GEOLOGY OF CORTES ISLAND AND ENVIRONS, STRAIT OF GEORGIA, BRITISH COLUMBIA

PART 2
PLEISTOCENE SEDIMENTS OF GEORGIA BASIN

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**Frontispiece.** Boulderfield on tidal flat north of Smelt Bay Bay, west side of southern Cortes Island.

The boulders and cobbles are lags of diamicts and gravels that accumulated during the erosion of the adjacent Pleistocene formations. The stones remained in place while their matrix was transported into nearshore and deeper waters of the Georgia Basin.
Marina Island Diamict Members A (Bouma sequences) and B and Cowichan Head Formation, upper member
Horizontal lamination and small-scale structures in Quadra Sand, Member A
Crossbedding in member A of Quadra Sand
Quadra Sand, Member B and Mansons Landing Diamict at section E
Quadra Sand, Member B, Mansons Landing Diamict, and Spilsbury beds at section F
Smelt Bay beds, lag of Vashon diamict, and post-glacial sediments (unit 8B)
Exposure on Whaletown Road, interpreted as post-glacial sediments, units 8A and 8B
Soil profile at locality q near skateboard park (2001)
“Cortes Archipelago” about 11 500 radiocarbon years ago
SUMMARY

The region investigated is divisible into two areas in which the contact between Mesozoic bedrock and Pleistocene sediments lies above or below sea-level, respectively. The latter comprises the southeastern extremity of Cortes Island, all of Marina Island, and northwestern Hernando Island. The approximate surface trace of the concealed boundary surface is referred to as the Uganda line, for the passage between Cortes and Marina islands.

The southeastern area has exposures of a succession of Pleistocene strata -- 110 m or more in total thickness -- that are older than the last glacial maximum (Vashon Stade of Fraser Glaciation). The succession had earlier been divided into five formations and one informal unit that are retained here with minor changes. These units are mostly of shallow marine origin and represent a late phase in the Late Cretaceous to Recent history of the Georgia Basin.

The Uganda surface was earlier interpreted as a normal fault but -- in the absence of physiographic evidence for Quaternary activity -- is now viewed as a slope on the northwestern margin of the Georgia Basin. The onlap of the pre-Vashon strata onto that slope appears to have been eroded.

The oldest unit (1) is the deltaic Cortes Sand (>20.5 m), the advance deposit of the Early Wisconsinan Semiahmooh Glaciation. It is overlain by the Marina Island Diamict (unit 2), divisible into two members. Member A (7 m), an ice-proximal deposit, consists mainly of dropstone-bearing, laminated sand and silt that is partly disturbed, and also includes a mass flow and classical turbidites (A-C Bouma sequences). Member B (17m), a massive diamict, is interpreted as a lodgement till.

The Marina Island Diamict is unconformably overlain by the upper member of the Cowichan Head Formation (unit 3), deposited during the Middle Wisconsinan Olympia Interglacial. It consists of a basal gravel (1 m) and a now concealed organic-rich silt from which a radiocarbon age of 35.4 ± 0.4 ka had earlier been obtained by J.T. Fyles.

The overlying Quadra Sand (unit 4), the deltaic advance deposit of the Fraser Glaciation, comprises a lower member (A, >26 m, possibly >40 m) of sand and minor silt and an upper member (B, 11.5 m) of sand and pebble gravel. It is conformably overlain by the stratified Mansons Landing Diamict (unit 5, 11 m), a partly disturbed dropstone deposit indicating that the glaciers had again reached tidewaters. On Hernando Island the latter is overlain by the Spilsbury beds (unit 6, >4 m) interpreted as a beach sand. The abrupt, probably disconformable contact may reflect a crustal rebound between the deposition of units 5 and 6.

Inferred diamict of the Vashon Stade (unit 7*) is represented only by gravel lag on the present land surface. This glacial event was followed by a brief interval of clastic marine sedimentation, deposits of which (unit 8) are found both southwest and northeast of the Uganda line. A lower subunit of disturbed stratified diamict (2-3 m), overlying a dyke in the basement, is known from one locality only. The upper subunit (> 1m) consists of shell-bearing shallow marine clastic sediments. Radiocarbon ages of approximately 11.7 and 11.1 ka have been obtained by James et al. (2005) from three sites on Cortes Island. The marine episode was terminated by a crustal rebound that continued into the Holocene.

In the area southwest of the Uganda line, groundwater is obtained mainly from Quadra Sand and probably also from the Cortes Sand. In the area northeast of that line it is drawn mainly from fractures in the bedrock and to a lesser extent from the Pleistocene cover.
INTRODUCTION

Location, accessibility, and physiography of report area

Cortes Island is located at the northwestern end of the Strait of Georgia, the northern part of the newly named Salish Sea. It is linked with Campbell River on Vancouver Island by means of two ferries via Quadra Island.

The generalized distribution area of the Pleistocene sediments can be divided into a northeastern area (Q1) where their contact with the underlying Mesozoic bedrock is above sea level, and a southwestern area (Q2) where it lies below sea level (Fig. 2-1, Fig. 2-2, cross-section Y-Y″). As far as known, only the southwestern area contains exposures older than the Vashon Stade, the climactic event of the Late Wisconsinan Fraser Glaciation. In the northeastern area these strata are concealed or eroded. The transition is covered by the sea or Holocene soil, but must lie close to the Uganda line, named for the passage between Cortes and Marina islands. Exposures of post-glacial Pleistocene sediments are present in both areas.

The landscape of southeastern Cortes Island and Marina Island (Q2) is characterized by plateaus up to 70 and 50 m a.s.l., respectively, in height. They are bounded on the seaward sides by steep, unstable slopes, in turn bordered by beaches and extensive, boulder-strewn tidal flats (frontispiece). Second and third-generation forest covers all of Marina and most of Hernando Island and to a lesser extent the southeastern part of Cortes Island. The landscape of the area northeast of the Uganda line, which is controlled by the bedrock, has been described in Trettin and Roddick (2002) and in Part 1 of this report.

Regional geological setting

In the northeastern area the bedrock consists mainly of a variety of granitoid rocks that probably range in age from late Middle Jurassic to Late Cretaceous with Upper Triassic to Upper Jurassic roof pendants of the exotic Wrangellia terrane.

The southwestern area (Q2) forms part of a discontinuous string of Quaternary deposits that fringes the northern margin of Georgia Strait from Quadra Island in the northwest to Savary Island in the southeast (Journeay et al., 2000; Part 1 of this report, Fig. 1-1). These strata form part of the fill of the Georgia Basin (geological term; Monger and Journeay, 1964) the surface extent of which coincides approximately with the present Georgia Depression (physiographic term). The latter includes the Strait of Georgia and the surrounding lowlands.

Georgia Basin has had a long history of subsidence and sedimentation, divisible into four main phases, as follows.

1. Sedimentary rocks of Late Cretaceous, Turonian to Maastrichtian age were deposited in a single, elongate basin, preserved mainly on east-central and southeastern Vancouver Island and the adjacent Gulf Islands with less extensive occurrences in the Fraser Lowland and on Lasqueti Island. Up to 4 km thick, they consist of sandstone, mudrock, and conglomerate assigned to the Nanaimo Group (Mustard, 1994). The basal sediments were laid down in alluvial and coastal marine environments on a rugged unconformable surface, the rest on submarine fans. Most sediments were derived from the Coast Mountains and the Cascades.

2. Sediments of Paleocene-Eocene age (Mustard and Rouse, 1994) are preserved only in southeastern parts of the basin. They are assigned to the Chuckanut Formation in the Puget Sound region of northwestern Washington State where they are up to 6 km thick, and to the Huntingdon Formation in the Fraser Lowland and on Lasqueti and some other small islands, where they are up to 4 km thick. They consist mainly of conglomerate and sandstone, derived from local sources and deposited in alluvial fan and fluvial environments.

The Nanaimo Group and the Huntingdon and Chuckanut formations were deformed together in late Eocene time; the former by thrust-faulting and folding (England and Calon, 1991), the latter two by folding (Mustard and Rouse, 1994 and references therein).
The Oligocene is represented only by igneous rocks including dykes, sills, other types of small intrusions, and rare volcanic flows (Hamilton and Dostal, 1994; Hickson, 1994). Although spatially associated with strata of the Georgia Basin, these igneous rocks are part of the Oligocene to Recent Cascade magmatic arc (Souther, 1992).

3. Sediments of Miocene age are well known only from the subsurface of the Fraser delta. Assigned to the Boundary Formation, they comprise up to 1180 m of sandstone and mudstone that are mainly of fluvial, less commonly of marginal marine origin (Mustard and Rouse, 1994). They are overlain by unnamed strata of early Pliocene age.

