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QUADRA SAND: A STUDY OF THE LATE PLEISTOCENE GEOLOGY AND GEOMORPHIC HISTORY OF COASTAL SOUTHWEST BRITISH COLUMBIA

J.J. CLAGUE

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QUADRA SAND: A STUDY OF THE LATE PLEISTOCENE GEOLOGY AND GEOMORPHIC HISTORY OF COASTAL SOUTHWEST BRITISH COLUMBIA

Abstract

Quadra Sand is a late Pleistocene lithostratigraphic unit with widespread distribution in the Georgia Depression, British Columbia and Puget Lowland, Washington. The unit consists of horizontally and cross-stratified, well sorted sand, minor silt, and gravel. It is overlain by till and related glacial sediments deposited during the Fraser Glaciation and is underlain by fluvial, estuarine, and marine sediments deposited during the preceding nonglacial interval.

The unit is part of an apparently unbroken stratigraphic succession which records the major climatic oscillations of late Pleistocene time: till deposited during a pre-Fraser glaciation; glaciomarine sediments laid down during the subsequent transition to nonglacial conditions; marine, estuarine, and fluvial sediments deposited during the Olympia nonglacial interval; outwash deposited during the following nonglacial-glacial transition; and till deposited under full glacial conditions of the Fraser Glaciation.

Stratigraphic evidence, paleocurrent data, sand mineralogy, and radiocarbon dates indicate that Quadra Sand was deposited progressively down the axis of the Georgia Depression and Puget Lowland from source areas in the Coast Mountains to the north and northeast. The unit is markedly diachronous; it is older than 29 000 radiocarbon years at the north end of the Strait of Georgia but is younger than 15 000 years at the south end of Puget Sound.

Aggradation of Quadra Sand is thought to have been climatically induced. The initial influx of sand into the Georgia Depression probably occurred during a period of climatic deterioration at the onset of the Fraser Glaciation. The sand was deposited, in part, as distal outwash aprons at successive positions in front of, and perhaps along the margins of, glaciers moving from the Coast Mountains into the Georgia Depression and Puget Lowland during late Wisconsin time. After deposition at a site, but before burial by ice, the sand was dissected by meltwater and the eroded detritus was transported farther down the basin to sites where aggradation continued.

Quadra Sand buried older fluvial and estuarine deposits which, in turn, were laid down over marine sediments filling much of the Strait of Georgia. The present patchy distribution of Quadra and older sediments is due, in large part, to scour by glaciers at the height of the Fraser Glaciation.

Résumé

Le sable de Quadra est une unité lithostratigraphique de la fin du Pléistocène, que l'on rencontre très fréquemment dans la dépression de Géorgie, en Colombie-Britannique, et dans les basses-terres de Puget, dans l'état de Washington. Cette unité est formée de couches horizontales et à stratification entrecroisée de sables, de quantités mineures de silts, et de graviers bien triés. Des tills et des sédiments glaciaires apparentés, déposés pendant la glaciation de Fraser, la recouvrent, et elle recouvre elle-même des sédiments fluviatiles, d'estuaires et marins, déposés pendant l'interglaciaire antérieur à cette glaciation.

Cette unité fait partie d'une succession stratigraphique apparemment complète, qui témoigne des principales oscillations climatiques de la fin du Pléistocène: des tills déposés pendant une glaciation antérieure à la glaciation de Fraser; des sédiments glaciomarins déposés pendant le passage ultérieur à un régime non glaciaire; des sédiments marins, d'estuaires et fluviatiles, déposés pendant l'interglaciaire d'Olympia; des sédiments fluvioglaciaires déposés pendant la transition ultérieure d'un régime non glaciaire à un régime glaciaire; et des tills, déposés pendant le maximum de la glaciation de Fraser elle-même.

Les indices stratigraphiques, les données relatives aux paléocourants, la minéralogie des sables, et les datations au radiocarbone indiquent que le sable de Quadra s'est déposé progressivement le long de l'axe de la dépression de Géorgie et des basses-terres de Puget, à partir de sources de sédiments situées dans la chaîne Côtière au nord et au nord-est. L'unité est fortement diachrone; la datation au radiocarbone indique que son âge dépasse 29 000 ans à l'extrémité nord du détroit de Géorgie, mais est inférieur à 15 000 ans à l'extrémité sud du fiord de Puget (Puget Sound).

On pense que le dépôt des alluvions sableuses de Quadra est dû à des conditions climatiques particulières. L'afflux initial de sable dans la dépression de Géorgie s'est probablement produit pendant une période de Transformation du climat, au début de la glaciation de Fraser. Le sable s'est déposé en partie sous forme de plaines alluviales proglaciaires successives à l'avant, et peut-être le long des marges, de glaciers progressant de la chaîne Côtière dans la dépression de Géorgie et les basses-terres de Puget pendant la fin de la glaciation du Wisconsin. Après s'être déposé, mais avant d'être enfoui par la glace, le sable a subi l'action érosive des eaux de fonte des glaciers et a été transporté dans le bassin à des niveaux inférieurs, où l'alluvionnement s'est poursuivi.

Le sable de Quadra a recouvert des dépôts d'estuaires et fluviatiles plus anciens, qui s'étaient eux-mêmes déposés au-dessus de sédiments marins qui comblaient une grande partie du détroit de Géorgie. La distribution sporadique actuelle des sédiments de Quadra et plus anciens résulte surtout de l'action abrasive (rabotage) exercée par les glaciers, pendant l'apogée de la glaciation de Fraser.

QUADRA SAND: A STUDY OF THE LATE PLEISTOCENE GEOLOGY AND GEOMORPHIC HISTORY OF COASTAL SOUTHWEST BRITISH COLUMBIA

INTRODUCTION

The Georgia Depression, an elongate sedimentation basin now largely covered by sea water, is located between the Coast Mountains and the Vancouver Island upland of British Columbia. Sediments within the Georgia Depression provide a detailed record of the late Quaternary environments and geomorphic history of coastal southwest British Columbia. Thick surficial materials cover much of the lowlands that border the Strait of Georgia and Puget Sound; they also occur widely beneath the seafloor of the Strait (Tiffin, 1969; Clague, 1975a, 1976a).

This succession of sediments includes a group of stratified materials deposited during the Olympia nonglacial interval preceding the Fraser Glaciation and during the initial phase of the Fraser Glaciation (Fig. 1, Table 1). These stratified sediments are subdivided here into two lithostratigraphic units, Quadra Sand and the Cowichan Head Formation (Armstrong and Clague, 1977). The character, distribution, provenance, and depositional history of Quadra Sand are the subjects of this paper.

Acknowledgments

J.G. Fyles, working on Vancouver Island, and J.E. Armstrong, working in the Fraser Lowland near Vancouver, have contributed extensively to an understanding of the late Quaternary geologic history of southwest British Columbia. Many of the ideas presented here originally were proposed by them.

Most of the paleocurrent and palynologic data were supplied by Fyles. G.J. Woodsworth and W.W. Hutchison provided chemical analyses of granitic rocks in the Prince Rupert area of British Columbia.

Drafts of the manuscript were reviewed by R.J. Fulton and J.G. Fyles.

This work is part of a study of the Quaternary geology of the Georgia Depression undertaken by the Geological Survey of Canada.

Table 1

Stratigraphic framework of surficial sediments in the Georgia Depression

Stratigraphic unit		Geologic-climatic interval
Salish Sediments		Postglacial
Fraser Glaciation drift	Sumas Drift Capilano Sediments Fort Langley Fm. Vashon Drift Quadra Sand	Fraser Glaciation
Cowichan Head Formation		Olympia nonglacial interval
Semiahmoo and Dashwood Drifts*		?
Highbury and Mapleguard Sediments**		?
Westlynn Drift		?

*Semiahmoo Drift (in Fraser Lowland) probably correlates with Dashwood Drift (on Vancouver Island).

**Relationship between Highbury Sediments (in Fraser Lowland) and Mapleguard Sediments (on Vancouver Island) is unknown.

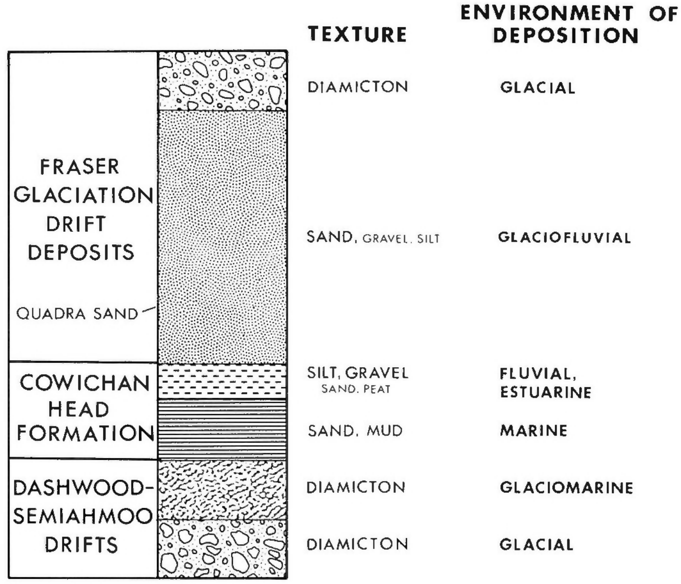

Figure 1. Composite columnar section showing generalized stratigraphy of Wisconsin sediments in the Georgia Depression.

STRATIGRAPHIC NOMENCLATURE

The stratigraphic framework of surficial materials in the Georgia Depression has been summarized by Fyles (1963), Armstrong et al. (1965), and Armstrong (1975). Numerous radiocarbon dates provide a chronology for late Quaternary geologic-climatic events in the area (Fulton, 1971).

Most exposed sediments were deposited during the following major geologic-climatic intervals, from oldest to youngest: Olympia nonglacial interval, Fraser Glaciation, and postglacial time (Table 1). Older sediment units have been recognized at a few localities (e.g. Fyles, 1963; Armstrong, 1975), but their age and correlation are not well established.

The stratigraphic succession in the Georgia Depression has been subdivided into numerous units (e.g. Armstrong, 1956, 1975; Fyles, 1963; Armstrong et al., 1965; Easterbrook, 1969; Hansen and Easterbrook, 1974). Local stratigraphic usage, however, has evolved with time, and certain lithostratigraphic terms have acquired more than one meaning. For example, various terms have been applied to the succession of stratified materials deposited during the Olympia nonglacial interval and during the early phase of the Fraser Glaciation. Although it is not the purpose of this paper to review the complete history of changes in stratigraphic nomenclature in southwest British Columbia and northwest Washington, a brief discussion of the term **Quadra** is included. This term has been widely applied to the stratified sediments described in this report.

The name **Quadra Group** was first applied to inter-till sediments exposed near Vancouver (Armstrong and Brown, 1953). Included in the stratotype was the Point Grey Formation considered by Johnston (1923) to be interglacial.

Fyles (1956) introduced the term **Quadra sediments** for inter-till sediments exposed on the east coast of Vancouver Island. Fyles (1963) subsequently subdivided Quadra sediments into three units, a lower unit of marine silt, clay, and stony clay; a middle unit of fluvial and estuarine, plant-bearing silt, sand, and gravel; and a thick upper unit of white

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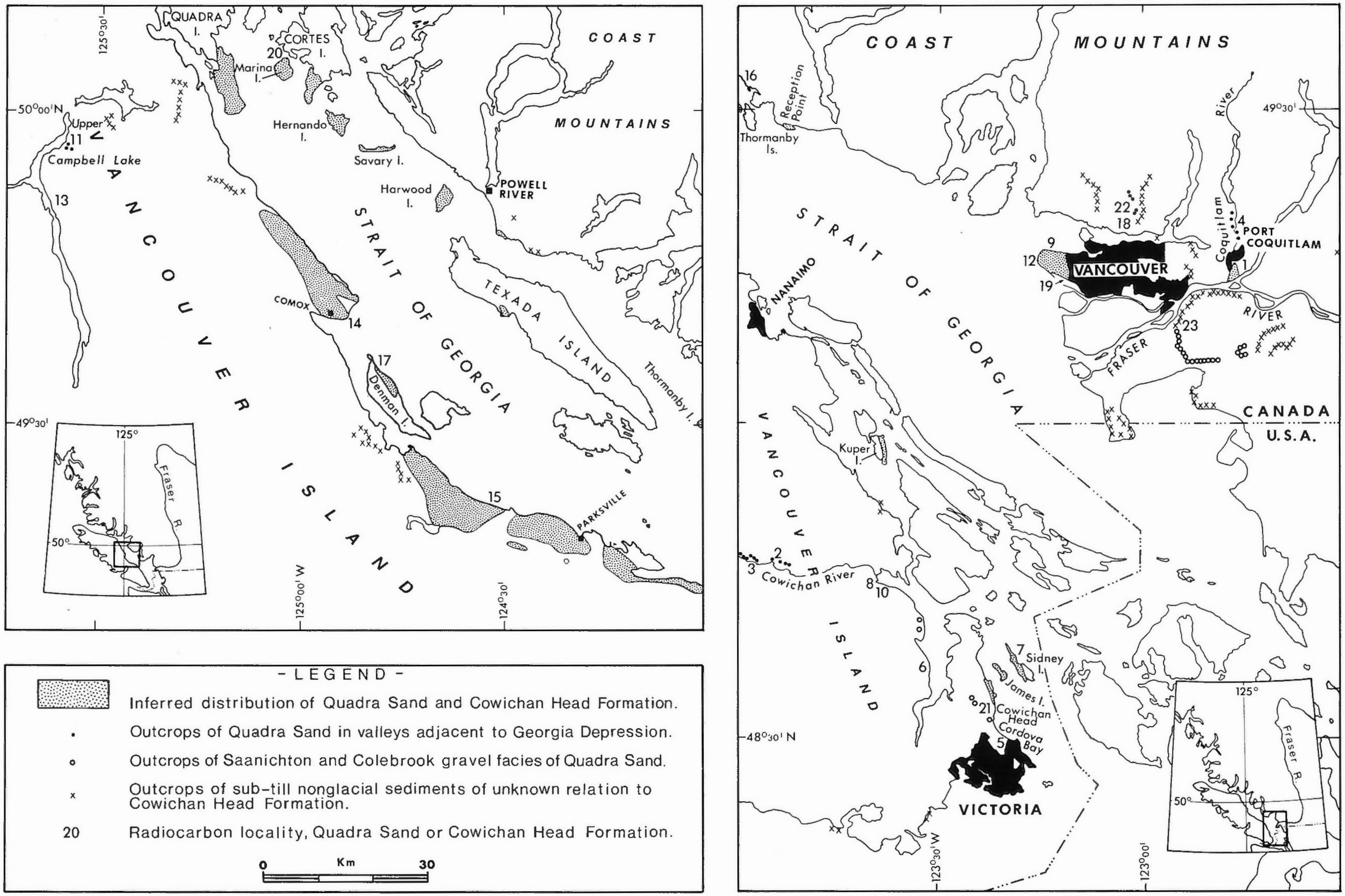


Figure 2. Distribution of Quadra Sand and Cowichan Head Formation in the Georgia Depression. Radiocarbon dates and localities are listed in Table 6.

