The basal unconformity of the Nanaimo Group, southwestern British Columbia: a Late Cretaceous storm-swept rocky shoreline[1]

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Abstract: The Turonian to Santonian Comox Formation forms the basal unit of the Nanaimo Group. In the southern Gulf Islands of British Columbia, the Comox Formation nonconformably overlies Devonian metavolcanic and Jurassic intrusive rocks and is interpreted to reflect a rocky foreshore reworked by waves and ultimately drowned during transgression. The nonconformity displays a relief of metres to tens of metres. Basal deposits vary in thickness, as does the facies character along the several kilometres of paleoshoreline studied. In the study area, three distinct but related environments are expressed, typical of a complex rocky shoreline with headlands and protected coves. Crudely stratified conglomerates represent gravel-dominated fans characterized by debris-flow processes, building out from local coastal cliffs and gullies directly onto the rocky shoreline. Fine-grained basal units represent shoreline environments protected from higher energy shoreline processes, presumably in small embayments. Sandstone facies associations reflect storm-dominated shoreface environments. The unusual thickness and coarseness of these shoreface intervals suggest a combination of increasing accommodation space, proximal and high sediment supply, and high frequency and energy of storm activity. This, in turn, suggests that the majority of the shoreline was exposed to the full effects of large, open-ocean storms. This interpretation differs from most previous models for the lower Nanaimo Group, which suggest that deposition occurred in more sheltered strait or bay environments.

Résumé : La Formation de Comox (Turonien à Santorien) comprend l'unité de base du Groupe de Nanaimo. Dans les îles du sud du golfe de la Colombie-Britannique, la Formation de Comox repose en discordance sur des roches métavolcaniques dévoniennes et sur des roches intrusives du Jurassique; cette formation est interprétée comme le reflet d'un estran rocailleux retravaillé par les vagues et finalement submergé au cours d'une transgression. La discordance présente un relief de mètres à des dizaines de mètres. Les dépôts à la base et le faciès ont une épaisseur variable le long des kilomètres de paléorivage étudié. Dans la région à l'étude, trois environnements distincts mais reliés sont définis; ils sont typiques d'un rivage rocailleux complexe avec des caps et des anses protégées. Des conglomérats à stratifications mal définies représentent des éventails de gravier caractérisés par des écoulements de débris; ils sont construits à partir de falaises côtières et de ravins, directement sur le rivage rocailleux. Les unités basales à grain fin représentent des environnements de rivage protégés contre des processus de rivage à énergie plus élevée, probablement dans de petites baies. Les faciès associés au grès reflètent des environnements d'avant-plage dominés par des tempêtes. L'épaisseur et la grosseur inhabituelles des sédiments de ces intervalles d'avant-plage suggèrent plus d'espace, un approvisionnement proximal et abondant de sédiments et une grande fréquence de tempêtes à énergie élevée. En retour, cela signifie que la plus grande partie du rivage était exposée au plein effet des grandes tempêtes en pleine mer. Cette interprétation diffère de la plupart des modèles antérieurs pour le Groupe de Nanaimo inférieur; selon ces modèles, la déposition aurait eu lieu dans des environnements de baies ou de détroits plus protégés.

[Traduit par la Rédaction]

Introduction

Geologic setting

The Nanaimo Group is a Turonian- to Maastrichtian-aged package of marine and nonmarine siliciclastic strata in the southwestern Canadian Cordillera. The modern remains of the Cretaceous Nanaimo Basin are exposed over an area measuring more than 200 km × 90 km, with a thickness of up to 4 km. The strata are well exposed on several islands in the Strait of Georgia and on southeastern parts of Vancouver Island, where they onlap Wrangellia Terrane, and on the San Juan Islands of Washington State, where they are in fault

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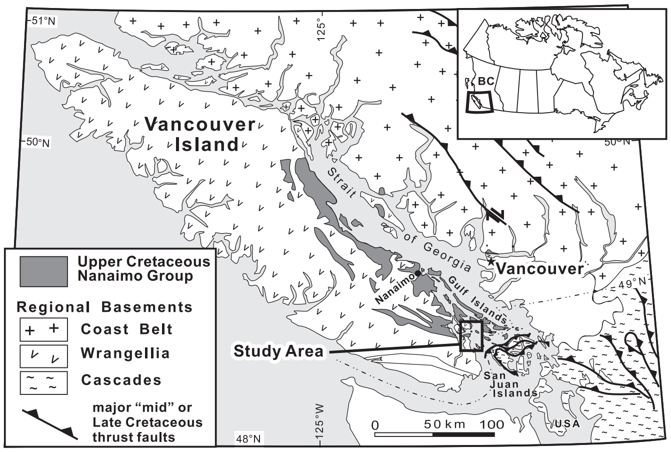
Fig. 1. Regional setting of the Upper Cretaceous Nanaimo Group. Detail of study area provided in Fig. 4.



contact with Paleozoic rocks of the San Juan terranes. Nanaimo Group strata are also present in the subsurface and limited surface exposure in the Greater Vancouver area of the British Columbia mainland, where they onlap the Coast Mountain Plutonic Complex (Fig. 1). The original extent of the basin has been significantly reduced by a combination of Cenozoic compression and unroofing of more than 2 km (England and Calon 1991; England et al. 1997).

At Late Cretaceous initiation of Nanaimo Group deposition, Wrangellia Terrane had accreted to the west coast of North America and was bordered to the west by the accretionary complex related to subduction of the Kula or Farallon ocean plate (Yorath 1991). The centre of coeval plutonism is located approximately 150 km to the east of the present location of the Nanaimo Group and at least twice that distance from the western edge of the Wrangellia Terrane, which had become the leading edge of the North American plate (Friedman et al. 1995). This places the centre of deposition within a very broad "ridged" or "shelved" arc-trench gap (cf. Dickinson and Seeley 1979). The basin itself, however, is best interpreted as a foreland basin, as thrust faulting in the adjacent arc massif is at least partially coeval with that in adjacent terranes to the south (Brandon et al. 1988; Umhoefer and Miller 1996; Brown et al. 2005) and directly related to both basin formation and sediment supply (Mustard 1994). Furthermore, the distance from the coeval arc and lack of active arc-related sediments in the basin suggest that the traditional fore-arc basin model is a poor fit for the majority of Nanaimo Group sedimentation.

Most of the Nanaimo Group has been structurally deformed by several Cenozoic tectonic events and generally dips gently to the northeast. Broad, predominantly northwest–southeast-trending folds and associated faults control the topography of the Canadian Gulf Islands within the Strait of Georgia and are associated with the Cowichan fold and thrust belt (CFTB) (England and Calon 1991). This Eocene-aged, southwest-verging thrust system is interpreted to be related to the collision and underplating of the Pacific Rim and Crescent terranes to the west side of Wrangellia (England and Calon 1991). More recent work has identified a younger northeast-verging fold and thrust system that partly crosscuts the CFTB, suggesting a later change from compressional to transtensional tectonics in the late Paleogene to early Neogene. This is expressed as the Gulf Islands Thrust System (GITS) in the outer Gulf Islands (Journeay and Morrison 1999). Further Pliocene-to-modern uplift of the Coast Mountains and eastward tilting of Wrangellia, associated with continued subduction of the Juan de Fuca Plate, represent a third cycle of deformation.

Stratigraphy

Strata of the Nanaimo Group were first described by Dawson (1890), who applied the term "Nanaimo Series" to the Cretaceous sedimentary rocks of eastern Vancouver Island. Extensive mapping and local study have been performed since coal mining of terrestrial units began in the mid-1800s. Initial work identified two separate depocentres, with the first detailed stratigraphic sections being produced of the northern "Comox" basin by Richardson (1872), and the first formal descriptions of the southern "Nanaimo" successions by Clapp (1914) and Clapp and Cooke (1917). Local and regional lithostratigraphic correlations were attempted by various workers, and biochronological zones from the Santonian to the Maastrichtian were established using plant fossils, mollusks, and foraminifera (summarized in Mustard 1994). Muller and Jeletzky (1970) established a unified lithostratigraphic succession for what they recognized as a single laterally continuous basin of deposition. This lithostratigraphy was refined into the commonly accepted 11 formations by Ward (1978) (see Fig. 2). This stratigraphy represents biostratigraphically defined zones from the Turonian to the Maastrichtian stages of the Upper Cretaceous Period while also recognizing the laterally diachronous nature of some formations.

The lithology of the Nanaimo Group is entirely siliciclastic, ranging from cobble conglomerate to mudstone, but is dominated by sandstone. Depositional environments range from alluvial to deep marine, with nearshore marine and submarine fan successions dominating the upper units and the lower units characterized by coastal to nonmarine settings. Economic coal measures within these basal units have been mined since the mid-1800s, and consequently the nonmarine parts of these basal units have been more thoroughly studied (see Mustard 1994, for a detailed review of lithostratigraphy and depositional environments).