4. Unconsolidated sediments of Pleistocene and Holocene age are most completely preserved in southeastern and central parts of the Strait of Georgia and beneath the Fraser River Delta. A stratigraphic framework and depositional history for the Pleistocene strata exposed onshore has been established mainly in the vicinity of Vancouver and on southern Vancouver Island with additional information from Quadra Island (Clague, 1989, 1991, 1994 and references therein). More recently the on-land information has been supplemented by offshore investigations which included seismic surveys, surface sampling and shallow drilling (Barrie and Conway, 2000). Whereas the glacial record of the Cordillera Ice sheet extends back to the late Pliocene (Duk Rodkin et al., 2010; Jackson et al., 2011) on the south coast of British Columbia it commences in the late Middle Pleistocene. There it represents the following climatic phases: the Sangamonian Interglacial; the Early Wisconsinan Semiahmoo Glaciation; the Middle Wisconsinan Olympia Interglacial; the Late Wisconsinan Fraser Glaciation with its two stades, Coquitlam and Vashon; and a post-glacial marine incursion, followed by uplift and erosion around the margins of Georgia Basin due to Crustal rebound.

Different tectonic mechanisms have controlled the subsidence and filling of Georgia Basin during the depositional episodes mentioned. During the Late Cretaceous Epoch, basin formation and sedimentation were controlled by strike-normal compression, evident in thrust faulting in the Coast Mountains (Mustard and Rouse, 1994 and references therein). During the Paleocene and Eocene Stages, in contrast, strike slip was the dominant mechanism (Mustard and Rouse, 1994 and references therein). Since Oligocene time Georgia Basin, lying between a non-volcanic outer ridge on Vancouver Island and the Cascade magmatic belt, has been a typical forearc basin (Monger and Journeay, 1994 and references therein). During the Pleistocene, the forearc basin was deepened by glacial erosion. Glacial loading and melting caused cycles of depression and rebound as well as gentle deformations of the glacial deposits.

Syntheses of seismic information shed light on the present structural setting and thickness the Quaternary basin fill. A cross-section of the Nanaimo Group within the basin, located about 33 km southeast of Cortes Island (England and Bustin, 1998, Fig. 4), reveals a gentle sag, tilted down to the northeast and bounded laterally by three slightly concave normal faults. The southwestern boundary fault lies about 12 km southwest of the east coast of Vancouver Island while the two northeastern boundary faults are close to the mainland coast. And a contoured map of the pre-Quaternary bedrock surface by Hamilton and Ricketts (1994) shows a depth of 700 m beneath the bathymetric basin axis, which, in turn, has a maximum depth of 410 m. This implies a maximum thickness of some 300 m for the Quaternary basin fill.

**Previous geological studies and current investigations**

On Cortes and the adjacent smaller islands, expanses covered by Quaternary sediments were mapped (but not further investigated) by Dawson (1887), Bancroft (1913) and Roddick and Woodsworth (1977, 2006). J.T. Fyles, in the course of an extensive regional reconnaissance of Pleistocene geology, recognized the presence of the Late Wisconsinan Quadra Sand and made some paleocurrent determinations (in Fig. 2 of Clague, 1977). He also obtained an important radiocarbon date (35.4 ± 0.5 ka) on fossil wood from an isolated outcrop on Marina Island (Olson and Broecker, 1961, p. 147, L-455B; Table 6 in Clague, 1977, GSC-202; Fig. 2-1, loc c of this report) that represents an older unit.
The area received no attention from Quaternary specialists during next decades because of the lack of conspicuous exposures. However, a systematic search for exposures from 1998 to 2003 enabled Trettin (2004) to erect a framework of five formations (units 1 to 5) and to relate them to the Early Wisconsinan Semiahmoo Glaciation, the Middle Wisconsinan Olympia Interglacial, and the Late Wisconsinan Fraser Glaciation. The overlying strata were assigned to several informal units of latest Pleistocene age.

In a parallel enterprise, fossils, found by members of the Cortes Island community on the present land surface, have been collated and identified by C.W. Gronau and J.W.Haggart (Haggart, 1995; Gronau, 2002a, b).

From 2001 to 2003, T.S. James and colleagues carried out a systematic collecting and drilling program around the margin of the Georgia Basin in order to obtain samples for high-precision radiocarbon dating, which included six sites on Cortes Island. The results provided information about the present elevation of the marine limit during the latest Pleistocene and early Holocene (Hutchinson et al., 2004a; James et al., 2005, 2009a). The resulting sea-level curves were used to compute the rate of postglacial rebound of the crust and the viscosity of the underlying asthenosphere (James et al., 2009b).

The purposes of this report are: to modify and reinterpret the upper part of the succession (units 6 to 9); to revise the interpretation of the Uganda line; and to provide additional photographs and verbal logs of the stratigraphic sections.

Acknowledgements

The acknowledgements made in the earlier report (Trettin, 2004) still are valid. Christian Gronau provided outcrop information and excellent photographs of stratigraphic sections C and D, two of which are reproduced in this report (Figs. 2-5b, 2-8b). For access to their properties — where dated shells had been found — I am grateful to E. Piggott and Robert Graham and Ann Dewar. Tom James informed me about the results of his ongoing work. John Clague made helpful comments on the earlier manuscript (Trettin, 2004). For a helpful review of the present version I am indebted to Lionel Jackson.

LOCAL STRUCTURE

Marina Island

The structure of southeastern Cortes Island is uncertain because of poor exposure but the structure of Marina Island is reasonably well known. Its southern part is characterized by a homocline dipping slightly less than 01/11. The dip angle has been determined from the elevation (determined by altimeter) of the base of Cowichan Head Formation, which decreases from circa 29.5 m above sea level at section A to about 9 m at locality a (Fig. 2-2). Projected onto a line perpendicular to strike, the distance is about 2.05 km, equivalent to a gradient of approximately 0.6° or 10m/km. The homocline is bordered on the north by a panel whose nearly horizontal attitude is inferred from the elevation of three closely spaced red bands at sections B and C. (A fourth band at section C is absent at B.)

Uganda line

As mentioned in the Introduction, the transition between those areas where the base of the Pleistocene sediments lies above or below sea level, respectively, is covered by Holocene soil or by the sea, but must lie close to the Uganda line. The corresponding boundary surface was earlier (Trettin, 2004) interpreted as a hidden normal fault (referred to as the Uganda lineament) and may indeed have originated as a fault in the more distant past. However, close examination of air photographs did not reveal any physiographic evidence for Quaternary reactivation, and it is therefore now interpreted as a relatively steep slope on the northwestern margin of the Georgia Basin. If so, the Pleistocene strata of units 1 to 5 or 6 must have lapped onto that slope originally.
In the interpretative cross-section Y-Y” (Fig. 2-2), the slope angle is 2.7° if the vertical exaggeration is taken into account, but the inclination shown is arbitrary. Limited evidence (discussed in a later section) suggests, that this onlap was removed -- at least locally -- before the deposition of post-glacial sediments.

PLEISTOCENE STRATIGRAPHY

Introduction

Stratigraphic sections (Figs. 2-4a, 2-4b) were measured with the aid of a measuring staff and a high-precision altimeter. Altimeter readings were calibrated with respect to survey points shown on detailed topographic maps (scale 1:50,000) issued by the British Columbia Department of the Environment or to the upper limit of beaches, which coincides with the 5 m contour. The information from these sections has been supplemented by more limited outcrop observations.

The present stratigraphic framework (Fig. 2-3) is divisible in two parts. The lower part comprises a continuous succession of six units, all established and interpreted in the earlier report (Trettin, 2004). The remaining part of Pleistocene succession is revised here. It comprises surface gravel interpreted as lag of diamicton correlated with the Vashon Stade (unit 7*), post-glacial marine sediments (units 8A and 8B), and the informal Smelt Bay beds whose stratigraphic position is uncertain.

Cortes Sand (units 1A, 1B)

The Cortes Sand is the oldest Pleistocene formation in the report area and its type section is on the southeastern coast of the island (section D, Figs. 2-1, 2-4a). There it is about 20.5 m thick and overlain by the Marina Island Diamict.

The lower 2 m consists mainly of sand with minor silt in the lower 2 m and minor pebbly sand in the following 2 m (Fig. 2-5a). The strata are yellowish grey with some reddish brown beds stained by limonite derived from weathered pyrite. Cross-lamination prevails with lesser horizontal lamination, flaser structure, and convolute lamination. Sets of crosslaminae are mainly concave and from a few centimeters to about 30 cm thick. These strata (designated unit 1A) evidently were deposited in high-energy fluvial or deltaic settings. The middle part of the section consists mainly or entirely of sand but no detailed information about the stratification was obtained because lack of access or poor exposure.

The upper part (unit 1B) is exposed at the top of section D, at the bottom of section A (Figs. 2-1, 2-4a) and also on the southwestern coast of Cortes Island (Fig. 2-1, locs. e, h). It consists largely of yellowish to greenish grey sand and minor silt and is characterized by horizontal lamination with some ripple marks and low-angle trough-crossbeds (Fig. 2-5b). These primary structures suggest quiet subtidal settings, probably in outer parts of a delta.

The contact with member A of the Marina Island Diamict (Fig. 2-5a) is covered at section D but probably conformable. The fact that the Cortes Sand is succeeded by this ice-proximal marine deposit of the Early Wisconsinan Semiahmoo Glaciation (see below) demonstrates that it is an advance deposit, analogous to the Quadra Sand, the advance deposit of the Late Wisconsinan Fraser Glaciation (cf. Clague, 1977, 2000). Although different in detail, the Cortes Sand is probably correlative with the Mapleguard Sediments of southern Vancouver Island (Fyles, 1963) abolished as a separate unit and included in the Dashwood Drift by Hickock and Armstrong (1983).