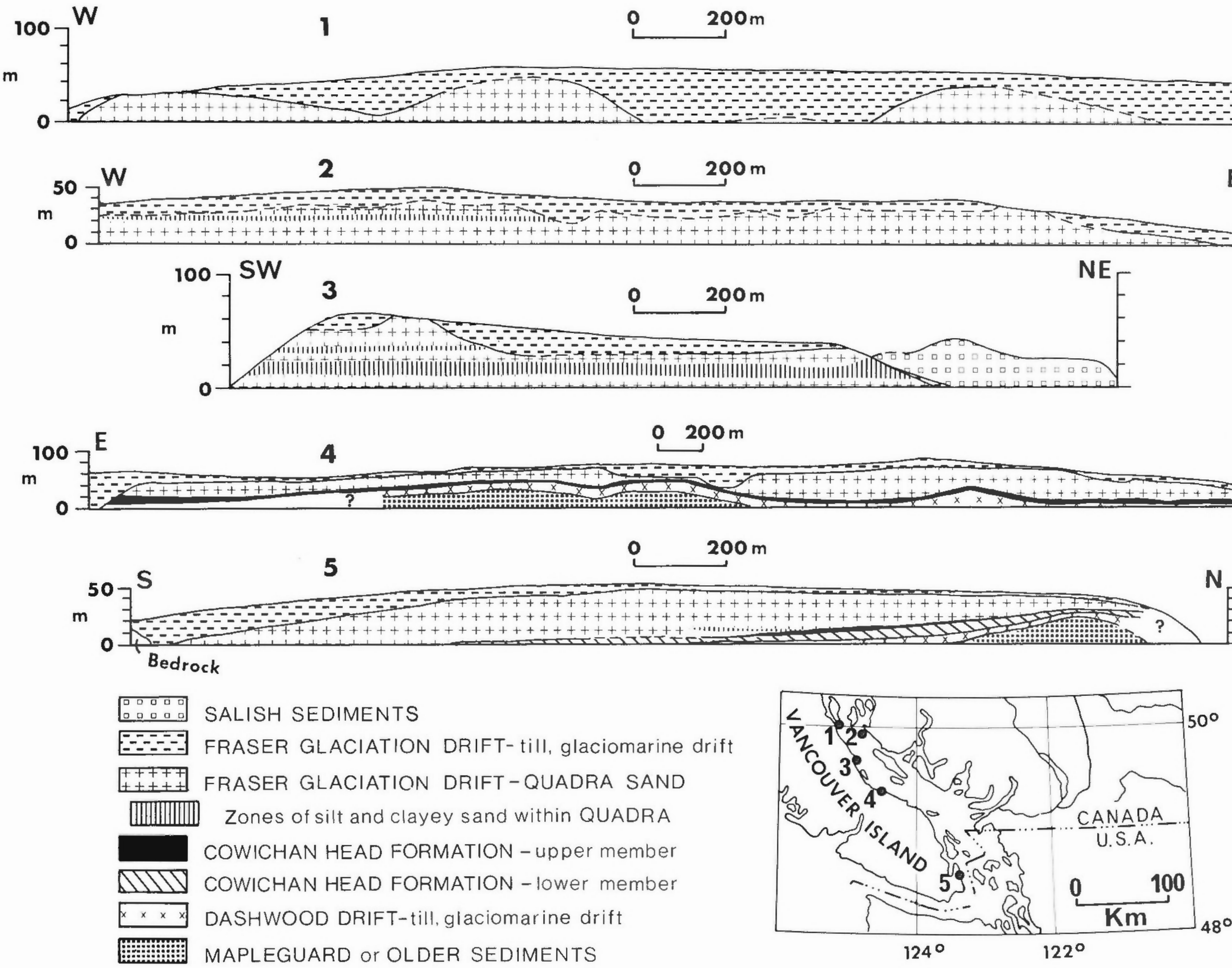


Figure 3. Stratigraphic sections showing relationships of late Quaternary sediments in the Georgia Depression.

sand with local gravel and plant-bearing silt. Armstrong et al. (1965) then replaced the term **Quadra Group** with **Quadra sediments,** designated sea cliffs at Vancouver as the type section, and assigned the unit to the Olympia nonglacial interval.

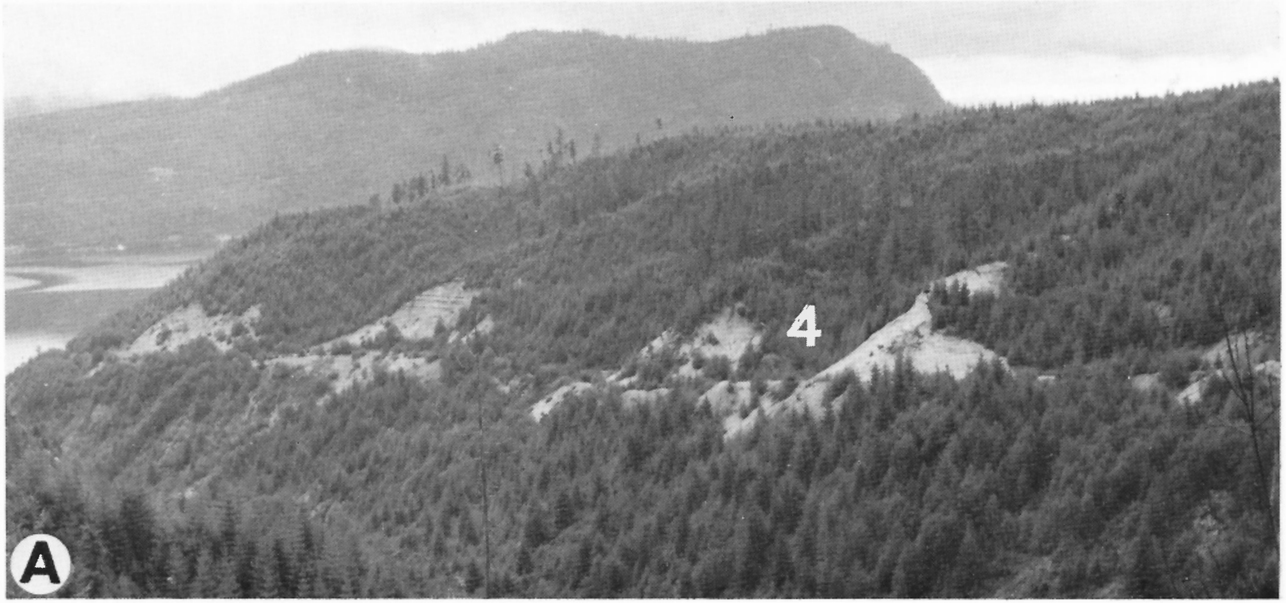
Easterbrook (1969), in a summary of the Pleistocene stratigraphy and chronology of the Puget Lowland, applied the name **Quadra Formation** to deposits of the Olympia nonglacial interval. Excluded from the Quadra Formation were sediments correlating with those at Armstrong's Quadra stratotype section at Vancouver and with the upper unit of Fyles' Quadra sediments on Vancouver Island. These sediments had been included in drift of the Fraser Glaciation and called the Esperance Sand Member of Vashon Drift (Mullineaux et al., 1965).

Armstrong (1975) and Armstrong and Hicock (1975) redefined Quadra Sediments to include not only the sediments exposed in sea cliffs at Vancouver but also underlying stratified materials found elsewhere in the Fraser Lowland. Thus defined, the Quadra was approximately equivalent to the upper and middle units of the Quadra sediments of Fyles. Excluded, however, was shell-bearing diamicton at the base of the Quadra sequence which Armstrong considered to be glaciomarine in origin and thus part of drift deposited during the penultimate (pre-Fraser) glaciation. Fyles, in contrast, included the diamicton within the Quadra sediments.

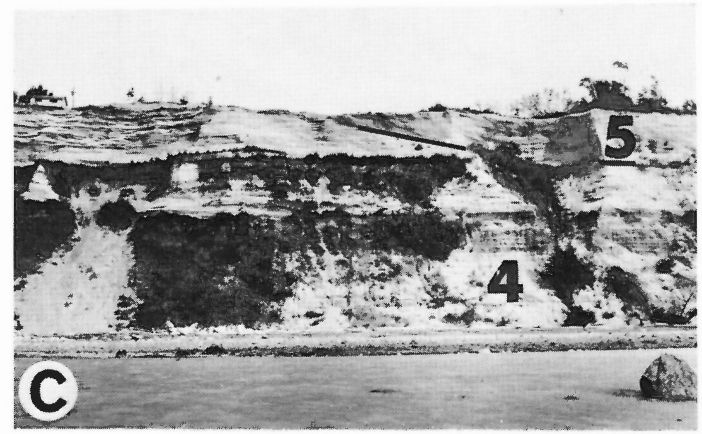
In summary, the term **Quadra** has been used in at least three different ways by including different units of the standard inter-till succession: (1) lower "clay" unit (include shell-bearing diamicton), middle plant-bearing silt-sand-gravel unit, upper sand unit (Fyles, 1963); (2) lower plant-bearing silt-sand-gravel unit, upper sand unit (Armstrong, 1975); and (3) plant-bearing silt, sand, and gravel (Easterbrook, 1969).

It is now believed that the upper unit of Quadra Sediments is glaciofluvial in origin (Mullineaux et al., 1965; Easterbrook, 1969; Clague, 1975a, 1976b) and thus is grouped with drift of the Fraser Glaciation. This unit is here referred to formally as Quadra Sand (Table 1).

Stratified sediments underlying Quadra Sand and overlying drift deposited during the penultimate glaciation are included within the Cowichan Head Formation. This formation consists of fluvial, estuarine, and marine strata, representing most of the lower and middle units of Fyles' Quadra sediments.

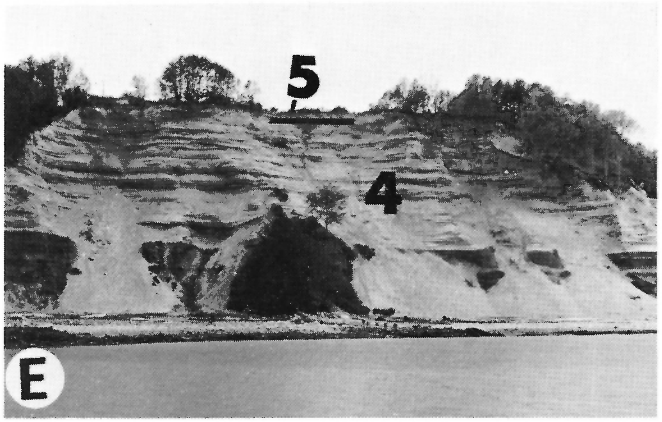


A -Upper Campbell Lake (49°57'N, 125°36'W)

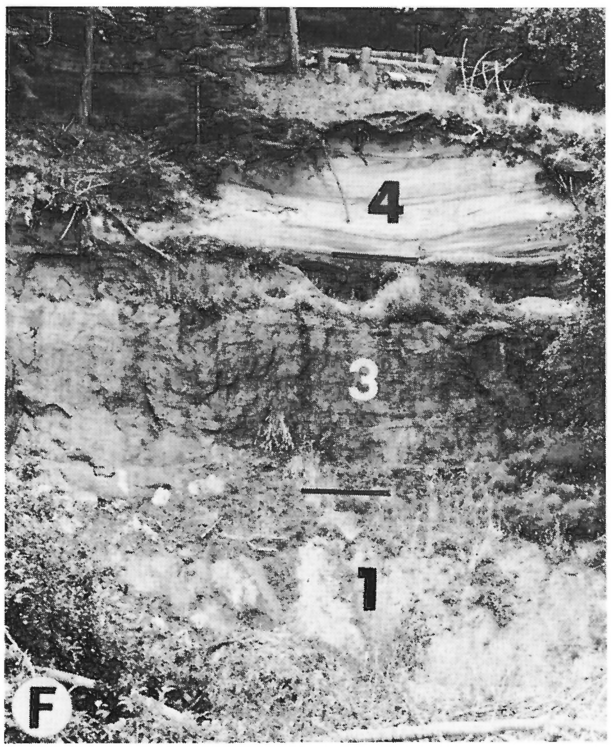


B - Savary Island (49°56'N, 124°50'W)

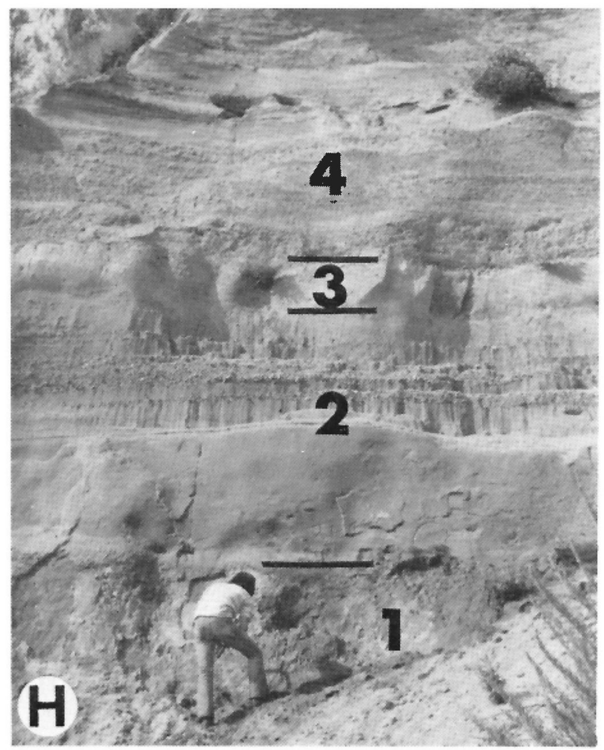
C and D - Comox (49°40'N, 124°54'W)



E - Vancouver (49°16'N, 123°16'W)



F - Denman Island (49°36'N, 124°49'W)



G and H - Cowichan Head (48°34'N, 123°22'W)

LEGEND

1 - glaciomarine sediments;
2 - marine sand (lower member, Cowichan Head Formation);
3 - fluvial and estuarine silt, sand, and gravel (upper member, Cowichan Head Formation);
4 - Quadra Sand;
5 - till, glaciomarine sediments, ice-contact outwash.

Figure 4. Exposures of late Quaternary sediments in coastal southwest British Columbia. Lines indicate contacts. Heights of coastal bluffs at B, C, D, E, F, and G are 45, 50, 50, 65, 20, and 50 m, respectively. Dark horizons within Quadra Sand (B, C, D, and E) are clayey sand and silt.

CHARACTERISTICS OF QUADRA SAND

Quadra Sand is well sorted, fine to coarse grained sand, minor silt, and gravel overlain by Vashon till and related glacial sediments and underlain by the Cowichan Head Formation. Quadra Sand was deposited by streams and rivers on flood plains extending over part or all of the Georgia Depression during late Wisconsin time (Fyles, 1963; Armstrong et al., 1965). A unit that is correlative with Quadra Sand has been described by Mullineaux et al. (1965) and Easterbrook (1969) and has been termed Esperance Sand.

At a few localities the sand is overlain by, and interbedded with, sandy gravel and gravelly sand. Units such as the Colebrook gravel (Armstrong, 1956, 1957) and Saanichton gravel (Halstead, 1968; Fulton and Halstead, 1972) lie stratigraphically above Quadra Sand and apparently formed as outwash in front of and along the margins of glaciers advancing into the Georgia Depression during the Fraser Glaciation. Although limited in distribution to small areas near Vancouver and north of Victoria (Fig. 2), the gravel is thought to be a coarse upper facies of Quadra Sand.

Type section

The type section of Quadra Sand is at the south end of Quadra Island (50°00'N, 125°09-11'W) where cross-bedded, well sorted sand up to 40 m thick is exposed in coastal bluffs beneath till (Fig. 3, loc. 1).

