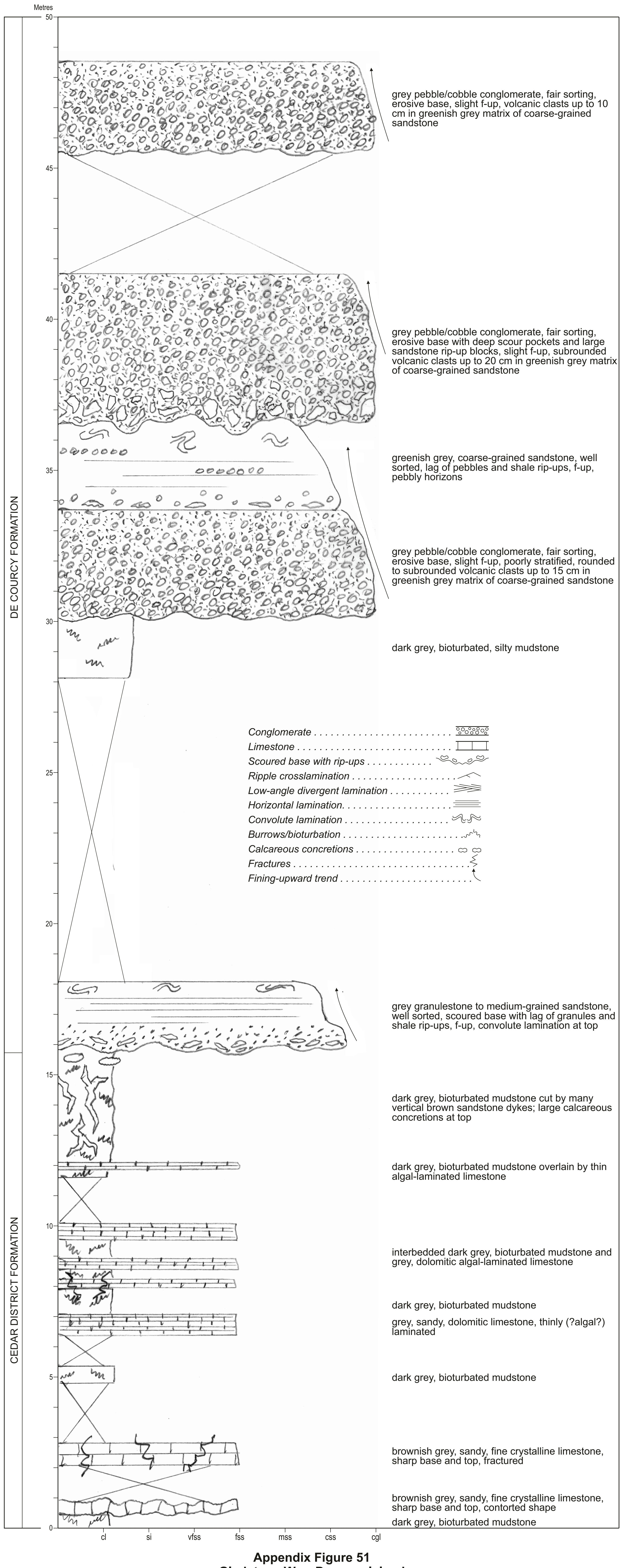
Appendix Figure 49
North Beach Road Shoreline

tidal platform exposure from beach access path on North Beach Road toward north,
2 km NW of Fernwood, Saltspring Island
Cedar District Formation
NTS Map 92B/13 (Duncan) 592194
48° 55' 32.6"N, 123° 33' 27.3"W; UTM Zone 10: 0459157E, 5419351N (base) to
48° 55' 32.0"N, 123° 33' 24.4"W; UTM Zone 10: 0459220E, 5419333N (top)