Marina Island Diamict (units 2A, 2B)

The name, Marina Island Diamict was introduced (Trettin, 2004) for a glacial deposit lying stratigraphically between the Cortes Sand and the Cowichan Head Formation of Armstrong and Clague (1977). At the type locality on the south point of Marina Island (Fig. 2-1, section A) the formation is 24 m thick and divisible into two members, A and B (Fig. 2-4a).
Member A (unit 2A), 7 m and 5.5 m thick, respectively, at sections A and D (Fig. 2-4a), consists chiefly of stratified diamict with minor massive diamict and turbidites. The stratified diamict (Figs. 2-6b, 2-7) is composed mainly of horizontally laminated sand and minor silt, similar to the upper part of the Cortes Sand (although slightly darker in tone), but also contains scattered, unsorted stones of pebble to boulder size interpreted as ice-rafted dropstones. A thin unit of massive diamict cutting across the stratified diamict at section D (Fig. 2-7), probably represents a massflow produced by slumping on a submarine slope. Turbidites 1 exposed at locality m on Cortes Island (Fig. 2-1), a few hundred metres north of stratified diamict exposed at locality k, probably are distal equivalents of such massflows. Representing divisions A to C of the Bouma model, they range in thickness from 24.5 cm to more than 53 cm, and in grain size from silt to coarse, pebbly sand with some larger intraclasts.

Member B (unit 2B), about 17 m thick at section A, consists of massive diamict. The boundary with member A was inaccessible there and its position is uncertain within an interval of about 3 m.

The Marina Island Diamict is correlative with the Semiahmoo and Dashwood drifts of the Fraser Lowland and southern Vancouver Island, respectively (Hicock and Armstrong, 1983) but differs from them in detail. Member A represents glaciomarine sediments deposited when the glaciers had reached tidewater. Member B is probably a lodgement till, formed during the maximum of the Semiahmoo Glaciation. If so, an unconformity should be present at the base of member B, but this has not been confirmed.

Cowichan Head Formation, upper member (units 3A, 3B)

The Cowichan Head Formation, named for outcrops near Victoria (Armstrong and Clague, 1977), underlies lowlands adjacent to the Strait of Georgia. Generally less than 10 m thick, it has been divided into two members. The lower member, consisting mainly of sand and mud, is of marine origin and conformably overlies sediments of the Semiahmoo and Dashwood drifts. It is less widely exposed than the upper member, which comprises organic-rich gravel, sand, and silt of fluvial and estuarine aspect. Where the lower member is absent, the upper member overlies “an irregular erosion surface developed on older drift” (Clague, 1989, p. 50). “Reliable radiocarbon ages from this unit range from 23.8 to 58.8 ka” (Clague, 1994, p. 187), a relatively warm climatic interlude correlative with the Oxygen Isotope Stage 3 (Olympia Nonglacial Interval).

A poorly exposed unit on Marina Island that disconformably overlies the Marina Island Diamict and is overlain by the Quadra Sand with a covered contact is interpreted as the upper member of the Cowichan Head Formation. This assignment is based on stratigraphic relations and a radiocarbon age (cf. Fig. 2-2, cross-section X-X’) and the limited information about its lithology is compatible with that interpretation.

Only two beds are known. The basal stratum (unit 3A) is best exposed on Marina Island at section A and locality a (Fig. 2-1) where it is 0.5 m and 1 m thick, respectively. At both sites it overlies member B of the Marina Island Diamict with an abrupt contact, marked by limonite stain at locality a (Fig 2-8b). It is similar to the latter with respect to the size (mainly pebbles and cobbles with some boulders) and composition of the stones (mainly granitoid rocks with less andesite or basalt), and their support by the (predominantly sandy) matrix, but differs from the diamict by a significantly higher proportion of stones versus matrix. This bed probably was derived from the Marina Island Diamict by the winnowing of its matrix in a high-energy, nearshore environment during the rebound that followed the Semiahmoo Glaciation (cf. Fig. 2-3). Owing to the slight northeasterly dip of the stratigraphic succession of southern Marina Island, units 2B and 3A disappear below sea level less than 100 metres to the northwest of locality a (Fig. 2-1, and cross-section X-X’ of Fig. 2-2) and a short distance farther along the coast, exposures of the Quadra Sand commence not far above beach level. Still farther northwest on the coast of Marina Island, at locality c, a “plant-bearing silt” (unit 3B) was discovered by J.G. Fyles “about 3 feet above high-tide level” (Olson and Broecker, 1961, p. 147). A piece of wood, submitted to the laboratories of the Lamont Geological Observatory and the Geological Survey of Canada yielded apparent ages of 35.4 ± 2.2 ka and 35.4 ± 0.4 ka, respectively (Olson and Broecker, 1961, L-455B; Table 6 in Clague, 1977, GSC-202). When revisited by Trettin in

1 The genetic relation between Bouma sequences and turbidity currents has been confirmed by a wealth of marine, experimental, and theoretical studies (cf. Arnott, 2010 and references therein).
2000, the stratification had been obliterated by root growth and no plant-bearing silt was found. The contact between Cowichan Head Formation and the Quadra Sand is concealed by a thin covered interval.

On southern Cortes Island, unit 3A may be represented by a massive bed of sandy gravel that disconformably overlies member A of the Marina Island Diamict at section D, and member B of that formation at locality d (Fig. 2-1). This interpretation is tentative because overlying strata of the Cowichan Head Formation and of the Quadra Sand are not preserved at these localities.

Quadra Sand (units 4A, 4B)

The Quadra Sand, a widely distributed Pleistocene formation in the Georgia Depression, has its type section on southern Quadra Island (Clague, 1977). It overlies mainly the Cowichan Head Formation, but also older sediments or bedrock and is overlain by glaciomarine or glacial deposits. The formation consists chiefly of light-colored sand that is generally well sorted and commonly cross laminated, with lesser proportions of silt and gravel. Organic material is very rare. The contact with the Cowichan Head Formation (covered in the study area) is sharp and readily determinable by lithological criteria. Recorded thicknesses locally exceed 50 m (Clague, 1989). Radiocarbon ages range from about 19 ka to 29 ka and overlap with the youngest radiocarbon ages from the Cowichan Head Formation (cf. Clague, 1977, Table 6). The Quadra Sand is clearly a diachronous unit, deposited in front of glaciers, which, after emergence from the Coast Mountains, flowed down the axis of the Georgia Depression in a southeasterly direction (Clague, 1977).

In the study area the Quadra Sand lies between the upper member of the Cowichan Head Formation and the Mansons Landing Diamict. The lower contact, concealed here, is probably disconformable because it is marked by an abrupt change in lithology (Clague, 1977, p. 6). The upper contact, exposed at section E on Cortes Island and at section F on Hernando Island, is conformable. The formation is divisible into two members, A and B, that are distinguished by the presence or absence of gravel. Its total thickness is uncertain as only partial sections of member A are exposed, but is estimated to be no less than 42.5 m and possibly greater than 50 m.

Member A (unit 4A) is composed mainly of sand with interbedded silt in the lower part and minor pebbly sand in the uppermost part. Only partial sections of this unit are known, the longest of which is section C on Marina Island, 26 m. It begins an estimated 5 m or so above the hidden Cowichan Head Formation (Fig. 2-2, cross-section X’-X”) and does not extend to the base of Member B. At section E on Cortes Island, only the upper 8.5 m are exposed. It is uncertain whether this interval overlaps with the top of section C, adds on to it, or is separated from it by a gap. So the total thickness of the member is no less than 31 m and possibly greater than 39.5 m.

Comparison of stratigraphically equivalent sections reveals considerable variations in sand/silt ratio and primary structures. Interbedded sand and silt and much of the sand show horizontal lamination (Fig. 2-9a), ripple marks (including climbing ripples, Fig. 2-9b) and small-scale waves of low amplitude. Sand, in addition, shows medium-scale trough-crossbedding (Figs. 2-10b, 2-10c) especially common at section F on Hernando Island. Less common are convolute lamination, slump structures (at section F) and lateral accretion-type crossbedding (at section C, Fig. 2-10a).

Member B (unit 4B) consists of interbedded sand and gravel. Silt and minor mud, partly dark grey, occur in the upper part of section E but are absent from section F. The thickness of the member is 11.5 m at section E and 10.5 m at section F. Sand and gravelly sand both show horizontal bedding and crossbedding, whereas gravel occurs mainly as lenticular or tabular bodies (Fig. 2-11b). Typical gravel beds at section E are 10-70 cm thick.