Comox Formation

The lowest unit in the Nanaimo Group stratigraphy is the Comox Formation. This basal conglomerate and sandstone unit unconformably overlies Paleozoic to Jurassic metavolcanic or intrusive rocks of Wrangellia Terrane, or intrusive rocks of the western Coast Belt. The unit is diachronous across the basin, with ages ranging from the Turonian to the lower Campanian, based on abundant Trigoniid and Inoceramid bivalves, gastropods, and ammonites. In early studies, the Comox Formation was considered in general to be Santonian in age (e.g., Muller and Jeletzky 1970). More recently the diachronous nature of this basal unit has been recognized, with newly described fossil occurrences suggesting that several basinal successions we include as Comox Formation are as old as Turonian to Coniacian, both in the study area (Haggart 1991, 1994) and in regions to the northwest of Comox (Haggart et al. 2003). It has recently been proposed

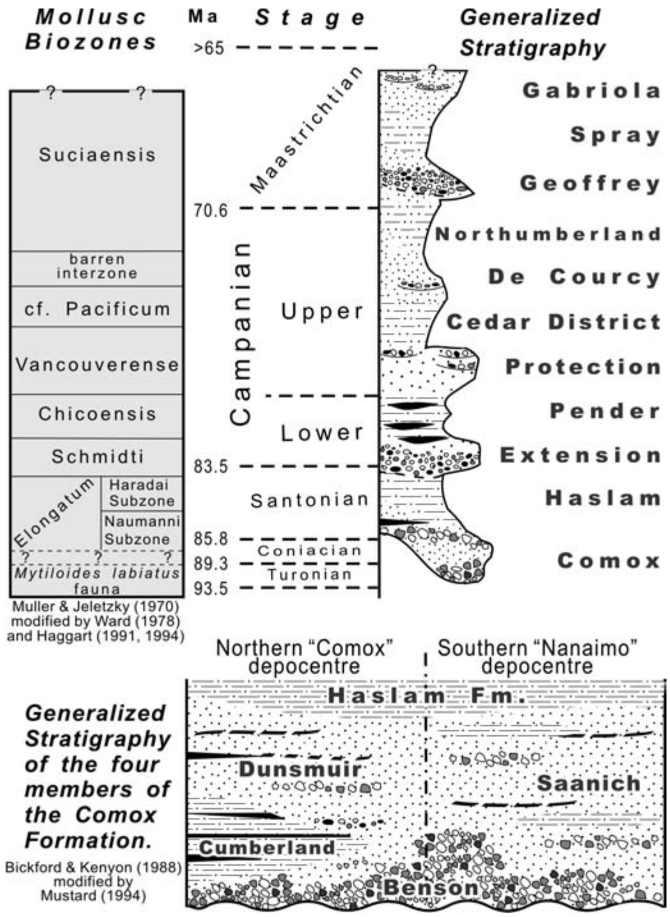


Fig. 2. (*a*) Molluscan biostratigraphy (after Muller and Jeletzky 1970 and modified by Ward 1978 and Haggart 1991, 1994) and (*b*) generalized lithostratigraphy of the Nanaimo Group (modified from Mustard 1994). (*c*) Generalized representative stratigraphy of the four members of the Comox Formation (after Bickford and Kenyon 1988 and modified by Mustard 1994).

that Turonian strata in this study area should be considered a lithologically distinct unit named the Sidney Island Formation (Haggart et al. 2005). We disagree with this suggestion (for reasons discussed in the Paleogeography section) and continue the established use of the term Comox Formation for the basal unit of the Nanaimo Group throughout the study area. The upper Comox Formation in some places contains fossils as young as early Campanian, although in most places it appears to be Santonian (Haggart 1991; Mustard 1994; Mustard et al. 2003).

The Comox Formation ranges in total thickness from a few metres to several hundreds of metres. A thickness of up to 650 m has been reported by some workers, although the thickest Comox Formation directly measured, and not fault-repeated, is 350 m (P.S. Mustard, unpublished data, 1991). In most places this formation is a few tens to hundreds of metres thick (Mustard 1994). It has been divided into four lithostratigraphic members. A basal conglomerate unit termed the Benson Member occurs basin wide, although it ranges in thickness from a few centimetres to over 300 m on Saltspring Island. The Saanich Member is a coarse- to medium-grained sandstone unit, with minor conglomerate, mudstone, and coal beds. It ranges in thickness from 50 to reportedly 500 m, although the latter may include overlying Haslam Formation strata. This member gradationally overlies the Benson Member where present and in turn grades into the overlying marine mudstone of the Haslam Formation. The Saanich Member contains both terrestrial plant fossils and marine fossils. It is laterally contiguous with the two remaining members of the Comox Formation, the Dunsmuir and the Cumberland, which are terrestrial to marginal marine coal-bearing sandstone and siltstone units, respectively. The Dunsmuir and Cumberland members are recognized only in the northern occurrences of the Nanaimo Group (Fig. 2).

Depositional environments of the Comox Formation range from alluvial fan and terrestrial, commonly reflected by unsorted basal conglomerates and significant coal measures, to shallow marine (reviewed in Mustard 1994). This study outlines the abundant physical sedimentologic, ichnologic, and body fossil evidence of a coastal marine depositional environment for southern sections of the Comox Formation.

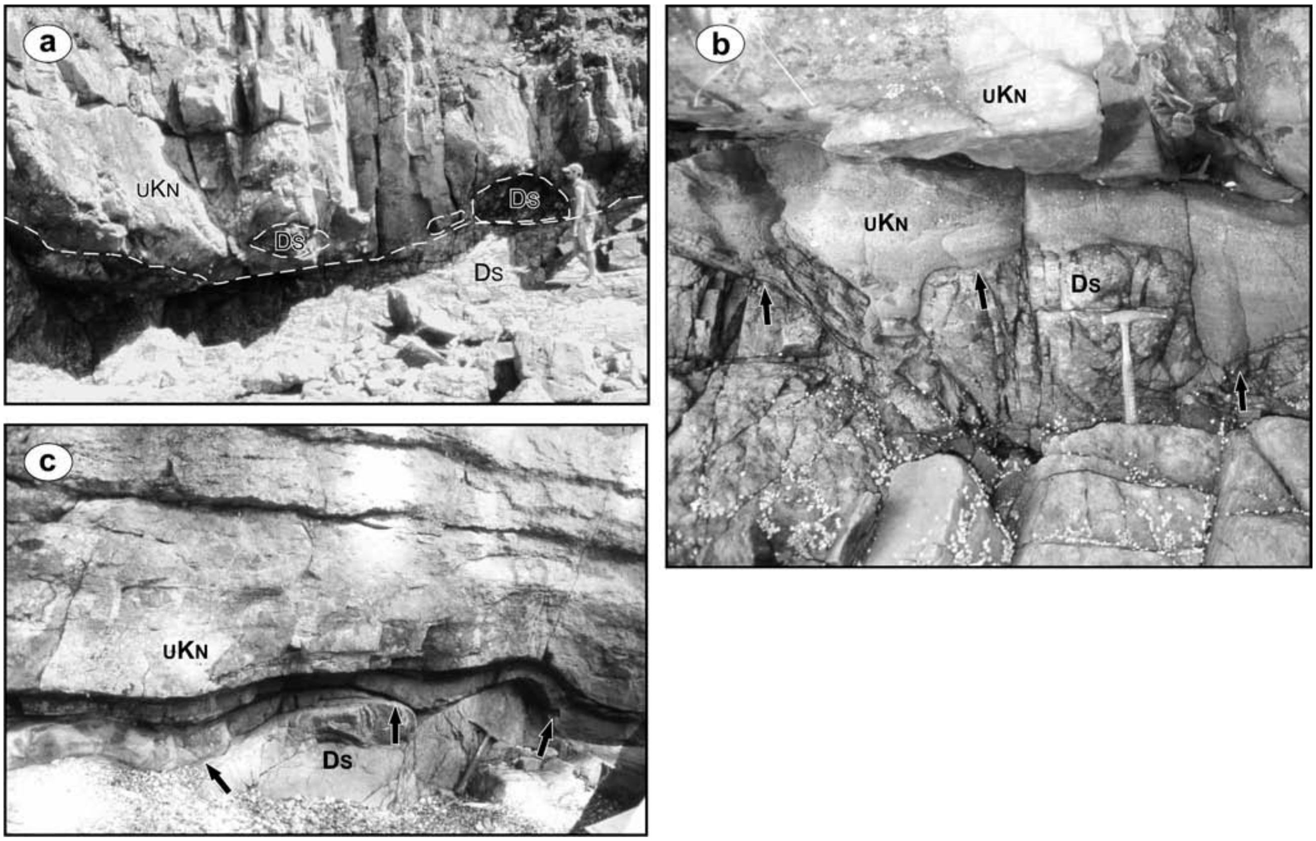
Basal unconformity

The basal unconformity is sharp, erosive, and undulatory over tens of metres (Fig. 3). The actual paleorelief of the shoreline, however, probably exceeds that of the visible outcrop by at least an order of magnitude across the basin. Broad, east–west-trending paleovalleys account, at least in part, for the varying thickness of the basal Benson Member, with relief in the hundreds of metres suggested in some places (Atchinson 1968; Kenyon et al. 1992; Mustard 1994; Read 1994). Identification of these valleys is complicated by Tertiary deformation of the basin, just as inferring major fault structures between islands in the study area is complicated by the unpredictability of this irregular stratigraphic datum.

There is a great amount of variation in the composition and nature of the immediately supra-unconformity material across the entire extent of the Nanaimo Group. This variability has been described by many previous workers, though rarely in detail (see especially, Atchinson 1968; Mustard and Rouse 1991; Kenyon et al. 1992; Mustard 1994; Read 1994). In some locations a basal breccia composed entirely of local basement materials is present, although rarely more than a few metres thick. In many locations, there is a juxtaposition of "fresh" unaltered clasts with highly weathered clasts. This suggests in situ weathering and some level of regolith development. The boulder breccia consistently grades into and passes laterally into boulder and pebble conglomerates and, in turn over a few tens of metres, into pebbly sandstone. Rarely, this basal conglomerate is up to 300 m thick. In some localities, the basal breccia is absent, and the unconformity is smooth and displays little weathering, although it is commonly intensely fractured. At these localities, the unconformity is overlain by moderately sorted to well-sorted sandstones (Fig. 3*c*).

Trypanites-type hardground burrows have not been identified in the underlying units, and clasts lack evidence of limpet, barnacle, or bivalve attachment. In many areas, however, the basal conglomerates and overlying pebbly sandstones contain broken shell material and, more rarely, complete fossils. Shell material commonly includes Oysteria or other

Fig. 3. Typical expressions of the basal unconformity of the Comox Formation. (*a*) Several metres of relief along the unconformity on Russell Island. Note large brecciated clasts of basement volcanics (Ds) entrained within Comox Formation pebbly sandstones (uKn). Unconformity marked with broken line. Person for scale. (*b*) Detail of unconformity near the north end of Moresby Island, with brecciated basement overlain by undulatory parallel laminated coarse- to medium-grained sandstones. Arrows mark unconformity. Hammer is 35 cm long. (*c*) Smooth unconformity on the north end of Moresby Island where basal breccia is absent. Arrows mark undulating unconformity surface. Hammer (right) is 35 cm long.



thick-walled shell forms, with lesser thin-shelled bivalve, gastropod, and ammonite types. Trace fossils common to shoreface and other shallow marine environments are also common. These areas occur throughout the outcrop extent of the Nanaimo Group, even in areas where most of the Comox Formation appears to be nonmarine. This suggests a coastal paleogeography during the deposition of the Comox Formation and, therefore, the first stages of Nanaimo Basin deposition. Exceptions to this occur where the basal Comox Formation appears to be dominated by nonmarine fluvial and alluvial fan conglomerate, sandstone, and coal. Even in these areas, however, the nonmarine components grade upward and laterally into shoreface successions, suggesting that these areas also represent coastal deposits of a rugged coastline (reviewed in Mustard 1994).