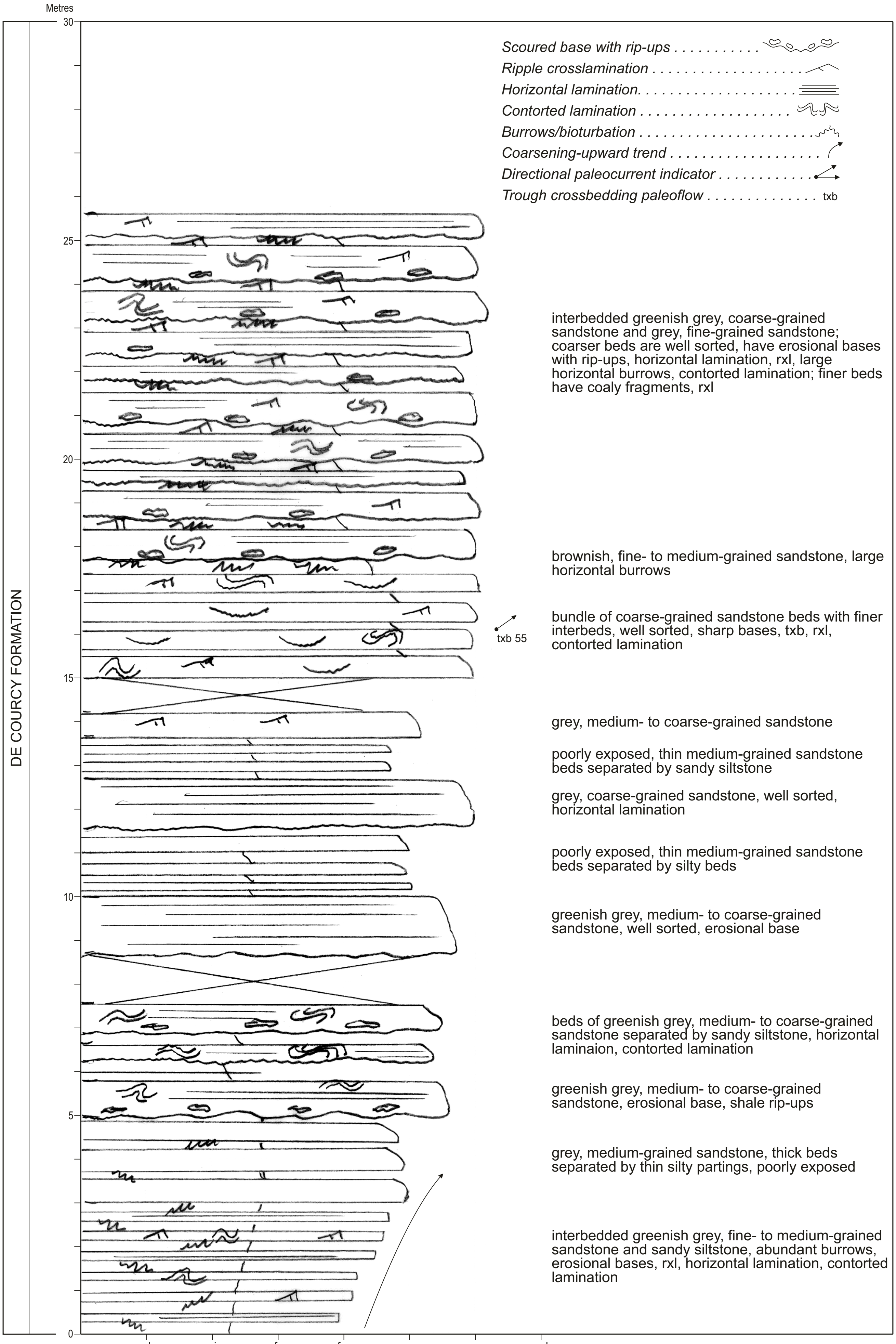


Appendix Figure 50
Denman Escarpment, Denman Island

small roadcut escarpment adjacent to Denman Road, E of ferry dock
Cedar District – De Courcy formations
NTS Map 92F/10 (Comox) 693887
49° 32' 15.1" N, 124° 48' 21.6" W; UTM Zone 10: 0369290E, 5488740N

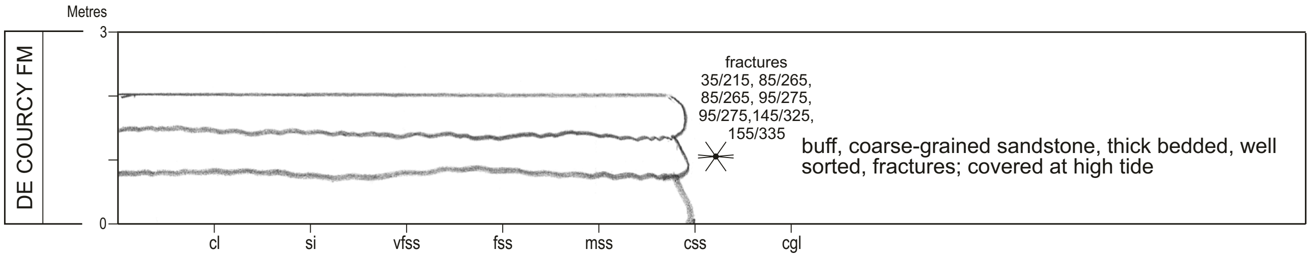


Appendix Figure 51
Gladstone Way, Denman Island
coastal section westward on NW shore of island
Cedar District – De Courcy formations
NTS Map 92F/10 (Comox) 671942
49° 35' 05.9" N, 124° 50' 21.2" W; UTM Zone 10: 0367061E, 5494118N at base
to 49° 35' 22.6" N, 124° 50' 19.2" W; UTM Zone 10: 0367113E, 5494627N at top



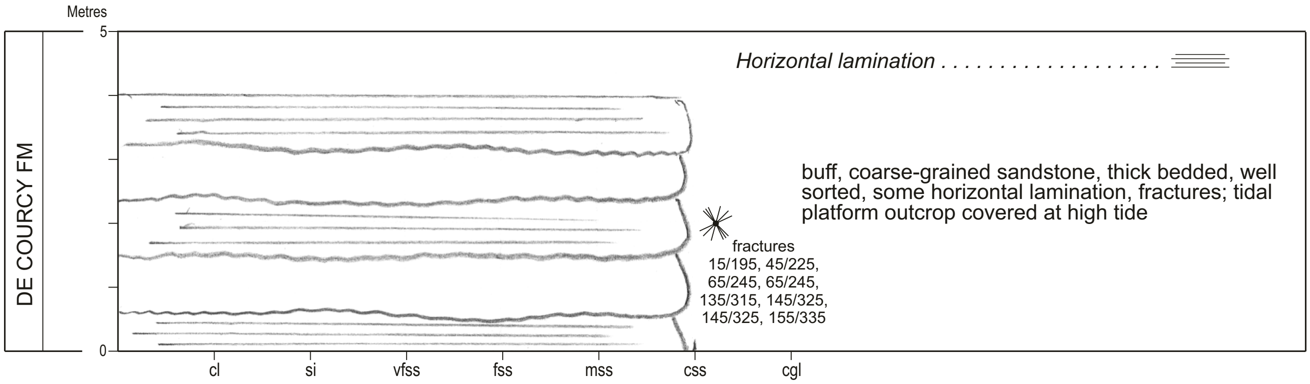
Appendix Figure 52
Southey Point, Saltspring Island