In the study area, the Quadra Sand is an upward-coarsening succession that reflects sedimentary progradation, caused by a glacial advance, into a shallow marine basin. The bulk of the formation probably represents a variety of delta-front settings with the cross-bedded sands indicative of high-energy, nearshore environments. Tidal features are not obvious although the lateral accretion-type crossbedding at section C may have originated in a meandering tidal channel. The crinkled lamination in the lower part of that section suggests sliding (without disaggregation) on a slightly inclined subaqueous slope.
Lenticular gravels in the lower part of Member B at sections E are suggestive of a braidplain environment, presumably forming the topset of a deltaic succession. The upper part of the same member, however, is probably of a subaqueous origin because it is similar to the matrix of the ice-rafted dropstones of the Mansons Landing Diamict (Figs. 12a, 2-12b). The subsidence apparent at this level may again reflect crustal subsidence under an approaching ice load, as inferred for the Cortes Sand.

**Mansons Landing Diamict (unit 5)**

The new name, Mansons Landing Diamict, was given (Trettin, 2004) to a stratified diamict that conformably overlies the Quadra Sand (Figs. 2-11a, 2-11b). The type section is at section E, 1 km southwest of the Mansons Landing dock. There it is about 11 m thick and forms a vertical cliff, accessible only in the lower few metres. The matrix of the diamict consists of thinly interstratified sand, pebbly sand, and dark grey mud, similar to the uppermost part of the Quadra Sand. The lower part shows horizontal lamination with some ripple marks, the upper part soft-sediment deformations (Fig. 2-11c). Scattered throughout this matrix are unsorted pebbles, cobbles, and boulders. At the type section, the formation is overlain by limonite-stained gravel and sand that represents the B-horizon of a soil profile.

At section F on northeastern Hernando Island, the diamict is only about 2.5 m thick (Figs 2-11a, 2-11b). The matrix consists of thinly bedded sand, gravelly sand, and pebble gravel – again similar to the underlying Member B of the Quadra Sand. The originally horizontal or lenticular stratification is strongly disturbed. Unsorted pebbles, cobbles and small boulders, as well as an isolated large boulder, are scattered through this matrix. Here it is overlain with an abrupt contact by the Spilsbury beds.

The coarse size and scattered, unsorted distribution of the stones in the Mansons Landing Diamict suggests deposition from melting or overturned ice rafts in offshore settings. The presence of dark grey silt and mud at section E indicates deposition in poorly oxygenated waters, probably deeper than those at section F. The soft-sediment deformation structures at section E are due to slumping whereas some deformations at section F could be attributed to the impact of dropstones.

The Mansons Landing Diamict clearly was deposited close to glaciers that had reached tidewater, but the absence of an overlying massive diamict representing till suggests that it does not represent the ultimate advance of the Fraser Glaciation known as the Vashon Stade but an earlier, less extensive advance – analogous to the Coquitlam Stade of the Vancouver area but not necessarily correlative with it.

**Spilsbury beds (unit 6)**

The informal name, Spilsbury beds, was introduced (Trettin, 2004) for an estimated 4-5 m of light grey, planar-laminated sand that overlies the Mansons Landing diamict in a steep, inaccessible cliff at section F near Spilsbury Point on northeastern Hernando Island (Fig. 2-12). The abruptness of the contact probably indicates a disconformity, but in the absence of a gravel lag there is no sign of intervening erosion. Overlying strata are not preserved. A beach environment of deposition is tentatively inferred from the planar lamination of the sand, which seems to be slightly inclined with respect to the basal contact and from its light grey tone, indicating oxidizing conditions.

In the earlier report, the Spilsbury beds were considered as an uncharacteristic, local facies of the Mansons Landing Diamict but this interpretation is here revised. The apparently disconformable contact with the Mansons Landing Diamict and the shallower depositional environment probably reflect a crustal rebound caused by a temporary glacial retreat.

**Smelt Bay beds (unit sb, stratigraphic position uncertain)**

In the 2004 report, the informal name, Smelt Bay beds, was used for scattered outcrops of deltaic deposits of gravel, sand and silt whose stratigraphic base and top were concealed or eroded.
The problematic strata are best exposed at locality o (Fig. 2-1), a small pit located between the junction of Sutil Point and Bartholomew roads (elevation 58 -60 m). There parallel planar foresets, composed of interbedded gravelly sand, sand, and laminated silt, dip southeast at an intermediate angle (13a, b). Thin mass flows and small, down-dip directed faults (marked by arrows) indicate a subaqueous environment of deposition. The strata are overlain by intensely rooted soil, in turn overlain by unsorted stones, ranging size grade from pebbles up to coarse boulders, that probably include relicts of the Vashon diamict (unit 7*).

Similar strata were observed in 2001 in the upper levels of an industrial gravel pit (elevation 62 m and less) at locality g. At the time, foresets of interbedded pebbly sand and pebble gravel showed moderately steep, westerly to southwesterly dips. These beds, too, were overlain by soil and unsorted, scattered stones up to boulder size. The outcrops have since been excavated.

The topographically relatively high elevation (with respect to the rest of the report area) of both exposures suggests a position in the upper part of the Wisconsinan succession. They resemble the Mansons Landing Diamict at the type section and may indeed be facies equivalents of this unit, but a higher stratigraphic position -- somewhere above the Spilsbury beds -- cannot be excluded. On the other hand, their position below surface boulders and cobbles interpreted as lag of the Vashon diamict indicates that they are older than similar strata at the bottom of the pit (Fig. 2-1, loc j) with which they had earlier been combined. A radiocarbon determination by James et al. (2005) has shown that the latter are post-glacial sediments (unit 8B) younger than the Vashon diamict.

Lag of Vashon diamict (unit 7*)

The Fraser Glaciation climaxed during the Vashon Stade, which had two major results. First, deep erosion: the stratigraphic continuity of units 1 to 5 between Marina, Cortes, and Hernando islands, for example, shows that the channels now separating these islands were carved during that event. And second, the glaciers likely produced a ubiquitous basal till. Although the latter is concealed or eroded in the study area, it probably is represented by part of a lag of boulders, cobbles and pebbles, scattered on the present land surface, whose original matrix has been removed by erosion. The winnowing of the Vashon diamict most likely occurred during the post-glacial crustal rebound when these sediments, during their rise from depth, passed through near-shore high-energy environments.

The same process, of course, must have affected all of the older gravel-bearing units (Mansons Landing Diamict; Member B of the Quadra Sand; upper member of Cowichan Head Formation; Marina Island Diamict) where they are transected by the present land surface -- the deeper the stratigraphic level of this surface, the more units must have contributed to the combined lag. That level is lowest on the tidal flats around the southeastern extremity of Cortes Island where conspicuous boulder fields are present (frontispiece).

Post-glacial sediments (units 8A, 8B)

Two informal members are tentatively distinguished. The problematic older one (unit 8A) is exposed on the Whaletown Road, a short distance north and west of the east end of Gorge Harbour (i.e. north of the Uganda line) at about 22-24 m elevation. It is a laminated diamict, about 2-3 m thick and composed mainly of laminated sand and minor silt with scattered stones ranging from pebble to coarse cobble grade. The laminations show small-scale, irregular folds (Fig. 2-14). At the east end of the exposure the stratum is seen to overlie a dyke in the Bartholomew quartz diorite-diorite pluton.

The diamict is abruptly and unconformably overlain by a bed of pebbly sand showing an undisturbed parallel lamination, which in turn is unconformably overlain by brownish soil with stones.

The Whaletown Road diamict clearly is the product of ice-proximal deposition in a marine environment, and the folds may have been produced by sliding on a submarine slope or by the differential loading of a water-saturated sediment. However, three different interpretations of its stratigraphic position and relative age are possible, as follows:
(1) It is an erosional relict of an upper part of the Mansons Landing Diamict.
(2) Its deposition immediately preceded the Vashon Stade of the Fraser Glaciation.
(3) It is a relict of early post-Vashon sedimentation.

All three interpretations require that the entire underlying succession was removed here prior to the deposition of this stratum. In the third alternative -- which appears to be the simplest -- much of this erosion was accomplished by the Cordilleran Ice Sheet during the Vashon Stade. The basal till of this ice sheet -- if deposited here -- likely was removed by submarine erosion on a steep slope. The site is near the top of bedrock cliff that descends to Gorge Harbour an angle of about 26°. If so, then the overlying laminated pebbly sand would represent the lowest stratum of unit 8B.

The assignment of three different exposures on Cortes Island to unit 8B is based on radiocarbon age determinations by T.S. James and co-workers (2005). The shells collected at these localities are all are of shallow marine origin, and the enclosing sediments lack dropstones. Two sites lie in the area southwest of the Uganda line (Q2) and preliminary results were reported (with permission) in Trettin, 2004. They have since been slightly modified because of the use of a different reservoir correction.

The present information on these three sites is briefly listed here in the order of decreasing elevation; for full information see James et al. (2005). (The gaps between their locality numbers represent sites on Quadra and Vancouver islands.) Their sites L6 and L7 were also examined by the author.

Locality L3, “Belansky well”, near the residence of Mrs. G. Belansky, 536 Olmsted Road (elevation of well-head 107 m). Here fragments of the scallop *Chlamis rubida* from blue-grey clay at depths of 4.3 to 5.5 m (i.e. at an elevation of *circa* 102 m) gave a radiocarbon age of 11 670 ± 121 years BP (“before present” by convention, means before 1950). The corresponding calendar age is 13 392- 13656 years, using one standard deviation to indicate confidence limits.