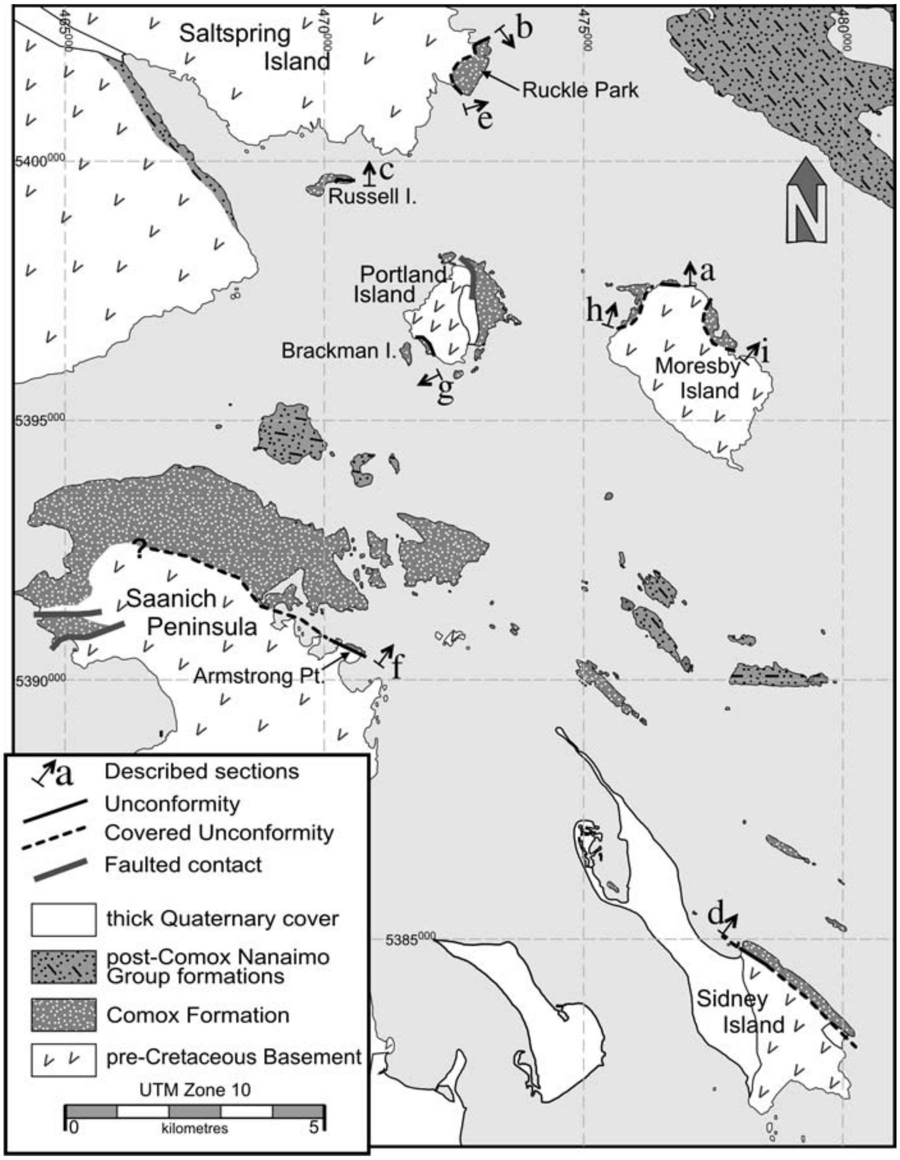
Study location

This project addresses a part of the Nanaimo Basin that is largely understudied by previous workers (Fig. 4). The collection of small islands adjacent to Saanich Peninsula is home to the southernmost exposures and oldest sediments in the Nanaimo Group (Haggart 1994). These islands are geographically adjacent to the San Juan Islands, which are a possible source area for basal Nanaimo Group sediments, as thrusting on the San Juan Islands has been inferred to be at least in part coeval with Comox Formation deposition (Brandon et al. 1988). Major Eocene deformation events that affect the entire Nanaimo succession crosscut the study area, and several major faults are “inferred” to pass through the area, although the islands are almost completely bereft of physical evidence of such faults.

The basal unconformity is well exposed at six locations on several of the islands in the study area (Fig. 4). There are two major sub-unconformity lithologic units. The first is a green, phyllitic, volcaniclastic, and volcanic unit, which is very well bedded and interpreted to be part of the Devonian Sicker Group of the Wrangellia Terrane (Muller 1980). The second unit is a distinctly salt-and-pepper, medium-grained granodiorite, which locally crosscuts the Sicker Group volcanics, interpreted to represent the Early Jurassic Island Intrusive Suite (Muller 1980).

In the study area, the basal unconformity represents erosion at or near the rocky coastline of the Late Cretaceous proto-Pacific Ocean. The Comox Formation overlying the unconformity comprises at least three distinct but laterally contiguous stratigraphic successions, with the units biostratigraphically constrained by their well-defined molluscan assemblages (Haggart 1994). The environments of deposition are herein defined by combining the physical sedimentology

Fig. 4. Detailed map of the study area, with generalized geology and locations of stratigraphic sections.



and paleontology (including ichnology). There are three types of coastline represented by outcrops of the unconformity, forming examples from more than 20 km of paleocoastline. The lateral relationships between these successions represent the diversity of depositional environments that may be preserved along even a relatively short stretch of a rocky shoreline. Analysis of these three coast types provides a clearer picture of the paleoenvironmental conditions along the leading edge of the Canadian Cordillera during the Late Cretaceous.

Facies analysis

A total of nine distinct lithofacies are identified in the study area (Table 1). Lithofacies are delineated by lithology, bedding types and scale, and the presence of body and trace fossils. Where appropriate, the degree of bioturbation is characterized by the bioturbation index (BI) according to the scale originally developed by Reineck (1963) and modified by Taylor and Goldring (1993) and Bann et al. (2004). The nine facies are grouped into three facies associations (FA) based on field descriptions and nine measured sections (Figs. 5, 7, 9). The facies associations are described in the following sections, followed by paleoenvironmental interpretations, characterizing a range of depositional environments along the Late Cretaceous rocky shoreline of a proto-Pacific ocean.

Facies association 1: storm-dominated rocky shoreline

This is the most typical facies association of the Comox Formation in the study area, and throughout the Nanaimo Group where the basal unit includes a marine component. Within the study area, this association is well exposed on the north shore of Moresby Island (location a), the north side of Ruckle Park on Saltspring Island (location b), Russell Island (location c), and Sidney Island (location d) (see Fig. 4). Measured sections in these four localities (Fig. 5) are similar in vertical succession but range markedly in the thickness of

Table 1. Facies descriptions.

	1	2	3	4	5	6	7	7b	8
Facies	Silty sandstone	Medium-grained sandstone	Basal conglomerate	Pebbly sandstone	Medium- to coarse-grained sandstone	Sandstone-mudstone	Poorly sorted conglomerate	Poorly sorted pebbly sandstone	Coarse-grained sandstone
Lithology	Medium- to fine-grained silty sandstone, locally muddy	Moderately sorted medium-grained sandstone, dispersed pebbles and granules, mud rip-up clasts, carbonaceous detritus, concretions, grading upward into silty mudstone	Conglomerate, pebble to boulder, mostly well rounded, rare angular to subrounded clasts, clast supported, pebbly coarse sandstone matrix, lesser pebbly medium- to coarse-grained sandstone	Interstratified pebble conglomerate, pebbly sandstone, and coarse-grained sandstone, dominantly matrix-supported, well-rounded clasts, moderately sorted coarse sandstone matrix	Upper medium- to lower coarse-grained sandstone, granule and less common pebble lags, very rare cobbles, carbonaceous muddy partings	Silty, dark coloured and carbonaceous mudstone intercalated with fine- to medium-grained sandstone	Pebble to cobble conglomerate, rarely boulder size, poorly sorted, angular to well rounded, matrix unsorted muddy sandstone with abundant pebbles, matching clast lithology	Poorly to moderately sorted pebbly, muddy sandstone, ranging from fine to coarse grained, with abundant silt and mud, locally carbonaceous	Well sorted coarse-grained sandstone, few dispersed pebbles or thin pebble lags, rare thin fine-grained sandstone to silt drapes
Bedding	Parallel planar laminated	Thin-bedded, low-angle undulatory parallel lamination, planar parallel lamination	Thick-bedded, grading upwards from coarser conglomerates to medium- to coarse-grained pebbly sandstones	Medium-bedded, some thick-bedded, horizontal planar stratification, low-angle planar stratification, local low-angle undulatory parallel stratification, sharp erosive bases, commonly swale-shaped	Medium- to thick-bedded, low-angle undulatory parallel stratified, abundant swales and less commonly convex-upward parallel lamination	Thin laminations or stratification, almost completely overprinted by bioturbation	Thick beds with crude normal and reverse grading over tens of centimetres, from matrix-supported to open-framework, rare parallel stratification of matrix, plug-shaped concentrations of clasts, erosive surfaces	Medium-bedded, commonly graded, erosive bases, planar parallel stratification, thin laminae in silty drapes, local tabular cross-beds and low-angle parallel stratification, soft sediment deformation, dewatering structures and clastic dykes	Medium-bedded, low-angle parallel stratification with swales, local trough cross-bedding, rarely grading from pebble lags
Ichnology	BI = 0–1; rare *Ophiomorpha, Palaeophycus*	Locally cut by *Glossifungites*-demarcated surface subtending from overlying unit	None	BI = 0–1; sporadic, *Ophiomorpha, Palaeophycus, Planolites*	BI = 0–2; sporadically distributed *Ophiomorpha, Palaeophycus, Planolites, Schaubcylindrichnus*, low-diversity *Skolithos* ichnofacies	BI = 5; *Ophiomorpha, Planolites, Thalassinoides, Palaeophycus, Skolithos, Chondrites, Asterosoma*, proximal *Cruziana* ichnofacies	None identified	Very rare *Bergueria* or *Conichnus*	BI = 0–4; locally abundant monospecific *Macaronichnus*
Body fossils	None identified	None	Very rare fragments	Bivalve fragments and disarticulated valves, commonly concentrated in lenses	Robust shell fragments, disarticulated finer valves, commonly concentrated into thin stringers	Locally abundant but generally rare bivalves and gastropods	None identified	None identified	Abundant robust shell fragments, local thin shell fragments associated with pebble lags
Thickness (m)	<1	2	0–3	1–25	10–30	2–10	10–30+	10–30+	>10
Base	Draped on unconformity	Gradationally or erosively overlies finer-grained unit	Deposited on basal unconformity	Grades abruptly out of lower conglomerates	Overlies coarser-grained pebbly sandstones, may intertongue	Interbedded with and grading out of lower sandstones	Deposited directly on basal unconformity	Grades up from poorly sorted conglomerates	Grades abruptly out of lower pebbly sandstones
Top	Overlain by coarser sandstone unit, contact locally erosive	Erosively overlain by coarser sandstones	Grades rapidly into finer-grained units	Grades into or intertongues with finer-grained, more pervasively bioturbated sandstones	Fines upward into heterolithic sandstone-mudstone unit	Top not identified	Fines upward into better statified sandstone and pebbly sandstone unit	Erosively overlain by sandstone with better sorting	Top not identified