Distribution

The distribution of Quadra Sand has been determined on the basis of surface exposures, drillhole records, and corroborating radiocarbon dates (Fig. 2). The unit is perhaps more extensive than indicated in Figure 2, especially in the Victoria and Vancouver areas, but available information is such that stratigraphic definition or correlation with Quadra Sand is not always possible.

The present distribution is controlled by the original depositional limits of the unit, by the topography of the surface upon which the sand was deposited, and by fluvial and glacial erosion following deposition.

Quadra Sand occurs mainly below 100 m in elevation in lowland areas between mountain ranges bordering the Georgia Depression. Large areas of the coastal lowland of eastern Vancouver Island are underlain by Quadra Sand, and many islands in the Strait of Georgia, including Quadra, Marina, Cortes, Hernando, Savary, Harwood, Thormanby, James, and Sidney, also have extensive Quadra deposits. The unit occurs as far north as 50°05'N on Marina Island and south into the Puget Lowland of Washington. In the Fraser Lowland Quadra Sand has been found as far east as Port Coquitlam at 49°14'N, 122°47'W. Farther east marine clay and silt probably occur at an equivalent stratigraphic position (J.E. Armstrong, pers. comm., 1975).

Quadra Sand also occurs in a few upland valleys adjacent to the Georgia Depression. For example, the unit outcrops between about 330 and 380 m in elevation east of Upper Campbell Lake (49°57'N, 125°36'W). Thick sand and gravel to above 200 m in elevation in Coquitlam Valley (49°19-20'N, 122°46-47'W) north of the Fraser Lowland correlate in part with Quadra Sand.

Quadra Sand has a maximum exposed thickness of 75 m in coastal bluffs around the Strait of Georgia. In many areas, however, the unit outcrops down to sea level and probably occurs below. For example, an apparently continuous sand sequence was logged in a well on Hernando Island between elevations of 18 and -25 m (Erdman and Brown, 1969):

Sediment description	Stratigraphic unit	Elevation (m)
Sand and gravel	Capilano Sediments	36 to 38
Till	Vashon till	18 to 36
Sand and silty sand	Quadra Sand	-25 to 18
Clay	?	? to -25

Sand samples recovered from the lowest part of the sequence are identical in grain-size distribution to Quadra Sand exposed in nearby cliffs between 0 and 18 m above sea level. This indicates that these sediments may have been deposited when sea level was at least 25 m lower relative to the present.

Bounding strata

Quadra Sand, in general, overlies plant-bearing silt, sand, and gravel, but locally rests upon marine and glaciomarine sediments and bedrock. The contact between Quadra Sand and the Cowichan Head Formation is sharp, the two units being distinguishable on lithologic criteria. Upper Cowichan Head sediments comprise horizontal beds of silt, sand, and gravel, commonly oxidized to reddish hues and containing abundant organic matter; cross-bedding is rare; and sand beds include large amounts of detritus eroded from volcanic and sedimentary rocks. In contrast, Quadra Sand consists largely of well sorted white sand which is extensively cross-bedded and has a scarcity of organic matter; the source area of most of this sediment is granitic.

Quadra Sand is overlain by Vashon till and related glacial sediments. In general, the contact between the two is erosional, but at a few localities the sand grades upward through gravelly sand and laminated stony clay and silt into till.

Examples of stratigraphic sections showing the relationships of Quadra Sand to bounding strata are shown in Figures 3 and 4.

Textures

Quadra Sand consists mainly of well sorted, fine to coarse grained sand (Figs. 5-7). Clay, silt, and gravel represent less than 10 per cent of the unit over the entire area, but are locally common. There is no systematic gradation in mean particle size either vertically through a section or areally along the length of the Georgia Depression. Fyles (1963, p. 31), however, noted that the unit coarsens westward from the edge of the coastal lowland on Vancouver Island to the mountain front. In general, Quadra Sand includes a larger proportion of gravel near the mountain front than in coastal areas. Also, most of the silt is present in the lower part of the unit, and gravel is most common in the upper part. For example, in major sea cliff exposures of Quadra Sand near Vancouver (49°16'N, 123°16'W), silt beds and laminae occur up to 18 m above sea level. Overlying Quadra sediments (from 19 to about 61 m above sea level) not only lack silt beds but are remarkably uniform in texture, consisting of medium to coarse grained sand and minor gravel.

Silt and clay occur as thin beds and laminae interstratified with sand. Many silt beds contain plant detritus and thus are similar to some organic-rich strata in the Cowichan Head Formation. Quadra silt beds, however, are interstratified with and underlain by cross-bedded sand, whereas silt beds in the Cowichan Head Formation are commonly interbedded with rusty gravel.

Most of the sand is loose and has neither silt-clay matrix nor cement. Some beds, however, consist of well sorted sand in which the void space partially is filled with clay (Fig. 8). This clay commonly constitutes 5 to 15 per cent of the sediment and is mainly 10 to 13 phi (1 to 0.1 μm) in size. Silt is rare, thus the sediment is characterized by bimodal grain-size distributions. Isolated pebbles occur within these clayey sands. The sediments are less permeable than associated clean sands; groundwater transmitted through the latter perches on top of the former and emerges in cliff faces at the contact between the two.

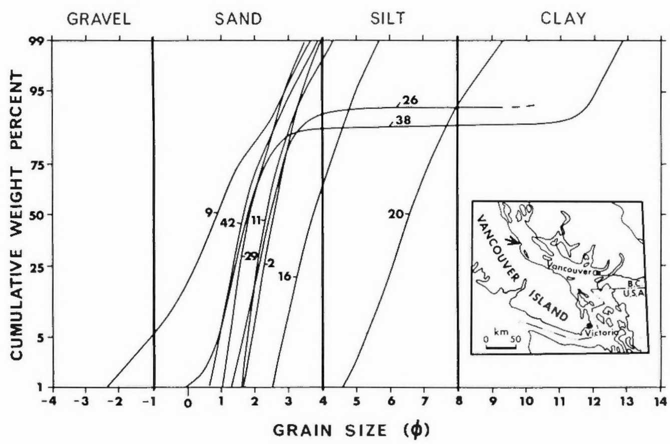


Figure 5. Cumulative frequency curves for Quadra Sand at Comox. Numbers attached to the curves are elevations (in metres) of analyzed samples at the collection site (see Fig. 4D).

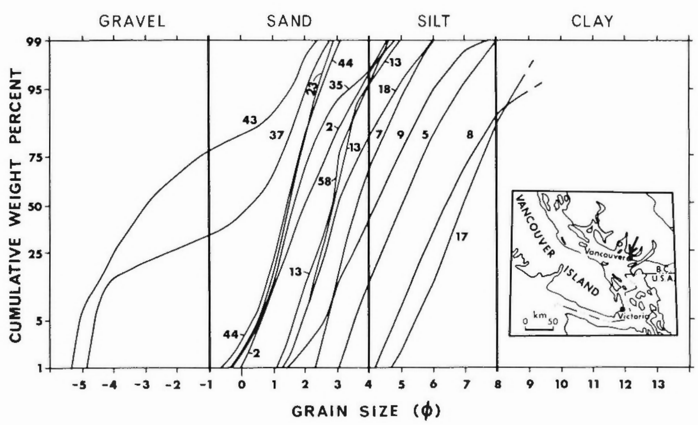


Figure 6. Cumulative frequency curves for Quadra Sand at Vancouver (see Fig. 4E).

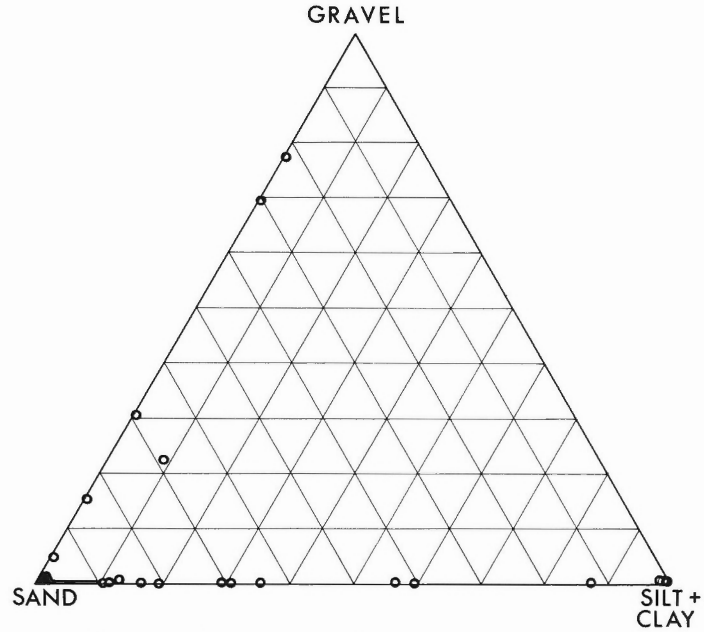


Figure 7. Gravel-sand-mud ratios of representative samples of Quadra Sand. About 80 per cent of the 104 analyzed samples fall within the darkened area near the sand apex of the diagram. The other samples, shown by circles, are mixtures of either sand and gravel, or sand, silt, and clay.

Clay-size material from the matrix of two clayey sand samples was analyzed by X-ray diffraction techniques in order to determine the mineral species present. The diffraction patterns (Fig. 8) indicate that no phyllosilicates produced by pedogenesis (e.g. kaolinite, montmorillonite) are present; rather, the clay-size fraction consists of quartz, feldspar, calcite, mica, and (?) amphibole.

Stratification and sedimentary structures

Quadra Sand is horizontally stratified. Some beds exposed in coastal bluffs are continuous at constant elevation for long distances. For example, marker beds in the sand sequence of Savary Island can be identified at the same elevation over a distance of 6 km, and it is possible that correlative strata occur on Harwood Island 18 km distant (Clague, 1975a).

The sand is extensively channelled and cross-stratified; large channels occur at a few sites. At the south end of James Island, for example, a channel wall is marked by a steep erosional contact cutting across 9 m of interbedded silt and sand (Fig. 9). These sediments are overlain across the contact by a channel fill of cross-bedded sand. Only one wall of the channel is preserved, and the structure is a minimum of 0.7 km wide. Channelling on a similar scale is present on Thormanby Island. Smaller scale cut-and-fill structures are present at all sites. Planar and trough cross-stratification are the dominant sediment structures within Quadra Sand (Fig. 10) and are thought to originate by the migration of asymmetric ripple marks on channel floors (Allen, 1963, 1965).

Detailed analysis of the axial orientation of trough cross-beds was undertaken in order to determine flow directions during deposition of the sand unit. The flow direction at each site was determined by excavating a horizontal platform in sand so as to expose a stratification surface. The axes of individual troughs were measured to the nearest 5 degrees; each measurement represents an orientation vector. The azimuth and magnitude of the vector resultant for each sample was then calculated (High and Picard, 1971). The resultant vector approximates the flow direction at the data collection site. At several localities paleocurrent data were collected at intervals vertically through the sand unit. These data sets were tested for equivalence[1] using the Kolmogorov-Smirnov test (outlined in High and Picard, 1971). Equivalent samples from the same locality were grouped prior to calculation of the vector resultant. Thus some data sets contain a number of samples, each of which consists of many orientation measurements.

The orientation vectors from Quadra Sand indicate regional flow towards the south and southeast (Fig. 11, Table 2)[2]. This suggests that the main sediment source was the Coast Mountains north and northeast of the Georgia Depression and not Vancouver Island west of the depression.

[1] Samples are equivalent in a statistical sense if they are drawn from a single population.

[2] Much of the data summarized in Figure 11 and Table 2 was collected by J.G. Fyles during the course of his surficial geology investigations in the Georgia Depression.

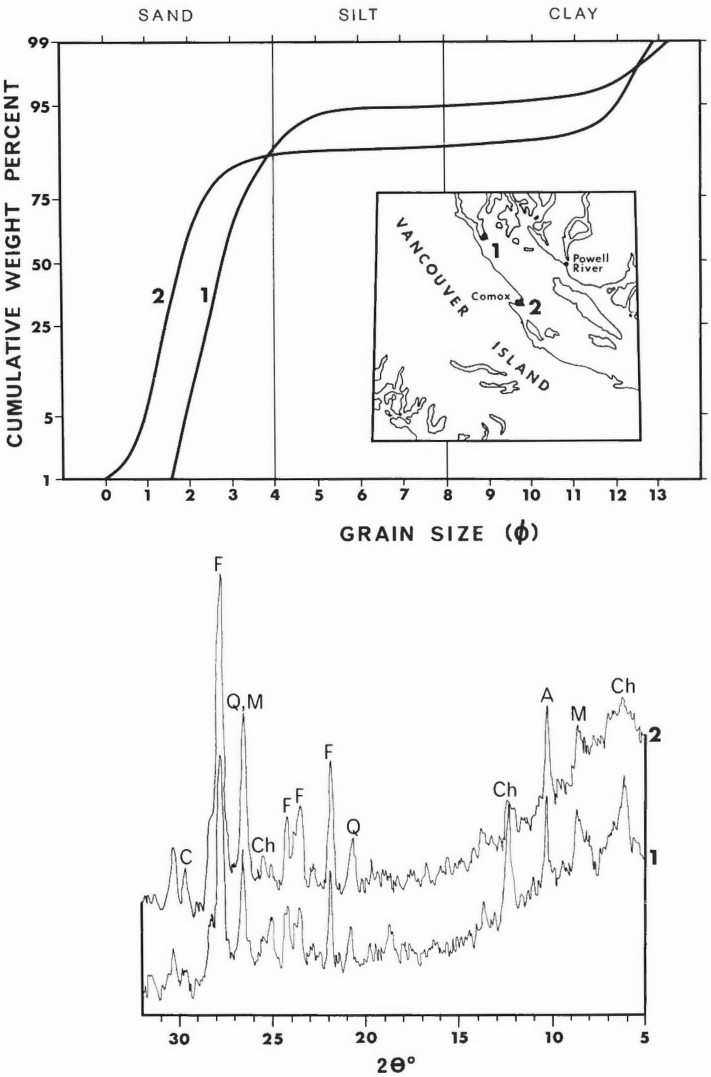


Figure 8

Cumulative frequency curves and X-ray diffraction patterns of clayey sand at Quadra Island (1) and Comox (2). The clayey sand occurs as interbeds within Quadra Sand. The clay-size material consists of quartz (Q), feldspar (F), amphibole (A), calcite (C), chlorite (Ch), and mica (M).

Figure 9. (below)

Sea cliff at the south end of James Island showing cross-section of large channel within Quadra Sand (darkened circles on photograph indicate channel wall). Marker beds are truncated at the wall of the channel near the northeast end of the exposure. Part of the channel apparently has been removed by glacial erosion subsequent to deposition of the unit, because the southwest wall of the channel is not present at the exposure.

