Quadra Sand and its relation to the late Wisconsin glaciation of southwest British Columbia

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

Quadra Sand was deposited progressively down the axis of the Georgia–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 the unit occurred during the climatic deterioration at the beginning of the Fraser Glaciation. Thick, well sorted sand was deposited in part as distal outwash aprons at successive positions in front of, and perhaps along the margins of, glaciers advancing from the Coast Mountains into the Georgia–Puget Lowland during late Wisconsin time.

The sand thus provides a minimum age for the initial climatic change accompanying the Fraser Glaciation. This change apparently occurred before 28 800 y BP, substantially earlier than glacial occupation of the southern Interior Plateau of British Columbia. Thus, several thousand years may have intervened between the alpine and ice-sheet phases of the Fraser Glaciation.

Le Sable de Quadra est une unité lithostratigraphique de la fin du Pléistocène dont l'extension est vaste dans la dépression de Géorgie, en Colombie Britannique, et dans les basses-terres de Puget, dans l'état de Washington. L'unité consiste principalement en un sable bien trié, à stratification horizontale on entre-croisée. Elle est surmontée par un till déposé durant la Glaciation de la Fraser et repose sur des sédiments fluviatiles et marins déposés durant l'intervalle non glaciaire précédent.

Le Sable de Quadra fut déposé progressivement le long de l'axe des basses-terres de Puget et de Géorgie; il provenait de la Chaîne Côtière située au nord et au nord-est de cette région. L'unité manifeste un diachronisme marqué: elle date de plus de 29 000 années C^{14} à l'extrémité nord du Détroit de Géorgie, mais est âgée de moins de 15 000 ans à l'extrémité sud de la baie de Puget.

L'édification de l'unité se fit durant la détérioration climatique du début de la Glaciation de la Fraser. Un sable épais, bien trié, fut déposé, constituant les dépôts distaux d'une plaine proglaciaire au front, et peut-être aux marges, des glaciers venant de la Chaîne Côtière qui s'avançaient dans les basses-terres de Puget et de Géorgie durant la fin du Wisconsin.

Le sable fournit ainsi un âge minimum au changement climatique initial corrélatif de la Glaciation de la Fraser. Ce changement débuta apparemment avant 28 800 ans AA, et donc nettement plus tôt que l'occupation glaciaire du sud du Plateau intérieur de la Colombie Britannique. Ainsi plusieurs milliers d'années peuvent avoir séparé la phase alpine de la Glaciation de la Fraser de la phase de glaciation continentale.

[Traduit par le journal]

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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. A variety of glacial and nonglacial deposits recording major Quaternary climatic oscillations occurs within the Georgia Depression and in the contiguous Puget Lowland of Washington. Most exposed sediments are assigned to the following local lithostratigraphic units, from youngest to oldest: Salish Sediments, Fraser Glaciation drift,[1] and Cowichan Head Formation (Table 1). Older sediment units have been recognized at a few localities (Fyles 1963; Armstrong 1975), but their age and correlation are not well

[1]Drift deposited during the Fraser Glaciation may be subdivided into the lithostratigraphic units listed in Table 1. In this paper the drift is referred to informally as Fraser Glaciation drift.

TABLE 1. Stratigraphic framework of surficial sediments in the Georgia Depression

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

*Semiahmoo Drift (in Fraser Lowland) probably correlates with Dashwood Drift (on Vancouver Island).
**Relation between Highbury Sediments (in Fraser Lowland) and Mapleguard Sediments (on Vancouver Island) is unknown.

established. The Cowichan Head Formation, on the basis of numerous radiocarbon dates (summarized in Fulton 1971), is assigned to the Wisconsin Stage; the Salish Sediments are of Holocene age.

Drift deposited during the Fraser Glaciation in the Georgia Depression consists of three parts: a lower unit of stratified sediments laid down prior to glacier overriding; a middle unit (mainly till) deposited when the area was covered by ice; and an upper complex of diamicton and outwash formed during deglaciation.

Fraser Glaciation drift overlies fluvial, estuarine, and marine sediments deposited during the Olympia nonglacial interval and termed the Cowichan Head Formation. The Cowichan Head Formation is divisible into a lower unit of marine clay, silt, and sand, and an upper unit of plant-bearing silt, sand, and gravel. The upper unit includes channel, overbank, and bog sediments deposited on flood plains, and possibly lagoonal and littoral sediments of transitional marine–terrestrial environments (Fyles 1963).

Thick, well sorted sand with silt and gravel interbeds underlies till and overlies the Cowichan Head Formation. This unit is called the Quadra Sand and is widely distributed around the Georgia Depression. The type section is at the south end of Quadra Island (50°00′ N, 125°10′ W), where cross-bedded, well sorted sand up to 40 m thick is exposed beneath till. Sediments in the Puget Lowland that correlate with Quadra Sand have been described by Mullineaux *et al.* (1965) and Easterbrook (1969) and termed the Esperance Sand Member of the Vashon Drift.