individual units. The southernmost Sidney Island section consists of thicker units throughout.

In this succession, the unconformity is irregular and fractured, but generally fresh looking and typically lacking a well-developed regolith. Where the basal conglomerate is absent, the surface appears smooth and polished.

Where present, the basal conglomerate (facies 3) ranges from a single clast to a unit 3 m in thickness, although in most areas it rarely exceeds 1 m (Fig. 6*a*). Clasts consist of large, angular boulders matching local basement lithology and smaller, moderately and well-rounded cobbles and pebbles. Non-local clasts are very rare. Most clasts appear to be only slightly weathered, similar to the condition of local basement, although uncommon, highly weathered clasts are locally present. The matrix comprises moderately to well-sorted, greenish-gray, medium to very coarse grained lithic arenite, dominated by rock fragments similar to those of the larger clasts. No trace fossils were identified in the conglomerate. Rare broken shell material is present locally on Saltspring Island.

The basal conglomerate fines upwards into interstratified pebble conglomerates, pebbly sandstones, and coarse-grained sandstones (facies 4). In some locations, this unit is dominated by matrix-supported pebble conglomerates, with well-sorted and rounded clasts reflecting the local basement (Fig. 6*b*). The matrix is a coarse-grained, moderately sorted lithic arenite, similar to that of the conglomerates of facies 3. The sandstones contain small bivalve fragments and disarticulated valves commonly arranged in hydrodynamically stable orientations, indicating their detrital nature. Locally, this unit is dominated by upper coarse-grained to lower coarse-grained sandstone with abundant dispersed pebbles and thin granule stringers. All of these units display horizontal planar stratification or low-angle planar stratification. A few beds are low-angle undulatory parallel stratified. Beds range from 20 cm to 1 m in thickness, although they are mostly in the 30 cm range, with generally sharp, erosive bases. Trace fossils are rare and sporadically distributed (BI = 0–1), limited to solitary *Ophiomorpha* and *Palaeophycus*.

The sandstones of facies 4 range in thickness from, <1 m on the north shore of Moresby Island to ~20 m on Russell Island. In most localities, they fine upwards abruptly out of the lower conglomerates and are, in turn, overlain by better sorted, finer grained, and more pervasively bioturbated sandstones. One exception to this is on north Moresby Island (Fig. 5, section a) where a very thin facies 4 sandstone is draped directly onto the unconformity surface and grades abruptly into a well-sorted, coarse-grained sandstone that persists for the approximately 10 stratigraphic metres of exposure, before Comox units dip below the subtidal position of the modern Strait of Georgia to the north (facies 8). This well-sorted unit consists predominantly of lower coarse-grained sandstone, with low-angle parallel stratification (with some swales). Rare trough cross-bedding is developed where cobble conglomerate lags exist, with several granule- or pebble-conglomerate lags and dispersed pebbles. Beds are 10–30 cm thick, although a single 50 cm thick bed contains a trough cross-bedded, cobble-conglomerate lag with well-rounded clasts that grade up through medium-grained sandstone and into a thin, silty, fine-grained sandstone drape. Abundant robust shell fragments and local thin bivalve shell fragments are present, especially in association with basal lags. Identified trace fossils are limited to locally abundant *Macaronichnus* in the well-sorted sandstones, both as *M. segregatis* and *M. simplicatus* (cf. Saunders and Pemberton 1986; Saunders et al. 1994) (Fig. 6*c*).

At other localities, pebbly sandstones are overlain by finer grained sandstones of facies 5 (Fig. 5, sections b–d). This upper medium- to coarse-grained sandstone contains dispersed pebbles and very rare cobbles. Granule lags are common along erosional bases of beds, and carbonaceous muddy laminae commonly mark bed-set partings. Beds are 20–40 cm thick and low-angle undulatory parallel laminated, with abundant swales and less commonly displaying convex-upward parallel lamination. Robust shell fragments and disarticulated finer valves are locally common and concentrated into thin stringers. Bioturbation is sporadically distributed (BI = 0–2) and comprises ichnogenera consistent with a low-diversity expression of the Skolithos ichnofacies. Common ichnogenera include *Ophiomorpha*, *Palaeophycus*, *Planolites*, and *Schaubcylindrichnus*. At Ruckle Park and on Russell Island, the unit comprises intervals up to 20 m thick, whereas it is represented on Sidney Island by two separate, 10 m thick packages separated by 15 m of facies 4 sandstone that has been deformed and crosscut by calcite veins.

At all localities, facies 5 becomes interbedded with a green-gray, moderately sorted, mud-dominated heterolithic mudstone and sandstone unit towards the top of the succession, assigned to facies 6. This heterolithic unit is pervasively bioturbated, with biogenic structures almost completely overprinting primary sedimentary structures (BI = 5). The sandstone is fine to medium grained, whereas the mudstone is silty, dark coloured, and carbonaceous. Bivalve and gastropod fragments are locally abundant, though generally rare. Bioturbation is uniformly distributed, with *Ophiomorpha*, *Planolites*, and *Thalassinoides* most common (Fig. 6*d*) and *Palaeophycus*, *Skolithos*, *Chondrites*, and *Asterosoma* found locally.

Interpretation

This succession is interpreted to represent deposition on a storm-swept, rocky shoreline that was gradually drowned by transgression of the Late Cretaceous proto-Pacific Ocean. The unconformity was overlain by a discontinuous thin breccia lag reworked by wave action or scoured smooth during wave ravinement. The lack of a regolith or highly weathered clasts in the breccia may reflect the high-energy conditions of the rocky beach, which would have acted to effectively break down and remove highly weathered, less competent lithologies.

The basal conglomerate comprises well-rounded basement clasts, washed and sorted by high-energy storms and infiltrated by well-sorted beach sands by relatively lower energy wave swash processes. Systematic shape differentiation among rounded clasts (cf. Bluck 1967) is not recognized, although intermittent exposure of these conglomerates limits the potential for such along-strike comparisons. With gradual transgression, the gravel beach deposits became overlain by pebbly sandstones of the upper shoreface. High-energy conditions persisted, reflected by preservation of fragments of robust shells and rare, low-diversity expressions of the *Skolithos* ichnofacies. Coinciding with the change in grain

Fig. 5. Measured sections displaying facies association 1 (storm-dominated rocky shoreline) successions. See Fig. 4 for geographic location of sections.