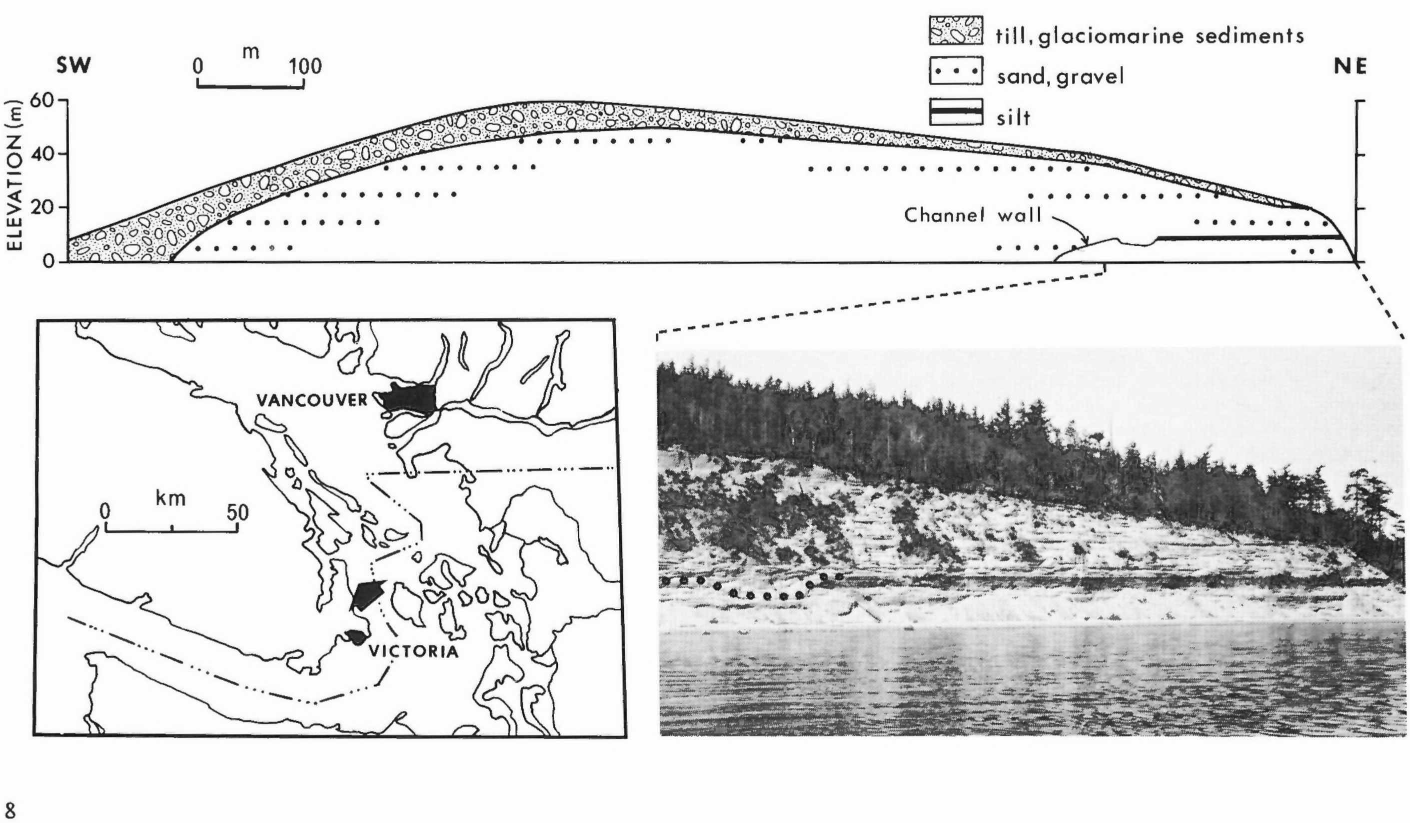


Table 2

Paleocurrent data from Quadra Sand

Data set*	Location lat. N	lat. W	n**	Θ†	r/n††
1A	50°05'	125°02'	11(3)	118	0.99
1B	50°05'	125°02'	8(1)	152	0.97
1C	50°05'	125°02'	10(2)	225	0.97
2	50°04.5'	125°04'	11(1)	210	0.97
3	50°01.5'	125°00'	5(1)	157	0.97
4A	50°00'	124°56'	5(1)	115	0.99
4B	50°00'	124°56'	11(3)	190	0.92
5	49°56.5'	125°35.5'	29(1)	190	0.96
6	49°56.5'	124°47'	15(1)	122	0.98
7A	49°56'	124°49'	7(1)	155	0.98
7B	49°56'	124°49'	20(3)	176	0.99
8	49°51'	124°40'	30(4)	88	0.97
9A	49°50'	125°03'	34(4)	157	0.96
9B	49°50'	125°03'	23(5)	178	0.99
9C	49°50'	125°03'	34(4)	210	0.97
10	49°48'	124°30.5'	20(1)	117	0.89
11A	49°46.5'	124°37.5'	8(1)	199	0.95
11B	49°46.5'	124°37.5'	15(1)	229	0.97
12	49°43.5'	124°56'	15(1)	133	0.60
13A	49°41'	124°30.5'	66(3)	209	0.96
13B	49°41'	124°30.5'	17(1)	224	0.98
14A	49°40.5'	124°53.5'	5(1)	89	0.99
14B	49°40.5'	124°53.5'	28(4)	112	0.97
14C	49°40.5'	124°53.5'	11(2)	168	0.96
14D	49°40.5'	124°53.5'	16(3)	218	0.98
15A	49°35.5'	124°49'	15(3)	92	0.98
15B	49°35.5'	124°49'	8(1)	128	0.99
15C	49°35.5'	124°49'	26(3)	167	0.96
16A	49°30.5'	124°00.5'	15(1)	102	0.96
16B	49°30.5'	124°00.5'	22(2)	162	0.99
17	49°28'	123°52'	20(1)	157	0.95
18	49°23'	124°35'	23(3)	102	0.94
19A	49°22'	124°31'	5(1)	82	0.99
19B	49°22'	124°31'	6(1)	109	0.99
20A	49°21.5'	124°27'	42(7)	117	0.93
20B	49°21.5'	124°27'	9(1)	169	0.89
21A	49°19.5'	124°23.5'	5(1)	90	0.97
21B	49°19.5'	124°23.5'	8(1)	130	0.99
22	49°18.5'	124°22'	4(1)	120	0.93
23	49°17.5'	124°15'	14(3)	122	0.97
24A	49°16'	123°15.5'	28(1)	37	0.96
24B	49°16'	123°15.5'	16(2)	68	0.94
24C	49°16'	123°15.5'	63(3)	93	0.94
24D	49°16'	123°15.5'	48(3)	146	0.93
24E	49°16'	123°15.5'	10(1)	258	0.93
25A	49°15'	124°10'	15(2)	100	0.97
25B	49°15'	124°10'	12(3)	127	0.99
26A	49°15'	124°09'	22(2)	106	0.97
26B	49°15'	124°09'	14(1)	141	0.95
27A	49°14'	122°46.5'	16(1)	192	0.90
27B	49°14'	122°46.5'	20(1)	220	0.99
28A	48°57'	123°37.5'	16(1)	140	0.99
28B	48°57'	123°37.5'	19(1)	213	0.95
28C	48°57'	123°37.5'	30(2)	235	0.96
29A	48°37'	123°19'	10(1)	79	0.97
29B	48°37'	123°19'	29(3)	146	0.97
29C	48°37'	123°19'	25(3)	160	0.97
29D	48°37'	123°19'	29(2)	180	0.92
29E	48°37'	123°19'	23(3)	208	0.96
30A	48°36.5'	123°21'	13(1)	113	0.95
30B	48°36.5'	123°21'	5(1)	149	0.98
30C	48°36.5'	123°21'	19(2)	173	0.99
30D	48°36.5'	123°21'	6(1)	217	0.99
31A	48°36'	123°18'	13(1)	136	0.99
31B	48°36'	123°18'	25(3)	186	0.90
32A	48°33'	123°22'	12(1)	89	0.92
32B	48°33'	123°22'	15(1)	108	0.99
32C	48°33'	123°22'	35(2)	145	0.99
32D	48°33'	123°22'	10(1)	175	0.94
32E	48°33'	123°22'	13(1)	202	0.99
32F	48°33'	123°22'	8(1)	257	0.97
33	48°30'	123°20.5'	22(2)	146	0.98
34A	48°29.5'	123°19.5'	8(1)	100	0.87
34B	48°29.5'	123°19.5'	11(1)	153	0.91

*Each number represents one location; letters indicate data sets at different levels within Quadra Sand. At sites where paleocurrent data were collected at several levels, statistically equivalent samples were combined.

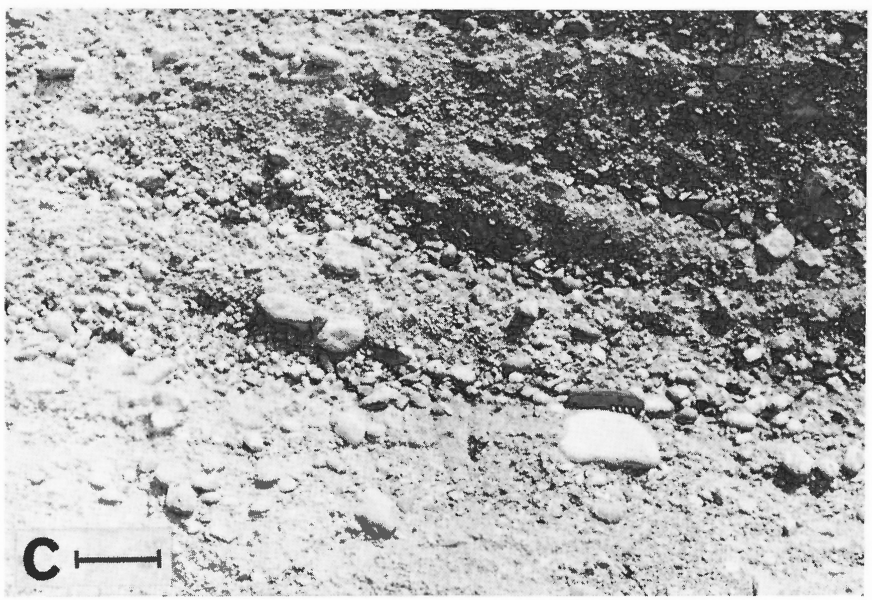
**n = number of observations in data set; parentheses enclose number of samples forming data set.

†Θ = azimuth of vector resultant.

††r/n = magnitude of vector resultant divided by number of observations.

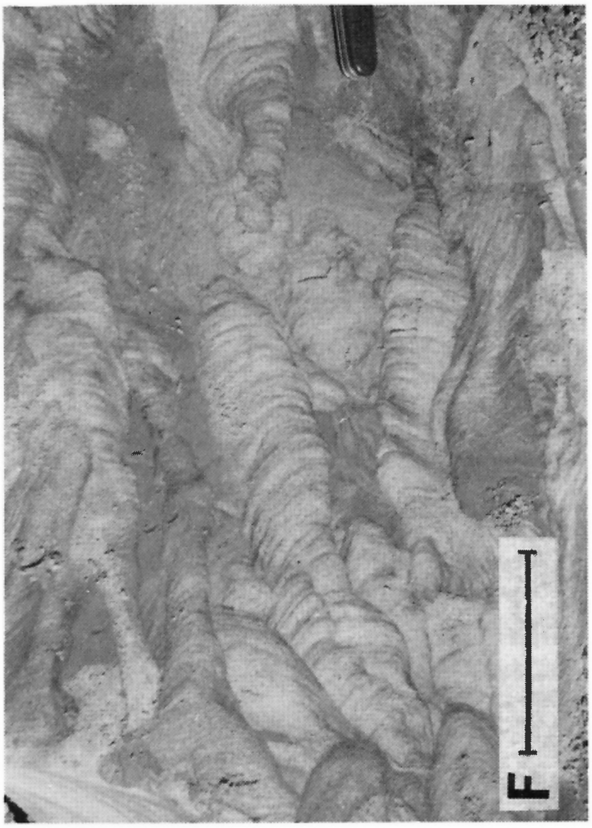
A - cross-bedded sand, Comox (49°40'N, 124°54'W)

B - interstratified silt and sand, Comox (49°40'N, 124°54'W)

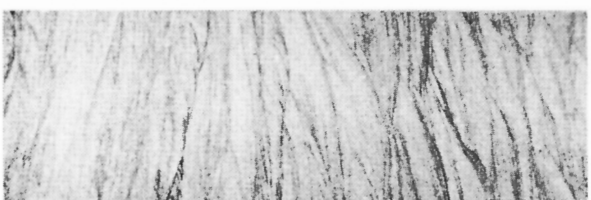


C - gravel, Parksville (49°18'N, 124°22'W)

D - cross-bedded gravelly sand, Cowichan Head (48°34'N, 123°22'W)



F - cross-bedded sand, Parksville (49°17'N, 124°15'W view of stratification surface)



E - cross-bedded sand, Denman Island (49°36'N, 124°49'W) viewed perpendicular to bedding plane)

Figure 10. Textures and sedimentary structures characteristic of Quadra Sand. Scale bars in B, C, E, and F are 10 cm.

At many sites the flow direction shifted during aggradation (Fig. 12). These shifts were rather abrupt, typically occurring vertically through the section within a few centimetres or tens of centimetres. Thus although the regional sediment transport direction was south to southeast, there were shifts in local flow patterns during deposition of the unit. It is probable that the local flow variability reflects shifts in the channel pattern of a braided river system. The presence of trough cross-strata and cut-and-fill structures, the dominance of sediment normally transported as bed load in an aggradational setting, the scarcity of organic horizons, and the lack of paleosols also support the existence of a braided river system.

Surface textures of sand grains

The surface textures of sand grains provide information as to the transportational and depositional history of sediment (Porter, 1962; Krinsley and Donahue, 1968; Krinsley and Margolis, 1971; Krinsley and Doornkamp, 1973).

Samples of Quadra Sand were observed at low magnification with a binocular microscope, and it was noticed immediately that most grains are angular to subangular (Schneiderhöhn, 1954). Additional information was obtained by observing quartz grains from Quadra Sand through a scanning electron microscope. Samples were prepared according to the procedure outlined in Krinsley and Margolis (1971) and were observed and photographed with a Cambridge Stereoscan (Fig. 13). The following surface texture characteristics are common on almost all quartz grains observed: (1) conchoidal breakage patterns of a range of sizes, (2) very high relief, and (3) semiparallel and arc-shaped steps. Parallel striations and imbricate breakage blocks also were observed on many grains. Although no single surface characteristic is definitive for a particular sedimentary environment, the occurrence of the above features as a group on most quartz sand grains indicates that the sand at one stage was transported by glaciers (Krinsley and Doornkamp, 1973; Whalley and Krinsley, 1974).

Mineralogy

Cummings (1941) studied the mineralogy of sands exposed around the Strait of Georgia. He noted (p. 3) that most **bank sands** (mainly Quadra) from the northern Strait of Georgia:

> ..... consist essentially of plagioclase and quartz, with lesser amounts of other minerals. The constituents of this group are present in proportions approximating those of quartz diorite. All of the accessory minerals, with the exception of topaz, tourmaline, kyanite and phlogopite, have been reported in Coast Range batholithic rocks.

Chemical analyses of Quadra Sand and intermediate plutonic rocks of the Coast Crystalline Complex further indicate the similarity between the two (Table 3).

About 100 samples of fine grained Quadra Sand were analyzed for their mineral content. The samples were collected from exposures throughout the Georgia Depression; each is thought to be representative of sand at the collection site. All samples have similar grain-size distributions and thus formed under similar hydraulic conditions. Because mineral species of different densities are sorted selectively relative to the energy level at the depositional site, it is important in provenance studies to compare hydraulically equivalent sediment samples (Hubert, 1971).

Each sample was sieved, and a split of the fine sand (125 to 250 μm) fraction was placed in bromoform (density = 2.89). Grain mounts of the light and heavy mineral separates then were prepared. Mineral species were identified optically and by magnetic separation and X-ray diffraction methods; in addition, light minerals were stained for feldspar.