Quadra Sand was deposited during the transition from nonglacial to glacial conditions at the beginning of the Fraser Glaciation. Evidence for the unit having been laid down as outwash is presented in this paper. On the basis of this evidence, Quadra Sand is considered to be part of Fraser Glaciation drift.

The distribution and character of Quadra Sand are presented below, and the significance of the unit in terms of the timing of the late Wisconsin glacial advance in southwest British Columbia is discussed.

Distribution and Character of Quadra Sand

Figure 1 shows those areas in the Georgia Depression known to be underlain by Quadra Sand. Also shown are areas where stratified gravel is exposed beneath till. This gravel, variously termed the Saanichton gravel (Halstead 1968; Fulton and Halstead 1972) and the Colebrook gravel (Armstrong 1956, 1957), is advance outwash of the Fraser Glaciation. Although limited in distribution to small areas near Vancouver and north of Victoria, the gravel is thought to be a coarse upper facies of Quadra Sand.

Quadra Sand occurs mainly below an elevation of 100 m on both sides of the Strait of Georgia and on islands within the strait. Here, the unit has a maximum thickness of about 75 m. It also crops out at higher elevations in a few upland valleys extending into the adjacent mountainous regions. In one such valley near Upper Campbell Lake (49°57′ N, 125°36′ W), Quadra Sand occurs to an elevation of about 380 m.

In general, Quadra Sand overlies the upper

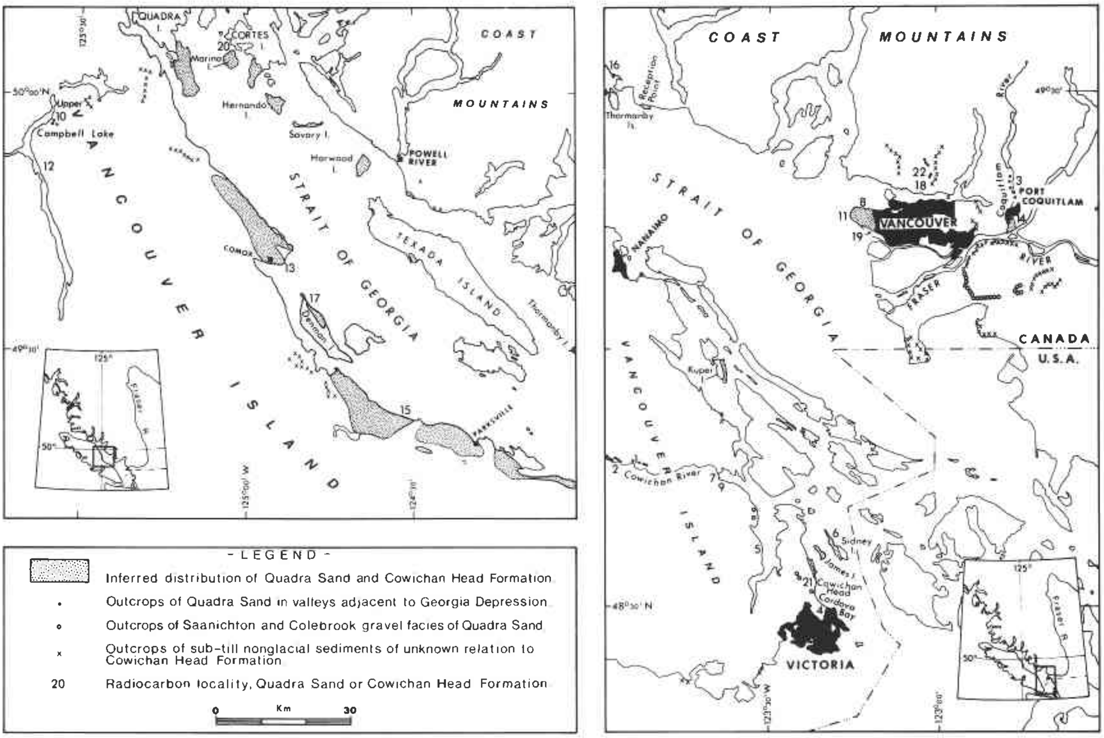

FIG. 1. Distribution of Quadra Sand in the Georgia Depression. Radiocarbon localities and dates are listed in Table 2.

member of the Cowichan Head Formation, but locally it rests upon older 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 unconformably overlain by till deposited during the Fraser Glaciation. Fyles (1963, pp. 38–39) concluded that the erosion recorded by this unconformity was accomplished by rivers before the sediments were overriden by glaciers, and also by the glaciers themselves. The unit's present patchy distribution is controlled, however, not only by fluvial and glacial erosion, but also by the original depositional limits of the sediment and by the topography of the surface upon which the sand was deposited.