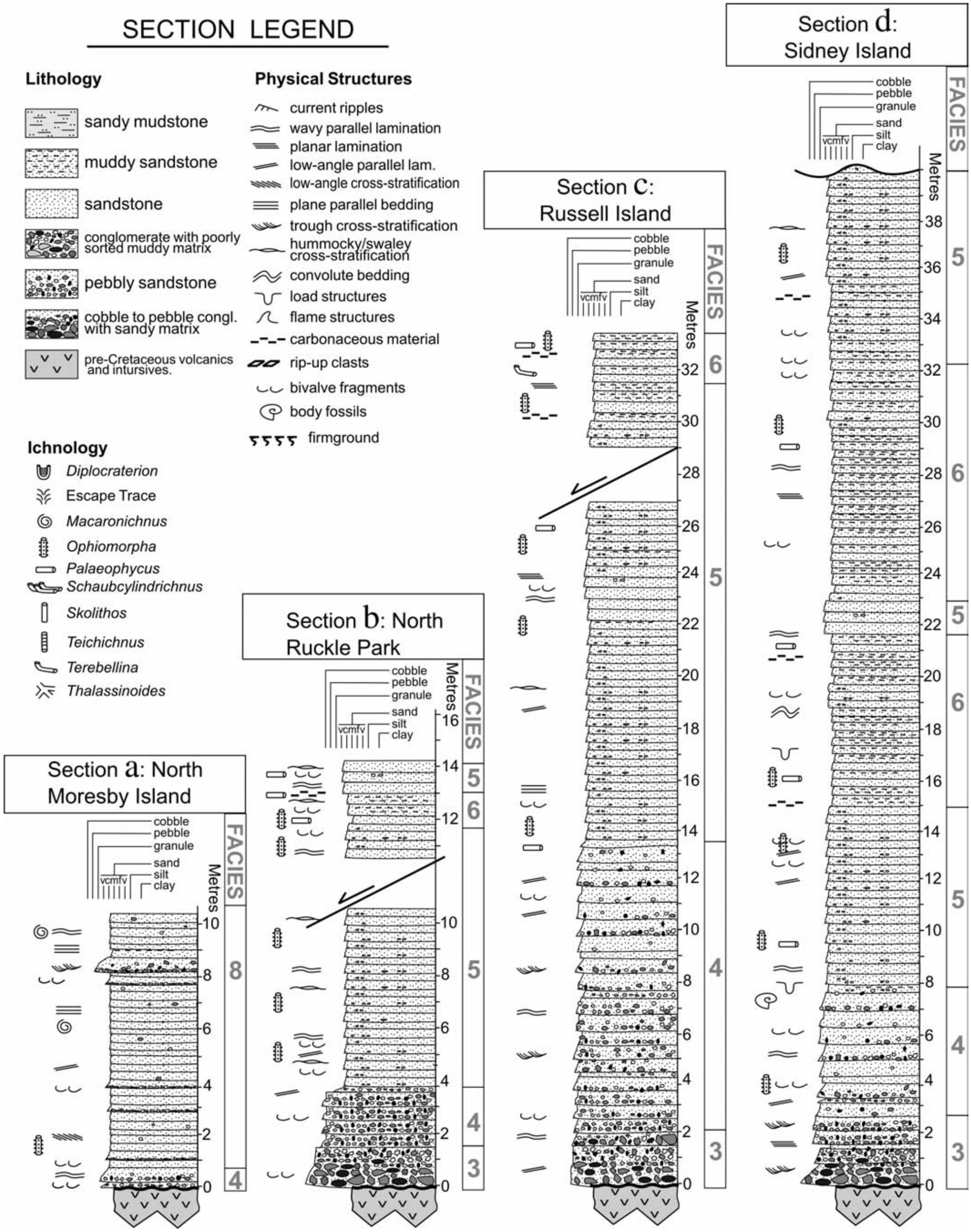
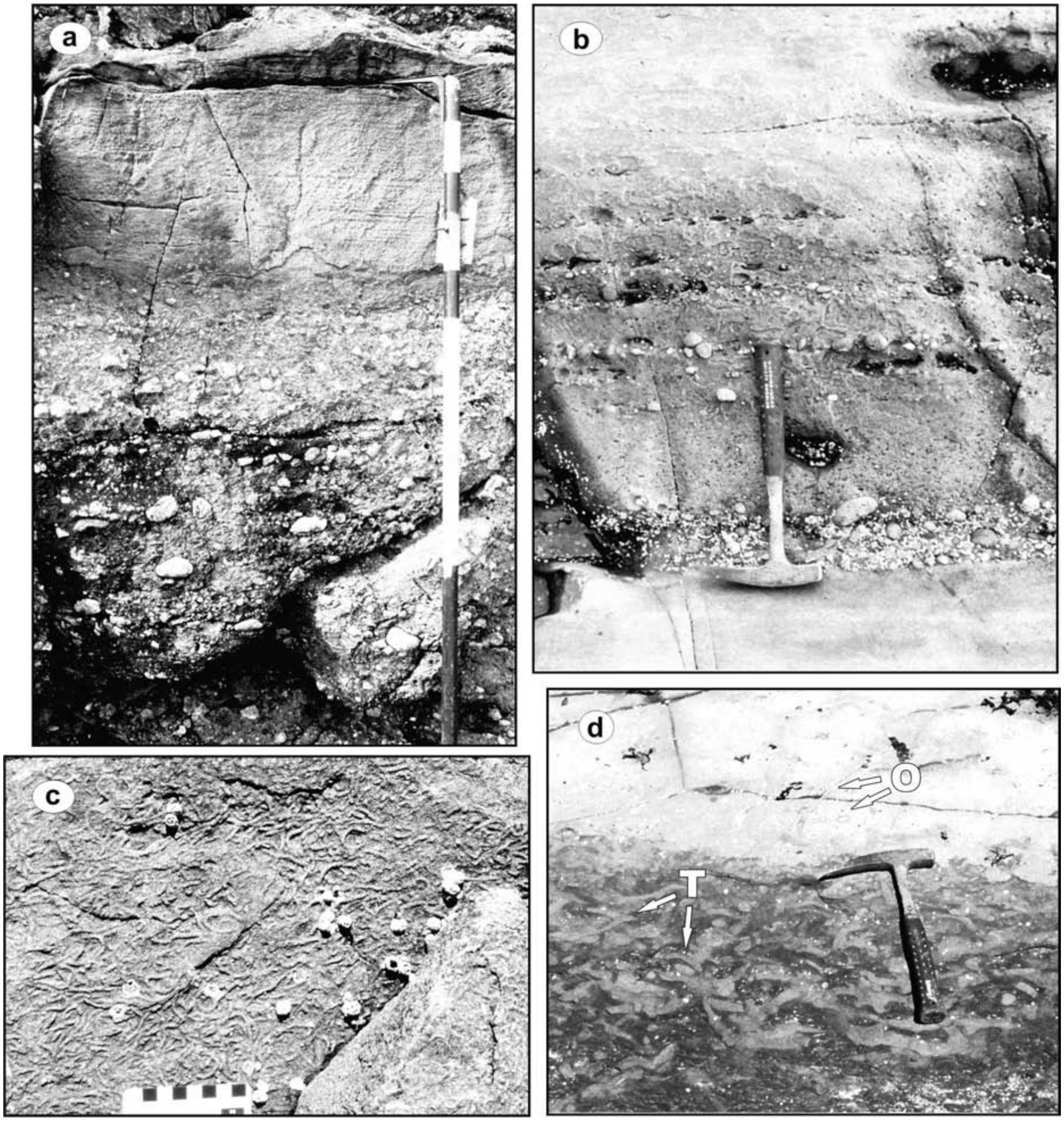


Fig. 6. Photographs of facies association 1 (storm-dominated rocky shoreline). (*a*) Facies 3 basal pebble conglomerate fining upwards into pebbly sandstone, Ruckle Park. Staff is 1.5 m long. (*b*) Facies 4 coarse-grained sandstone and pebbly sandstone with well-rounded pebble lags and stringers, Sidney Island. Hammer is 35 cm long. (*c*) Facies 8 well-sorted upper medium-grained sandstone with well-preserved monospecific suite of trace fossil *Macaronichnus segragatis*, north end of Moresby Island. Scale bar at bottom is 8 cm long. (*d*) Upper medium sandstone interbed within facies 6 muddy sandstone, west Moresby Island. Identified ichnogenera include *Ophiomorpha* (O) in upper sandstone and *Thalassinoides* (T) in muddy sandstone below with numerous y-branches visible. Hammer is 35 cm long.



size, horizontal planar stratification passes upwards into swaley cross-stratification (SCS), in response to continued deepening.

The middle shoreface pebbly sandstones become dominated by erosionally amalgamated SCS and lesser hummocky cross-stratification (HCS). HCS is increasingly abundant upward, corresponding to continued deepening. These thick stacked beds contain stringers of granules and rare pebbles, abundant shell fragments, and a low-diversity suite reflecting the *Skolithos* ichnofacies. The top-down relationship of burrowing of the event beds represents post-storm colonization of tempestites. Most suites are truncated by overlying tempestites, and therefore the nature of the fair-weather suite is unknown in these shallow-water units. Continued deepening into the lower shoreface is reflected by muddy sandstones with higher intensity bioturbation and heightened diversity of ichnological suites than is seen elsewhere in the lower Comox Formation. Less fragmented shells are present, as well as trace fossil suites attributable to a proximal expression of the *Cruziana* ichnofacies (cf. MacEachern et al. 1999).

On the north shore of Moresby Island where the basal conglomerates are thin and overlain by upper shoreface sand-

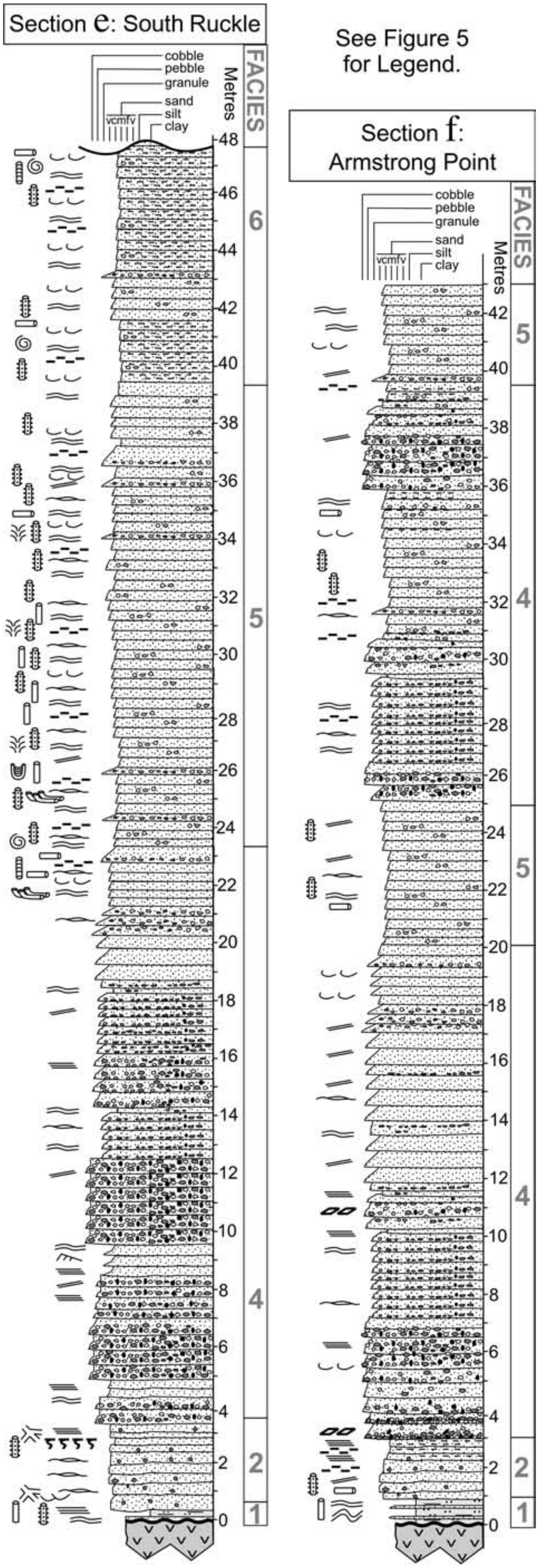


Fig. 7. Measured sections displaying facies association 2 (low-energy rocky shoreline) successions. See Fig. 4 for geographic location of sections and Fig. 5 for legend.

stones, the sandstone near the top of the succession hosts locally abundant *M. segregatis*, which in monospecific suites associated with well-sorted sandstones is common to upper shoreface to foreshore settings (Saunders and Pemberton 1986; Saunders et al. 1994).

