Stratigraphy and evolution of Tertiary Georgia Basin and subjacent Upper Cretaceous sedimentary rocks, southwestern British Columbia and northwestern Washington State

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Abstract: Georgia Basin encompasses Strait of Georgia, eastern Vancouver Island, Fraser Lowland, and northwest Washington State. At Vancouver, a succession of Late Cretaceous clastic rocks less than 500 m thick unconformably overlie Coast Belt intrusions or Albian-Cenomanian sedimentary rock. The Late Cretaceous rocks correlate with the lower Nassano Group and were deposited in alluvial fan and fluvial-floodplain environments. Tertiary Georgia Basin is dominated by Palocene-Eocene clastic rocks 2.5 km thick in the Fraser Lowland, and thicken to nearly 6 km at Bella Coola. Paleogene strata previously named Kitsilano and Burrard formations are included with the better exposed and coeval Huntington Formation, a northern continuation of the Chehalis Formation, not a younger unit as previously interpreted. Deposition occurred in a terrestrial basin with proximal lower alluvial fan deposits changing to fluvial systems towards the basin axis. Paleocurrents and provenance suggest derivation from local sources. The Miocene Boundary Bay formation is less than 1.2 km thick and preserved in the Fraser delta subsurface. It comprises fluvial sandstone and mudstone similar to the underlying Paleogene rocks, although marine microfossils also suggest marginal marine environments. Oligocene rocks are limited to scattered exposures of igneous intrusions and rare subsurface dikes and sills. Tertiary Georgia Basin formed as an intracratonic strike-slip basin where dextral strike-slip faults were active in the western Cordillera. Late Eocene compression deformed the basin into northwest-trending and plunging folds. Thraps and poros sandstone are present, but low thermal maturity and lack of marine kerogen in the sub-Miocene succession indicate gas as the most likely potential hydrocarbon.

Résumé: Le bassin de Georgia englobe le détroit de Georgia, l’est de l’île de Vancouver, les basses terres du Fraser et le nord-ouest de l’État de Washington. À Vancouver, une succession de roches clastiques du Crétacé tardif de moins de 500 m d’épaisseur recouvre en discordance les intrusions survenues dans la chaîne Côtière ou dans des roches sédimentaires d’âge albanien-cénomanien. Les roches du Crétacé tardif sont mises en corrélation avec la partie inférieure du Groupe de Nanaimo et se sont déposées dans des milieux de clms alluviaux et de cours d’eau-plaines d’ondoyation. Le bassin de Georgia (Tertiaire) contient principalement des roches clastiques paléocène-océennes qui ont 2.5 km d’épaisseur dans les basses terres du Fraser et qui s’épaississent jusqu’à presque 6 km à Bella Coola. Les strates paléocéennes antérieurement appelées formations de Kitsilano et de Burrard sont incluses dans la Formation de Huntington, qui est contemporaine et mieux exposée et qui constitue le prolongement vers le nord de la Formation de
INTRODUCTION

The Georgia Basin is a northwest-oriented structural and topographic depression encompassing Strati, of Georgia, eastern Savannah Basin, and the Fretter River lowlands of south-west British Columbia, and the northwest mainland of Washington State. Sedimentary rocks of the Georgia Basin comprise two major tectonic stratigraphic packages: the Upper Cretaceous Nanaimo Group, well-exposed on eastern Vancouver Island, and the Como Hills and Strait of Georgia, and a Tertiary basin mostly preserved in the Vancouver area and northwest Washington State (Fig. 1, 2). The Tertiary part of Georgia Basin formed a regional depocenter for the Jurassic–Cretaceous and Cretaceous–Tertiary stratigraphic columns of the Green River Valley area, linking the Canadian stratigraphy to the Tertiary Chalkstonian foreland Basin by some authors, e.g., Miller and Michel, 1963; Hopkins, 1968) has recently been the target for renewed hydrocarbon exploration, with three unsuccessful wells drilled in 1991 and two in 1993 (Fig. 3, Table 1). As part of the Geological Survey of Canada project, the stratigraphy and extent of the Tertiary part of Georgia Basin have been re-examined. Field studies of Tertiary and underlying Late Cretaceous strata of the Greater Vancouver area and of Tertiary outcrops on the margins of the Tertiary part of Georgia Basin have been combined with continuing palynological studies of these rocks and samples from recent exploration drilling in the basin. This paper summarizes these results, reviews revisions to the Late Cretaceous and Tertiary stratigraphic nomenclature of the Green River Valley area, linking the Canadian stratigraphy to the Tertiary Chalkstonian foreland Basin, and provides a summary of the models for the evolution of the Tertiary part of Georgia Basin.

Table 1. Major hydrocarbon exploration wells in Tertiary Georgia Basin. Well locations are shown in Figure 3.

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<thead>
<tr>
<th>Well</th>
<th>Date</th>
<th>Depth (ft)</th>
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<tr>
<td>1</td>
<td>1991</td>
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<td>2</td>
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Figure 1. Regional setting of Georgia Basin with Tertiary Georgia Basin shown in dark grey.

REGIONAL SETTING

As shown in Figure 3 and documented in this study, the Tertiary rocks of Georgia Basin unconformably overlie sedimentary rocks of the Late Cretaceous Nanaimo Group (Mustard, 1994) at the present west and northwest outcrop margins, at Vancouver, and in the subsurface of the Fraser Delta. In the eastern Fraser Valley the Tertiary rocks unconformably overlie Cretaceous rocks of the Early Cretaceous Coast Belt granitic intrusives and remnants of submarine to marginal volcaniclastic cover sequences (Mengel, 1990; Woodworth and Mengel, 1991). In northwest Washington State, the Tertiary strata unconformably overlie the northwest Cascades, a complex series of small and large arc-related terranes dominated by oceanic sedimentary and metamorphic rocks (mostly argillaceous to cherty successions), but with significant volcanic, ophiolitic, and intrusive units (see Tubbs et al., 1989 and McGroder, 1991 for recent reviews).

The main structural control on the sub-Georgia Basin rocks and to some extent Georgia Basin itself is southwest to west-vergent thrusting that took place from the Cretaceous to the Eocene, a response to underthrusting of the Ferrall or Kila oceanic plates beneath the North American plate (Yorath et al., 1985; Monger, 1991a, b). A mid-to-Late Cretaceous, west-vergent thrust system is preserved at the southeast margin of the Georgia Basin (Brandan et al., 1988; McGroder, 1991) and in the eastern Coast Belt (Journey et al., 1992; Journey and Friedman, 1993) and includes thrusts and slumps active during much of the basin formation and major periods of Nanaimo Group sedimentation. Dextral strike-slip faults influenced depositional patterns during the Tertiary stage of Georgia Basin fill (Johnson, 1984d, c, this study). The basin was also affected by early Tertiary compression, resulting in southwest-directed thrusting that included the Nanaimo Group (Englund and Calon, 1991) and northwest-plunging and-trending folds in the Tertiary Chalkstonian Formation (Johnson, 1982).

The extent of the original Tertiary basin can be estimated from the stratigraphic architecture, facies relationships, and provenance summarized in this paper and also discussed in Mustard and Roux (1991, 1992). Source proximal alluvial fan and fluvial conglomerates are present in the northwest (Lasqueti Island, west (Tumbo and Soosia Islands), east (U.S. and Canada Sumas Mountains), and southeast outcrop areas (much of the Chalkstonian Formation). All pre-Mesozoic strata are terrestrial and both paleosol and clast types indicate derivation from their respective outer margins, suggesting the original basin margins were near and the basin was probably not significantly more extensive than implied by current outcrop patterns (with the exception that England and Calon, 1991 suggest about 20% shortening in a southwest direction in the underlying Nanaimo Group due to Eocene compression). There is no clear control on the south margin of the basin. Precise estimates of original basin extent are hampered on the east side by extensive late Neogene Coast Belt uplift (Harish, 1983) which has caused erosion of most early Tertiary strata east or northeast of the present outcrop areas.
STRATIGRAPHY OF TERTIARY GEORGIA BASIN

With the exception of isolated occurrences of Paleocene rocks on Lanier, Tumbo, Suica, and nearby islands (Rouse et al., 1990; Mustard and Rouse, 1991, 1992; this study), the Tertiary rocks of the Georgia Basin are mainly exposed in the lower Fraser Valley along the north and northeast margins of the present Fraser Delta, and in mainland northwestern Washington State (Fig. 2, 3). The main stratigraphic components of this area (summarized in Fig. 4) are: Paleocene-Eocene rocks of the Georgia Basin, formerly termed the Ksitulino and upper Burrrd formations, but here renamed Huntington Formation in recognition of their correlation to the overlying Paleocene-Eocene Huntington Formation of the Canadian Sumas Mountain (formerly believed to be upper Eocene to Oligocene age); the Paleocene-Eocene Chuckanut Formation of Washington State; minor Oligocene igneous rocks; and Miocene sedimentary rocks known from surfacem drilling.

Previous studies and stratigraphic terms

Early investigations of the Vancouver area geology are reviewed by Johnston (1923) and Rouse et al. (1975). A report of coal on the south shore of Burrard Inlet (Wood, 1859, pers. comm. to Captain G.H. Richards, H.M. Surveying Ship "Flapper" reproduced in Bullock, 1971) provided the first mention of the sedimentary rocks of the Vancouver area. Subsequent investigations included brief descriptions of the sedimentary rocks of the area, but no stratigraphic subdivision and early studies suggested a Cretaceous, and later studies a Tertiary age for the entire succession (e.g., Baumber, 1885; Bowman, 1888; LeRoy, 1906; Bowen, 1913; Cameron, 1918). Daly (1913) defined the first formation, suggesting a Eocene age and the name Huntington Formation for the sandstones and conglomerates of Canadian Sumas Mountain (Fig. 7).