tidal flat exposures from Southey Bay westward around tip of point, northern tip of Saltspring Island
Cedar District – De Courcy formations
NTS Map 92B/13 (Duncan) 563213
48° 56' 33.5" N, 123° 35' 48.5" W; UTM Zone 10: 0456299E, 5421240N at base;
48° 56' 26.6" N, 123° 35' 52.5" W; UTM Zone 10: 0456215E, 5421039N at top

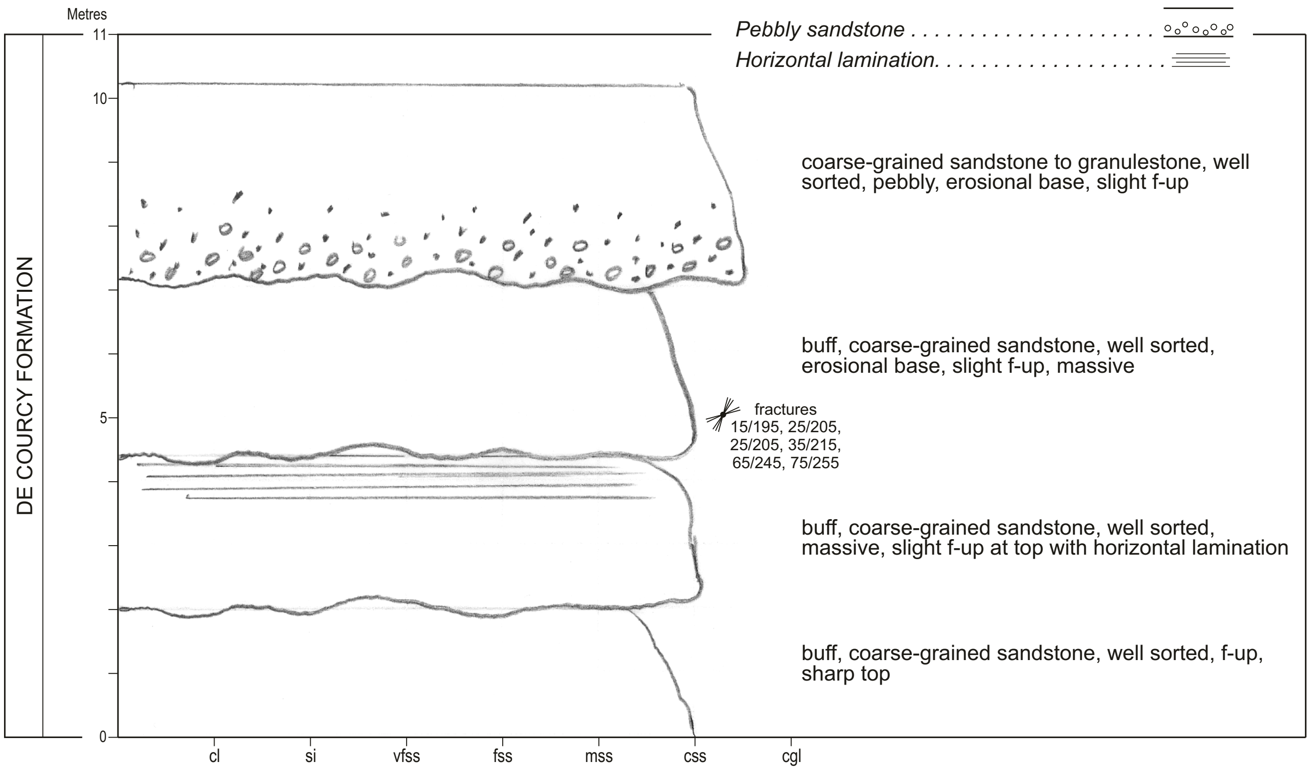


Appendix Figure 53
Blue Heron Park

along Stuart Channel shoreline, off Yellow Point Road, 8.5 km E of Nanaimo Airport
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 02' 41.3"N, 123° 45' 22.6"W; UTM Zone 10: 0444732E, 5432706N