Facies association 2: low-energy rocky shoreline

The second coastline environment is interpreted to reflect a protected embayment. This succession is displayed along strike from the first succession at the south end of Ruckle Park on Saltspring Island (location e) and at Armstrong Point on the Saanich Peninsula (location f) (Figs. 4, 7).

The unconformity is draped with a relatively thin unit of medium- to fine-grained silty sandstone (facies 1). At Ruckle Park, this unit is 20 cm thick, planar parallel laminated, and weakly burrowed (BI = 0–1) with rare *Ophiomorpha* and *Palaeophycus.* No body fossils and only a few dispersed pebbles are present. The sandstone is draped by a thin, carbonaceous mudstone. At Armstrong Point (Fig. 7, section f), this unit is muddier and less well bedded, and the unconformity surface is more undulatory with a few large breccia clasts (Fig. 8). The matrix between the breccia clasts is the same muddy fine- to medium-grained sandstone. Bioturbation (BI = 1–2) and (or) soft-sediment deformation have disrupted the stratification, with planar parallel stratification more apparent above the breccia. The entire thickness of the basal breccia and muddy sandstone is less than 90 cm.

At both locations, this unit passes upwards into a moderately sorted, medium- to coarse-grained sandstone with dispersed pebbles and granules. The unit contains low-angle undulatory parallel lamination (less well defined at Armstrong Point) and planar parallel lamination in beds 10–25 cm thick (facies 2). Mudstone rip-up clasts, carbonaceous detritus, and numerous rust-coloured concretions are found at the Armstrong Point site. The unit fines upwards over a 2 m interval into a silty mudstone. Thin lenses of pebble conglomerate with well-rounded and well-sorted clasts are locally intercalated within the sandstone.

The medium-grained sandstone is erosively overlain by the pebbly sandstone of facies 4, similar to that of facies association 1. At Ruckle Park, this contact is marked by a firm ground, with a suite of trace fossils attributable to the *Glossifungites* ichnofacies subtending into the lower units, and passively infilled with coarser sand from the overlying unit. Although no *Glossifungites* ichnofacies demarcated surface is displayed at Armstrong Point, the base of the overlying unit is erosive, with a pebbly lag containing shell fragments and mudstone rip-up clasts. The unit is more than 25 m thick at Armstrong Point, with low-angle planar lamination, bed sets over 1 m thick, and shallow troughs or swales more than 10 m across. Bed sets commonly have pebble or granule lags at the base and grade upward (rarely) into thin partings of finer muddy sandstone, which are commonly burrowed. Shell fragments and ichnofossils are rare, however, an abundance

Fig. 8. Facies association 2 at Armstrong Point. Basement intrusives (Jg) are draped with sandy mudstones of facies 1 (F1), passing up into facies 2 sandstones (F2) which are erosively overlain by pebbly sandstones of facies 4 (F4). Broken lines indicate facies changes, although the gradational change from F1 to F2 is only estimated.

of small, rust-coloured concretions may represent poorly preserved examples of either.

At both localities, the succession fines upwards into stacked, well-sorted, medium- to coarse-grained sandstones of facies 5, which are interrupted by thin pebble-conglomerate interbeds. This probably represents an intertonguing relationship with facies 4, with repeated fining-upward successions from facies 4 to facies 5. In both localities, this upper unit is less than 10 m thick. Although the top is covered, it can be correlated at Ruckle Park with a similar unit in facies association 1, where facies 5 passes upward into facies 6.

Interpretation

This succession is interpreted to represent transgressive drowning of a rocky shoreline, although, unlike facies association 1, the initial shoreline was of lower energy. Neither the ichnology nor the physical sedimentology suggests a lagoonal or backshore environment. The deposition of laminated, fine-grained silty sandstone and mudstone with a higher bioturbation index (BI = 2) near the unconformity suggests that the shoreline was exposed to significant erosion while protected from the full force of open-ocean storm and wave activity. Such sheltering may have been accorded by a rocky headland or bar. On Armstrong Point, the transgression and transition to higher energy deposits seem more gradual, resulting in a more disorganized and variable facies 2. The firm-ground transition at Ruckle Park, on the other hand, suggests a more persistent, low-energy stage, with an abrupt, erosive introduction of higher energy shoreface deposits.

At both locations, flooding by transgression led to erosional overlapping by higher energy shoreface deposits, and eventually to amalgamated storm beds in a storm-dominated middle shoreface environment. These amalgamated storm beds are similar to the middle to lower shoreface deposits of facies association 1.

Facies association 3: drowned fan delta

The third paleo-coastal environment consists of a small, drowned alluvial fan or fan delta. This is represented by the basal deposits on the west coast of Portland Island extending onto adjacent Brackman Island (location g) and successions on the west coast (location h) and east coast (location i) of Moresby Island (Fig. 9). Where the basal unconformity is intermittently exposed at these locations, the basement below the unconformity appears very weathered. Units are ash gray and rusty compared to the “fresher” dark green phyllitic volcaniclastics nearby.

The Comox Formation deposited onto the unconformity comprises a thick (greater than 10 m) succession of cobble and pebble conglomerates (facies 7). The conglomerate is poorly sorted, with both angular and rounded clasts, and reflects local basement lithologies. Some clasts are markedly more weathered than others and are comparable to material within the regolith zone beneath the unconformity (Fig. 10*a*). Clasts rarely reach boulder sizes. There is crude grading, with examples locally of both normal and reverse grading. Units range from open-framework, clast-dominated conglomerate to poorly sorted, pebbly and muddy sandstone with abundant dispersed pebbles and cobbles. Overall, bedding is poorly developed, with graded beds exceeding metre-scale thickness (Fig. 10*b*). Elongate clasts do not share an apparent overall orientation. Clast-rich lenses commonly have a plug-shaped morphology. Clasts reflect both the local volcaniclastic and intrusive basement rocks and are locally monomictic within lenses. The matrix comprises an unsorted, green-gray muddy sandstone. Body fossils, trace fossils, and carbonaceous detritus are not present in the basal units.

At all localities, the unit fines upwards after 10–30 m into a better stratified sandstone and pebbly sandstone, with minor pebble conglomerate (facies 7b). The sandstone beds commonly grade from granule lags at erosive bases to medium-grained sandstones commonly showing planar parallel lamination and some thin, silty, and carbonaceous interlaminae towards the top of 10–30 cm thick bed sets (Fig. 10*c*). These fine laminations are rarely crosscut by thin, silty, sand-filled clastic dykes. More commonly, primary bedding structures are disrupted by apparent soft-sediment dewatering or loading structures (Fig. 10*d*). Bioturbation is either absent or

Fig. 9. Measured sections displaying facies association 3 (drowned fan delta) successions. See Fig. 4 for geographic location of sections and Fig. 5 for legend.