Locality L6 (identical with loc. f of Fig. 2-1), “Piggott’s Pond” (elevation 47 m), is on the property Mr. E. Piggot, east of his residence at 602, Potlach Road. There about 1.5 m of slightly inclined strata are exposed on the rim of a small pit. They consist mainly of sandy pebble gravel, light grey or brown, with 20 cm of interbedded, vaguely laminated, light grey sand. A fragment of *Chlamys rubida*, recovered earlier (E. Piggot, pers. com., 2001) from underlying beds that are now concealed, yielded a radiocarbon age of 11 660 ± 112 years (13 389-13 641 calendar years).

Locality L7 (loc. j of Fig. 2-1), “Graham’s Gravel Pit” is close to an industrial building on Sutil Point Road at the bottom (elevation 45 m) of the same pit that has locality g at its top. Here about 1.2 m of strata were exposed in 2001 (Fig. 2-13c) that have since been excavated. They consisted of two beds of partly graded gravel, separated by planar laminated sand with some shell fragments (arrows). The bed dips at a low angle in an easterly direction. Fragments of a *Saxidomus giganteus* valve and of *Humiliara kennerleyi* from the upper gravel have a radiocarbon age 11 140 ± 103 years (12 939-13 120 calendar years). A short distance northeast of the shell-bearing bed, a few metres of laminated sand and minor pebbly sand have recently been exposed by excavation, the base of which is at nearly the same elevation as the shell-bearing bed originally was. These strata dip in the same easterly direction as the shell-bearing bed. The dip appears to be low near the bottom of the exposure but becomes intermediate near the top of the present exposure. The setting suggests that these strata overlay the shell-bearing bed (before the latter’s removal) and that both represent foresets of a subaqueous delta.

As mentioned, these strata are now thought to be separated by a concealed disconformity from those exposed at locality g, because the latter are overlain by scattered cobbles and boulders, at least some of which represent lag of the Vashon Diamict. If so, then the inferred disconformity descends in elevation by more than 15 m over a distance of less than 100 m in a northwesterly direction. This relation was not recognized in the earlier report (Trettin, 2004) which – because of similarities in lithology and inferred
depositional environment -- assigned the exposures not only at localities j and o, but also those at g to the Smelt Bay beds.

According to entries in Wikipedia (2012) Saxidomus giganteus (from locality L 7) occurs at intertidal depths to 40 m, and Chlamys rubida (from localities L 13 and L6) at depths from 0 to 200 or 300 m. Because of the wide depth range of the habitat, especially of Chlamys rubida, the differences (or coincidences) in the elevation and radiocarbon age of these three collections cannot be interpreted closely in terms of the uplift of the island.

Before explaining the purpose and some of the technical aspects of the investigations of James and co-workers let me summarize their information on two other localities on Cortes Island.

Locality L12, “Gorge Harbour” is separated from the sea by a sill that rises to 22 m below sea level. Three piston cores were obtained in water depths of 30 to 40 m. The two longer cores grade upwards from silty clay with silt laminae, sand, granules and pebbles, to a shell-rich mud, containing pelecypod valves and unidentified shell fragments. Three radiocarbon ages on this material range from 12, 360 ± 121 years (14 102-14 611 calendar years) to 11 960 ± 112 years (13 713-13 945 calendar years).

The shorter, third core is composed of “stiff” silty clay overlain by an olive-grey clay. Unidentified shell fragments from the top and base of the latter yielded early Holocene radiocarbon ages of 8720 ± 127 years (9702-1088 calendar years) and 7760 ± 120 years (8510-8850 calendar years) respectively. In summary the bottom of Gorge Harbour at site 12 was below sea level 12, 360 years ago and has remained so ever since.

Locality L9, “Cortes Bay”, an archeological excavation at the end of Cortes Bay, revealed cultural deposits, generally about 1 m thick, overlying a former beach (Mathews, 2003). A mixed sand-shell layer at the base of the cultural deposits is probably of littoral origin. Slightly wave-worn fragments of clam shells (elevation 1.3 m) have a radiocarbon age of 2260 ± 108 years (2190-2510 calendar years). The age of charcoal (elevation 1.5 m) that may have been deposited by water is 1950 ± 60 radiocarbon years (1825-1925 calendar years). In addition to this dated material, the bed includes a burnt clam shell and wave-rolled mammal bone fragments, “indicating probable human occupation at slightly higher elevations”. “If the littoral deposits are high-tide deposits, then this suggests that sea level was at about 1.5 m elevation at 2000 years BP. Alternatively, if the site is an area of cultural accumulation on a former storm beach, the sea level must have stood lower at 2000 years ago, perhaps near its present level. In either case at 2000 BP sea level probably stood less than 1.5 m higher than its present level.”

The following technical comments are necessary to explain the data listed above. Whereas previously radiocarbon ages were accepted at face value, two corrections were applied during these investigations (Hutchinson et al., 2004b and references therein): “normalization” to a “δ value” (a conversion factor relative to an isotopic standard) of – 25 0/00; and a “reservoir correction” of – 950 ± 50 years applied to marine shells older than 10 000 radiocarbon years, and of 720 ± 90 years to younger ones. Moreover, radiocarbon ages older than about 1000 years are everywhere significantly smaller than the corresponding calendar years that have been established by other methods. This discrepancy is due to temporal variations in the isotopic composition of the atmospheric CO₂.

The studies by T.S. James and colleagues had several purposes. The first was to produce graphs showing the present elevation of the marine limit of the post-glacial sediments versus its inferred age (in radiocarbon and calendar years) in three different parts of the Georgia Basin: southern Vancouver Island near Victoria (James et al., 2009 and references therein); around the central Strait of Georgia (Hutchinson et al. 2004a and references therein); and in the northern Strait of Georgia on Cortes, Quadra, and Vancouver islands (James et al. 2005). The marine limit was defined as the transition from saline marine water to brackish or fresh water as indicated by the contained biota. Most useful for this purpose were drill cores from small “isolation basins” that initially were accessible to sea water but became separated from it owing to crustal rebound. For these basins, the water depth of the sill separating them from the sea was critical. No such basins were investigated on Cortes Island -- all the dated shells originated in sea water.
In the northern Strait of Georgia (James et al., 2005, Figs. 6 and 7 and p. 122) sea level may have been maintained near 175 m elevation for few hundred years during ice-proximal sedimentation around 12 250 radiocarbon years BP (14 100 calendar years BP). Subsequently it fell rapidly from above 145 m to below 50 m between about 11 800 and 11 000 BP. The rate of sea-level fall then slowed substantially, reaching 15 or 20 m elevation by 10, 000 BP. Sea level is relatively unconstrained in the early and mid-Holocene, but probably did not drop below 8 m depth or rise above 20 m elevation. A shallow low-stand phase in the early Holocene is possible but, if so, sea level would have recovered in the mid or late Holocene. Sea level stood at, or slightly below, 1.5 m by 2000 BP. In the last 2000 BP it dropped to its present level.

The fall of the present elevation of the marine limit is due to the calving and melting of the ice, which caused a flexural rebound of the crust, controlled by viscous flow of the underlying asthenosphere. However, the glacial melting, together with thermal expansion of the sea water, caused an increase in its total volume and a corresponding world-wide wide (“eustatic”) rise in sea level, most accurately determined on Barbados. To obtain the value of the rebound, the authors subtracted this eustatic component from the sea level curve discussed. Because the thickness of the Cordilleran ice sheet decreased in a southwesterly direction the isostatic depression and subsequent rebound also decreased in that direction, and the calving and melting began earlier. (For a discussion of the geophysical implications, see Hutchinson et al., 2004a and James et al., 2005 and 2009a, b.)

The actual depth below sea level of the present coast lines of Cortes Island at a certain point in time is depicted in Figure 2-16. It is based on the sea level curve for the northern Strait of Georgia by James et al. (2005, Fig.; here shown as inset in inverted form). The curve intersects the -100 m level at about 11 500 radiocarbon years, and the 100 m contour of the available digital base map (scale 1:50,000; compiled by Silva Foundation) has been used to trace the outline of the “Cortes Archipelago” at that time.

**INDURATION, COMPOSITION, AND SOURCES OF SEDIMENTS**

Most sediments are loose with two exceptions. Silty strata exposed to surface water tend to be plastic or solid, owing to cementation by clay minerals. And sand and gravel lying in B-horizons of the podzol soil profile are locally indurated by limonite.