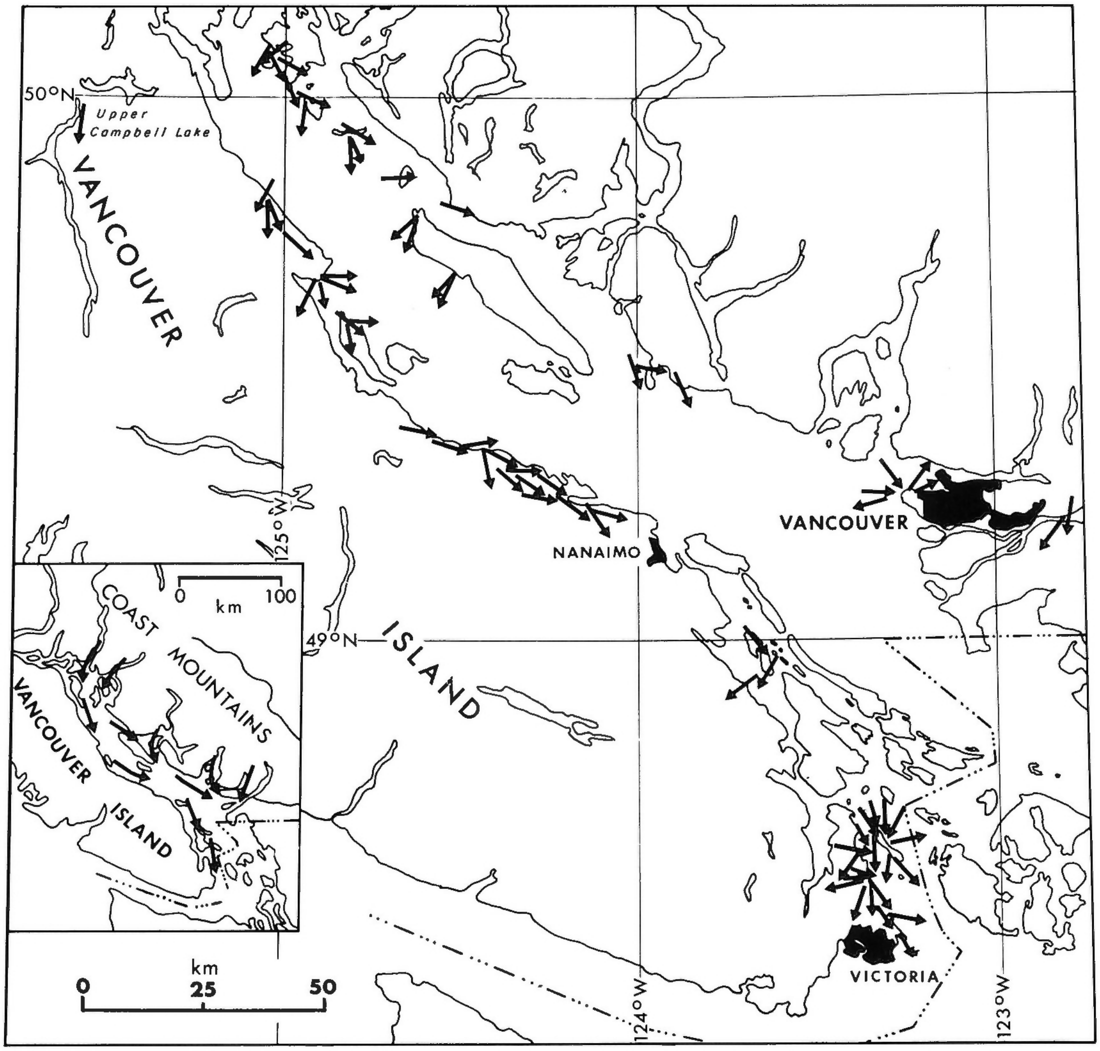


Figure 11. Paleocurrent data, Quadra Sand. Arrows are vector resultants based upon the axial orientation of trough cross-beds. At some sites where multiple samples were collected, paleoflow directions are indicated by more than one arrow; each arrow is the vector resultant of those samples which are statistically equivalent (Table 2). Inset map shows the regional flow pattern generalized from paleocurrent and mineralogic data.

On the basis of these analyses, Quadra Sand may be subdivided broadly into three mineralogic groups, which are identified in Table 4 as A, B, and C.

Type A sand is the most widespread, occurring throughout the central and northern Georgia Depression. It is characterized by the dominance of plagioclase and quartz in the light mineral fraction, abundant hornblende in the heavy mineral fraction, and low amounts of rock fragments as sand grains. As indicated by Cummings (1941) and Fyles (1963), this sand represents detritus eroded from intermediate plutonic rocks of the Coast Mountains.

Type B sand occurs at the southeast corner of Vancouver Island, north of Victoria. It is characterized by comparatively large amounts (about 25 to 30 per cent in most analyzed samples) of fine sand size rock fragments, mainly of sedimentary and volcanic origin. Mineral and lithic grains partially altered to epidote, sericite, and other secondary minerals are abundant. Epidote and hornblende are the most common heavy minerals, the latter occurring in lower amounts than in type A sand. Type B sand includes detritus of granitic, volcanic, and sedimentary sources and may represent type A sand mixed with locally derived, lithic constituents.

Type C sand occurs only at Vancouver (49°14-17'N, 123°12-16'W) and consists mainly of volcanic rock fragments (including glass), feldspar, and quartz. Hypersthene is the dominant heavy mineral; hornblende is less common than in the sands described above. Type C sand includes detritus of both granitic and volcanic origin. The provenance of the volcanic component is the Mount Garibaldi area, located about 70 km north of Vancouver. The volcanic detritus is mixed with sediment eroded from granitic rocks of the Coast Mountains.

At Vancouver sediment from the lower part of the Quadra Sand contains more hypersthene and volcanic rock fragments and less quartz, feldspar, and hornblende than sediment from the upper part of the unit (Fig. 14). The change in mineralogy is at 18 m above sea level and coincides with a textural change (Fig. 4E); below this elevation the sand unit contains horizontal beds of organic-rich silt, whereas above this elevation such beds are absent. It is probable that sand in the lower part of the section was transported largely from the Mount Garibaldi area and that a later influx of granitic sediment from the northwest and west diluted the Garibaldi-provenance sand and led to aggradation of the

Table 3

Geochemical comparison of Quadra Sand in the northern Georgia Depression and plutonic rocks in the Coast Mountains

	Quadra Sand*		Plutonic rocks: Bute Inlet**		Jervis Inlet†		Prince Rupert††	
	m	σ	m	σ	m	σ	m	σ
SiO_2	67.7	1.5	64.6	8.3	60.6	7.6	63.2	5.3
TiO_2	0.5	0.2	0.7	0.2	0.4	0.2	0.6	0.2
Al_2O_3	16.6	0.7	16.1	1.9	17.3	1.5	17.7	1.8
Fe_2O_3	2.2	0.7	0.9	0.3	2.5	1.0	1.8§	0.8§
FeO	1.6	0.3	3.4	2.0	3.5	1.8	2.6§	1.3§
MgO	1.7	0.3	2.1	1.8	2.7	1.5	1.9	1.2
CaO	5.6	0.4	4.5	2.4	5.8	2.2	4.5	1.6
Na_2O	3.3	0.4	3.7	0.3	3.8	0.7	4.3	0.8
K_2O	0.9	0.5	2.0	0.9	1.7	0.6	2.0	0.9

Note: m = mean, σ = standard deviation.

*Cummings (1941, p.3); number of samples, n, is 7.

**Woodsworth (1974, Table 3); n = 5.

†Bacon (1957, Table 1); n = 10.

††W.W. Hutchison (unpublished data); n = 311.

§n = 276

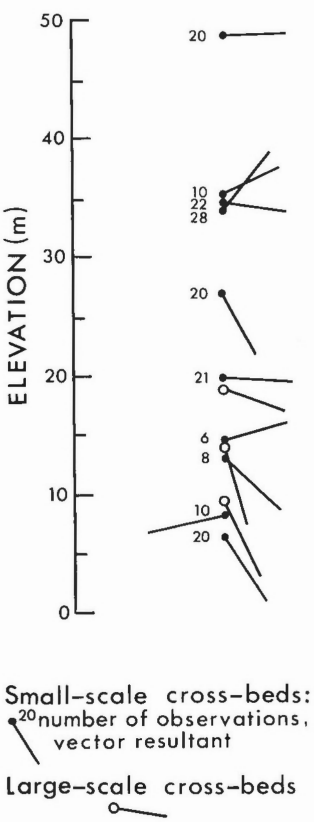


Figure 12.

Paleocurrent data, Quadra Sand at Vancouver (49°16'N, 123°16'W). Vector resultants show the variation in flow direction vertically through the unit at one site. North-south lines are parallel to the elevation axis (vertical); most vectors indicate flow to the southeast or east.

upper part of the unit. Paleocurrent data seem to support this conclusion in that flow indicators from the upper part of the unit at Vancouver are more from the west than those from the lower part (Fig. 12).

In summary, the Quadra consists mainly of sand eroded from granitic rocks of the Coast Crystalline Complex. Only at Vancouver and at the southern end of the Georgia Depression is this granitic sediment mixed with material from other sources. At Vancouver Quadra Sand consists of a mixture of granitic and volcanic detritus (the latter derived from Cenozoic volcanic rocks in the Mount Garibaldi area); on southeast Vancouver Island, the Quadra consists of granitic sediment diluted by sand eroded from local sedimentary and volcanic rocks.

Palynology

Samples of peat and organic-rich silt from Quadra Sand were collected by J.G. Fyles during his geologic investigations of the Georgia Depression and were analyzed for microfossils by J. Terasmae. Terasmae found, however, few, poorly preserved pollen grains and spores in most of these samples.

The arboreal pollen is dominated by **Pinus** (largely **P. contorta**) and **Picea** (Table 5). **Abies** and **Alnus** are abundant in some samples and **Tsuga mertensiana** is present in most. Less common palynomorphs include **Tsuga heterophylla Betula**, and **Salix**. Non-arboreal pollen and spores include the following genera and families, **Artemisia** Caryophyllaceae, Chenopodiaceae, Compositae, Cyperaceae, Ericaceae, Gramineae, **Nuphar**, Onagraceae, Ranunculaceae, **Shepherdia**, Umbelliferae, **Equisetum**, **Lycopodium**, Polypodiaceae, and **Selaginella**. **Pseudotsuga** was not found in the samples from Quadra Sand analyzed by Terasmae, although it is present in plant-bearing sediments of the Cowichan Head Formation (N.F. Alley, pers. comm., 1975).

The feldspar is mainly plagioclase; the mica is biotite, chlorite, and minor muscovite; and the opaques are magnetite and hematite. Accessory heavy minerals identified in one or more samples of Quadra Sand include andalusite, apatite, clino-pyroxene, garnet, kyanite, olivine, rutile, sphene, staurolite, tourmaline, and zircon.

Table 4

Mineralogy of Quadra Sand

	A Plutonic provenance	B Plutonic-volcanic-sedimentary provenance	C Plutonic-volcanic provenance
Light constituents			
Per cent of total	85-95	85-95	85-95
Feldspar	a	b	b
Quartz	b	c	c
Rock fragments	d	b	a
Heavy minerals			
Per cent of total	5-15	5-15	5-15
Amphibole	a	a	c
Orthopyroxene	d	d	a
Epidote	d	c	d
Mica	d	d	d
Opaques	d	d	c

Notes: Letters indicate abundance of constituent in light or heavy mineral separate (based upon analysis of 125-250 μm size fraction): a - > 50%; b - 20-50%; c - 10-20%; d - 1-10%.

Table 5

Arboreal pollen in organic-rich strata of Quadra Sand

	Campbell Lake (n=3)	Comox-1 (n=1)	Comox-2 (n=10)	Thormanby Island (n=4)	Reception Point (n=1)	Sidney Island (n=2)	Cordova Bay (n=14)
Gymnosperms							
Abies	9	3	5	6	8	6	20
Picea	60	11	41	49	5	30	19
Pinus	24	84	40	38	59	43	24
Pseudotsuga	-	-	-	-	-	-	3
Tsuga heterophylla	-	-	1	<1	8	6	21
Tsuga mertensiana	2	-	3	1	7	5	3
Angiosperms							
Alnus	5	-	7	5	13	6	9
Betula	<1	-	<1	<1	-	2	1
Salix	-	2	2	-	-	2	-

Notes: n = number of analyzed samples containing pollen. Values represent per cent of arboreal pollen (if n > 1, the values are averages for the n samples). All assemblages except that at Cordova Bay are from Quadra Sand. The Cordova Bay samples are from stratified sediments underlying two tills; these sediments probably predate the Olympia nonglacial interval. Samples collected by J.G. Fyles and analyzed by J. Terasmae.

Locations: Upper Campbell Lake - 49°56'N, 125°35'W; Comox-1 - 49°42'N, 124°52'W; Comox-2 49°40'N, 124°54'W; Thormanby Island 49°30'N, 123°59'W; Reception Point 49°28'N, 123°52'W; Sidney Island 48°38'N, 123°19'W; Cordova Bay 48°30'N, 123°19'W.

Trees and shrubs represented in this assemblage all presently grow in the area, but:

> ..... the assemblage, lacking in Douglas fir and with abundant spruce, is more typical of the lowland coastal forests bordering the Gulf of Alaska than those of Vancouver Island, and thus appears to record a climate somewhat cooler than the present one (Fyles, 1963, p. 28).

In order to assess further the climatic implications of the Quadra palynomorph assemblage, Terasmae analyzed samples of organic-rich sediment from beneath two tills at Cordova Bay (48°30'N, 123°19'W) near Victoria. He found that these older materials contain **Pseudotsuga** and have more **Abies** and **Tsuga heterophylla** than organic-rich beds in Quadra Sand (Table 5). This suggests that a climate as warm as or warmer than the present occurred at an earlier time.

Age

Organic matter from Quadra Sand and bounding strata has provided radiocarbon dates from which a chronologic framework for late Pleistocene events in the Georgia Depression has been established (Fulton, 1971).

Table 6 summarizes finite radiocarbon dates obtained from the Cowichan Head Formation and Quadra Sand in the Strait of Georgia region. Dates beyond the radiocarbon dating range, which have been obtained from sediments resembling the Cowichan Head Formation beneath a single till in the Georgia Depression, are listed in Table 7 (see also Fyles, 1963, p. 33-36).

Wood and peat from estuarine and fluvial deposits of the Cowichan Head Formation underlying Quadra Sand and from correlative strata in northwest Washington have yielded finite radiocarbon dates from 15 000 ± 400 years B.P. (W-1227) to 36 800 ± 1800 years B.P. (UW-31). In addition. two samples of wood from what is probably part of the Cowichan Head Formation near Port Coquitlam have dated 40 200 ± 430 years B.P. (GSC-2137) and 40 500 ± 1700 years B.P. (GSC-2167). Stratified sediments underlying a single till in the Fraser Lowland, which recently were dated at 58 800 $^{+2900}_{-2100}$ years B.P. (QL-195), may represent the lowest part of the Cowichan Head Formation. Because of the low activity of ^{14}C in the sample, however, the date must be considered a minimum.