Johnston (1923) conducted the first comprehensive regional geological study of the Vancouver area. He subdivided the sedimentary rocks of Vancouver into a basal Burrrd Formation and overlying Ksitulino Formation.
suggested both formations were Eocene age, and described strata from a hydrocarbon exploration drillhole (wellsite 4 on Fig. 3), which he suggested were Pliocene to Miocene in age and named the Boundary Bay Formation. Subsequent studies of the Burrrard Formation determined that the lower 600 m of the succession is Late Cretaceous in age (Rouse, 1962; Crickmay and Pocock, 1963), leading Rouse et al. (1975) to propose redefinition of this Upper Cretaceous succession as the Lions Gate Member of the Burrrard Formation (discussed below). Hopkins (1968) confirmed the presence of a thick succession of Miocene strata in the subsurface at the Fraser Delta area.

Paleogene sedimentary rocks exposed in the Bellingham area and to the east in southwest Washington State are classified as the Chuckanut Formation, with the exception of a small outlier of sedimentary rocks exposed on a ridge named Sumas Mountain (termed "U.S. Sumas Mountain" in this study) to distinguish from the "Canadian Sumas Mountain" of the Abbotsford area and correlated with the Huntington Formation by Miller and Misch (1963). The Chuckanut Formation comprises up to 600 m of limestone, dolomite, and chert. The underlying sequence consists of 70-80% clasts in a medium-grained gravel matrix. The lower, poorly sorted and clast-rich matrix-supported conglomerates are present. Clasts are subangular to subrounded, generally subrounded and randomly oriented, but rarely display poor tabular clast imbrication. Clasts compositions are >50% diorite or granite, and the remainder mafic volcanic or ultramafic, all types typical of the lower Coast Belt basement. Bed contacts are indistinct. Conglomerate intervals several metres to more than 10 m thick contain poor normal or reverse grading in some parts, indicating amalgamation of thinner (?1-3 m thick?) beds. Rare interbeds of coarse grained arkose are up to 1 m thick are commonly observed as cross-stratification and imbrication of tabular clasts, and are erosive into underlying sandstones in a geometry of overlapping irregularly based sheets. Sandstones are crudely banded to wavy and discontinuous and contain rare silt-filled logs up to 20 cm diameter and 1 m length. Drillhole data and intermittent exposures in Brokerr Creek show that this basalt conglomerate-rich interval is overlain by more than 50 m of brown weathering, medium grey, arkosic arkite with mudstone interbeds increasingly common upwards (unit 2 of Rouse et al., 1975). The sandstone is medium to coarse grained, slightly thick bedded, and occurs in discontinuous overlapping sheets with curved bases (some pebble-rich). Poorly exposed through crossbeds are rarely present.

The covered interval between Brothers Creek and Prospect Point at Stanley Park can be characterized from extensive engineering test drillhole information from Burrrard Inlet and the Burrrard River delta. Originally described in Rouse et al. (1975) this interval is about 350 m thick, although minor faults may be present, and consists of a lower section about 150 m thick of interbedded sandstone and sandy siltstone which is probably a continuation of the glacially floored

Figure 5. A) Main area of outcrop of Upper Cretaceous strata underlying Palaeocene-Eocene rocks in west end of North Vancouver, outlined and uplifted and andesitized. B) Simplified cross-section A-B-C-D, modified and extended from the section of Rouse et al. (1975). Line of section is located on Figure 5A. C) Ternary plot summary of sandstone detrital clast compositions (redrafted from data of Neufeld, 1973, sandstone classification boundaries of Detto, 1964).
upward succession exposed in Brothers Creek. This section gradationally changes upward to about 150 m of mudstone, siltstone, and minor sandstone. ("sandy shales" in the original engineering reports, unit 3 of Rouze et al., 1975). This sandstone-rich interval is overlain (either abruptly or with a thin gradational contact) by about 40 m of medium- to coarse-grained sandstone which is the basal part of the exposed sandstone unit at Stanley Park (unit 4 of Rouze et al., 1975). The Late Cretaceous sandstone which makes up the cliffs in Stanley Park north of Third Beach are about 200 m thick and comprise coarse- to medium-grained arkose arenite organized into overlapping troughs or channel forms each 10 m to more than 30 m in length and up to 5 m thick. Complex overlapping and erosion of layers by higher channels has obscured the original sequence, but a composite complete cycle typically has a pebble rich, curved base which changes upward to trough crossbedded or wavy planed bedded sandstone, capped by plant crossbedded or plane bedded sandstone and rarely by silty mudstone. Mudstone ripples are common in the sandstones, especially at channel edges. Coalesced plant material (including large branches) are rare to common. No marine micro- or macrofossils have been recovered. Paleocurrents measured from planar crossbeds are consistently southwest directed (Fig. 6A-B).

The lithofacies described above suggest alluvial fan debris flows and lower fan braided stream and sheetflow deposition for the lower conglomerate-rich succession, braided plain and perhaps floodplain fluvial deposition for the sandstone and mudstone of Brothers Creek and most of the Burnet Island covered interval (possibly including lacustrine deposition for the mudstone dominate part of this interval), and coarse-load sand-dominant meandering river deposition for the upper part of the succession. The locally derived clasts, lack of sorting or organized bedforms in the lower conglomerate, submat and coarse, arkosic nature of the sandstones, and generally south to southwestern paleocurrents all indicate provenance from nearby uplifted Coast Belt sources.

Subsurface Cretaceous strata

In addition to the exposed "Lions Gate Member", several exploration wells in the Fraser delta area have intersected Upper Cretaceous strata. Hopkins (1966) identified probable Late Cretaceous palynomorphs from the lower 1300 m of the Richfield Point Roberts well and the lower 600 m of the Richfield Sunnyside well (wells 7 and 8 on Fig. 3, also shown on Fig. 15, below). This was confirmed for the Sunnyside well by more recent palynological studies (Mustard and Rouze, 1991) which also identified Cercomamnium and Albian sedimentary rocks in the lower 20 m of the well. A recent exploration well in northwest Washington State (AHEIL Birch Bay, well 11 in Fig. 3; also shown on Fig. 15, below) intersected about 1000 m of strata interpreted as Late Cretaceous (to possibly Paleocene) at the base of the 2781 m deep well (Hurst, 1991). Resampling of the Birch Bay well cuttings and continued work on the Sunnyside well samples for this study has allowed a more precise definition of the Cretaceous strata in the subsurface of these areas. In addition, re-examination of the well cutting from the Point Roberts well for this study showed that this well drilled completely through the Cretaceous-Tertiary section (not reported in original drill logs), intersecting quartz diorite in the lower 30 m of the hole, and providing the only complete penetration of the Georgia Basin succession in this part of the basin.

Palyzoon

The Upper Cretaceous rocks flanking English Bay and from wells in Boundary and Birch bays have yielded a large and well preserved palynoassemblage. Some of the more characteristic spores and pollen are illustrated in Plate 1. Others have been reported earlier by Rouze (1962, 1977), Crickmay and Proctor (1965), Hopkins (1965), Rouze et al. (1971), and Mustard and Rouze (1991). The overall assemblage is dominated by fern spores (Pl. 1, fig. 1-6, 9, 10), and the angiosperm pollen Protoceratites submagnus (Pl. 1, fig. 11, 12) and Tricolpoites diversus (Pl. 1, fig. 14-16), together with pollen representing the tree genera Fraxinus (ash) and Quercus (oak). The other pollen represent herbaceous genera that comprised most of the ground cover. Taken together, the assemblage represents most closely a fen-type of vegetation colonizing relatively flat lowland areas between estuarine or deltaic depositional sites. Based on the affiliation of the spores and pollen with modern taxa, together with the leaves identified by Bell (1957) from the Nanaimo Group on Vancouver Island, the paleoclimate is interpreted as very warm temperate to subtropical, probably similar to the present-day climate of the Gulf Coast of North America.

The English Bay palynoassemblage has been equated most closely to palynoassemblages of the Protection Formation of Vancouver Island, described as mid-Campanian by Muller and Keltzky (1970). However, some of the key palynomorphs such as Protoceratites submagnus, Capesicacites spp., Clepionisporites spp., and Quercosporites spp. also occur in other Nanaimo Group formations (e.g., Extensia, Comox, and Spray). Although many of these have been reported from other rock units in the western region of North America, e.g., the Maastrichtian-Danian of California (Drugg, 1967), and the Maastrichtian of Wyoming (Fairbairn and Cankite, 1986), the assignment of the English Bay assemblages to a Sanonan-Campanian range would seem to be most reasonable until additional detailed analyses are undertaken.

Correlation to Nanaimo Group of Vancouver Island

The relationship of the Upper Cretaceous stratigraphy on the east side of the Georgia basin to the Nanaimo Group is not well defined. The scant palaeocurrent data from the lower Burnet Formation suggests southwestward and westward paleoflow directions towards the main area of Nanaimo Group sedimentation (Fig. 6A, B, also Johnston, 1923; Rouze et al., 1975; Mustard, 1990). The subsurface strata tentatively identified as Cretaceous appear to thicken to the west and are continuous across the basin (Machacek, 1971, White and Clowes, 1984; Goddy, 1988). The palyxooassemblages are most similar to those from the Campanian Protection Formation on Vancouver Island, although several key types occur.
in other Nanaimo Group formations. A lithostratigraphic comparison to Vancouver Island Nanaimo Group rocks suggests a slightly different correlation, with the poorly sorted and lithologically derived basaltic conglomerate strongly resembling the lower part of the Comox Formation, the basal unit of the Nanaimo Group elsewhere in the basin (generally Sarmatian in age). In the lower unit, the finest upward trend into interbedded sandstone and mudstone, and subsequent coarsening upward into pebbly sandstone at the top. This successional pattern is similar to the Comox-Harlan-Bawnan facies successions on parts of Vancouver Island.