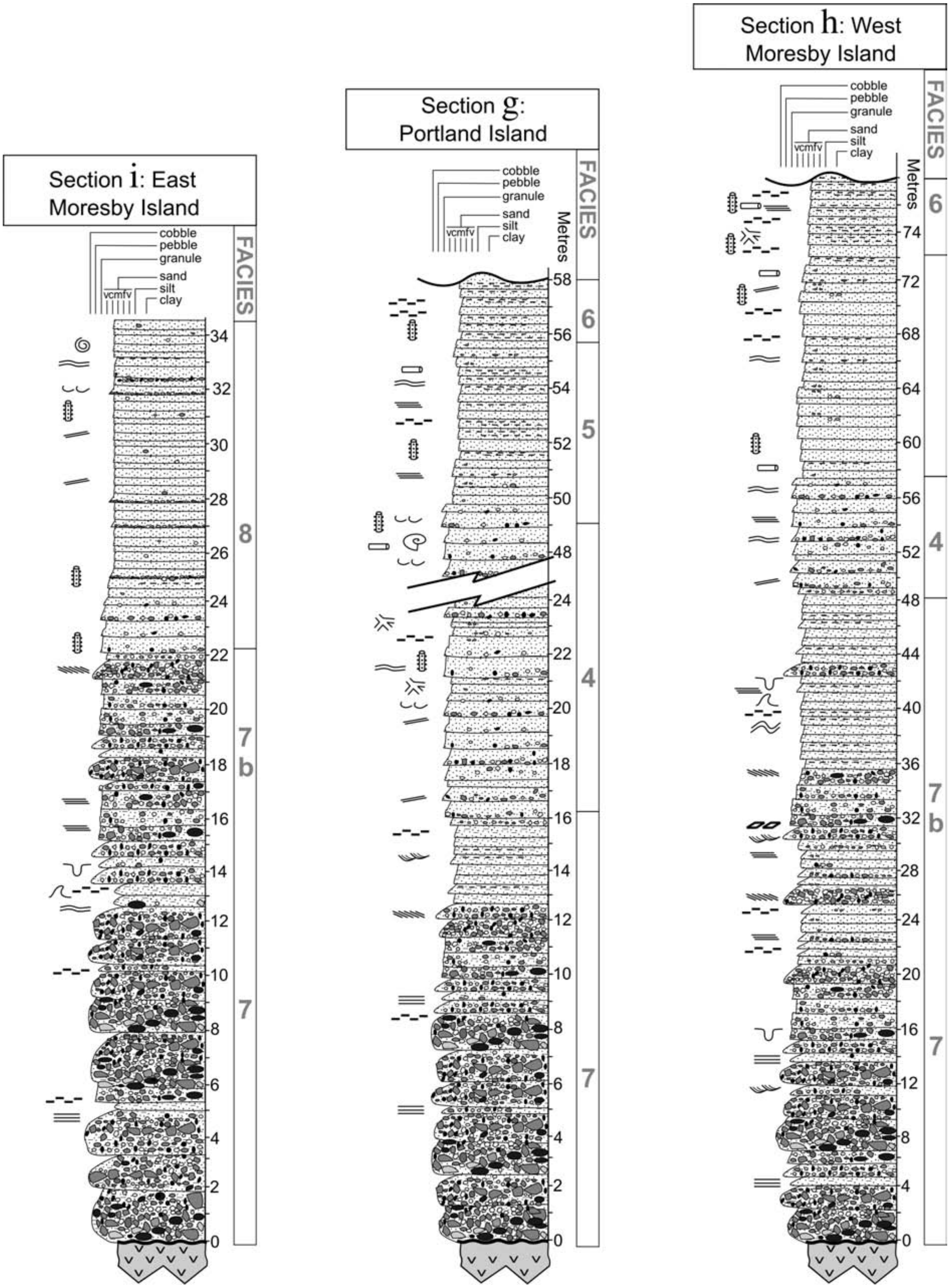
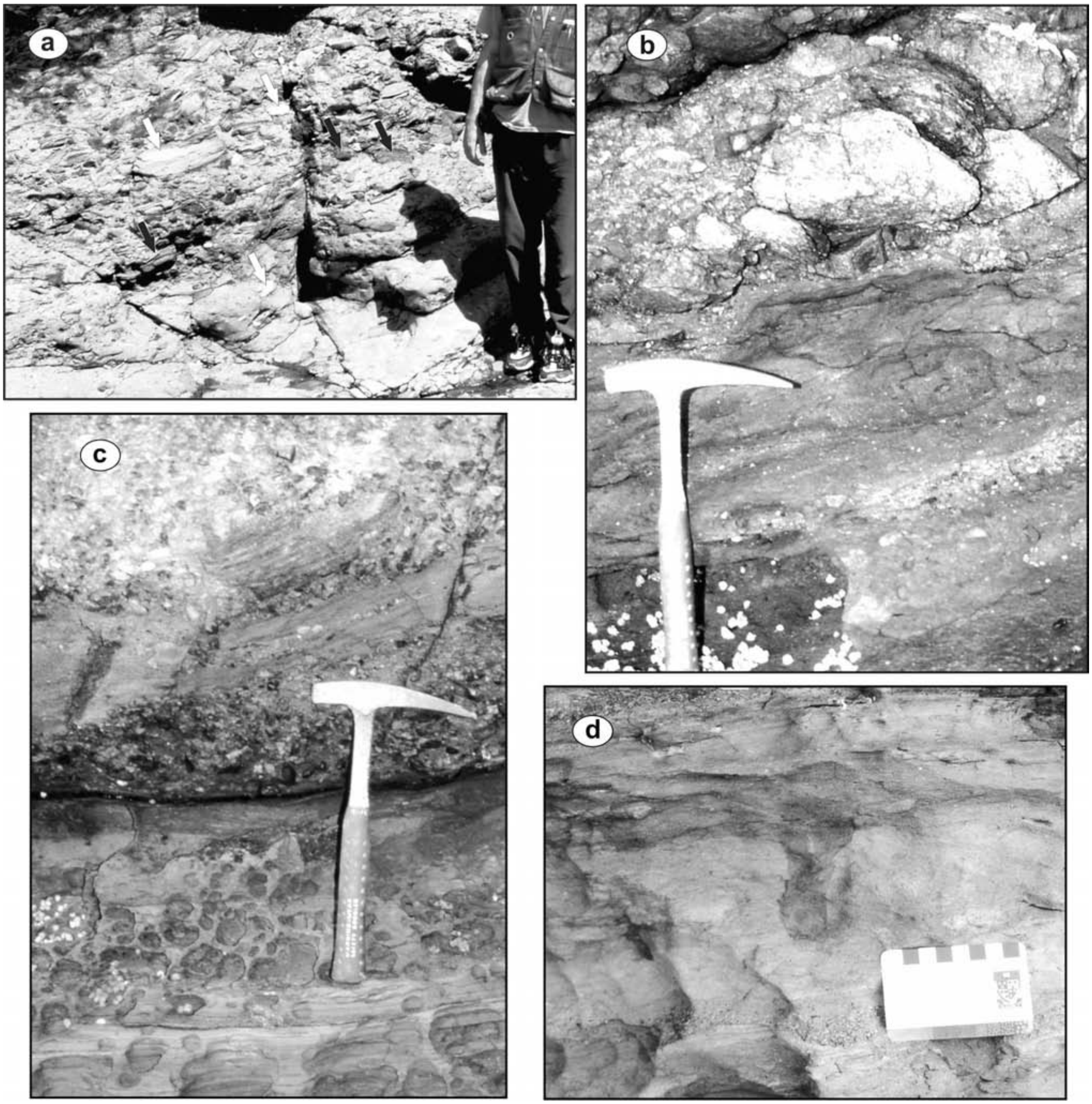


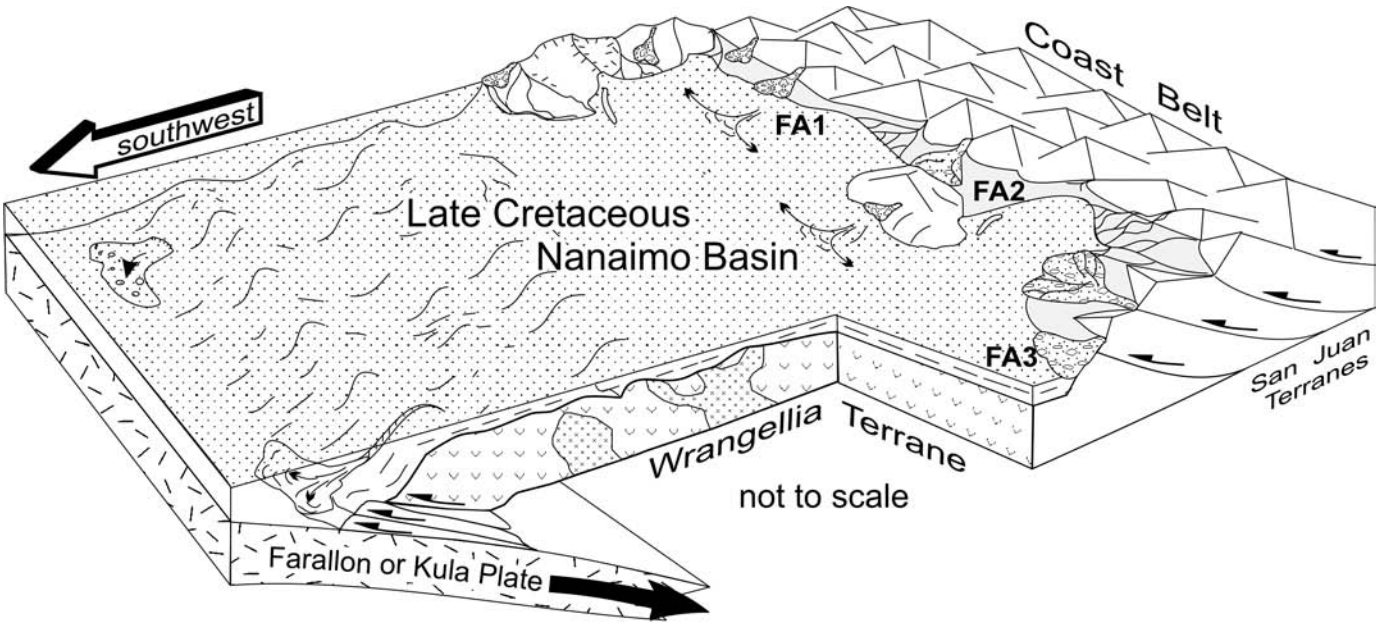
Fig. 10. Photographs of facies association 3 (drowned fan delta). (*a*) Facies 7 basal pebble to cobble conglomerate on Portland Island. Clasts are poorly sorted with highly weathered white clasts (white arrows) intermixed with dark-coloured "fresh" clasts (black arrows). (*b*) Facies 7 muddy sandstone matrix in poorly sorted and crudely graded conglomerates, east side of Moresby Island. Note large "plug" of mixed clasts near top loading into clast-poor muddy matrix below. Hammer is 35 cm long. (*c*) Facies 7b on west side of Moresby Island. Cross-bedded pebbly sandstones (top) and parallel laminated muddy sandstones (base) represent increased textural maturity compared to facies 7. Hammer is 35 cm long. (*d*) Facies 7b poorly sorted muddy sandstone with granule lenses. Poorly developed bedding is distorted by burrowing and soft-sediment deformation, including large burrow in centre, with only faint laminations preserved. Scale card has 1 cm colour bands along top.



sparse and indeterminate (BI = 0–1), although rare, large-diameter *Bergaueria* and *Conichnus* mark several bedding surfaces. Pebbly sandstone beds are tabular cross-bedded or low-angle parallel stratified and commonly grade upward from moderately sorted pebble conglomerate to medium-grained sandstone. This moderately sorted unit is thickest on the west shore of Moresby Island (Fig. 9, section h), where it is exposed for more than 30 m of section. In contrast, at east Moresby Island (Fig. 9, section i) and on Portland Island (Fig. 9, section g), this unit is thin and only serves as a transition into the overlying, well-sorted sandstones.

On the east shore of Moresby Island, the transition is very abrupt, passing into well-sorted, medium- to coarse-grained sandstone. Beds are locally pebbly and (or) normally graded.