Dates from Quadra Sand indicate that the unit is progressively younger towards the south (Fig. 15). Wood either at the base of Quadra Sand or at the top of the Cowichan Head Formation at the north end of the Georgia Depression (50°05'N, 125°02'W) yielded a radiocarbon age of 35 400 ± 400 years B.P. (GSC-202), whereas at the south end of the depression (48°30'N, 123°19'W) plant material in Quadra Sand dated at 22 600 ± 300 years B.P. (GSC-84). Farther south in Puget Lowland (48°06'N, 122°43'W), peat from Esperance Sand has been dated at 18 000 ± 400 years B.P. (I-2282; Easterbrook, 1969). In the Seattle area (47°38'N, 122°19'W) stratified clay yielding radiocarbon dates as young as 15 000 ± 400 years B.P. (W-1227) underlies Esperance Sand (Mullineaux et al., 1965).

Sedimentation rates

In addition to the diachronous nature of the sand, aggradation apparently occurred in a relatively short period of time at any one site. For example, at 49°17'N sand at least 50 m thick was deposited after 24 500 ± 500 years B.P. (GSC-108) but prior to glacier invasion of the area not more than a few thousand years later. Likewise, a similar thickness of Esperance Sand on Marrowstone Island (48°06'N, 122°43'W) was deposited after 18 000 ± 400 years B.P. (I-2282) but before the area was overriden by ice less than 3000 years later.

An estimate of the average rate of aggradation of Quadra Sand may be made at sites where organic materials at different levels have been dated. Near Vancouver (49°16'N, 123°15'W) wood at elevation 0.3 m dated at 26 100 ± 320 years B.P. (GSC-1635); peat at elevation 7.6 m, 25 100 ± 600 years B.P. (GSC-109); and wood at elevation 15.2 m, 24 500 ± 500 years B.P. (GSC-108). Thus, the probable average

Table 6

Finite radiocarbon dates from Quadra Sand and the Cowichan Head Formation

Site no. (Fig. 2)	Laboratory dating no.*	Date list**	Date (± 2σ)	Location lat.N	long.W	Material	Stratigraphic unit †
1	GSC-2194		18 600 ± 190	49°14'	122°47'	Wood	Q?
2	GSC-210	7(36)	19 150 ± 250	48°47'	123°54'	Organic silt	Q
3	GSC-195	7(36)	21 070 ± 290	48°46'	123°57'	Wood	Q
4	GSC-2203		21 600 ± 200	49°20'	122°47'	Wood	Q
2	GSC-317	8(111)	21 730 ± 230	48°47'	123°54'	Wood	Q
5	GSC-84	5(50)	22 600 ± 300	48°30'	123°19'	Plant fibers	Q
6	GSC-518	9(173)	23 840 ± 300	48°37'	123°31'	Wood	CH
7	GSC-59	5(51)	23 920 ± 420	48°39'	123°20'	Wood	Q
8	GSC-318	8(111)	24 060 ± 300	48°45'	123°40'	Peat	CH
8	GSC-385	8(111)	24 380 ± 350	48°45'	123°40'	Peat	CH
9	L-502	3(148)	24 400 ± 900	49°17'	123°13'	Wood	Q
9	GSC-108	5(47)	24 500 ± 500	49°17'	123°13'	Wood	Q
10	I-1225		24 560 ± 800	48°45'	123°38'	Wood	CH
11	GSC-58	5(48)	25 000 ± 400	49°57'	125°36'	Wood	Q
12	GSC-109	5(48)	25 100 ± 600	49°16'	123°15'	Peat	Q
13	GSC-96	5(49)	25 190 ± 470	49°51'	125°37'	Wood	Q
1	GSC-2273		25 800 ± 310	49°14'	122°47'	Wood	CH
1	GSC-2277		26 000 ± 310	49°14'	122°47'	Wood	CH
12	GSC-1635		26 100 ± 320	49°16'	123°15'	Wood	Q
14	GSC-53	5(49)	26 100 ± 400	49°40'	124°54'	Wood	Q
1	GSC-2191		26 200 ± 320	49°14'	122°47'	Wood	CH
1	GSC-124	6(171)	26 450 ± 520	49°14'	122°47'	Peaty silt	CH
1	GSC-2217		26 900 ± 320	49°14'	122°47'	Wood	CH
1	GSC-2263		27 000 ± 490	49°14'	122°47'	Wood	CH
1	GSC-536	9(173)	27 180 ± 460	49°14'	122°47'	Wood	CH
1	GSC-2107		27 400 ± 420	49°14'	122°47'	Wood	CH
15	GSC-263	7(37)	27 670 ± 410	49°22'	124°31'	Peat	CH
16	GSC-232	7(37)	27 960 ± 420	49°30'	124°00'	Wood	Q
1	GSC-2139		28 200 ± 200	49°14'	122°47'	Wood	CH
14	GSC-95	5(49)	28 800 ± 740	49°40'	124°54'	Wood	Q
17	L-424C	1(10)	29 300 ± 1400	49°36'	124°49'	Wood	CH
1	GSC-2140		29 600 ± 200	49°14'	122°47'	Peat	CH
17	L-424E	1(11)	30 000 ± 1200	49°36'	124°49'	Wood	CH
17	L-424B	1(10)	30 200 ± 1300	49°36'	124°49'	Peat	CH
18	I(GSC)-214	4(35)	32 200 ± 3300	49°19'	123°03'	Peat	CH
19	GSC-221	7(35)	32 580 ± 720	49°15'	123°11'	Wood	CH
15	GSC-2050		32 600 ± 550	49°22'	124°32'	Wood	CH
20	L-455B	3(147)	35 400 ± 2200	50°05'	125°02'	Wood	?
20	GSC-202	7(26)	35 400 ± 400	50°05'	125°02'	Wood	?
21	GSC-200	7(36)	35 600 + 3000 − 2200	48°34'	123°22'	Soil	CH
22	GSC-93	7(26)	36 200 ± 500	49°21'	123°02'	Wood	CH
1	GSC-2137		40 200 ± 400	49°14'	122°47'	Wood	CH?
1	GSC-2167		40 500 ± 1700	49°14'	122°47'	Wood	CH?
23	QL-195		58 800 + 2900 − 2100	49°09'	122°56'	Wood	CH?

*GSC - Geological Survey of Canada; I - Isotopes; L - Lamont Geological Observatory; QL - Quaternary Research Center, University of Washington.

****Radiocarbon:** volume (page); data also from Fulton (1971), Lowdon and Blake (1973), Armstrong and Hicock (1975), and Armstorng (pers. comm., 1976).

†CH - Cowichan Head Formation; Q - Quadra Sand and coeval sediments in valleys adjacent to the Georgia Depression.

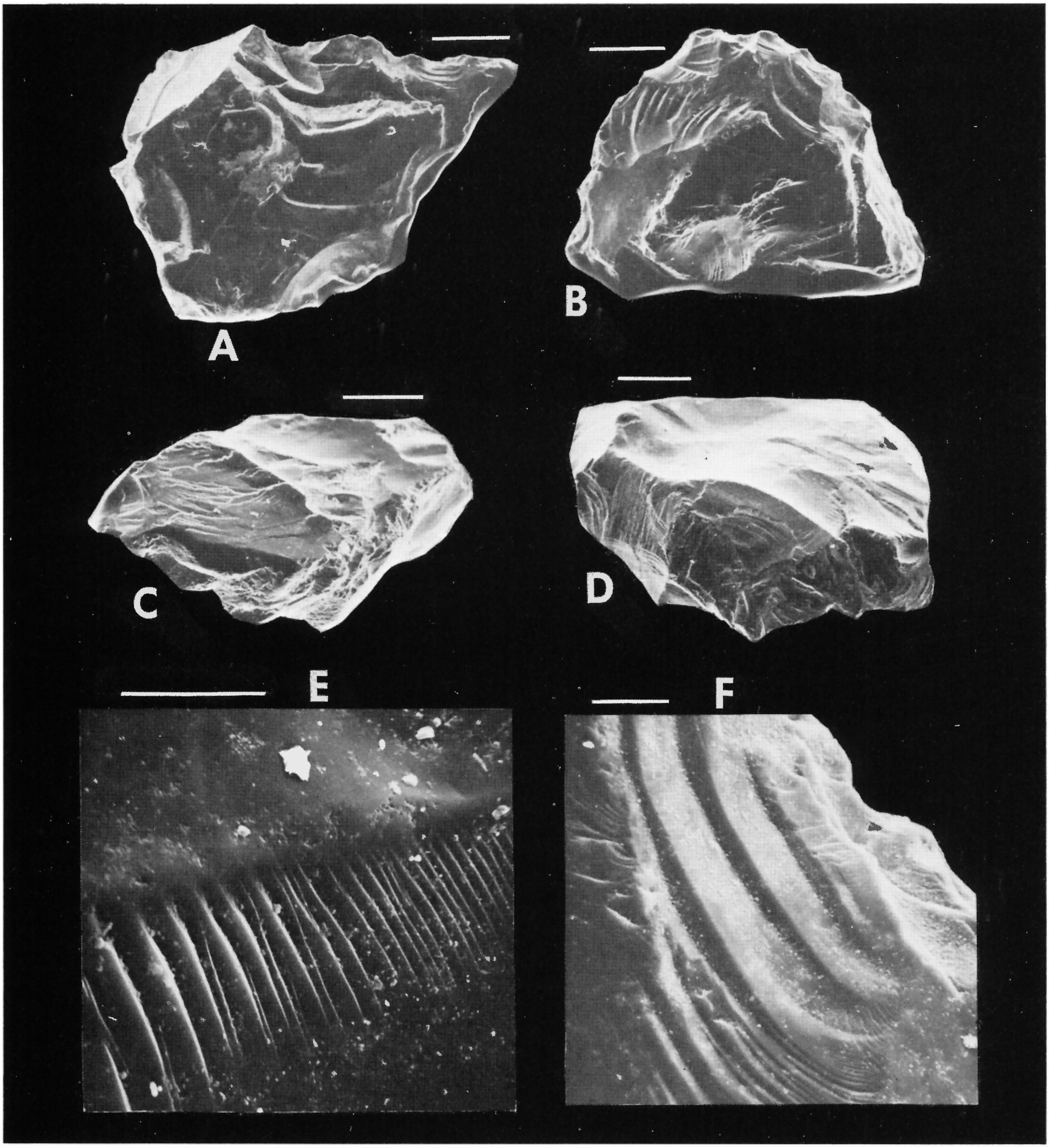


Figure 13. Representative quartz grains from Quadra Sand photographed with a scanning electron microscope. The grains exhibit glacial surface textures characterized by high relief, conchoidal breakage patterns, semiparallel and arc-shaped steps (e.g., C and E), and imbricate breakage blocks (e.g., F). Scale bars in A, B, C, and D are 100 µm, and in E and F are 10 µm. Grains are from Quadra Sand at Comox (49°40'N, 124°54'W) and Quadra Island (50°00'N, 125°10'W). GSC Photo 203170-C.

accumulation rate of sediment between 0.3 and 15.2 m is about 1 cm per year. However, if calculations are based on the extremes (95% confidence limits) rather than most probable age values for GSC-1635 and GSC-108, rates as low as 0.6 cm per year and as high as 2 cm per year are determined. Similar calculations based on dates GSC-53 and GSC-95 (Table 6) for 14.6 m of sand near Comox yield a probable average sedimentation rate of 0.5 cm per year with extemes of 0.4 and 0.9 cm per year.

These rates, however, are only averages and likely are not representative of the rate of deposition of individual sedimentation units. Cross-beds and channels within Quadra Sand indicate that sediment deposition was periodic rather than continuous; thus instantaneous rates of deposition were probably in excess of those cited above. Also, because organic matter is generally preferentially preserved in fine grained sediment, the sedimentation rates calculated above are for those parts of the unit containing numerous silt beds. The silt undoubtedly accumulated more slowly than the associated sand.

ORIGIN AND GEOLOGIC HISTORY OF QUADRA SAND

The following is a discussion of the provenance and history of Quadra Sand based on field observations and laboratory data. Some of the interpretations are speculative to the extent that no single piece of evidence is conclusive, but, taken together, the data favour the interpretations rendered.

Quadra Sand formed subaerially on flood plains which extended across or along the margins of the Georgia Depression. Sedimentary structures indicate deposition by braided rivers (Doeglas, 1962; Allen, 1965). Although the unit presently consists of a series of relatively small isolated bodies located around the Strait of Georgia and on islands within the strait, available evidence indicates that it was originally more extensive in distribution. Exposed Quadra beds are horizontal, uniform in character, and continuous over distances as great as 6 km. It is believed that the present patchy distribution is due largely to erosion of an originally more extensive sediment body or group of bodies.

Paleocurrent data, sand mineralogy, and radiocarbon dates show that the unit was deposited progressively from northwest to southeast down the Georgia Depression. The sand in most areas consists mainly of plagioclase, quartz, amphibole, and magnetite derived from granitic rocks of mainland British Columbia north and northeast of the Georgia Depression rather than from the mafic volcanic and sedimentary rocks underlying much of Vancouver Island. The source area in the southern Coast Mountains is the region with the highest peaks (up to 4017 m) and largest glaciers in southern and central British Columbia. Under existing conditions, sand-size detritus produced by weathering and erosion of the Coast Crystalline Complex is deposited as alluvium along river courses and as deltaic sediments at the heads of fjords. The rate of sand production, however, is insufficient to account for a body of sediment the size of the Quadra in a comparable time framework. It is probable, then, that the rate of sand production and hence conditions during deposition Quadra Sand differed from those of the present. It is proposed that rapid aggradation of sand began during an interval of climatic cooling at the end of the Olympia nonglacial interval.

With the advance of valley glaciers out of high mountainous areas and into fjords, sediment production in the Coast Mountains probably increased. This would be due, in large part, to an increase in area affected by glacier scour and periglacial activity, and perhaps also to the loss of stabilizing vegetation cover. The erosion products would be transported into the valleys and fjords but would only be introduced into the Strait of Georgia proper after the fjords were filled with sediment or after valley glaciers had advanced to the fjord mouths. As the glaciers advanced, they perhaps entrained large amounts of sediment deposited earlier in the fjords. This sediment then was available for transport both by glaciers and meltwater and would have been redeposited farther down the strait.

Table 7

Dates beyond radiocarbon dating range from terrestrial sediments beneath one till in the Georgia Depression

Laboratory dating no.*	Date list**	Date	Location lat.N	Location long.W	Material
I-1385	8(171)	>35 400	48°59'	123°01'	Wood
GSC-98	6(171)	>36 200	49°14'	124°01'	Peat
GSC-153	6(172)	>36 500	48°52'	123°39'	Wood
GSC-196	7(37)	>36 650	49°14'	124°01'	Peat
GSC-81	5(48)	>36 800	49°15'	123°11'	Peat
GSC-60	5(47)	>37 000	49°07'	122°54'	Wood
GSC-52	4(19)	>37 200	50°08'	125°18'	Wood
GSC-78	5(50)	>37 600	49°28'	124°50'	Peat
GSC-99	5(50)	>37 900	49°27'	124°45'	Wood
GSC-36	5(48)	>38 100	49°15'	123°06'	Wood
GSC-163	6(171)	>38 800	48°52'	123°39'	Peat
GSC-62	5(47)	>39 000	49°10'	122°55'	Wood
GSC-396	8(111)	>40 000	49°12'	123°06'	Wood
GSC-30	4(19)	>40 000	50°15'	125°48'	Wood
GSC-358	8(112)	>40 300	48°21'	123°45'	Peat
GSC-2228		>43 000	49°18'	122°59'	Wood
GSC-2131		>47 000	48°59'	123°01'	Wood
GSC-163-2	8(111)	>47 400	48°52'	123°39'	Peat
GSC-2123†		>50 000	49°09'	122°56'	Wood

*GSC - Geological Survey of Canada; I - Isotopes.