The orientation of inlets and channels in the vicinity of Cortes Island shows that glaciers flowed down the southwestern slope of the Coast Mountains and were deflected to the southeast in the Georgia Depression (Fig. 1 in Clague, 1994). The composition of the Pleistocene sediments is compatible with derivation chiefly from the southwestern slope of the Coast Plutonic Complex. Sands of different stratigraphic units (examined microscopically in smear slides and/or by whole-sediment X-ray diffraction) all consist mainly of quartz, plagioclase, and K-feldspar, with lesser biotite, hornblende, and magnetite of granitoid provenance. Stones in gravels and diamicts also consist mainly of granitoid rocks. Fairly common are also aphanitic or porphyritic rocks of intermediate to mafic aspect that represent dykes and/or volcanics. As pointed out in Part 1 of this report, dykes locally make up as much as 40 to 50 percent of the granitoid rock volume. The stones on the present land surface and tidal flats are similar but, in addition, comprise some sedimentary and metamorphic rocks, including a large boulder of marble.

Some clasts of volcanic-derived sandstone siltstone found on the present land surface – not only on Cortes but also on nearby Hill Island -- have yielded an Early Cretaceous fauna dominated by the pelecypod *Buchia* (Haggart, 1995, 2001; Gronau, 2002a, b) including diagnostic species of late Valanginian-Hauterivian age. A total of 17 occurrences were known by 2005, but their provenance is still problematic. According to Haggart (2001), shallow marine sediments with buchiid bivalves and less common belemnites occur in two extensive sub-parallel belts. The outer belt runs discontinuously from Baranof Island in southwestern Alaska through Haida Gwai (Queen Charlotte Islands) to the northern end of Vancouver Island and reappears in the San Juan Islands. A part of the inner belt is represented by those outcrops of the Lower Cretaceous Gambier Group located on the southeastern side of the Coast Mountains. On the other hand, fossils have not been recovered from outcrops of the same group on the southwestern slope of the Coast Mountains (cf. Journeay et al., 2001) although they, too, likely include strata of Valanginian-Hauterivian age. As a working hypothesis, Haggart (2005) proposed that the latter represent an arc.
that was flanked on both sides by the two belts of fossiliferous shallow marine sediments mentioned. If so, the fossils on Cortes and Hill islands must have come from the outer belt.

**HOLOCENE EROSION, DEPOSITION, AND SOIL DEVELOPMENT**

The post-glacial rebound, which continued, at a diminishing rate, far into the Holocene, caused additional erosion, as well sedimentation and soil development. Obviously, areas covered by the unconsolidated Pleistocene strata have been far more vulnerable to that erosion than the bedrock. In contrast to the predominantly vertical erosion during the Vashon Stade of the Fraser Glaciation, this phase has been characterized mainly by the rapid lateral retreat of the steep sea cliffs bordering the Pleistocene plateaus of Marina and southeastern Cortes islands. The derived sediments, deposited at the bottom of the cliffs, are reworked by storm-enhanced high tides, which leave coarse gravel in place (frontispiece) and remove fine fractions to subtidal depths. Elsewhere the sediments derived from Quaternary strata are deposited by creeks in lowlands and on small deltas.

Current bedrock erosion is most pronounced on steep cliffs and rocky shore lines, and the sediments derived from them are deposited on scree slopes and beaches or in the sea. However, most of the present topographic relief of the bedrock surface (cf. Fig. 2, cross-section Y’-Y”) was not created during the latest Pleistocene and Holocene but dates back to the Vashon Stade and earlier glaciations.

Most of the present soils were formed by biological and chemical processes in the upper one meter or so of the Pleistocene strata. Numerous organic processes must have played a role; most obvious from a geological viewpoint is the mixing of the sediments and the destruction of their stratification by the roots of trees and shrubs (Fig. 13a). Classified as podzols (Soil Classification Working Group, 1998), they are typical of forest soils in temperate humid climates, which have acid groundwaters -- a feature here enhanced by the scarcity of limestone. These waters tend to dissolve all unstable minerals of the E-horizon and wash out the surviving clay minerals. Precipitation of the dissolved material -- especially iron derived from biotite, chlorite, and hornblende, and redeposition of Al-rich clay minerals produces B-horizons that commonly are impermeable (“hardpan”) and colored in hues of yellow, brown, and red or are dark. My very limited observations suggest that well developed soil profiles may be rare on Cortes Island, probably as a result of root removal after logging (Fig. 15).

**FRESHWATER RESOURCES**

Hydrogeology is beyond the scope of this report, but the following generalized conclusions can be drawn:

1. All fresh water resources are of local meteoric origin. Although some water in the deep subsurface may have been derived from the Coast Mountains, it would be highly contaminated with undesirable elements (A. Kohut, pers. com., 2002).

2. In contrast to other, more densely settled areas, at present there is no shortage of freshwater on Cortes Island. While some of it is taken from lakes and creeks, most comes from groundwater. Available information about wells is provided by the Groundwater Database System of the British Columbia Ministry of the Environment. The records published for Cortes Island inform on the depth (below the well head), rate of flow, and rocks or sediments penetrated but are insufficient to decipher the subsurface stratigraphy. Unfortunately, the coverage is incomplete because many records have not been submitted to the Ministry.

3. In the area northeast of the Uganda line, most groundwater is obtained from local fracture systems in the bedrock, the depth and capacity of which are not predictable from surface observations. Lesser volumes are drawn from the Pleistocene cover, but some Pleistocene reservoirs are depleted during the summer.

4. In the area southwest of the Uganda line, groundwater is drawn exclusively from sands in the Pleistocene succession. In the vicinity of the Mansons Landing village, the Quadra Sand (unit 4) appears to be the principal aquifer. Farther southeast, however, this formation has been eroded and only units 1 to 3 are
exposed at the surface (Fig. 2-1, section D and locs. d, e, h, k, m, n). The only potential aquifer known in this part of the Pleistocene succession is unit 1, the Cortes Sand. The potential of the post-glacial sediments (locs. j and f) is unknown.

EARTHQUAKE HAZARDS

Most earthquakes are caused by movements on pre-existing fractures or faults, a lesser number by volcanic eruptions or nuclear explosions. The displacements produce two different types of seismic waves: body waves, which travel through the Earth’s interior, and surface waves. The commonly used Richter scale is a logarithmic scale based on certain amplitudes recorded in seismographs. It ranges up to 9, and energy levels separated by a full unit vary by a factor of 30. (A single earthquake of strength 6, for example, has the total energy of 30 earthquakes of strength 5).

Surface waves cause much more damage than direct fault displacements. The extent of the damage, however, depends not only on the strength of the earthquakes but also on their duration and the geological material affected. The effect is far greater in unconsolidated sediments, especially those that are fine grained, than in bedrock; and in the latter category it is stronger in sedimentary and low-grade metamorphic rocks than in gneisses and granitoid plutons. The strength and flexibility of human constructions play an analogous role. The number of human casualties, of course, depends on the population density. Tsunamis, landslides, and the liquefaction of water-saturated sediments are potentially disastrous indirect effects.

The most important and best understood faults are those separating tectonic plates. Two types of fault movements prevail: horizontal strike slip and underthrusting (subduction), commonly of oceanic under continental crust. Important for southwestern British Columbia is the Cascadia Subduction Zone along which the oceanic Juan de Fuca Plate and a southern part of the Explorer Plate are thrust beneath the North American Plate (Hyndman et al., 1996 and references therein; Clague and Bobrowski, 1999 and references therein). This subduction zone extends along trenches at the base of the continental slope from west of Cape Mendocino, California, to west of northern Vancouver Island and dips to the northeast, attaining a depth of about 100 km below the Cascade volcanics.

The Cascadia Subduction zone is connected with two major strike slip faults, the San Andreas in the southeast and the Cape Charlotte Fault in the northwest. The character of movement along such faults varies from nearly continuous creep with very weak seismicity to large displacements, accompanied by large earthquakes. The magnitude and frequency of the seismic events have an inverse logarithmic relation: the larger they are, the less common.

Subduction zones, in contrast, only have large displacements, which are separated by intervals of hundreds of years. The associated earthquakes have magnitudes greater than 8. Perpendicular to strike, they have a central segment of blockage, flanked on both sides by segments of continuous motion. The extent of these segments is controlled by the temperature and hence metamorphic state of the down-going slab of oceanic crust, which in turn is controlled by its age: the younger, the hotter. The central segment of the Cascadia Subduction Zone extends from 60 km to 120 km northeast of the trench, close to the southwestern coast of Vancouver Island.

Detailed studies have revealed that seven large earthquakes have occurred on this subduction zone during an interval of 3500 years, i.e. on average every 500 years. During the nonseismic intervals, steadily increasing pressure between the Juan de Fuca Plate and North America forms a bulge above the blocked segment. The pressure is caused by seafloor spreading, in opposite directions, from the Midatlantic and Juan de Fuca Ridges. When the stress exceeds the strength of the blockage, disruption occurs and the bulge collapses into a depression up to 2 m deep. A minor bulge, formed on the oceanic side of the depression, then initiates a tsunami. Although the most severe effects of these ruptures are confined to the continental shelf and western Vancouver Island, the shock waves are felt hundreds of kilometres away. The last giant earthquake on the Cascadia Subduction Zone has been dated to January 26, 1700 on the basis of a tsunami that reached Japan 10 hours later. While such tsunamis
have had widespread, devastating effects on the coasts of the Pacific Ocean, they have not affected the Strait of Georgia.