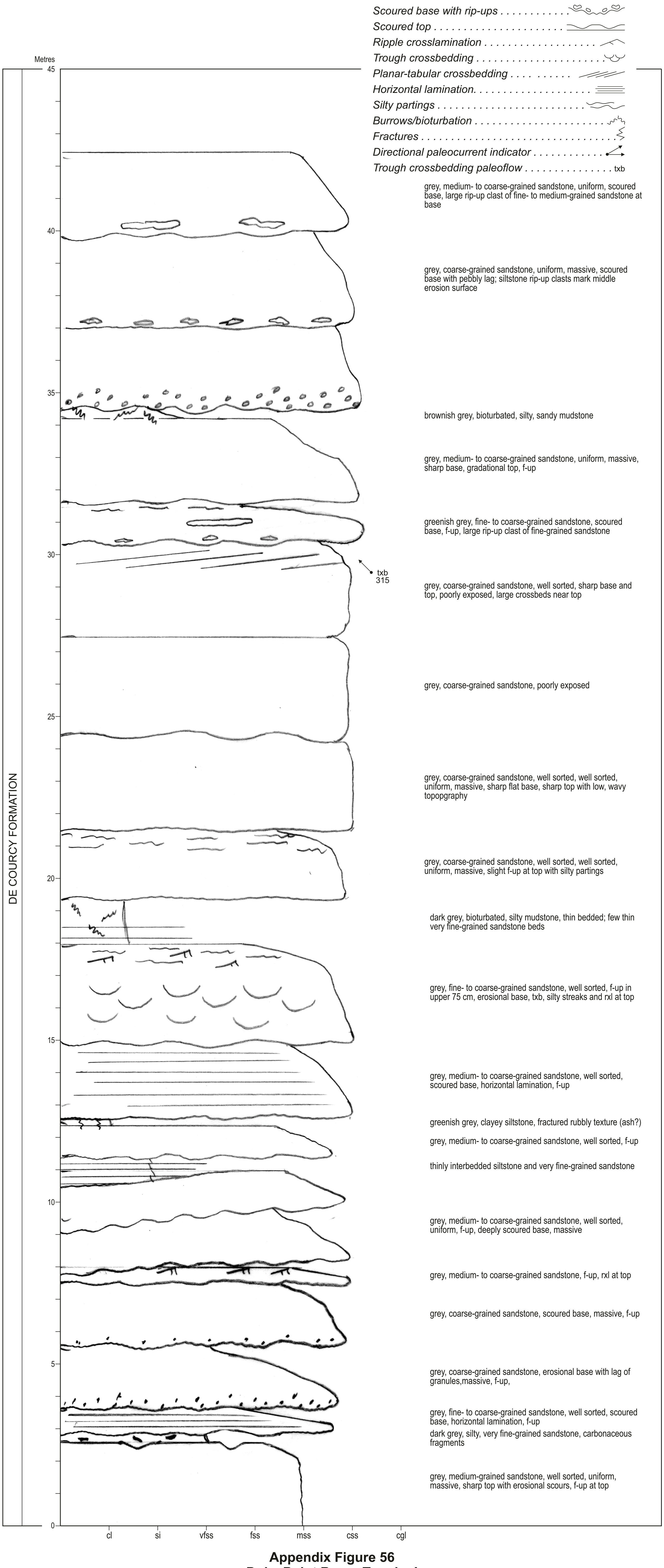


Appendix Figure 54
Robert's Memorial Provincial Park
along Stuart Channel shoreline, off Yellow Point Road, 7.5 km E of Nanaimo Airport
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 03' 46.3"N, 123° 46' 12.0"W; UTM Zone 10: 0443752E, 5434732N



Appendix Figure 55
De Courcy Road Shoreline

end of De Courcy Road, along Stuart Channel, N of Robert's Memorial Provincial Park, 8 km SE of Cedar
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 04' 57.8"N, 123° 47' 18.1"W; UTM Zone 10: 0442493E, 5436952N



Appendix Figure 56
Duke Point Barge Terminal
partway up Duke Point peninsula at 870 Jackson Road, 5 km southeast of Nanaimo
De Courcy Formation
NTS Map 92G/14 (Nanaimo)
49° 08' 27.2"N, 123° 52' 30.7"W; UTM Zone 10: 0436164E, 5443504N

Scoured base with rip-ups
Ripple crosslamination
Trough crossbedding
Low-angle divergent lamination
Horizontal lamination.
Contorted lamination
Hummocky cross-stratification
Troughy surface
Soft sediment deformation
Water-escape structures
Burrows/bioturbation
Fractures
Fining-upward trend
Directional paleocurrent indicator
Ripple crosslamination paleoflow rxl
Trough crossbedding paleoflow txb

greenish grey, coarse-grained sandstone, erosional base with thick dispersed pebble lag, heavily fractured

greenish grey, coarse-grained sandstone, uniform, txb, faulted and folded, black shale rip-ups

greenish grey, coarse-grained sandstone, erosional base with pebble lag, low-angle lamination; capped by bioturbated, fine-grained sandstone

greenish grey, coarse-grained sandstone, well sorted, erosional base, low-angle lamination

greenish grey, arkosic, coarse-grained sandstone, well sorted, uniform, erosional base, low-angle lamination; capped by thin dark grey, silty, medium-grained sandstone

greenish grey, coarse-grained sandstone, well sorted, erosional base with scour pockets of pebbles

greenish grey, coarse-grained sandstone, well sorted, f-up to medium-grained sandstone, pebble lag, horizontal lamination

thinly interbedded, rippled, fine-grained sandstone and siltstone

grey, coarse-grained sandstone, well sorted, uniform, erosional base with rip-up clasts, f-up to medium-grained sandstone, large troughy planes, hummocky and swaley cross-stratification at top, fractures

set of greenish grey, medium- to coarse-grained sandstone beds separated by darker, finer-grained beds, low-angle lamination, troughy surfaces, dish structures, burrows

several thick coarse-grained sandstone beds separated by thin darker, fine-grained sandstone beds; poorly exposed