****Radiocarbon:** volume (page); data also from Fulton (1971) and Armstrong (pers. comm., 1976).

†This sample also was dated at the University of Washington, and an age of $58\,800 \pm {}^{2900}_{2100}$ years B.P. (QL-195) was obtained.

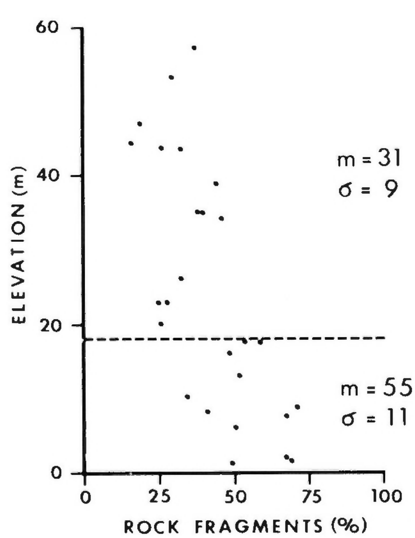


Figure 14.

Per cent of volcanic rock fragments (including glass) in light mineral fraction of Quadra Sand at Vancouver (49°16'N, 123°16'W). Volcanic detritus, largely of Mount Garibaldi provenance, is more common in the lower part of the unit (mean and standard deviation = 55% and 11%, respectively) than in the upper part (31% and 9%). The mineralogic break, at an elevation of 18 m, coincides with a textural break; silt beds are present below this elevation but are absent above.

Sand aggradation occurred first at the northern end of the Strait of Georgia, perhaps as early as about 35 400 years B.P. (GSC-202)[1]. By 28 800 years B.P. (GSC-95), deposition was occurring at 49°40'N, and by 26 100 years B.P. (GSC-1635), at 49°16'N. Aggradation of Quadra Sand was still occurring 26 100 years B.P. (GSC-53) at 49°40'N at the same time that sand was being deposited at 49°16'N.

During or after deposition of the unit in the Vancouver area at 49°16'N, Quadra Sand was deposited in an upland valley on Vancouver Island adjacent to the northern Strait of Georgia (Fig. 2, site 11). The unit here is present at a few hundred metres above sea level and probably was laid down as outwash in an ice-marginal environment. The sediment was deposited by flow up Campbell Lake valley from the Strait of Georgia (Fig. 11). Presumably ice blocked drainage to the east and provided sediment to the depositional site; however, local glaciers from central Vancouver Island had not expanded sufficiently at this time to cover the Campbell Lake area. At one site in the valley horizontally bedded sand overlies dipping, parallel bedded sand and gravel thought to be deltaic in origin. The contact between the two units occurs at an elevation of 330 m which is also the elevation of the lowest drainage divide bordering the valley. Thus it is probable that ice blocking the valley impounded a lake which overflowed at an elevation of 330 m. Somewhat later, Quadra Sand was deposited locally over the deltaic sediments of this lake.

It is likely that at about this same time Quadra Sand was being deposited in the southern Strait of Georgia or Puget Sound, perhaps from outwash reworked by the advancing trunk glacier to the north. If so, a Quadra Sand blanket probably did not exist over the entire Strait of Georgia at one time; rather, sand deposited at an early stage might have been re-entrained by meltwater or active ice from southward-advancing glaciers and then redeposited farther south. The absence of a gradation in the mean grain size of Quadra Sand down the strait from the presumed source area supports this concept of reworking. If a sand blanket occupying the entire Georgia Depression was deposited from essentially a point source, systematic areal grain-size gradations might be expected. But such gradations do not exist; indeed, some of the finest Quadra deposits are the northernmost and, therefore, nearest the ultimate source area.

One unusual characteristic of Quadra Sand is its uniform texture. Most of the unit consists of well sorted, fine to coarse grained sand; clay, silt, and gravel are comparatively uncommon. The absence of mud and gravel at one site may be explained by selective sorting during fluvial transport and deposition. Selective sorting, however, does not adequately explain their rarity in the unit throughout the basin. Perhaps the fines were transported south to be incorporated in coeval estuarine and marine sediments, but there is no direct evidence of this. Perhaps sand was the dominant erosion product of the granitic source area so that little gravel or fines were produced.

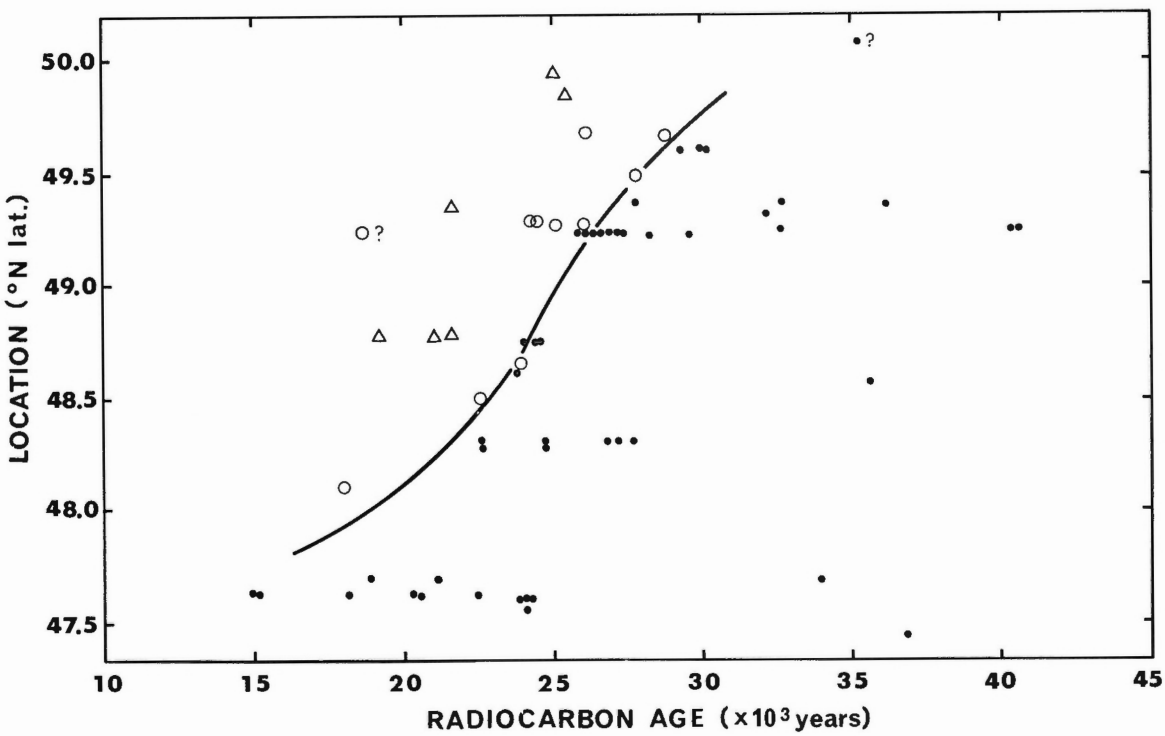


Figure 15. Age relation of Cowichan Head Formation and Quadra Sand. Radiocarbon dates from the Cowichan Head Formation (Olympia nonglacial sediments in Washington) are shown by dots; those from Quadra-Esperance Sand by circles; and those from probable Quadra correlatives in upland valleys adjacent to the Georgia Depression by triangles. The curve marks the transition from fluvial to glaciofluvial sedimentation. Radiocarbon dates are listed in Table 6.

[1] This radiocarbon date is from organic-rich silt exposed near sea level beneath thick sand. It is not known, however, whether the dated material is within Quadra Sand or at the top of the Cowichan Head Formation (see discussion by Fyles in Olson and Broecker, 1961, p. 147). If the material is part of the Cowichan Head Formation, sand deposition within the strait began after 35 400 years B.P. but before 28 800 years B.P., the age of dated material in Quadra Sand farther south in the strait.

Some Quadra Sand has a matrix of fine, clay-size material (Fig. 8). This matrix consists of quartz, feldspar, mica, calcite, and (?) amphibole. Because most of the material is finer than 1 µm and consists of primary rather than pedogenically produced minerals, it is considered to be glacial rock flour. The clay matrix probably formed when meltwater filtered down through porous sand underlying outwash surfaces.

Quadra Sand grains have surface textural characteristics attributed to glacial transport. Recently, many surface features on quartz sand grains cited as indicative of the glacial environment (Krinsley and Donahue, 1968; Krinsley and Margolis, 1969) have been shown to occur on grains from known nonglacial deposits (Fitzpatrick and Summerson, 1971; Setlow and Karpovich, 1972; Krinsley and Doornkamp, 1973; Margolis and Krinsley, 1974; Baker and Dott, 1975). However, when several glacially diagnostic surface features are observed on the same grain and when most grains exhibit one or more of these features, glacial transport is indicated (Krinsley and Margolis, 1969; Whalley and Krinsley, 1974; Rehmer and Hepburn, 1975). Nearly all Quadra Sand grains that were observed under the scanning electron microscope have one or more "glacial" surface textural characteristics, and it is concluded that these features were generated in a glacial environment. Fluvial transport did not modify the grain surfaces significantly and thus perhaps was relatively short.

Glacial surface textures on detrital quartz grains indicate that the sand either has been reworked from older glacial materials or has been transported englacially and subglacially to the general area of depositon during Quadra time. The latter is considered more likely for the following reasons. If the sand formed from older glacial deposits independently of sedimentologic changes that might have accompanied late Wisconsin glaciation, Vancouver Island would have been a significant sediment source. Paleocurrent and mineralogic data, however, indicate that the island was a negligible supplier of sand during Quadra time; rather, the sand was supplied almost completely from the Coast Mountains. Furthermore, the pronounced lithologic differences between the Cowichan Head Formation and Quadra Sand are inconsistent with the latter having formed by reworking from pre-existing drift. Presumably, this drift also would have been a sediment source throughout the period of Cowichan Head sedimentation. Yet, at any one site, it was only after a lengthy period during which organic-rich silt, gravel, and subordinate sand were deposited that rapid sand aggradation commenced.

Clearly, an increase in glacierized area is required to explain the inception of Quadra deposition. This increase probably was linked with the transition from nonglacial to glacial conditions at the beginning of the last major glaciation.

Peat and organic-rich silt collected from Quadra Sand contain a sparse flora. This is partly due to poor preservation of pollen and spores but probably also reflects the absence of diversified vegetation on the flood plain during deposition of the unit. The number of species is low, and, taken as a group, the plants record a climate cooler than the present. Detailed palynological studies are required to assess further the climatic implications of the flora and to compare it with the floral assemblage of the underlying Cowichan Head Formation.

On the basis of the above evidence, it is concluded that Quadra Sand formed as outwash in front of, and perhaps along the margin of, glaciers advancing into the Georgia Depression during late Wisconsin time. In the northern Strait of Georgia the unit occurs as remnants near the centre of the depression as well as along the margins. This indicates that Quadra Sand was deposited across the full width of the strait in this area. In the central and southern Strait of Georgia, remnants of the unit are restricted to the margins of the depression. Here, the sediments were deposited either as a basin-wide sand blanket as in the northern strait or as kame terraces on both sides of the trunk glacier advancing down the axis of the depression. Quadra Sand, however, lacks features characteristic of kame terrace deposits, such as ice-contact structures and textural heterogeneity. Rather, the

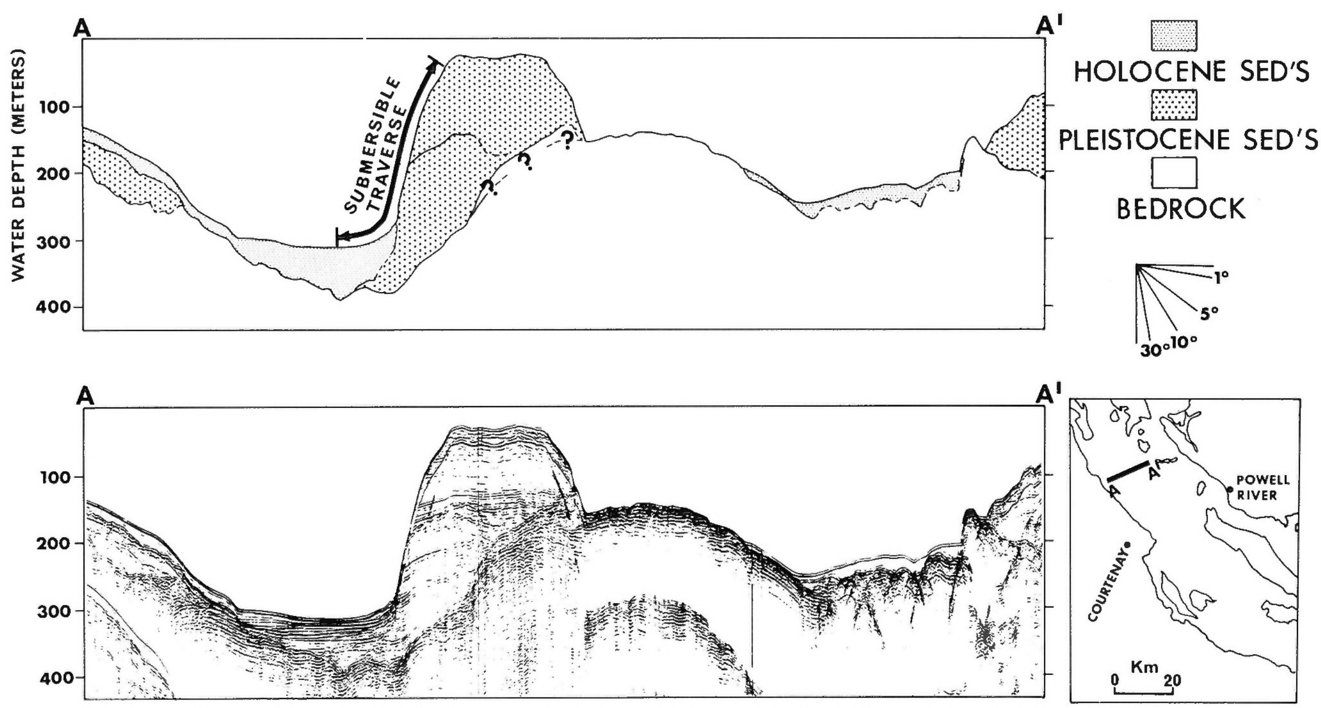


Figure 16. Continuous seismic profile across a shallow bank underlain by stratified Pleistocene sediments. These sediments predate Quadra Sand and represent remnants of a more extensive marine fill upon which the sand unit was deposited at the beginning of the Fraser Glaciation. A major unconformity occurs within the sediment pile.

sand is horizontally stratified and well sorted. Stratification is continuous over long distances on cliff faces, and the sediments exhibit no signs of collapse or shear due to deposition against a shifting ice front. Thus the unit is probably distal outwash deposited progressively farther south as glaciers advanced down the Georgia Depression.

Much of the sand may have been recycled repeatedly during the southward advance of the glaciers. Fyles (1963, p. 38-39) partly attributed the erosion recorded by the unconformity between Quadra Sand and Vashon till to river incision of the sand before the area was overriden by ice. Evidence for fluvial erosion includes "broadly curved, steep scarps, 100 feet or more in height" (Fyles, 1963, p. 39). The change from aggradation to degradation may have been caused by an increase in hydraulic energy without a corresponding increase in sediment supply as glaciers approached the site. The eroded sand might then be transported farther south to be redeposited as part of the sand unit.