We suggest that this poorly exposed succession is best termed lower Nanaimo Group and does not warrant formal formation status. Previous practice referring to this unit as the lower Burred Formation (Loots Gate Member) promotes confusion with Paleocene-Eocene age rocks previously assigned to the upper Burred Formation, which we suggest below should be amalgamated with rocks previously assigned to the Kiskilano Formation and termed the Kiskilano Member of the Huntington Formation. In addition, the scattered and generally poorly exposed nature of the outcrops in the Burred Inlet-East Bay area probably definition of a type section or even meaningful reference sections, a prerequisite of formal formation definition as used in the North American Stratigraphic Code (1983). For these reasons, we suggest the term Burred Formation, and thus Loots Gate Member, should be abandoned.

**Paleocene-Eocene Huntington Formation (redefined)**

The Huntington Formation was originally described by Daly (1923), based on exposures at Canadian Sumas Mountain (Fig. 2, 3, 7A-C), and named for the town of Huntington (Fig. 2). The age of the Huntington Formation based on paleontology was considered Middle to Late Eocene (Hopkins, 1966), or Late Eocene to Early Oligocene (Daly, 1912; Roux et al., 1990). Detailed examination of new exposures at Sumas Mountain has provided evidence that the Huntington Formation includes Late Eocene to Early Eocene strata at the base and thus is coeval with strata previously termed upper Burred and Kiskilano formations at Vancouver (documented below). The open pits and cliffs at Canadian Sumas Mountain provide vertical and lateral exposure of this succession and are suitable for further exploration elsewhere in Fraser Valley or Greater Vancouver area. For these reasons, we here formally redefine Huntington Formation to encompass the ~Late Eocene to Early Eocene stratigraphy of the lower mainland, superseding the terms upper Burred Formation and Kiskilano Formation. Kiskilano Formation we suggest be redefined as the Kiskilano Member to denote the Paleocene-Eocene successions in the Vancouver-Summes area. Hopkins (1966) also concluded that upper Burred and Kiskilano formations were part of a continuous and indistinguishable succession and named the Kiskilano Formation. Fortunately (but a common name should be used for these strata and that the Huntington Formation be used for the entire age of the upper Burred and Kiskilano formations. The original definition of the Huntington Formation by Daly (1923) did not include a type section. Figure 8 illustrates a proposed composite-type section (located on Fig. 7A), all from Canadian Sumas Mountain.

**Huntington Formation: Canadian Sumas Mountain**

The Huntington Formation at Canadian Sumas Mountain, British Columbia, includes Late Paleocene and Early Oligocene successions of terrestrial clastic rocks greater than 425 m thick (top not exposed). Stratification unconformably overlies intensely weathered and altered Jurassic volcanic rocks of the Harrison Lake Formation (Fig. 7A). The weathered material (kaolinitic saprolite) on the unconformity is incorporated into mudstones of the lower Huntington Formation and includes highly refractory clay (fireclay), which have been mined since the 1920s (Kerr, 1942; Cummings and McCammon, 1952; Horton, 1978).

**Lithofacies and sedimentology**

The transition coarsens upward (Fig. 8) from a mudstone- and fine-grained sandstone-dominated lower section (Fig. 9A) of about 100 m thickness to an increasingly conglomerate-rich upper part which is roughly organized in repeated coarsening-upward cycles (50-100 m scale). Sandstone is fine- to very coarse-grained, chert-rich arenite, and in the lower part of the formation occur in large lenses 100 m in width and up to 10 m thick (Fig. 9B, C). These are interpreted as major fluvial channels in a floodplain environment. Previous interpretations of depositional environments have focused on the origin of the fireclays, which Horton (1978) concluded were either preserved relictly or slightly transported and deposited as fluvial or dune sheet sands. These occur as complexly stacked and overlapping channelized beds at the tops of the coarsening-upward intervals (Fig. 9E). They are interpreted as lower alluvial fan facies and braided stream deposits which prograded over the floodplain facies. Cross-bedding in sandstone and conglomerate clast fabrications indicates palaeoflow ranging from southwest to northeasterly (Fig. 7B). Conglomerate clast compositions are dominated by dark gray to black chert (Fig. 7C), probably derived from the Vedder Complex or Cascade. Sources to the east or south, where such chert types are common.

**Huntington Formation: Kanaka Creek**

Johnston (1923) briefly described a succession of sandstone and mudstone at Kanaka Creek on the northeast side of the Fraser River west of Mission (Fig. 2, 16A-D) which he tentatively correlated with the Kiskilano Formation. A borehole described by Johnston from near the mouth of Kanaka Creek contained 380 m of interbedded sandstones and mudstones grading sandstone, blue and grey shale, and minor conglomerate and lignite. The basal contact with nonmarine sediments rocks was not reached in this well. The outcrop at Kanaka Creek is about 65 to 75 m thick and probably represents a lower part of the drillhole described by Johnston (1923). Projected for the lowest sedimentary beds northwardwards exposed Coast Belt intrusions suggests the exposed sedimentary succession is within 100 m stratigraphically of the underlying granitic rocks.

**Figure 7**: Canadian Sumas Mountain, summary maps.
Figure 8. Measured stratigraphic sections from Canadian Sumas Mountain. Main section at left is a composite drawn from the detailed sections at right (measured in mining pits and cliff exposures located on Fig. 8), while section measurements by the senior author in streams on the south side of Sumas Mountain, drillhole data from nine explorations summarized in Cummings and McCommon (1952), and section measurements by Kerr (1947). Conglomerate clast composition plots use same symbols as pits of Figure 7.

Figure 9. Canadian Sumas Mountain outcrop photos. A) Pit wall exposure of lower Huntingdon Formation mudstone (darker units in photo are red-brown in outcrop) which cap fine grained sandstone and siltstone (light to medium grey). Units appear laterally continuous on scale of open pits (about 100 to 200 m) and are massive to faintly laminated and fine upward slightly. Sandstone-siltstone bases are planar to broadly convex up on underlying mudstone. Interpreted as floodplain and small lacustrine deposits. GSC 1994-712A. B) Part of central pit at Sumas Mountain showing parts of overlapping pebbly sandstone channel forms (main wall on right). These major sandstone units have convex upward bases which are erosive on underlying fine grained sandstone and siltstone. Thickest exposed pit wall is about 35 m high. GSC 1994-712B. C) Part of central pit displaying small and laterally discontinuous medium- to course-grained sandstone units (with thick more continuous pebbly sandstone at top of pit) contained within fine grained sandstone and planar laminated siltstone to silty mudstone. Interpreted as small fluvial channels and crevasse splay deposits in a floodplain environment. GSC 1994-712C. D) One of several upper cliffs of Canadian Sumas Mountain. Cliffs consist of complexly overlapping and laterally discontinuous normal graded pebbly conglomerate beds and very coarse grained sandstone (rarely cobble-rich at bases of beds). Beds are generally internally stratified with wavy planar bedding and small trough or planar crossbeds (commonly at tops of beds). GSC 1994-712D. E) Upper cliff exposure showing complexly overlapping trough crossbedded and discontinuous pebble conglomerate and coarse grained sandstone. Interpreted as deposits of braided stream bar forms. Scale card is 9 cm on longest edge. GSC 1994-712E.
The fining-upward cycles dominated by coarse- to medium-grained sandstone, overlapping curved erosive bases, abundance of mudstone ripples and plant debris, and moderate sorting of these sandstone units is similar to both the lower part of the Canadian Sumas Mountain exposures and lower Kitiliano Member facies described below. These cycles are interpreted as sand-dominated meandering river deposits. The discontinuous interbeds of plant-rich mudstone represent areas of channel bank or interchannel deposition in floodplains and small lacustrine bodies of water.

Huntingdon Formation, Kitziliano Member of the Vancouver area (formerly Upper Burrud and Kitiliano).

The Kitziliano Formation was defined by Johnston (1923) to include a thick package of conglomerate, sandstone, and minor mudstone which he suggested disconformably overlies the Burrud Formation in the Vancouver area, both dipping 10-15° to the south. As discussed above, the lower Burrud Formation contains Late Cretaceous palynomorphs and is correlated with the lower Nisnasino Group. Johnston (1923) suggested an unconformity is present on the south shore of Burrard Inlet (in outcrops no longer exposed) in which a succession (up to 300 m thick) of conglomerate unconformably overlies a sandstone-dominated unit. He interpreted the conglomerate as basal Kitziliano Formation and the under- laying sandstone as upper Burrud Formation. Examination of temporary exposures of this conglomerate unit during road construction in this area (shown on the Fig. 11 map by an X south of Second Narrows bridge) and of the original photograph of the interpreted unconformity (Johnston, 1923, his Plate III) suggests this contact is one of several erosive channel bases within the conglomerate-rich facies of this lower Tertiary unit (as in Fig. 12A), and does not represent a significant time gap or formation boundary, as confirmed by the new palynological information presented below (Hopkins, 1966 reached a similar conclusion based on the general aspect of the two successions and his palynology study). Thus we suggest that these strata be treated as a single entity and propose the term Kitziliano Member in recognition of the previously widely published term Kitziliano Formation. The latter we propose to replace with the regional name Huntingdon Formation, which also includes strata previously termed upper Burrud Formation.

Lithofacies and sedimentology

Hopkins (1966) measured 750 m of the Kitziliano Member north of Matilco, during construction of a major sewer tunnel in this area. To this minimum thickness, about 300 m can be added from the Paleocene-Lower Eocene strata of Stanley Park, formerly termed upper Burrud Formation, to give a total minimum thickness of more than 1000 m for the Kitziliano Member, but with no top defined. The projected thickness calculated from the map pattern and assuming no major faults is about 1200 to 1300 m. This is slightly thinner than the 1500 to 2400 m thickness of Paleocene-Eocene strata present in the few subaqueous wells on which detailed palynological studies have been completed (wells 5, 7, 9, 12, and 14 in Fig. 3; detailed in a separate section below), and significantly thinner than the estimated 6 km thickness of Paleocene-Eocene strata measured in the Bellingham area as calculated by Johnson (1982, 1984a, b).