grey, coarse-grained sandstone to granulestone, scattered small dark pebbles, fair sorting, troughy surfaces, low-angle lamination, few silty partings near top; capped by dark grey, silty, fine-grained sandstone with floating granules

greenish grey, coarse-grained sandstone, well sorted, uniform, erosional base with lag of granules, thick bedded, large troughy surfaces, f-up to interbedded sandy siltstone and silty, fine-grained sandstone, thoroughly bioturbated

brownish grey, medium-grained sandstone, hummocky cross-stratification and low-angle lamination

greenish grey, coarse-grained sandstone, f-up to interbedded fine-and medium-grained sandstone, well sorted, with abundant bioturbation, erosional base, txb

greenish grey, medium- to coarse-grained sandstone, well sorted, f-up to dark grey, silty, fine-grained sandstone, poorly exposed

grey, coarse- to very coarse-grained sandstone, poorly exposed

pale grey, coarse- to very coarse-grained sandstone, deeply erosional base with scour pockets and shale rip-ups, troughy surfaces, f-up to medium-grained sandstone with horizontal lamination

pale grey, coarse- to very coarse-grained sandstone, well sorted, f-up to medium- to coarse-grained sandstone with horizontal lamination and soft sediment deformation

brownish grey, arkosic, coarse-grained sandstone, well sorted, horizontal lamination, f-up to fine-grained sandstone

greenish grey, coarse-grained sandstone, well sorted, massive, f-up to fine- to medium-grained sandstone; poorly exposed

pale grey, coarse- to very coarse-grained sandstone, erosional base with large shale rip-ups, large troughy surfaces, f-up to interbedded fine-grained sandstone and medium-grained sandstone, soft sediment deformation, fractures

greenish grey, medium- to coarse-grained sandstone, uniform, massive, f-up to fine-grained sandstone

light grey, coarse- to very coarse-grained sandstone, well sorted, deeply erosional base, large-scale txb, f-up to interbedded silty, fine-grained sandstone and medium-grained sandstone

pale grey, coarse- to very coarse-grained sandstone, troughy surfaces, f-up to silty, fine-grained sandstone, horizontal lamination, soft sediment deformation at top

pale grey, coarse- to very coarse-grained sandstone, f-up to fine-grained sandstone with thin carbonaceous shale streaks, fractures

grey, coarse- to very coarse-grained sandstone,uniform, massive; scoured base, capped by fine- to medium-grained sandstone

greenish grey, arkosic, medium- to coarse-grained sandstone, well sorted, uniform, f-up to silty fine-grained sandstone, fractures

brownish grey, medium- to coarse-grained sandstone, well sorted, erosional base with large shale rip-ups, troughy laminations, chaotic water-escape structures, f-up to fine-grained sandstone with rxl and contorted lamination

brownish grey, arkosic, fine-grained sandstone to granulestone, scoured base, f-up, fractures

multistoried unit of arkosic, coarse-grained sandstone to granulestone, well sorted, massive, erosional bases with large dark grey shale rip-ups

thin fine- to medium-grained sandstone beds cutting each other

greenish grey, medium- to coarse-grained sandstone

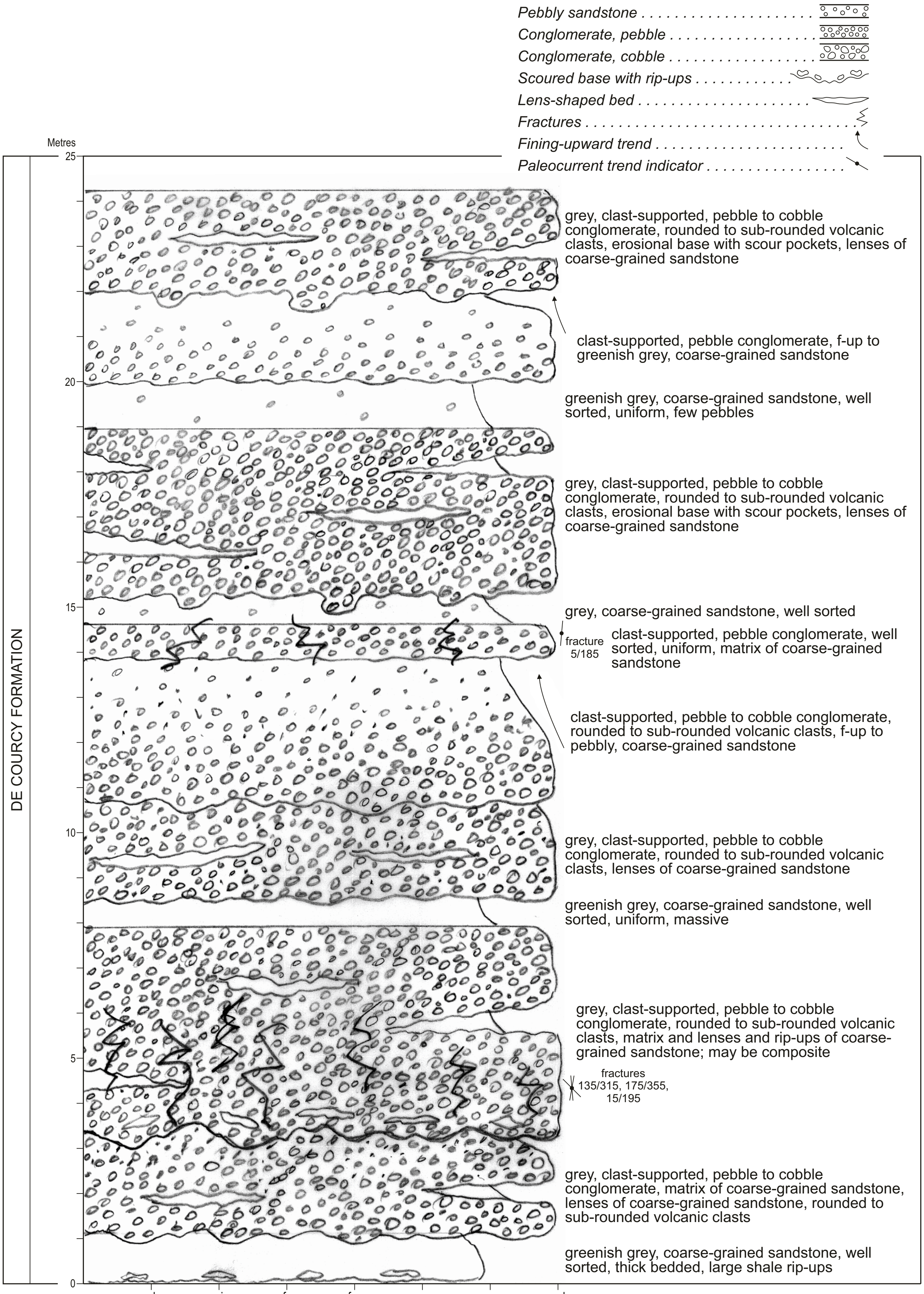
thin beds of discontinuous fine- to medium-grained sandstone with scoured bases cutting into each other; poorly exposed