Another factor contributing to the incision of Quadra Sand may have been a fall in sea level during deposition of the unit. Although details of land-sea fluctuations during Quadra time are not well known, it is probable that sea level during at least part of this time was as low as at present or lower. Fluvial sand outcrops down to sea level at many places around the Strait of Georgia. The occurrence of what is probaby Quadra Sand to a depth of -25 m in a well on Hernando Island indicates that sea level was at least 25 m lower during deposition of part of the unit. This is in agreement with an anticipated low stand of the sea at a time when sea water was being removed to nourish expanding glaciers.

The extensive occurrence of Quadra Sand to elevations of about 100 m on both sides of the Strait of Georgia and on islands within the strait suggests that the basin was filled or nearly filled with sediment before being overriden by glaciers. Continuous seismic profiles across the northern Strait of Georgia (Clague, 1975a, 1976a) show that remnants of this fill are widespread in distribution, locally occurring to several hundred metres below sea level and exceeding 550 m in thickness. The sediments are characterized by numerous, horizontal, internal seismic reflectors, and they underlie Quadra Sand exposed on islands in the northern Strait of Georgia. Some shallow banks in the strait are glacially scoured remnants of this fill (Fig. 16).

In order to obtain additional information on the nature of this fill, a traverse was made up the side of a bank of sub-Quadra sediments with the submersible **Pisces IV** (see Fig. 16 traverse location). Outcrops of horizontally bedded silty clay were encountered between depths of 80 and 225 m. These sediments are thought to be marine in origin, in large part, because of their position relative to present and past sea levels. Whatever its origin, the fill likely represents more than one depositional episode because major unconformities occur within the sediment piles (Fig. 16).

Bathymetric elements in the Strait of Georgia include ridges, troughs, and basins elongate in a northwest-southeast direction. Water depths locally exceed 400 m. The bottom topography of the strait has been produced largely by glacial erosion; much of the marine fill described above was removed during the Fraser Glaciation. Since the end of the Fraser Glaciation, marine and deltaic sedimentation partially has filled the strait, but most of this deposition has occurred in the central and southern parts of the depression off the mouth of the Fraser River; Holocene sediments in the northern Strait of Georgia, except in some deep troughs, are thin (Clague, 1975a, 1975b). It is apparent that, under existing sedimentologic conditions, several tens of thousands, probably hundreds of thousands, of years would be required to fill or nearly fill the Strait of Georgia.

If parts of the strait were filled with sediment before deposition of Quadra Sand, one or a combination of the following must be concluded: (1) The fill predates the Olympia nonglacial interval, thus the Strait of Georgia region was not as extensively scoured by ice during the penultimate glaciation as during the Fraser Glaciation. (2) The fill is Olympia in age, thus there was a relatively long period of time during which nonglacial conditions existed in the Georgia Depression after the glaciation which formed the Semiahmoo-Dashwood drift complex but before deposition of Quadra Sand.

Figure 17 summarizes diagrammatically the possible depositional models of Quadra Sand. The most likely model (Fig. 17A) shows the unit deposited as distal outwash on a subaerial platform of older sediments. Part of the sand was recycled repeatedly as glaciers advanced down the depression. In a variation of this model (Fig. 17B), sand was deposited as proximal outwash along the lowland margins while ice occupied the adjacent axis of the depression. A third model (Fig. 17C) shows Quadra Sand deposited over the entire Georgia Depression before glaciers advanced far out of the fjords. The absence of a decrease in mean grain size away from known source areas argues against this last model.

In each of these models the initiation of sand deposition is climatically induced. This climatic change, which probably relates to an early alpine phase of the Fraser Glaciation, occurred before 28 800 years B.P., perhaps as early as about 36 000 years B.P. On the basis of palynological evidence from a site on the Olympic Peninsula approximately 100 km southwest of Victoria, British Columbia, Heusser (1972) concluded that there was a change from a nonglacial to a glacial climate during this same time interval. This, however, is substantially earlier than glacial occupation of the Interior Plateau of southern British Columbia. For example, the Fraser Glaciation ice advance in the Bessett Creek area (50°18'N, 118°51'W) of the southern Interior Plateau probably occurred about 19 100 years B.P. (GSC-913; Fulton, 1971). This indicates that many thousand years may have intervened between the alpine and ice sheet phases of the Fraser Glaciation.

QUADRA ANALOGUES

Contemporary outwash bodies with morphologic and structural similarities to Quadra Sand are found in glacierized, mountainous regions. Wide outwash plains, or plain sandurs (Krigstrom, 1962), occur on Iceland's south coast, and valley trains (long, narrow outwash bodies confined by valley walls) are common in glacierized mountainous areas such as Canada's Western Cordillera and Eastern Arctic.

Icelandic sandurs were described by Ahlmann and Thorarinsson (1937), Hjulström et al. (1954-1957), and Krigström (1962). Scandinavian sandurs were studied by Frödin (1925, 1954), Mannerfelt (1945), and Krigström (1960). Investigations of other European valley and plain sandurs have been summarized by Charlesworth (1957) and work in the United States by Flint (1971). Valley trains and fluvial processes in the Canadian Arctic were studied by Church (1972). Fahnestock (1969), Williams and Rust (1969), and McDonald and Banerjee (1971) have described valley trains in Western Canada. Sandurs also have been identified in most other alpine areas (Charlesworth, 1957).

The largest contemporary outwash bodies, those in front of Iceland's Vatnajökull, are of similar shape and size to those which existed in the Georgia Depression at the beginning of the Fraser Glaciation. The sedimentary structures produced by braided rivers traversing the sandurs are also characteristic of Quadra Sand.

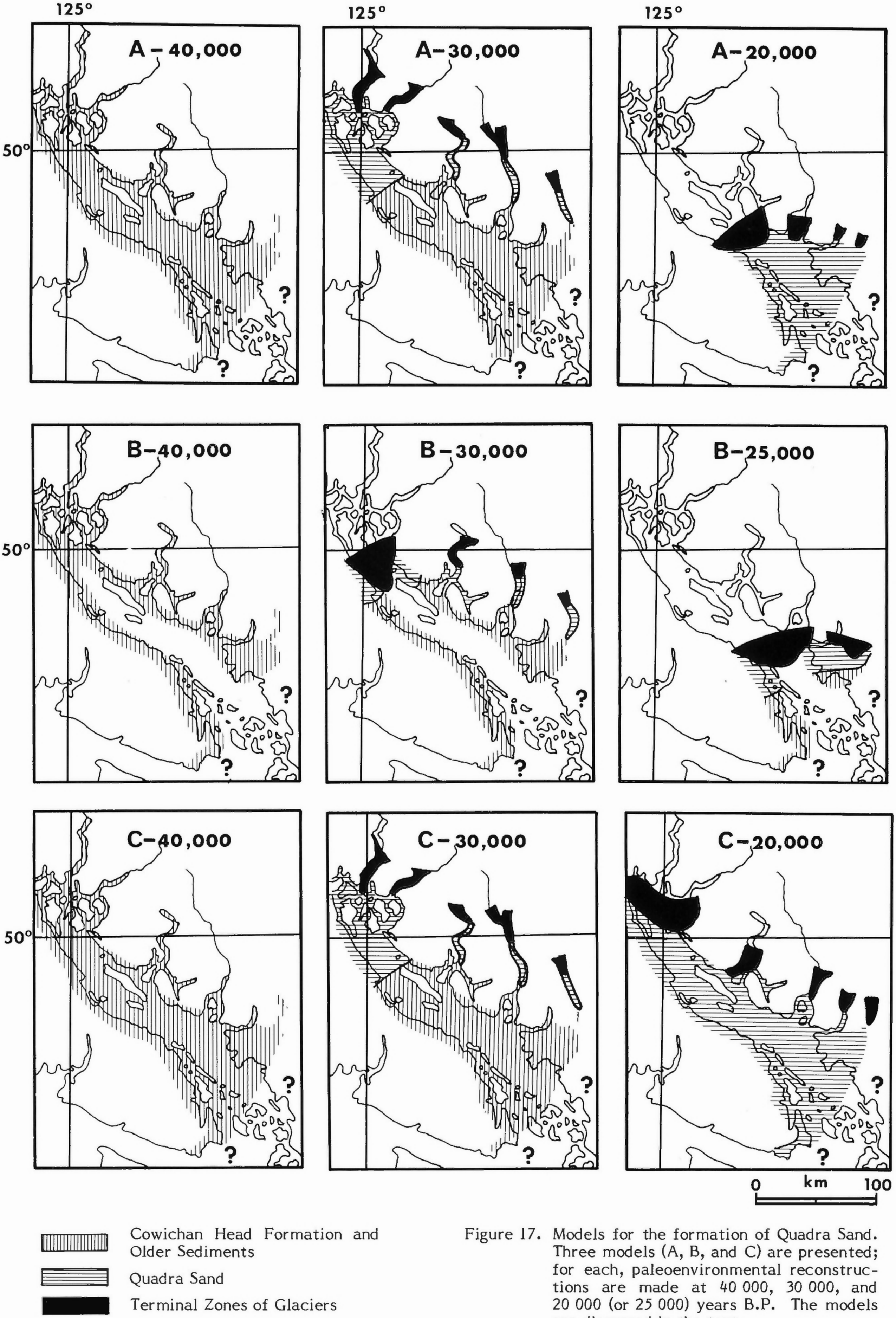


Figure 17. Models for the formation of Quadra Sand. Three models (A, B, and C) are presented; for each, paleoenvironmental reconstructions are made at 40 000, 30 000, and 20 000 (or 25 000) years B.P. The models are discussed in the text.

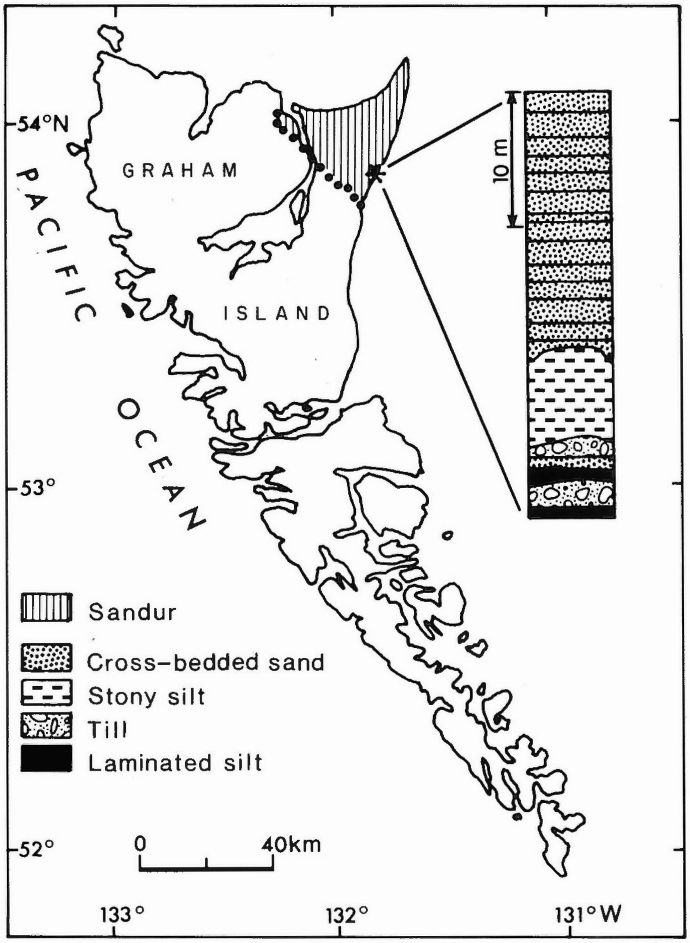


Figure 18. Quadra analogue from the Queen Charlotte Islands, British Columbia. At the northeast corner of Graham Island a late Pleistocene outwash surface is underlain by well sorted, cross-bedded sand which is texturally similar to Quadra Sand. Diagram adapted from Sutherland Brown (1968, his Figs. 3 and 4).

Most recent outwash, however, differs from the Quadra in at least two important ways:

1. Quadra Sand consists mainly of sand and is well sorted. In contrast, most contemporary outwash is heterogeneous in grain size; gravel is more common than sand; sorting is variable but generally poor; and facies variations are common. Nevertheless, outwash of some Icelandic sandurs, such as the Hoffellssandur, has a large sand component. Indeed, the word **sandur** is Icelandic in etymology and means sand or sand plain.

2. Quadra Sand exhibits none of the spatial trends in grain size which are found on active sandurs (for example, see Church, 1972). On most sandurs grain size decreases in a downstream direction due to progressive abrasion and selective sorting during transport. The absence of such variations in the Quadra may be a consequence of repeated re-entrainment and redeposition of sand as glaciers advanced down the Georgia Depression. In other words, a relatively fixed volume of sand-size sediment perhaps was continuously recycled in front of glaciers advancing down the lowland trough.

Outwash deposited during a glacier readvance within the Fraser Glaciation blankets the northeast corner of Graham Island of the Queen Charlotte group (Fig. 18). The outwash consists of sand and minor gravel underlying a gently sloping surface of approximately 600 km^2 which is dissected by meltwater channels. This surface is a sandur formed by meltwater flowing northeast from an ice front to the southwest (Sutherland Brown, 1968, p. 27). Sediments underlying the sandur are well exposed in sea cliffs at the northeast end of Graham Island. At the section shown in Figure 18, 20 m of sand are underlain by a complex of till and glaciomarine sediments. The sand is similar in texture, structure, and mineralogy to Quadra Sand. It is well sorted and characterized by prominent cross-beds. Sand grains are mainly quartz and feldspar which probably have been derived from the granitic complexes of the British Columbia mainland or southeast Alaska.

CONCLUSIONS

Major conclusions drawn from this study and from unpublished data collected by J.G. Fyles are as follows.

Stratified sediments overlying drift of the penultimate glaciation in coastal southwest British Columbia include the Cowichan Head Formation (older) and Quadra Sand (younger).

These units form part of an apparently continuous stratigraphic sequence recording the major climatic fluctuations of Wisconsin time in the Georgia Depression: deposition, first, of till under glacial conditions, followed by glaciomarine sediments during the transition to nonglacial environments, then the Cowichan Head Formation under nonglacial conditions (Olympia nonglacial interval), Quadra Sand during the transition back to glacial conditions, and, finally, till under full glacial conditions (Fraster Glaciation).

Quadra Sand occurs in the Georgia Depression and Puget Lowland from below sea level to an elevation of about 100 m as remnants of formerly more extensive bodies and also is present in a few mountain valleys adjacent to lowland areas.

Available stratigraphic, textural, and radiometric evidence indicates that Quadra Sand formed as distal outwash aprons at successive positions in front of, and perhaps along the margins of, glaciers advancing down the Georgia Depression during late Wisconsin time. After deposition of the unit at a site, but before burial by ice, the sand was dissected by meltwater, and the eroded detritus was transported farther down the basin to sites where aggradation continued. The sand also was eroded extensively by glaciers during the Fraser Glaciation.

Quadra Sand is a diachronous lithostratigraphic unit. Radiocarbon dates show that it is older than 29 000 years at the north end of the Strait of Georgia, but is younger than 15 000 years at the south end of Puget Sound. Paleocurrent and mineralogic data are in agreement with the radiocarbon dates in showing the sand to have been derived from the Coast Mountains and deposited by south to southeast flowing streams and rivers. Quadra Sand was deposited locally in upland valleys while ice filled adjacent portions of the Strait of Georgia.

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