In many areas Quadra Sand crops out down to sea level, and probably occurs below. For example, on Hernando Island (Fig. 1) an apparently continuous Quadra sequence was logged in a well to an elevation of −25 m (Erdman and Brown 1969).

Examples of stratigraphic sections showing the relationships of Quadra Sand to bounding strata are presented in Figs. 2 and 3.

The unit consists mainly of well sorted, fine to coarse grained sand (Fig. 4). Clay, silt, and gravel represent less than 10% of the sediment over the entire basin, but are locally common. There is no systematic gradation in mean particle size either areally over the Georgia Depression or vertically at a site. However, Quadra sediments near the Vancouver Island mountain front include a larger proportion of gravelly sand and pebbly gravel than those of adjacent coastal areas (Fyles 1963). Also, most silt is found in beds and laminae in the lower part of the unit, and gravel is most common in the upper part. Some silt beds contain plant detritus and thus

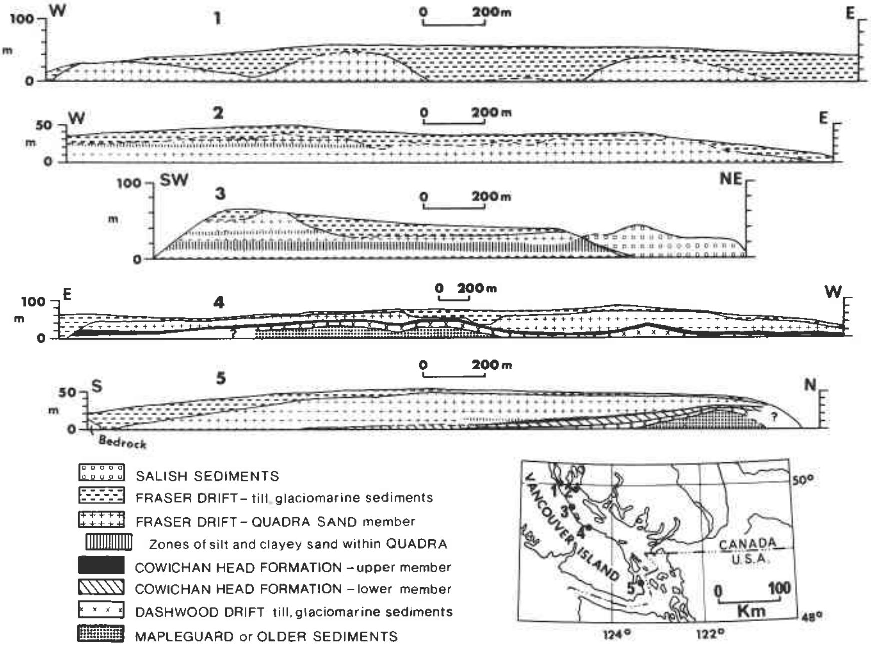

FIG. 2. Stratigraphic sections showing relationships between Quadra Sand and bounding strata.

are similar to organic-rich strata in the underlying Cowichan Head Formation. However, the former are interstratified with and underlain by cross-bedded sand, whereas the latter are commonly interbedded with rusty gravel.

Stratification within the unit is horizontal. Some beds exposed in sea cliffs are continuous at constant elevation for several kilometres. Planar and trough cross-stratification (Fig. 5) is everywhere common and is thought to originate by the migration of asymmetric ripple marks on channel floors (Allen 1963, 1965). Very large channels occur at a few sites. At the south end of James Island (48°36′ N, 123°20′ W), for example, is a channel within the sand unit that is at least 0.7 km wide.

Detailed analysis of the axial orientation of trough cross-beds was undertaken in order to determine flow directions during deposition of the sand. The paleocurrent data were analyzed according to the method outlined in High and Picard (1971), and the results are summarized in Fig. 6. The regional flow direction is south and southeast, indicating a source in the Coast Mountains north and northeast of the Georgia Depression. Vancouver Island was not a significant sediment source. At many sites, the flow direction shifted repeatedly during aggradation. The shifts were rather abrupt, typically occurring vertically through the section within a few 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 this 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.