greenish grey, medium- to coarse-grained sandstone, uniform, massive, scoured base; poorly exposed

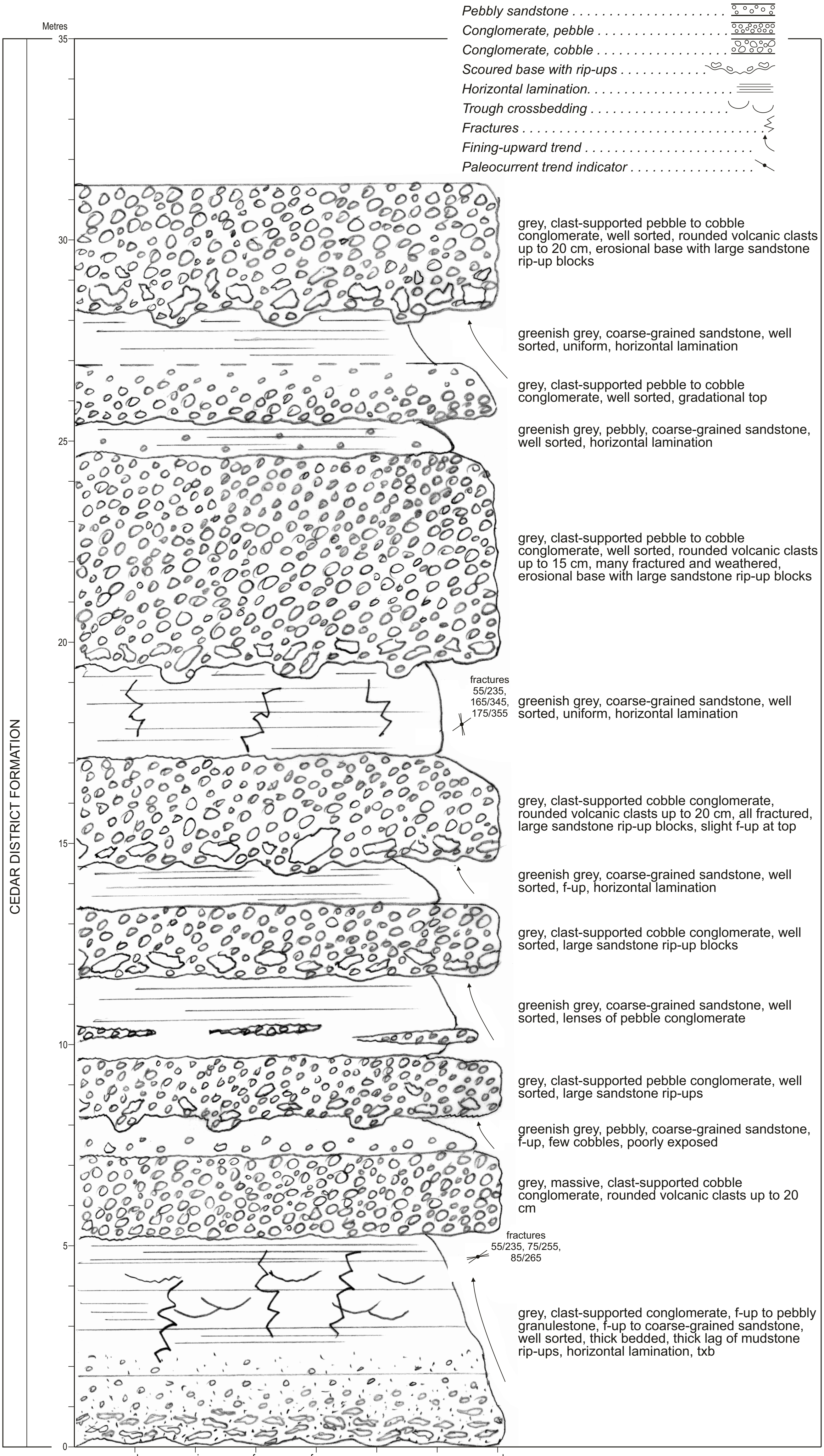
greenish grey, medium- to coarse-grained sandstone, uniform, massive, scoured base, f-up to very fine- to fine-grained sandstone