The main lithofacies of the Kitziliano Member are known from scattered outcrops in Stanley Park, Kitziliano Beach, Burrud Mountain, Brunette Creek, the Granville railway cut (Broadway and Victoria streets), and from a 1991 drill core near Capilano Hill (Fig. 11). In addition, temporary exposures are common at construction sites in downtown Vancouver and areas immediately to the east and south and several were examined for this study (1992) also summarized logs of drill core from two hydrocarbon exploration wells drilled about 1918-1920 southwest of Burburn Mountain (wells 1 and 2 in Fig. 5). These wells intersected 610 m and 876 m of sedimentary strata (about 575 m and 850 m true thickness), all probably Kitziliano Member, but possibly including an unknown amount of Upper Cretaceous rocks. From the relative stratigraphic position of these outcrops and the associated wells the Kitziliano Member appears to consist of three units: a lower unit (about 250-300 m thick) of interbedded sandstone and minor mudstone, a middle unit (about 200-300 m thick) in which conglomerate is common, and an upper unit (300 m thick) of sandstone and mudstone similar to the lower unit. However the conglomerate-rich facies is not laterally persistent and conglomerates are less common to the southwest and south of the Burrud Mountain-Second Narrows areas.

A recent (1991) drill core from the Chevron Refinery north of Capilano Hill is illustrated in Figure 11 and is typical of the sandstone-mudstone lower and upper units of the Kitziliano Member. Map relationships suggest the drill core section represents basal Kitziliano Member and the lower part of the hole could include Upper Cretaceous strata, although palynology samples from this core proved barren. The best outcrop exposures of this facies occur on the southwestern part of Stanley Park (e.g., Ferguson Point), at Kitziliano Beach, in the Granville railway cut (Fig. 12B), and at Brunette River east of Brunette Lake, the latter part of the upper unit of the Kitziliano Member (all located in the Fig. 11 map). The lower succession comprises repeated 1-5 m thick fining-upward cycles of medium- to coarse-grained lithic to arkosic arenites which grade upward to fine-grained sandstones, siltstone, and dark grey mudstone, commonly carbonaceous (see Thomson, 1958 for detailed petrography of the sandstone). The bases of the fining-upward cycles commonly have erosive contacts, and pebbles and mudstone ripples are in many places present in the lower 10 cm of the sandstone beds. Sandstone is massive to planar crossbedded or wavy and trough-crossbedded in lower, coarser sections and wavy bedded or planar crossbedded in upper, finer sections. Plant debris and coaly lenses are common in some places. Mudstone and siltstone sections are generally less than 50 cm thick, rarely 5 m thick, and finitely laminated to massive where thin, but consist of 1-2 cm thick normal graded siltsolate-mudstone rhythmites in thicker sections.

Conglomerate in the middle unit of the Kitziliano Member is rarely exposed. Figure 12A illustrates an unusually well exposed example of the conglomerate-rich facies at the base of Brunette Mountain (now covered). Conglomerate occurs as moderately sorted stacked discontinuous sheets or lenses which overlap laterally and have slightly curved bases erosive into underlying strata. The conglomerate comprises about 80-90% pebble and small cobbles in a coarse grained to granular arkosic matrix. Clasts are generally subrounded, but tabular clasts are present and a few to white feldspar imbrication can be defined in some places. Conglomerate beds are generally 0.5 to 1 m thick and grade upward into coarse pebbly sandstone (Fig. 12C) and in rare complete sections are capped
A) Temporary vertical exposure (1993) on Barnett Highway at southwest end of Burnaby Mountain, illustrating typical conglomerate facies of central Kitsilano Member in this area. Pebble-cobble conglomerates grade in upper 10-20 cm to coarse- to medium-grained sandstone which are planar to slightly wavy-bedded (rarely crossbedded) and rarely capped by carbonaceous silty mudstone. Shallowly left-dipping beds in centre of photo represent lateral migration of conglomerate channels and sand bodies with complex intertonguing of facies laterally. Total height of outcrop is about 30 m. GSC 1994-712F

B) North-facing cliff at Grandview railway cut (about 50 m vertical in 1992 photo, now partly covered) illustrating slightly irregular stacked sheets of coarse-grained sandstone beds (light grey in photo) with discontinuous silty mudstone caps (medium grey in photo) which are cut out by slightly erosive and irregular base of overlying sandstone. GSC 1994-712G

C) Same outcrop area as in A, showing stacked and laterally overlapping bedded pebble-cobble conglomerates with rare discontinuous capping coarse-grained sandstone. Bedding is defined by rare sandstone and by slight normal graded layers at tops of some conglomerates. Larger cobbles are also generally concentrated at the bases of beds. GSC 1994-712H

D) Outcrop on Joe’s Trail, Burnaby Mountain showing lenticular pebble-cobble conglomerate which fines in upper part and intertongues laterally with coarse- to medium-grained sandstone. Outcrop is about 5 m maximum vertical exposure. GSC 1994-712I

Figure 12. Kitsilano Member outcrop photos.
by a few tens of centimeters of brown to medium gray siliciclate and silty mudstone, in total defining mudstone-shale cycles about 2-3 m thick (Fig. 12A). The mudstone and shale are characterized by their fine grained and plant debris content. More commonly, mudstone with some silt and fine sand can be recognized in some samples. Lateral and vertical facies changes result in these cycles, with the most noticeable change occurring in color from dark brown to gray-brown to black. The facies of the Kitssham Member are similar to those described above from Canadian Sumatran Mountain and Kanka Creek in a similar alluvial interpretation. These facies are dominated by fine-grained sediments, such as silt, mud, and clay. The lower part of the cycle is characterized by fine-grained sediments, including sandstone and siltstone, while the upper part is dominated by fine-grained sediments, such as silt and clay. The lower part of the cycle is characterized by fine-grained sediments, including sandstone and siltstone, while the upper part is dominated by fine-grained sediments, such as silt and clay. The lower part of the cycle is characterized by fine-grained sediments, including sandstone and siltstone, while the upper part is dominated by fine-grained sediments, such as silt and clay.
area (the few mining attempts are reviewed) in Moen, 1962). However, the overall coarsening-upward trend of the Canadian exposures is not apparent in the Washington State exposure. Basal conglomerates at the unconformity is composed of blocks of the underlying lithologies (well exposed over laterally short intervals at the contact with the ultramafic body as shown in Fig. 13A). These are overlain by conglomerate interbedded with fine- to coarse-grained lithic arenite. Many of the conglomerate units in the lower part of the succession are cobble rich, with rare boulders and display vague bedding, poor sorting, no internal fabric, and high amounts of poorly sorted matrix to granule matrix (both matrix-supported and matrix-rich clast-supported types are present). However, most conglomerate is moderately sorted and generally occurs as overlapping lenses of normal-grained pebbles-cobbles with slightly channelized bases erosive into underlying beds (Fig. 14A). Both plane and trough cross-bedding is present in some conglomerates (Fig. 14B). These conglomerate beds are interbedded with medium- to very coarse-grained lithic arenite, commonly with 10-20% small pebbles. Some sandstone beds either are gradational from underlying conglomerate, forming fining-upward beds 1-2 m thick, or sharply overlie conglomerate as separate pebbly sandstones. Both types are commonly horizontally thin bedded, with less common planar or trough crossbeds, and massive or normally graded. Crossbeds and clast imbrication indicate paleoflow directions ranging from north to southwest (Fig. 13B). The conglomerate contains high percentages of ultramafic, metavolcanic, and metaaquatic clasts (Fig. 13C), all types common in older rocks underlying and east of the formation, suggesting a local source.

The most likely depositional environment was a braided stream and shelf/sand deposit system on the lower part of an alluvial fan or fan-proximal braided plain. The overlying, moderately sorted, and shallowly channelized conglomerate sheets and interbedded coarse-grained conglomerates are typical of the gravel and sandy bar forms of braided fluvial systems (Miall, 1992). The gravel-rich and generally poorly sorted cyclic to noncyclic succession is similar to the Scott type of braided fluvial facies model, although transitional in some places to a Donjek type system (both defined in Miall, 1997). The poorly sorted, disorganized conglomerate units of the lower succession are interpreted as debris flows and suggest a lower alluvial fan setting for at least the lower part of the succession. The abundance of locally derived clasts and the coarse, poorly organized textures strongly suggest deposition along one margin of the basin for this time period. As at Canadian Samas Mountain, prolonged weathering at the unconformity surface is interpreted to have produced the kaolin-rich regolith, but most of the U.S. Samas Mountain fireclays appear to have been transported and deposited in small ponds or lakes (with dilution by other clastic material accounting for the lower quality fireclays).

Palynology and age controls
Miller and Misch (1963) correlated the sedimentary rocks on U.S. Samas Mountain with the Huntington Formation of Canadian Samas Mountain based on a perceived similarity of compositions, especially the presence of kaolin-rich clay
The Paleocene-Eocene component of this subsurface strata appears to be slightly thicker than implied from northern cutout exposures, with about 1500 m of section present in the Richfield Point Roberts and Richfield Sunnyside wells, increasing in thickness to about 2400 m at the American Hunter Birch Bay well.

Lithofacies and sedimentology

The main features of this subsurface unit and the overlying Mioocene strata are determined from electric logs, core and cut samples from the Conoco-Mad Bay well (provided courtesy of Conoco Exploration Ltd., Calgary, Alberta) and descriptions of the older wells (Johnson, 1923). The Eocene-Eocene intervals in these wells are sandstone-dominated, with interbedded mudstone and a common coarser-grained, moderately to well-sorted arkose to lithic arenite. Clay or siliceous cements are typical; clay or minor chlorite alteration of feldspars and rock fragments is common. Porosity varies from poor to good (generally <2%). Lithic fragments generally make up 10-30% of the sandstone framework with volcanic and plutonic rock fragments, chert, and micas all common. Mudstone is generally grey and variably carbonaceous with rare to abundant plant fragments. Coal occurs as thin, ribbon-like units. There is no evidence from the core lithofacies or from the core macrofossils of any marine component in this succession.