Fig. 11. Block model of Nanaimo Basin during early Comox Formation deposition. Within the study area, the Comox Formation was deposited upon a partially emergent Wrangellia Terrane, with the majority of the terrane submerged, exposing the shoreline to the full force of proto-Pacific Ocean storms. A rocky shoreline with high local relief result in varied energy conditions and three distinct facies associations: FA1, storm-dominated rocky shoreline; FA2, low-energy rocky shoreline; and FA3, drowned fan delta.



Trough cross-beds or low-angle planar stratified beds with swale-shaped bases and dispersed pebbles or cobbles are present. Cross beds measured for paleocurrent analysis give dispersed, non-uniform trends. Beds are commonly poorly defined by local thin, parallel-laminated partings of rusty, fine-grained silty sandstone. Bivalve molds are abundant locally (3–5 cm, unornamented; possible Inoceramid), although shell material is not preserved. Rare examples of *Macaronichnus* are present. This unit represents facies 8, similar to the unit seen on the north shore of the island, although primary bedding is not as well preserved here.

On the west coast of Moresby Island, the transition is an upward fining over several metres into a gray, buff-weathering, upper medium- to coarse-grained sandstone with common granule stringers and dispersed pebbles. Some granule stringers form lags in broad swale-shaped erosional surfaces, although low-angle undulatory parallel lamination is only poorly developed. This 5 m of sandstone is assigned to facies 4 and is erosively overlain by a similar, moderately sorted to well-sorted, lower coarse-grained sandstone, which is intercalated with muddy sandstones.

The well-sorted sandstone unit is lower coarse-grained to upper medium-grained, with generally well-developed, 30 cm thick, parallel laminated beds. Bases are commonly erosive and swale-shaped, with granule stringers and very rare dispersed pebbles, stacked into bed sets on a metre scale. Sporadically distributed, low-intensity bioturbation (BI = 0–1) is dominated by *Ophiomorpha*, with minor *Planolites* (facies 5). This unit is intercalated with a green-gray, muddy, lower medium- to fine-grained silty sandstone with abundant bioturbation (facies 6). The interstitial units are slightly carbonaceous, with some rust-coloured nodules, and are intensely bioturbated (BI = 5) with *Thalassinoides*, *Ophiomorpha*, and *Planolites* present. The recessive nature of the unit, combined with intense bioturbation, make primary bedding indicators difficult to distinguish. Local facies 5 sandstone interbeds, ranging from 10 to 100 cm thick, are also pervasively bioturbated. This sand passively infills burrows that subtend from these beds. The mudstone becomes darker and more carbonaceous up section.

Interpretation

This succession is interpreted to represent a near-coastal alluvial fan, which was initially subaerial but became marine influenced as transgression progressed, thus developing into a small fan delta. The basal conglomerates in this succession are thickly and poorly bedded and texturally very immature. The relatively unsorted matrix, plug-shaped lenses of large subangular clasts, and crudely developed normal and reverse grading all suggest deposition by cohesive debris flows. The presence of regolith in the basement directly below these deposits, coupled with the lack of grain-size sorting or reworking of the deposits, suggests that the alluvial fan was initially subaerially exposed. The juxtaposition of heavily weathered clasts with “fresher” ones suggests the development and exhumation of a Cretaceous regolith.

The coarse-grained basal deposits on the west coast of Moresby Island dip to the north at inclinations approximately 20° steeper than strike-parallel, shallowly dipping, finer grained units farther up section. One interpretation of this discrepancy would involve the tectonic folding of the units, presumably a drag fold associated with an unseen fault, but no other evidence of this fault was found in the surrounding outcrops of Nanaimo Group or basement rocks. A more favourable interpretation attributes the bedding discrepancy to nonhorizontal deposition of the conglomerates on the flanks of a fan, with an angle of repose of about 20°, an interpretation that also fits with the lithology and sedimentology of the facies.

The transition from thick, disordered conglomerate to better organized pebble conglomerate and coarse-grained sandstone represents increased sorting, presumably by differential settling and wave reworking. Biogenic reworking suggests progressive marine conditions replacing alluvial conditions, as the fan delta was drowned by ensuing transgression. Subaqueous deposition for this part of the fan is further supported by planar lamination of finer grained units, interpreted to represent sheet flows of fan material into a standing water column, and trough cross-bedding, representing increased sorting and traction flow of coarse-grained detritus. Better developed normal grading and soft-sediment loading structures are more common upwards, reinforcing progression towards a subaqueous deposition. Clastic dykes may have formed from dewatering associated with loading of saturated sediments or from dilational cracks developed by slumps in the fan delta.

A shift of the locus of deposition in the fan delta, possibly coeval with continued transgression, resulted in the onlap of thick, erosionally based, amalgamated tempestites. These subsequently pass into lower shoreface sandstones characterized by a reduction in grain size and a corresponding increase in fossil material and bioturbation intensity. On the west Moresby Island succession, this transition is especially thick, with almost 50 m of gradually thinner and more distal tempestites, and a thick interval of lower shoreface – transitional offshore deposits.

The east Moresby Island succession (much like the succession in facies association 1 just north of it) is incomplete, and the fan delta deposits are directly overlain by well-sorted upper shoreface sandstones. Deeper water units are presumed to have been deposited above this but are not exposed above the modern intertidal zone.

Paleogeography

Within the Nanaimo Group, depositional environments ranging from alluvial to deep sea are represented, reflecting the rapid subsidence of a foreland basin along the Late Cretaceous Cordilleran active margin. The location and nature of the Nanaimo Group make it appropriate for studying the paleogeography of the western Canadian Cordillera in the Late Cretaceous. Such an exercise may shed light on the veracity of various terrane accretion models and plate reconstructions in the eastern proto-Pacific Ocean.

At the southern end of the preserved Nanaimo Basin, the Upper Cretaceous unconformity is well exposed and reflects gradual transgression of a storm-swept, rocky shoreline. The multiple exposures of the unconformity within the study area show the variety of environments that can develop within a few kilometres of an irregular rocky paleoshoreline, all reflecting small variations in the orientation of the shoreline with respect to wave-propagation and storm-tract positions of the proto-Pacific Ocean. The spatial distribution of these environments leads to a more refined model of the nature of the west coast of the Canadian Cordillera in the Late Cretaceous. During the initial deposition of the Comox Formation in the southern end of the basin, a rocky shoreline composed of Wrangellian rocks existed west of the Coast Mountains Plutonic Complex arc system. Wrangellia was at least partially emergent, with open-ocean conditions to the west. With protected embayments and alluvial fans, there must have been hundreds of metres of local relief, acting as a source of alluvial material and forming barriers that sheltered lower energy coves from the full force of the oceanic swells.

The recent reinterpretation by Haggart et al. (2005) that the Cretaceous strata from Sidney Island represent a unit lithologically distinct from the Comox Formation is not supported by the data in this study. The lithology and sedimentology of this proposed "Sidney Island Formation" are similar to those of other Comox Formation localities within the study area, with minor differences that may be attributed to rugged paleotopography and transgression as described earlier. The presence of a Turonian fossil suite on Sidney Island is better explained by the established diachronous nature of the Comox Formation, evidenced by the presence of fossils from the Turonian, Coniacian, and Santonian within the Comox Formation in other parts of the basin (Muller and Jeletzky 1970; Mustard 1994; Haggart et al. 2003). We point out that the rocky shoreline model presented here, developed on a very irregular and locally high relief paleotopographic surface, in fact predicts that the basal unit overlying this unconformity surface will be diachronous laterally.

Amalgamated storm deposits found on Saltspring and Sidney islands, along with other areas in the Comox Formation, are thick and coarse grained. Bed sets >5 m thick and beds up to 50 cm thick composed of medium- to coarse-grained sandstones suggest tempestite origins. This contrasts with typical examples from the Cretaceous Western Interior Seaway, with bed sets in the range of 1–2 m (Frey and Howard 1990; Duke et al. 1991), although they are in scale with Eocene tempestites from the Pacific coast of Oregon State (Chan and Dott 1986). The scale difference implies that the Cretaceous shoreline in the Nanaimo Basin was open to the full force of proto-Pacific storms, and not within a large protected embayment behind a generally emergent Wrangellia (Fig. 11). This contrasts with earlier interpretations of the paleogeography of the Nanaimo Group, in which Wrangellia was interpreted to be largely emergent to the west, and with the Nanaimo Basin in a geographic setting similar to that of the modern Georgia Basin where it is now exposed. Even Mustard (1994), who suggested that the upper Nanaimo Group deposition occurred into an open ocean with Wrangellia submerged, shows early Nanaimo Basin sedimentation within a major enclosed embayment sheltered from the open ocean. This interpretation is also at odds with the ridged fore-arc model for the Nanaimo Basin, suggested by some workers (England 1990; England and Bustin 1998), which would require a broad emergent Wrangellia west of the study area.

Lastly, the gradational succession exposed on the unconformity suggests a gradual but persistent transgression. Episodic pauses in transgression most likely represent tectonic fluctuations associated with coeval thrusting to the east, eustatic changes, or a combination of both factors. There are no significant upward-coarsening sequences, which would be expected with persistent shoreline progradation associated with increased sediment flux. We suggest that this gradual retrogradation of the shoreline in response to increasing accommodation and concomitant deepening is an underutilized concept in transgressive systems tract models.

Conclusions

This study outlines the abundant physical sedimentologic, ichnologic, and body fossil evidence of a coastal marine depositional environment for southern sections of the Comox Formation in southwestern British Columbia. The interpretation of a rocky marine shoreline on the laterally extensive basal unconformity of the Comox Formation is supported by the morphology of the unconformity and facies analysis of the overlying rocks. Three distinct facies associations display the contrast of local depositional systems which may be preserved along even a relatively short stretch of rocky marine shoreline. The development and preservation of these varied environments are enhanced by high coastal paleorelief and steady, gradual marine transgression. The identification of large-scale tempestite deposits indicates that the basin was exposed to large proto-Pacific storms and was located on a portion of Wrangellia where the terrane was not broadly emergent.

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