Appendix Figure 57
Coffin Point
southern tip of Coffin Point, east of Evening Cove, 4 km east of Ladysmith
De Courcy Formation
NTS Map 92B/13 (Duncan)
48° 59′ 14.2″N, 123° 45′ 54.9″W; UTM Zone 10: 0444012E, 5426310N

Appenidix Figure 58
Nanaimo Observation Well #390 Corehole (OW-11-01)
corner of Holden Corso and Lofthouse roads, Cedar
De Courcy Formation, 112.5 m
NTS Map 92G/14 (Nanaimo)
49° 06' 29.1"N, 123° 49' 23.6"W; UTM Zone 10: 0438917E, 5439794N

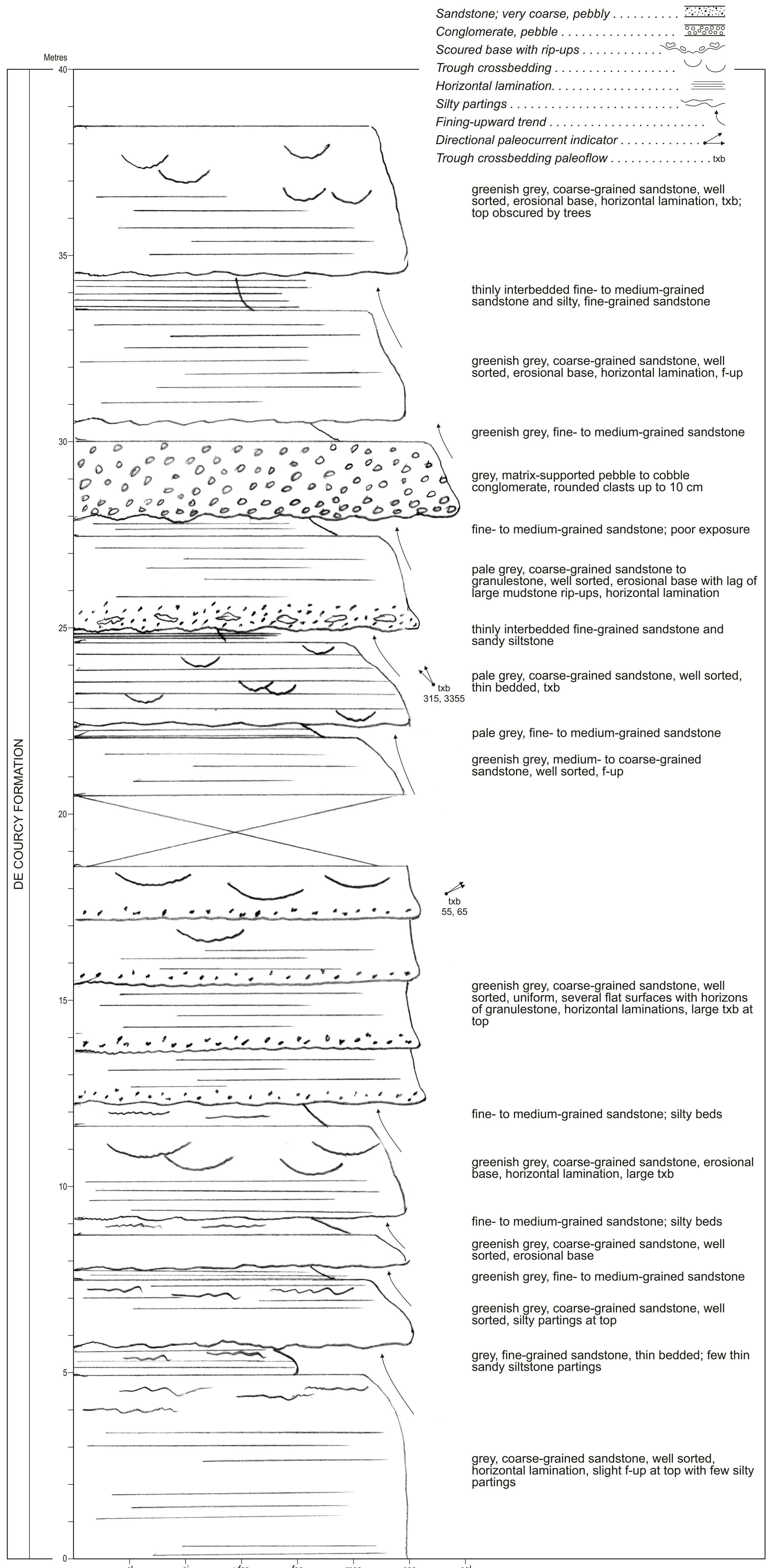


Appendix Figure 59
Bill Mee Park, Denman Island
coastal exposure on SE shore of Denman Island, SE of Hornby Island ferry dock
De Courcy Formation
NTS Map 92F/7 (Home Lake) 775833
49° 29' 19.4" N, 124° 41' 37.8" W; UTM Zone 10: 0377328E, 5483167N at base;
49° 29' 27.7" N,124° 42' 10.0" W; UTM Zone 10: 0376685E, 5483436N at top