The general character of the subsurface Paleocene-Eocene strata is consistent with that of the surface exposures. The entire succession is interpreted as a thick (more than 2 km in some wells) fluvial sequence overlapped by a much shallower marine environment, as seen in the underlying channels as part of a sand-dominated fluvial floodplain. There is no evidence from the core lithofacies or from the core macrofossils of any marine component in this succession.

Lithofacies and sedimentology

The strata consist of poorly indurated, intercalated sandstone and mudstone with minor pebble conglomerate and coal. Electric logs show blocky and bell-shaped patterns typical of interbedded sandstone-mudstone interbeds and fining-upward sandstone-mudstone successions ranging from about 2 to 10 m thick. Sandstone are generally medium- to coarse-grained, arkose to lithic arenite, and moderately sorted, and with high clay matrix in some samples. Pebble conglomerate is rare, although sand- and silt-size quartz-rich beds are present in some thick sandstone units. Mudstone is generally grey (but green-grey and red muds are present) and commonly carbonaceous, with several thin sub-humiteous to lignitic coal parts or beds present at the top of fining-upward cycles. Johnson (1923) reported several thin ash beds in this succession, but at least two are not reported in subsequent well descriptions. Distinctive horizons are not present in well sections or geophysical logs and thus correlation between the widely spaced wells is not attempted. In general, formation-tops vary in grain size or composition are not apparent. An exception is the succession intersected in the Mad Bay well which shows a distinctive overall coarsening-and-thickening-upward trend from a lower unit about 150 m thick which comprises mostly mudstone, siltstone, and thin, fine grained sandstone interbeds to an upper unit about 700 m thick in which thick sandstone beds are common and are organized in stacked fining-upward cycles.

The stacked fining-upward sandstone-mudstone cycles of this Miocone sequence are interpreted as fluvial deposits similar to those of the underlying Eocene sections. Thicker cycles with pebbly sandstone bases represent major channels. Thin cycles and interbedded sandstone-mudstone successions represent meander, shallow pond, and possibly coarse sandy deposits. The presence of dinocon in some parts of

Figure 15. Stratigraphic cross-section from Burrard Inlet in North to Chukachau Mountain in south showing main Tertiary and Late Cretaceous units of Georgia Basin in this area. Exploration wells in which palynological age control are sufficient to delineate major unit boundaries are shown (except the Pelican Dome well which has no palynological control, but is shown because it intersects local basement on the line of section). Main faults are either projected from surface traces or known from petroleum exploration seismic lines in the southern part of the basin.
the sections provides the only evidence of marine influence in any of the Tertiary strata of the Georgia Basin. A marginal marine or estuarine setting is the most likely depositional environment for these marine intertongues.

Palywogy

Hopkins (1966, 1968) studied the palynovassemblages from cuttings obtained in two drillholes (Fig. 15 and wells 7 and 8 of Fig. 3). He determined a Miocene age for the upper succession in these wells, estimating the thickness of the Miocene to be about 1200 m in both drillholes. A more recent palynological study of the well material by Rouse et al. (1990) also determined a Miocene age for these strata and informally termed the "South Westminster formation" for a single poorly exposed outcrop south of the Fraser River in South Westminster.

Chuckanut Formation, northwest Washington State

Johnson (1982, 1984a, b, c, 1985, 1991) completed the most recent sedimentological and stratigraphical analysis of the Chuckanut Formation. Several M.S. graduate theses provide additional studies of local areas or specific aspects of the Chuckanut Formation deposition (Kelly, 1970; Pontigapich, 1970; Hartwell, 1979; Robertson, 1981).

Lithofacies and sedimentology

Johnson (1984b) subdivided the 6 km thick Chuckanut Formation into seven members, since revised to six (Johnson, 1991; Fig. 3, 16A). To simplify this brief review, the Chuckanut Formation has been grouped into lower, middle, and upper subdivisions. The lower subdivision comprises the Bellingham Bay Member, a 3300 m thick succession of stacked and overlapping fining-upward cycles of conglomerate (sandstone and mudstone). Johnson (1984b) provides a detailed description of Bellingham Bay Member stratigraphy and sedimentation. The member is both thickest and coarsest in eastern exposures and paleocurrents demonstrating a radial but in general south to southwest pattern of paleoflow (Fig. 16B). Conglomerate clasts are predominantly chert, mafic volcanic, or sedimentary, but several other types are present (Fig. 16C). Bellingham Bay Member sandstone is arkose (micaceous in places) and generally medium- to coarse-grained in lower parts of cycles, and fine-grained in upper cycles. The stacked sandstone (conglomeratic in places) to mudstone cycles occur both as multi-story sheets or as tabular bodies with the deposits of fluvial meandering river systems and as ribbon sandstones within relatively mudstone rich units, interpreted as floodplains channel or crevasse splay deposits. The middle Chuckanut Formation comprises the Governor Point Member which directly overlies the Bellingham Bay Member in western and central outcrop areas (Fig. 3, 16A), the Slide Member, present only in the eastern outcrop areas, and the Padden Member which is the western equivalent to the Slide Member (and probably equivalent to the upper Chuckanut Formation described below). The Governor Point Member thins eastward from a maximum of 375 m in western exposures and consists of amalgamated fining-upward couplets of trough crossbedded and planar bedded medium- to coarse-grained lithic arenite with a central succession of massive to crudely stratified conglomerate and poorly sandstone. The Slide Member is about 2 km thick and consists of fining-upward sandstone-mudstone cycles with similar geometries and compositions to those of the underlying Bellingham Bay Member. The Padden Member thickness is not well-constrained, but a thickness of more than 3 km is suggested from map patterns in western outcrop areas. The upper part of the Padden Member is poorly exposed and dips beneath Quaternary cover at the northern limit of Chuckanut Formation exposures east of Bellingham (Fig. 3). A Palogene succession more than 500 m thick on Sucia Island was included with the Padden Member by Johnson (1982, 1984b), but is discussed separately in this study. The Padden Member is dominated by medium- to coarse-grained lithic arenite, complexly interbedded with massive to crudely stratified or crossbedded conglomerate, both rock types alternating with laminated mudstone and minor coal.

A) Schematic diagram of the six members defined by Johnson (1982, originally as seven members, modified in Johnson, 1991). Pattern fills reflect the major lithofacies of the member as summarized in the text.
B) Summary of paleocurrent data for mainland Chuckanut Formation occurrences (not including the Coal Mountain area studied by Robertson, 1981, or the Sucia Island chain, reported on separately in this study). Data compiled from Johnson (1982; pers. comm., 1992) and Hartwell (1979). Lower, middle, and upper Chuckanut divisions are as defined in Figure 16D.
C) Conglomerate clast compositions from mainland Chuckanut Formation (not including Sucia Island chain, reported on separately in this study). All data from Johnson (1982). Clast composition patterns are the same as defined in Figure 22.
D) Summary of sandstone detrital clast data for mainland Chuckanut Formation using the framework mode subdivisions and tectonic provenance divisions of Dickinson and Suczek (1979) as modified by Dickinson et al. (1983 for QFL and QmFL plots). The mean value of each stratigraphic subdivision is shown with the defined symbol with a polygon representing the standard deviation of the mean. Table 2 provides numerical summaries of the data and sources of information. Figure 22A provides an explanation of the tectonic provenance field divisions.

Figure 16. Chuckanut Formation summary diagrams.
Paleocurrents generally indicate northerly to eastern source areas (Fig. 16B). Sandstone is arkose to lithic with a distinctively higher component of chert and volcanic lithic fragments than the underlying Chukatch Formation (Fig. 16C). Conglomerate clast compositions also show an increased abundance of chert relative to the Bellingham Bay Member (Fig. 16D). All clast types are typical of local basement lithologies, suggesting local derivation of clasts from marginal, high relief areas. The Slade Member is interpreted as primarily a series of fineto sand-sized meandering fluvial systems, similar to the Bellingham Bay Member. The Governors Point Member is interpreted as braided fluvial deposits derived from local high relief areas, possibly related to syndepositional faulting Johnson, 1982, 1984, inferred north of the deposit. The Padles Member is interpreted as coarse-to-fine gravel and braided river deposits mostly derived from the north or northeast. Conglomerate clast types suggest a predominantly Coast Belt source, especially for Padles Member deposits.

The upper Chukatch Formation consists of the Maple Falls and Warnick Members, both restricted to eastern outcrop areas (Fig. 3, 16A). The Maple Falls Member is estimated to be about 300 m thick and appears to traditionally intergrade with the Slade and Skide members to the west and south, and to intergrade with the Warnick Member to the east, although original contact relationships are obscured by faulting and poor exposure. The Maple Falls Member consists of clast-supported conglomerate in thick (some 12 m), massive, boulder-rich beds and thinner more stratiﬁed beds with common clast imbrication. These conglomerates are interbedded with crossbedded to massive sandstone and massive to laminated mudstone. In addition, thicker interbeds are dominated by mudstone containing abundant lenticular beds of massive sandstone to pebbly sandstone. The Warnick Member is possibly up to 1000 m thick (based on map patterns) and contains conglomeratic-rich and mudstone lithofacies similar to the Maple Falls Member. Both members are interpreted as interfingering alluvial fan and alluvial plain deposits. Palaeocurrents are west to southeast-directed in the Warnick Member and south directed in the Maple Falls Member. Conglomerate clasts are dominantly chert and maﬁc volcanic rock types and sandstone contain significantly more chert and volcanic lithic clasts than other members, although the Maple Falls Member is also arkosic in some places. Both conglomerate clast and sandstone compositions are compatible with local northern sources as implied by the palaeocurrent data.