Earthquakes of smaller magnitude occur within the western part of the North American Plate. The largest known nearby event occurred on June, 23, 1946 and had a magnitude of 7.3. Its focus lay beneath the Forbidden Plateau near Courtenay at a depth of approximately 20 km (Wikipedia, 2012). Located in a forested area, its tectonic origin is poorly known. The most plausible explanation invokes strike slip on the Beaufort Range Fault, which parallels the axis of Vancouver Island. This earthquake caused two human casualties and widespread building damages, especially in the communities of Cumberland, Union Bay, Courtenay, and Comox with lesser damages reported from Port Alberni, Victoria, Vancouver, and Powell River. Topographic effects included landslides, subsidence at some localities around the Strait of Georgia, and a 3-m ground shift on Read Island. (Cortes Island is not mentioned in the report cited but must have been affected in some manner.)

Earthquake hazards on Cortes Island can be summarized as follows:

1. This island is far less endangered by seismic waves and tsunamis than western Vancouver Island, but, lying in an active mountain belt, more so than most of the continental interior.

2. So far faults have only been mapped in the Von Donop Extensional Domain, which extends from the vicinity of Von Donop Inlet to the east coast of the island -- an area containing few dwellings (see Part 1 of this report and Geological Map). Moreover, the faults mapped probably date back to the Cretaceous and there is no obvious evidence for recent reactivation.

3. Earthquakes would affect houses based on bedrock far less than those based on Quaternary sediments. And obviously, buildings on flat or gently inclined Quaternary ground are would be far safer than those on slopes or close to them. Steep slopes are present on the flanks of the plateau forming the southeastern peninsula of Cortes Island (vicinity of Beasley, Potlatch and Southpoint Roads), and also south of Hague Lake (part of Sutil Point Road) and north of the east end of Gorge Harbour (Whaletown Road).

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APPENDIX: VERBAL LOGS OF STRATIGRAPHIC SECTIONS

Section A

Location: steep cliffs on southern point of Marina Island. Base 6 m above upper beach limit, about 11 m above sea level. Underlying strata concealed.

Cortes Sand
Member B (4m+)
0-4 m
Sand, minor interlaminated silt; light grey and yellow to brown; horizontal lamination and minor ripple marks.

- conformable contact –

Marina Island Diamict (24 m)
Member A (7 ± 1.5 m)
4-11 (± 1.5) m
Stratified diamict: sparse, unsorted stones, pebble to boulder size, in sand and minor silt showing horizontal lamination or thin bedding with rare trough-crossbedding. Strata weather greenish grey and are slightly indurated. Stones are mainly granitoid rocks with lesser proportion of dark aphanitic rocks (andesite, basalt). Very steep slope, inaccessible in uppermost part.

- disconformable contact? -

Member B (17 ± 1.5 m)
11 (± 1.5) – 28 m
Diamict as below, but matrix is not stratified.

-disconformable contact-

**Cowichan Head Formation, upper member (0.5 m)**
(28-28.5 m)
Gravel; unsorted pebbles, cobbles and minor boulders in sandy matrix. Composition is similar to underlying diamict, but matrix is far less abundant. Lower few cm stained by limonite. Resistant, ledge-forming bed.

Top of section: extensive flats, overlying strata eroded.

**Section B**

Location: steep cliffs on west coast of central Marina Island. Base 5.5 m above upper beach limit, about 10.5 m above sea-level. Underlying strata concealed.

**Quadra Sand**
**Member A (24.5 m+)**
0-10 m (10 m)
Interbedded sand and silt; common ripple marks and some horizontal lamination (especially in lower 1-2 m); proportion of silt decreases upwards in the unit. Sand: very fine and fine grained, mainly light grey to yellowish grey with sprinkling of dark heavy minerals (biotite, hornblende, opaques). Silt: clayey (sticky) and sandy, pale olive.

10-24.5 m (14.5 m)
Sand, fine to coarse, commonly medium grained; light grey to yellowish grey (as before) with sprinkling of dark heavy minerals; abundant ripple marks.
19 m: trough-crossbeds; a typical trough is about 0.40 m deep, 1.5 m long; succeeded by climbing ripple marks.
20-23 m (altitude 30.5-33.5 m): horizontal lamination and ripple marks; three sets of yellowish orange weathering bands cut across the latter.

Top of section: steep slope covered with sand and minor gravel.

**Section C**

Location: steep slope on west side of northernmost Marina Island. Base of section about 4 m above upper beach limit, altitude about 9 m. Underlying strata concealed

**Quadra Sand**
**Member A (26 m +)**
0-14.0 m (14 m)
Thinly interbedded sand and silt. Sand: light grey with sprinkling of dark heavy minerals (biotite, hornblende, opaques); mainly very fine and fine grained, but up to medium grained. Silt: light olive grey, sticky, cohesive. Horizontal and undulating or crinkled lamination.

14.0 - 17.2 m (3.2 m)
Sand with lesser interbedded silt; some sand laminae are rich in heavy minerals; ripple marks common. Some soft-sediment deformation These strata are truncated laterally by a concave-up crossbed, about 2 m thick, perhaps 8 m long, suggestive of lateral accretion in meandering channel.

17.2- 26.0 m (8.8 m)
Sand, very fine grained, interbedded with lesser proportion of silt; climbing ripple marks common in sandy strata; 21.2-21.8 m, trough cross-bed, lateral extent about 4 m; silt-dominated beds, 1-30 cm thick, show horizontal or
undulating lamination; pale yellowish brown weathering, horizontal bands cut across ripple marks @ 21.3, 23.1, 23.2, 23.8 m (alt. 30.3-32.8 m)

Top of section: upper limit of accessible beds but not of exposure, which terminates perhaps 3 m higher. Overlying strata are similar to those described.

Section D

Location: steep slope on southeastern coast of Cortes Island, about 1.8 km north-northeast of Sutil Point. Base of section 0.5 m above upper beach limit, altitude about 5.5 m

**Cortes Sand** (20.5 m +)

**Unit A** (4.5 m +)
0-2.0 m (2.0 m)
Sand, yellowish grey to medium light grey with interlaminated, darker silt; concave cross-lamination predominant; sets of cross-laminae, 7-17 cm thick, dip in different directions; horizontal lamination, flaser structure, and contorted lamination are less common.

2-4.5 m (2.5 m)
Sand, fine to coarse, commonly medium grained, pebbly, except in upper 30 cm; trough cross-lamination; troughs to about 30 cm deep, 4 m long; minor horizontal lamination; unit weathers mainly yellowish grey with conspicuous light brown layer, bounded by sharp contacts, at 2.0-2.5 m.

**Unit B** (16.0 m)
4.5-5.5 (1.0 m)
Sand, mainly fine and medium grained, yellowish grey, horizontal lamination

5.5-15.5 m (10 m)
Covered

15.5-20.5 m (5 m)
Sand, medium grey to greenish grey; lamination mainly horizontal with rare low-angle trough cross-lamination; a typical trough is about 10 cm deep, 3 m long

- conformable contact –

**Marina Island Diamict**

**Member A** (5.5 m)
20.5-26.0 m
Stratified diamict: sparse, unsorted stones, pebble to boulder size (observed max. diameter 1 m) in matrix of sand and minor silt, showing mainly horizontal lamination or thin bedding with rare, isolated trough-crossbeds (a typical trough is 10 cm deep, 50 cm long). Strata weather greenish grey and are slightly indurated. Stones are mainly of granitoid rocks with lesser proportion of andesite or basalt. In the lower part of the section, an inclined bed of massive diamict, estimated to be about 2 m thick, cuts across the horizontal bedding.

- abrupt, disconformable contact-

**Cowichan Head Formation, upper member, or younger unit** (0.3 m)
26-26.3 m
Gravel, pebble to cobble grade, sandy matrix less abundant than in Marina Island Diamict

Top of section: 10 cm of soil, dark, rich in organic material. Overlying strata eroded.
Section E

Location: steep, west-facing slope, 1 km southwest of Mansons Landing dock. Base of section is at about 34 m altitude, underlying strata are concealed.

**Quadra Sand (20 m+)**

**Member A (8.5 m +)**

0-8.5 m

Mainly sand, very fine to very coarse grained, with scattered pebbles (predominantly granitoid); horizontal lamination and some concave cross-lamination; sets of cross-laminae 5-20 cm thick; beds are pale yellowish grey (due to quartz and feldspar); yellowish grey (due to limonite derived from pyrite); or medium dark grey (due to concentrations of heavy minerals)

**Member B (11.5 m)**

8.5-9.5 m (1.0 m)

Interbedded pebble gravel and sand, as follows:

- 35 cm: lens of pebble gravel, 6 m (or more) in length; coarse pebbles (to 5 cm in diameter) in lower 15 cm and upper 15 cm, in between fine pebbles to 2 cm, rusty weathering
- 25 cm: sand, pebbly, fine to very coarse grained, cross-bedded
- 40 cm: lens of pebble conglomerate; horizontal bedding and cross-bedding; pebbles are granitoid rocks and basalt or andesite

9.5-15.5 m (6 m)

Mainly sand, minor gravelly sand or sandy pebble gravel; horizontal lamination and cross-lamination as in Member A (0-8.5 m).