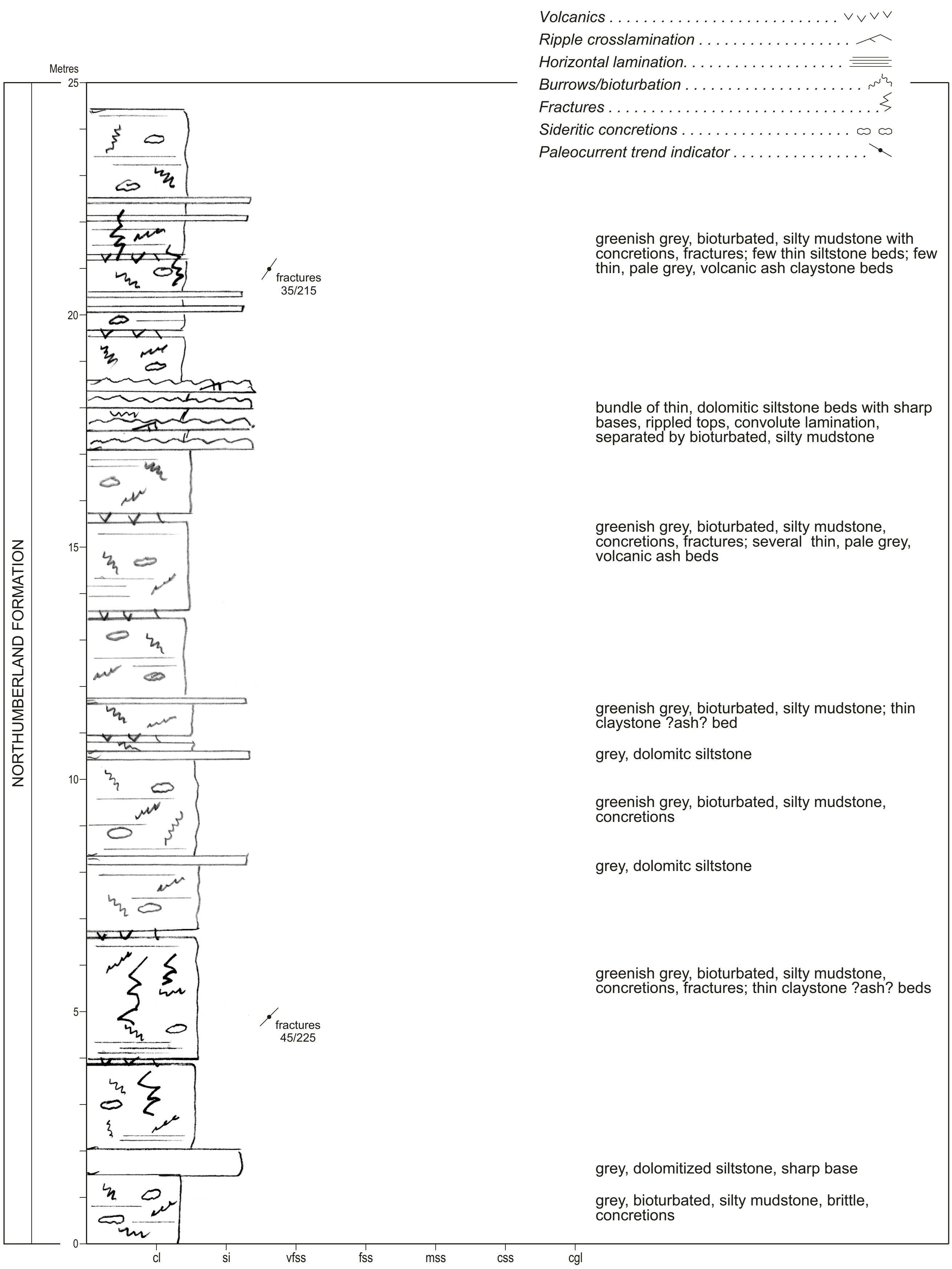


Appendix Figure 60
Whalebone Point, Denman Island

coastal tidal platform and cliff NW along shoreline from cove, along E shore of island
De Courcy Formation
NTS Map 92F/10 (Comox) 745855
49° 30' 14.8" N, 124° 43' 52.5" W; UTM Zone 10: 0374660E, 5484938N at base;
49° 30' 42.1" N, 124° 44' 16.4" W; UTM Zone 10: 0374197E, 5485793N



Appendix Figure 61
Lindsey Road
large roadcut along escarpment 1.5 km NE of Cedar
De Courcy Formation
NTS Map 92G/4 (Nanaimo) 385416
49° 07' 29.6" N, 123° 50' 55.1" W; UTM Zone 10: 0438080E, 5441583N



Appendix Figure 62
St. Mary Lake Roadcut, Saltspring Island

roadcut on St. Mary Lake Road, across from small swimmer's parking spot, E shore of lake
Northumberland Formation
NTS Map 92B/13 (Duncan) 607159
48° 53' 47.2" N, 123° 32' 09.6" W; UTM Zone 10: 0460721E, 5416094N at base;
48° 53' 33.8" N, 123° 32' 09.2" W; UTM Zone 10: 0460723E, 5416052N at top