Polyvortex and other age controls

The age range of the Chukatch Formation, based on early plant and palynological studies, was generally suggested to be Late Cretaceous to Eocene (Miller and Misch, 1963; Hopkins, 1966; Pabst, 1963; Griggs, 1971; Finzel, 1979). Rasmussen (1982) restudied the palynology and concluded that the Late Cretaceous palynoassemblages were reworked and that the non-reworked palynological evidence suggested a Middle Eocene to Early Eocene age. The recent palynological study of Rouse et al. (1990) also suggested a Paleocene maximum age. Johnson (1982, 1984b) obtained a zircon fission-track age of 49.9 ± 1.2 Ma from a buff bed situated in the middle of the Chukatch Formation succession (near the top of the Boundary Bay Member). He also estimated a maximum age for the Chukatch Formation from fission-track ages of detrital zircons as about 55 Ma, that is late Paleocene or Early Eocene, depending on the exact placement of the Paleocene-Eocene boundary (56.5 ± 2.5 Ma in Halden et al., 1990).

Oligocene igneous rocks

A series of igneous rocks occur as scattered separate dykes, sills, and possible flows along the northern edge of the preserved Tertiary basin (unit TV on Fig. 2). These were collectively termed the Prospect Point intrusives by Johnston (1923), named from the greater than 50 m thick dyke exposed at Prospect Point in Stanley Park (Fig. 5A). Other major igneous bodies include circular intrusions at Sentinel Hill (Fig. 5A) and Little Mountain, thin dykes at Kitson’s Bluff and in Brothers Creek and the Capilano Canyon, and a thick sill exposed at Grant Hill and Silverdale Hill west of Mission (Fig. 2). Other small igneous bodies, generally identified as sills or flows, have been reported from construction sites in the greater Vancouver area. A comprehensive study of these igneous bodies is contained in the unpublished theses of Blanchet (1943) and Wescott (1959) and by Hamilton and Dostal (1944). The igneous bodies are fine to medium crystal-line, have diatreme textures, are vesicular and angulp- bearing, and of andesitic to basaltic compositions. Columnar jointing is common in the thickest bodies. Most are otherwise intrusive into the containing sedimentary rocks. Wescott (1959) suggested some of the bodies could be either sills or flows, including the Sentinel Hill, upper Prospect Point, and Little Mountain bodies. Sketchley and Coffee (1976) con- ducted a gravity study of the Little Mountain body and suggested it was more likely a flow than a sill. Blanchet (1943) suggested that all occurrences originated as shallow intrusion, either dykes, sills, or small laccoliths. Potassium-argon dating of the Prospect Point and Little Mountain occurrences suggests they are Early Oligocene (32 ± 1, and 34 ± 1 Ma respectively, R.A. Armstrong, 1980, unpublished geochro- nological database, University of British Columbia). The Prospect Point body intrudes Late Cretaceous sandstone and the Little Mountain body occurs in the upper part of the Eocene Kitilsan Member; their near coeval dates suggest intrusive origin for both bodies. A sill interpretation is likely for the lower-dipping igneous bodies of this area such as the Grant Hill and Silverdale Hill examples, although neither has been studied in detail. The similar types of occurrences and roughly similar igneous bodies of this area such as the Grant Hill and Silverdale Hill examples, although neither has been studied in detail. The similar types of occurrences and roughly similar igneous bodies of this area such as the Grant Hill and Silverdale Hill examples, although neither has been studied in detail. The similar types of occurrences and roughly similar igneous bodies of this area such as the Grant Hill and Silverdale Hill examples, although neither has been studied in detail. The similar types of occurrences and roughly similar igneous bodies of this area such as the Grant Hill and Silverdale Hill examples, although neither has been studied in detail. The similar types of occurrences and roughly similar igneous bodies of this area such as the Grant Hill and Silverdale Hill examples, although neither has been studied in detail.
Tumbo and Sucia islands

Tumbo Island rocks, shown on published maps as part of the Late Cretaceous Nanaimo Group, contain Paleocene polymorphs (Mustard and Rowe, 1992). Most rocks of the Sucia Island chain (Fig. 18A) also contain Paleocene pollen, allowing correlation with Tumbo Island and the lower Chuckanut Formation on the mainland (Mustard and Rowe, 1992; suggested earlier by Vance, 1975; Johnson, 1982).

Lithofacies and sedimentology

The preserved section on Tumbo and Sucia islands is more than 500 m thick (Fig. 18B), comprising a lower sandstone-dominated succession of laterally overlapping and vertically stacked fining-upward sequences, each about 1.5 m thick. The sandstone is generally a medium- to coarse-grained, feldspathic to lithic arenite (Fig. 18E), with abundant broken carbonate and rare siliciclastic feldspar. Trough crossbedding is abundant (Fig. 19A). Planar crossbedding and pebble imbrication is common (Fig. 19B, C). The paleocurrent indicators display a wide variance in paleoflow directions, but the predominant flow direction ranged from northeast to southeast (Fig. 18D). An overall coarsening-upward trend is evident with conglomerate much more abundant in the upper part of the Tumbo Island succession and slightly more so at Sucia Island (Fig. 19D). The most abundant conglomerate clast type is black chert, commonly containing deformed and faulted white quartz veins. Aphanitic green-grey volcanic clasts are slightly less common, followed by subequal amounts of white chert (rarely quartzite), red chert (including jasper), and feldspar intrusive and sedimentary clasts (Fig. 18B, C), the last mostly massive, fine- to medium-grained arkosic sandstone.

Deposition occurred in a braided stream to lower alluvial fan system, flushed by mines with abundant feldspar and feldspar components, and low areas supporting angiosperms and coastal lowland conditions, compatible with a floodplain environment suggested above. The general lack of algal cysts also supports a terrestrial interpretation.

Figure 18. A) Composite measured stratigraphic section from Tumbo Island (located on inset map at lower left). B) Geology of the Tertiary and associated rocks of Tumbo Island, British Columbia and the Sucia Island chain, northwest Washington State. Paleontology sample sites are indicated by X. C) Conglomerate clast compositions combined from all thirteen sites from the four islands. See Figure 5 of Mustard and Rowe (1992) for compositions from individual sites. Clast counts were conducted by identifying all clasts encountered on a random line to a total of one hundred per site. D) Summary diagram of paleocurrent measurement data. Measurements have been corrected for fold plunge and bed tilt. Paleocurrent measurement sites are located on each island with an arrow which is also the vector mean. Current vectors for each site are shown near each locality and the same spatial grouping of the sites has been generally maintained. Current vectors are plotted using a nonlinear scale as advocated by Nemec (1988). Only sites with a Rayleigh significance test value less than 0.05 were used for paleocurrent analysis (method of Curray, 1956). Circular standard deviation was calculated using the method of Krause and Geioper (1987). E) Sandstone lithofacies compositions plotted on tectonic provenance ternary diagrams. Ternary plot fields and mode compositions are explained in Figure 23A. Numerical summaries of data and sources of information are given in Table 2.

LEGEND

- covered mudstone
- sandstone
- conglomerate
-... clastic imbrication
- trough crossbedding
- planar crossbedding
- ripple cross-stratification
- wavy bedding
- horizontal bedding
clasts are all compositions common on the San Juan Islands to the southwest. The sandstone clasts are identical to sandstone of the upper Nanaimo Group preserved in locations northwest of Tumbo and Sancia islands. The palaeocurrent and provenance and the proximal sedimentation patterns suggest these deposits formed near the western margin of the early Tertiary basin.

Palmology

Reasonably well preserved and representative palynomassensments were recovered from samples collected on the Sancia Island chain and Tumbo Island (Fig. 18A). The assemblages are dominated by fungal spores, with fewer angiosperm pollen and fern spores. Both are correlated with those from other rock units previously assigned to the Late Paleocene, particularly those from the Arctic and Rocky Mountain foothills region (Rouse, 1977), and from Lacquel Island (Mustard and Rouse, 1991). Diagnostic species include Multiloculiporites irregularis, M. giganteus, Inuptarpiorites elongatus, Staphilasporites allornus, Brachypappiporites cotaiti, B. cainana, Calilisetitites per balli, and Dictyastiliporites luteus among the fungal spores (and reproductive units). Diagnostic angiosperm pollen are Intrahtporecopollenin-Spp. (X-Tilia), Rhoipites cryptoporus, and Parasphragnites alterniporus. These species occur in assemblages immediately below the Eocene containing the earliest true Tilia pollen, i.e. Tilia wulvatitn and Tilia crassipilis. The angiosperm pollen Rhoipites cryptoporus, first described by Stefanska (1972) from the Paleocene in Alabama, is a diagnostic middle and late Paleocene palycocenfrom Arctic and western Canada (Rouse, 1977).

A) Cliff on southwest Tumbo Island showing large overlapping trough crossbedded, medium grained sandstone of Lower Paleocene unit in this area. Kayak is about 5 m in length. GSC 1994-7121
B) Overlapping irregular beds of planar crossbedded sandstone from central part of the Paleocene unit on Tumbo Island, probably formed as small bar complexes in this fluvial system. Measuring staff is 1.5 m long. GSC 1994-7122
C) Irregular to convex-up based pebble conglomerate grading up to and interbedded with coarse grained sandstone. Interpreted as braided fluvial deposits. Scale card is 9 cm on longest side. GSC 1994-7120
D) Exposure at Sancia Island from upper part of Paleocene section showing a 7.9 m thick succession of basal pebble-cobble conglomerate (base is at left edge of photo) which interfingers and grades at top into coarse grained sandstone. Sandstone is wary to planar crossbedded and includes several discontinuous beds (barforms) of planar and trough crossbedded pebbly sandstone. Conglomerate tongue at right edge of photo thickens to right into basal conglomerate of overlying conglomerate-sandstone cycle. Kayak is about 5 m long. GSC 1994-7120

Figure 19. Photos from Tumbo and Sancia islands.