15.5-16.4 m (0.9 m)

Gravel and sand, as follows:

- 70 cm: horizontal bed of pebble and cobbles gravel, massive; stones up to 15 cm in diameter, unsorted, (approximately equal proportions of granitic rocks and basalt or andesite) unsorted; sandy matrix; includes lens of concave crossbed, composed of: 20 cm pebbly sand and 25 cm: pebble gravel (pebbles to 5 cm)
- 10 cm: lens of sand, muddy, horizontally laminated
- 10 cm: pebble gravel, sandy

16.4-20.0 m (3.6 m)

Mainly sand, very fine to very coarse grained; minor interstratified pebbly sand, silty sand, and mud; predominantly horizontal lamination with some cross-lamination of mm-cm scale; mud, medium to dark grey, weakly indurated; beds, 1.5-2 cm thick, are impermeable to groundwater which seeps out above them.

- conformable contact –

**Mansons Landing Diamict (11 m +)**

20.0-31.0 +

Nearly vertical cliff; only lower 3 m and upper 1 m are accessible.

Unsorted, scattered pebbles, cobbles, and boulders in matrix of horizontally stratified sand, pebbly sand and mud; predominantly horizontal lamination with some ripple marks in lower 3 m; extensive soft-sediment deformation higher in the section.
Top of section:
About 1 m (or more) of sand, gravelly sand, gravel; yellow brown and reddish weathering; variably cemented and
indurated; overlain by about 10 cm of dark grey silt or sand. These strata clearly represent a Holocene soil profile
(Podzol) but it is uncertain whether the profile is developed in the Marina Island Diamict or younger strata
(Spilsbury beds?).

Section F
Location: Hernando Island; steep coastal bluff, about 0.6 km southeast of Spilsbury Point. Base of section: upper
beach limit, altitude about 5 m.

Quadra Sand (27.5 m +)
Member A (17 m +)
0-2.75 m (2.75 m)
Mainly silt, clayey and sandy, mainly pale olive, also yellowish grey; massive, or with faint horizontal lamination or
ripple marks; less sand, very fine to fine grained, showing ripple marks and some convolute lamination.

0-0.55 m
Silt, very fine sandy, muddy, sticky, nearly consolidated; lower and middle parts seem to be massive or
only vaguely laminated, upper 8 cm shows horizontal lamination.

0.55-0.97 m
Sand, fine to predominantly very fine grained; ripple marks throughout (not of climbing type), 2-10 cm
from crest to crest, depth about 2 cm and less.

0.97—1.05 m
Sand and silt interlaminated; yellow brown; discontinuous ripple marks.
1.05-1.36 m
Silt, sandy, clayey, greenish and yellow brown; horizontal lamination in upper 8 m, otherwise massive.

1.36-1.62 m
Sand, silty, medium grey.

1.62- 1.71 m
Silt, greenish as in lowermost bed.

1.71- 1.80 m
Sand, very fine and grained; convolute lamination.

1.80-2.12 m
Clayey silt as before.

2.12-2.21 m
Sand, very fine to fine grained, silt as before; convolute lamination.

2.21-2.75 m
Silt as before.

2.75-3.25 m (0.5 m)
Sand, very fine and fine grained with interlaminated silt, coarse; two troughs (side by side), 2 m from crest to crest, about 40 cm deep; passing laterally into ripple marks with minor convolute lamination; ripple marks also in the triangle between the two troughs.

3.25-4.3 m (1.05 m)
Mainly silt, minor sand, as in 0-2.75 m.

4.3-10 m (5.7 m)
Sand, very fine to coarse grained; horizontal lamination, ripple marks, cross-lamination, mainly low-angle, concave; troughs to 3 m long, generally 10-15 cm deep.

10-17 m (7 m)
Sand, fine to very coarse, locally with small amounts of fine pebbles; high-angle trough-cross-lamination common; cross-laminated units commonly 20 cm thick; convolute lamination at 15 m, slump structures (with some fine pebbles within it) approximately, from 13-15 m; direction of slumping NE (50º az.).

Member B (10.5 m)
17-27.5 m
Sand, minor pebbly sand, sandy gravel; trough cross-bedding, some horizontal lamination.

- conformable contact –

**Mansons Landing Diamict** (2.5 m ± 0.5 m)
27.5-30 ± 0.5 m
Sand, minor pebbly sand and pebble gravel as in Member B with lenses (a few m long or less, a few decimetres thick) of unsorted coarser gravel, pebble to cobble or small boulder size; also contains an isolated large boulder (est. 1 m diameter) in uppermost part.

- disconformable contact –

**Spilsbury Beds** (estimated at 4-5 m)
30-35 ± m
(Inaccessible, seen from below and also known from grab sample). Sand, mainly very fine to fine grained, but up to medium grained. Planar lamination, inclined at a low angle in a westerly direction. Uppermost strata disturbed by roots.

Top of section: soil (in accessible).
Figure 2-1. Setting of Pleistocene sediments, stratigraphic sections, and other localities.
Figure 2-2. Structural cross-sections. (Sea level is 5 m below upper beach limit.)
Figure 2.3. Stratigraphic chart. (Radiocarbon years only for determination <50 Ka. Vertical axis not to scale.)
Size grades
1: Sand and silt
2: Mainly sand ± silt
3: Sand
4: Pebble, silt, sand
5: Pebble gravel, sand
6: Pebble to boulder gravel

Sediments
- Mainly sand
- Sand, silt
- Silt (organic-rich in 3B)

Diatom, massive; pebbles to boulders in sand-silt matrix

As above, mainly flat-laminated, minor trough-crossbedding

Gravel; cobbles, boulders in sandy matrix

Sand, pebbly sand, pebble conglomerate

Sand, silt, pebbles

Mainly horizontal, minor undulating lamination

Ripple marks

Trough-crossbedding, medium scale

Trough-crossbedding, large scale (accretionary)

Disturbed stratification

Disconformity (observed, inferred)

Figure 2-4a. Stratigraphic sections A and D
Figure 2-4b. Stratigraphic sections B, C, E, and F.
b) Cortes Sand, upper part (unit 1b) at locality h of Fig. 1. Note flat lamination and minor low-angle cross-lamination.

Figure 2-5. Exposures of Cortes Sand.
Figure 2-6. Cortes Sand and Marina Island Diamict, member A, at section D.
Figure 2-7. Marina Island Diamict, Member A at section D. (About 5 m of strata of unit 2A are shown.)
b) Marina Island Diamict, Member B (2B: massive, scattered stones) overlain by Cowichan Head Formation, upper member (3: clast-supported gravel) at locality a, Marina Island. Contact is marked by limonite (red arrows). (Staff is 1.5 m long.)

Figure 2-8. Marina Island Diamict and Cowichan Head Formation.
b) Climbing ripple marks at section C, Marina Island. (Photograph by C.W. Gronau.)

a) Thick interval with predominant lay horizontal lamination and superimposed minor structures at section E, Cortes Island. (Staff is 1 m long.)

Figure 2-9. Horizontal lamination and small-scale structures in member A of Quadra Sand.
Figure 2-10. Crossbedding in member A of Quadra Sand.
a) Member B of Quadra Sand (4B) and Mansons Landing Diamict (5).

b) Gravel and pebbly sand in member B of Quadra Sand.

c) Close-up of dropstone in distorted strata of Mansons Landing Diamict.

Figure 2-11. Quadra Sand, Member B, and Mansons Landing Diamict at section E.
Figure 2-12. Quadra Sand, member B (4B), Mansons Landing Diamict (5) and Spilsbury beds (6) at section F.
c) Postglacial sediments (unit 8B) at locality j, Cortes Island. Planar foresets of laminated sand, underlain and overlain by gravel. The upper gravel contains shell fragments (arrows).

Detailed view of exposures shown in (a), the lower stratum is a poorly sorted, matrix-supported gravel. It is underlain and overlain by laminated sand and silt with scattered pebbles. Note small "thrust faults", indicating sliding on a submarine slope. (Staff is 1 m long).

Figure 2-13. Smelt Bay beds, lag of Vashon diamict (unit 7*), and postglacial sediments (unit 8B).
3: Soil, red-brown, rich in stones.
2: Sand, mainly coarse, pebble-rich, regular parallel lamination (unit BB).
1: Diamict: Sand, mostly fine-grained with minor silt; lamination disturbed; scattered stones, here pebbles elsewhere up to coarse cobble grade (unit BA). (Staff is 1 m long.)

**Figure 2-14.** Exposure of postglacial sediments on Whaletown Road, northwest of east end of Gorge Harbour.

3: Boulders, cobbles, and pebbles, probably lag of Vashon diamict or Mansons Landing Diamict.
2a: A and O horizons (dark, rich in plant debris).
1: Pleistocene sediments, showing horizontal layering.

**Figure 2-15.** Incomplete soil profile at locality q. (Staff is 2.5 m long.)
Figure 2-16. “Cortes Archipelago” about 11,500 radiocarbon years ago. Inset adapted (inverted) from James et al. 2006, Fig. 6.