A) Proximal to lower alluvial fan facies with sediment gravity flow gravel and pebbly mudstone deposits interbedded with sheetflood pebbly sandstones, all partly reworked in broad braided fluvial channels.
B) Lower alluvial fan to proximal braidedplain comprising low sinuosity shallow channels in which gravel and pebbly sand sheets, longitudinal and transverse bars are the major deposits.
C) Sandy braidedplain deposition in large barforms with relatively deep channels. Deposits from this type of fluvial system include thick compound bars or sand shoals and complexly overlapping gravel-sand channel sequences.
D) Sandy mixed-load meandering river. Deposition occurs in well defined channels by migration of channels and lateral accretion. In a sand-dominated system such as envisioned for most of the Paleocene-Eocene Tertiary Georgia Basin well developed fining-upwards cycles with thick mudstone capped are less likely than overlapping sheet sand geometries showing complex channel fill sequences and poor preservation of the finer components of channel fills.

Figure 20. Summary diagram of main fluvial depositional types interpreted for the Paleocene-Eocene parts of Tertiary Georgia Basin examined for this study. Schematic diagrams are modified from Miall (1985, 1992).
PROVENANCE AND SEDIMENTOLOGY SUMMARY

The lithofacies descriptions and interpretations of the previous sections indicate that the basin was dominated by alluvial depositional systems with alluvial fan debris flow; are both gravel-rich and sand-rich braided stream deposits common at the basin margins. Sand-rich braided and meandering fluvial deposition is the main process accounting for the bulk of the basin fill, with associated fluvialplain and possibly minor lacustrine facies also present. Figure 20A-D illustrates the main depositional processes interpreted for these environments. Sandstone occurs in predominantly overlapping irregular to sheet-like bodies where meanderstone facies occur as minor interbeds or capsing fining-upward channel cycles. The coarse sand and gravel facies are interpreted as the product of deposition in large sand- or gravel-bed braided rivers, more properly termed multiple-channel bedload rivers in recognition of the many variations and transitions between traditional braided and meandering channel models (Miall, 1985). In modern analogues, the overlapping sand or gravel sheets form by continued deposition as small and large bars forming in wide or small channels (see reviews in Cant, 1982; Miall, 1985, 1992). Where meanderstone interbeds are common, sandstone occurs both as sheets and ribbons, the latter probably representing small channel fills or crevasse splays deposits in major fluvialplain areas. In these environments, larger channels show evidence of lateral migration and both lateral and vertical accretion, possibly as point bars and typical of classical meandering river systems (Smith, 1987). However, a wide variety of vertical and lateral sediment bodies that span the range from low-mobility braided deposition to sinusoidal, singlechannel meandering deposition access more characteristic of the Tertiary Georgia Basin.

The presence of lower alluvial fan conglomerate and sandstone facies in eastern (Canadas and U.S. Summit Mountains), southeastern (Chuckanut Formation), northern (Kitsalano Member near Burrard Inlet), and western outcrop areas (Timbo and Sicilia Islands) provides some control on the original extent of the basin. Palaeocurrent patterns and conglomerate clast types all suggest local derivation from nearby margins present to the north and east for the mainland outcrop areas, and to the southwest through northwest for the Timbo/Sicilia Island areas (summarized in Fig. 21.22). The lack of marine facies in any part of the study area, combined with the evidence for terrestrial deposition on most sides of the preserved basin suggests the basin was entirely intracraton-ian at least until the Miocene, when minor marine facies are present in the subsurface strata. This was first suggested by Johnson (1982) for the Chuckanut Formation. The Late Palaeocene sandstone and conglomerate of the Sicilia Island are terrestrial and could have been deposited near the original northern margin of the basin. However, there is no direct evidence that the Sicilia Island outlier on the island was part of a single basin which included the other Palaeocene deposits of this study. It is also possible that the Sicilia Island strata is a remnant of Palaeocene deposition not connected to the Vancouver-Bellingham area. Regardless of the inclusion or exclusion of the Sicilia Island outlier, on at least three sides the Vancouver-Bellingham basin appears to have been intracratonic with separation of only a few tens of kilometres between these areas. There is no sedimentological or palaeontological evidence for marine component to the basin before Miocene time. The main caveat to this conclusion is that there is no control on the southern margin to the Tertiary Georgia Basin.

Provenance evidence for Tertiary Georgia Basin is summarized in Figures 21, 22, 23A-B. Numerical summaries and sources of information for sandstone and conglomerate composition compilations are provided in Tables 2 and 3.

Dental sandstone compositions for the basin are predominantly derived from studies of the Chuckanut Formation and the Timbo/Sicilia Island strata. These are shown on Figure 21A-B, as ternary diagrams where the dental framework compositions have been subdivided into the grain populations recommended by Dickinson and Suczek (1979). The three main provenance categories distinguished by Dickinson and Suczek are continental blocks, magmatic arcs, and recycled orogens. These major groups are further subdivided depending on features such as the degree of uplift and dissection of arc terranes, compositional variation in recycled orogen...
Figure 23. A) Sandstone detrital framework compositions subdivided into grain populations and plotted on ternary diagrams showing the tectonic provenance fields of Dickinson et al. (1983). QFL and OmpFL plots) and Dickinson and Suczek (1979, QFL vs QFL and OmpFL plots). The mean value of all Tertiary Georgia Basin is shown (crossed circles) with a polygon representing the standard deviation from the mean. Sources of information are summarized in Table 2. Note that for ten samples grain sizes were not identified in the original study to the level allowing plotting on any but the QFL plot, accounting for the increase in total number of samples used between the QFL plot and the other plots. B) Individual point counts for entire Tertiary Georgia Basin shown split into major stratigraphic subdivisions (defined for Chuckanut Formation on Fig. 16D). Numerical summary and sources of information are provided in Table 2.

Table 2. Numerical summary of sandstone detrital clast compositions using rhodochrosite classifications of Dickinson and Suczek (1979). Compiled from sources of information listed in right column.

Table 3. Conglomerate clast composition summary statistics. All clast compositions measured by the senior author. Individual sites generally consist of 100 random clast identification.

sandstones, and the importance of stable shield versus sedimentary source in continental block terranes (Dickinson and Suczek, 1979). Dickinson et al., 1983). Using these broad classifications, the subsequent and immediately adjacent source areas for the Tertiary Georgia Basin can be described as two different deformed arcs (Wanggilia terrane and the Coast Belt), and a complex recycled orogen (northwest Cascades/San Juan terranes). The Wanggilia terrane is distinctive for its high proportion of mafic to intermediate volcanic rock types (e.g., Common Area and Karmakom formation), significant bodies of intrusives (feldspar fersites), and mixed sedimentary packages of the Sicker Group (see Monger, 1991 for a recent overview). The Coast Belt is dominated by granitic intrusions, but contains several pendants of volcanic successions suggesting that during Cretaceous and possibly early Cenozoic time it had an extensive volcanic cover (Woodworth and Monger, 1991). The northwestern Cascades comprises a complex series of small and large accreted terranes dominated by oceanic sedimentary and metasedimentary rocks (mostly argillaceous to cherty successions), but with significant volcanic, ophiolitic, and intrusive slices, all deformed in mid-to Late Cretaceous contractional and transpressional events (Tabor et al., 1989).

The composition of the entire basin clearly reflects the variety of local basement lithologies, with the data spanning deformed arc, transitional continental, and collision orogen tectonic source fields (Fig. 23A-B, QFL plots). An evolution is apparent for mainly Chuckanut Formation data where upper Chuckanut Formation sandstones are skewed towards the recycled orogen field. This probably reflects local uplifts on synsedimentary faults controlling late stages of sedimentation in these units, with local (lithic-rich) Cascade terrane sources providing the dominant detrital component (also suggested by Johnson, 1982). Lower members (especially Bellingham Bay and Slide members) of the Chuckanut Formation are considerably more arctic than upper members. The traditionally interpreted sources for these lower units is...
high-grade metamorphic and plutonic rocks exposed to the east and northeast with some dunite from Coast Belt rocks to the north and northeast. (Kelly, 1970; Hartwell, 1979; Johnson, 1982).

A recent isotopic provenance study by Heller et al. (1992) of Paleogene sandstone from several parts of western Washington State included samples from the Chuckanut Formation, Rubicon Creek, and an area west of the Columbia River. Both rock and detrital white mica samples, and K-Ar, chemical, and stable isotope data from detrital white mica were analyzed. Two conclusions of Heller et al. (1992) are directly relevant to the provenance of Tertiary Georgia Basin sediments. First, there is a possible correlation of the continental Georgia Basin sandstone to marine sedimentary packages of the Olympic Mountains, suggesting both a much larger single basin than postulated in this study and a marine component for what we interpret as an intracratonic basin. Second, Heller et al. (1992) suggested a common source for the white mica from metamorphic and plutonic complexes of the southern Olympic Peninsula and that transport occurred in major rivers flowing from the east. Johnson (1983, 1985) proposed a similar source area for much of the Chuckanut Formation based on its detrital sandstone and eustatically controlled depositional environment (partially paleoflow patterns).

The early Tertiary transpressional regime and associated strike-slip faults of the Fraser-Straight Creek and other systems show a strong north to northwesterly structural trend (Fig. 24). The major river systems of Heller et al. (1992) would have to cut this trend almost at right angles, crossing several active strike-slip systems with associated components of dip-slip movement and northwest to northeast-oriented en echelon pull-apart basins. This drainage pattern is opposite to that of many strike-slip basins, where flow may be at high angles to master fault systems at the basin margins, but is redirected toward a direction roughly parallel to the main strike-slip trends (e.g., Nilsen and McLaughlin, 1985). Our study suggests that the Chuckanut Formation part of the larger Tertiary Georgia Basin, which includes Paleogene strata of the sub-Fraser Delta area. Using this new information, the paleocurrent patterns for the entire basin display a southwest to southeast orientation on the east and north side of the outcrop areas (Fig. 21), rather than the west orientation suggested by Heller et al. (1992) or Johnson (1982, 1985). In addition, the nonmarine sedimentary rocks of the Tumwater and Siaich formations show a significant component of sandstone, which in association with the detrital sandstone and conglomerate clast compositions suggest derivation from local sources to the west and northwest. This finding is consistent with the eastern source interpretation of Heller et al. (1992) or linkage of Chuckanut Formation to the Olympic Mountains marine strata west of the Olympic Mountains. This requires a different source for the white mica, which is a distinct component of some Chuckanut Formation sandstone units as well as other west coast and Olympic Peninsula Paleogene sandstones. A source not considered by Heller et al. (1992) or Johnson (1982, 1985) is the Late Cretaceous Nanaimo Group where white mica is common, and some of the clastic detrital rocks are from sandstone in the top formation of the Nanaimo Group (Gabriola Formation), indicating derivation from the eastern

Conditions, including the southern Oregon Belt plutonic and metamorphic complexes (Mustard et al., 1994). Thus an abundant local source of white mica is present for the Tertiary succession, but these detrital areas should contain the isotopic signature of their original source in the western Cordilleran. As documented in this study and Mustard (1994) the upper formations of the Nanaimo Group are missing at Vancouver and Laxaun Island. In both places Late Paleocene sandstones unconformably overlie lower Nanaimo Group formations. It seems clear that a substantial thickness of white mica-bearing sandstone has been eroded from the top of the Nanaimo Group during the early Tertiary.

The common presence of arkose sandstone clasts identical to typical upper Nanaimo Group formations in the Paleocene conglomerates at Siaich and Tumwater Island provides strong evidence that the Nanaimo Group was emplaced to contribute detritus to Tertiary Georgia Basin. We therefore suggest that this local source is more likely for the isotopically distinctive micas described by Heller et al. (1992), than a source requiring major river systems to cut laterally across the trend of active structures in central and western Washington State during the Paleogene. A logical test of this hypothesis would be a similar isotopic study of detrital micas from the sandstone of the upper Nanaimo Group.

TEC TONIC SETTING

Engblom et al. (1983) provided a summary of the known plate positions and convergence vectors for the Late Cretaceous and early Tertiary. They show a change in Late Cretaceous time (about 80 Ma) at the latitude of present Vancouver Island from a strongly convergent margin with the Farallon plate being subducted at a high angle beneath the North American plate to an increasing transpressive regime, including major dextral strike-slip faults, as the Kula plate was subducted obliquely to the north and northeast. Major Late Cretaceous to early Tertiary dextral strike-slip faults are common in southwest British Columbia and northwest Washington State (Fig. 24).

Several indirect lines of evidence suggest Tertiary Georgia Basin formation and deposition was controlled by strike-slip faulting (which also had major dip-slip offsets). The most complete detailed study of the Paleogene sedimentary rocks of Georgia Basin was that of Johnson (1982, 1984a, b, c, 1985, 1991), although restricted to the Washington State part of the basin (Chuckanut Formation). The estimated 6 km+ thickness of the Chuckanut Formation, which Johnson considered to have been deposited entirely in the Eocene, required abnormally high sedimentation rates and continuous uplift of marginal rocks, both features typical of pull-apart basins (see reviews of Reading, 1986; Nilsen and McLaughlin, 1985). However, the more complete palynology dataset provided in this study indicates deposition spanned the Late Paleocene and Eocene, possibly into the Early Oligocene, perhaps 30 Ma instead of the 20 Ma estimated by Johnson (1992). In addition, the thickness of the Paleocene to Eocene succession in Guliches in the basin north of Boston Island exceeds 2.5 km, considerably less than the 6 km+ accumulated total thickness suggested by Johnson (1982).

active during sedimentation and contributed significant vol- umes of sediment to the basin, this likely caused locally anomalously thick successions to be deposited. Johnson (1982, 1984a, b, c) considered these southwestern- trending faults to form the northern boundary of the Chuckanut Formation and thus part of a basin separate from the early Tertiary sediments on the Canadian side of the international border. Our new palynological data, plus seismic

![Figure 24. Major Tertiary faults of southwest British Columbia and north- west Washington State. Major sources of information are Johnson (1985), Tabor et al. (1989), England and Galen (1991), Wheeler and McFeeley (1991), Monger and Fournier (1992), and unpublished seismic data used with permission of Conoco Exploration Ltd., Calgary, Alberta.](image-url)
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Figure 25. A) Schematic diagram of envisioned strike-slip basin setting for the main period of deposition of Tertiary Georgia Basin (Paleocene to Eocene or Early Oligocene). Dextral strike-slip faults (magenta) on left side of basin show large dip-slip components of movement providing periodic reactivation uplifted eastern source for coarse clastic basin fill. Internal basin sources to north reflect synsedimentary minor normal faulting at high angles to main oblique-slip faults as shown in Figure 25B. Presence of major master faults on western boundary of basin is speculative; its western margin may have been bounded by minor fault zone showing mostly dip-slip sense of fault movement (a common feature of many large strike-slip basins, as discussed in text). B) Schematic pull-apart basin model showing major dextral strike-slip fault and minor normal faults forming subsutuences within the main pull-apart basin (modified from a similar diagram in Maniscek, 1965).

Figure 25 cont...
thermal maturity was reached and migration into the abundant fluvial sandstone reservoirs occurred. Thus hydrocarbon in the Tertiary Georgia Basin are likely to be gas derived from terrestrial organic matter (mostly Type III kerogen). One possible exception to this statement is presented in a recent summary of the petroleum geochemistry of Washington State by L. J. Fauquier (1991). They suggested that some coals and shales in the 1988 AHET, Birch Bay well 11, Fig. 3) include Type IIB kerogen prone to light hydrocarbon production.

The generally low thermal maturity values from both previous studies (Bustin, 1990; Mustard and Rouse, 1991) and from this study also suggest the hydrocarbon potential of Tertiary Georgia Basin is restricted to gas. For this study, measurements have been made on the TAI (Thermal Alteration Index) using the Chevon colour scale (0-4), which predicts the likelihood of hydrocarbon generation. On this scale, values of about 2.0-2.5 indicate paleotemparature conducive to gas generation, mainly diagentic dry gases (methane, CO2, N2), values from 2.5 to about 3.2 denote the oil/water window values about 3.0-3.3 represented in this zone for optimum generation of wet gases (condensate).

The TAI from both surface and subsurface samples indicate only marginal maturation levels. This includes samples from the blue sediments at Blue Mountain (described in Mustard and Rouse, 1991) and at depths of over 3300 m both in the Sonosny and Point Roberts exploration wells (4 and 7 in Fig. 3). Hence, the prognosis for substantial hydrocarbon generation is not very favorable. This is corroborated by assessment of vitrinite reflectance values by R.M. Bustin (U.C.B., pers. comm., 1990), however, Walsh and Phillips (1983) showed that the rank of coal coes in the Chuckanut Formation becomes significantly and systematically towards post-lithification ages increases in the near shore lutts in about immediate area of the Fraser Lowlands. He postulated a mid-Tertiary age for these inferred fauls.

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APPENDIX

The following are formal descriptions of one new genus (Varulincopsinites) and eleven new species of fungal paleynomorphs recognized in this study. The names, citations, and descriptions follow the catalogue "Genera Fossil de Fossil Spores and Pollen" by Janoušková and Hils (1976, 1979), which includes fungal spores. The photographs cited in the descriptions refer to those contained in the plates in the text. In most cases, the magnification of photographs is x1000. Where different, the magnification is noted in the figure legends.

It appears from this study that fungal paleynomorphs are a highly useful tool in dating and correlation, particularly in Paleogene successions throughout western North America. Because of the warm temperate to subtropical conditions that prevailed throughout much of the Paleogene, it is also apparent that modern counterparts of Paleogene fungal spores, fruiting bodies, and mycelial remnants should be looked for in extant myco-assemblages from the Gulf Coast-Caribbean region, especially in deltoide, shallow, and low floodplain depositional sites.

Genus Intratropolipollites Thomson and Plag, 1953
Intratropolipollites precristatus sp. nov.

Holotype: PL 3, fig. 13, 3rd Beach, Sect. 4, S-12, slide 3, Leitz, 1.1, 114.8, Huntington Formation, Late Paleocene.

Diagnosis: Ambiessentially circular, brevitectolaroporate, with apertures equatorial, colpi short and wide, with rounded-oval ends; vestibulum present but weakly developed; annulus expressed only in the outer flanks of the colpus, forming subsingularly offsetting outlines in section. Sculpture reticulate, with annuli eclaveate in section, laminae <1 µm, essentially uniform in size from apocollica to margin.

Dimensions: Range in diameter 33-42 µm; holotype 40 µm.

Age range: Late Paleocene.

Remarks: L. precursorites sp. nov. alludes to the similarity to Tilia crassispites Wodhouse (PL 7, fig. 11) that ranges from the Early Eocene-Miocene. It differs mainly by having very local development of annulus flanking the outer (mostly) colpoid borders. Together with L. precrus- spites sp. nov. this species is a good index paleynomorph for the Late Paleocene in western and northern North America, where it occurs with Psilolithipollites megacorn- (PL 3, fig. 15, 16), Subtrispiniplites A (PL 3, fig. 21) and Trispiniplites A (PL 3, fig. 22). See also Reuss (1977).

Genus Involucrispiniplites Clarke, 1985
Involucrispiniplites minutus sp. nov.

Holotype: PL 4, fig. 6

Diagnosis: Planispiral fungal spores, with few (usually 4) cells enclosing a uniform open area in the center; outer walls about 0.25 mm thick and levispiculate; inner walls of cells about 0.1-0.5 mm thick; septa about 0.25 mm thick, with a single faint pore.

Dimensions: Range 16-21 mm.

Age: Late Paleocene.

Remarks: This spore is smaller than the type species L. foraminatus, with fewer and no alobate cells. It is usually found on fragments of leaf, and hence is likely the spore of an epiphytic fungus.