Sand mineralogy is in agreement with the paleocurrent data in showing that the sand was derived from granitic rocks of the Coast Mountains north and northeast of the Georgia Depression rather than from volcanic and sedimentary rocks of Vancouver Island. Quadra Sand in the northern Georgia Depression consists of plagioclase, potassium feldspar, quartz, amphibole, mica, and opaque minerals in proportions approximating those of intermediate plutonic rocks (Cummings 1941). The sand contains more detritus of Vancouver Island provenance near the southern end of the Georgia Depression and near the inland edge of the

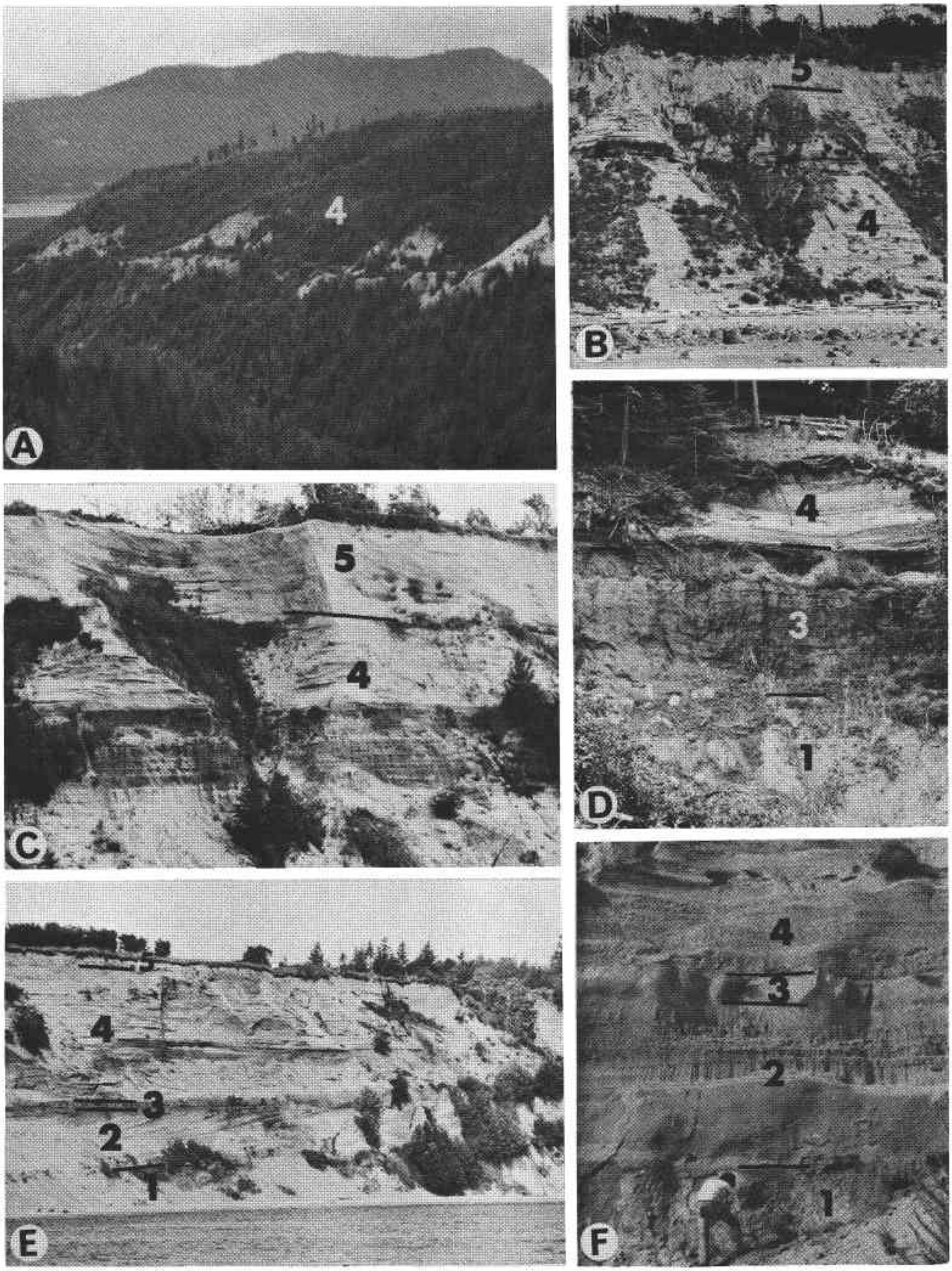

FIG. 3. Exposures of Quadra Sand and bounding strata. 1—glaciomarine sediments; 2—Cowichan Head Formation, marine unit; 3—Cowichan Head Formation, fluvial unit; 4—Quadra Sand; 5—till (includes some ice-contact and glaciomarine sediments). Lines indicate contacts. Heights of coastal bluffs at B, C, D, and E are 45, 50, 20, and 50 m, respectively. A—Upper Campbell Lake (49°57′ N, 125°36′ W); B—Savary Island (49°56′ N, 124°50′ W); C—Comox (49°40′ N, 124°54′ W); D—Denman Island (49°36′ N, 124°49′ W); E and F—Cowichan Head (48°34′ N, 123°22′ W). Dark horizons within Quadra Sand (Fig. 3B, C) are clayey sand and silt.

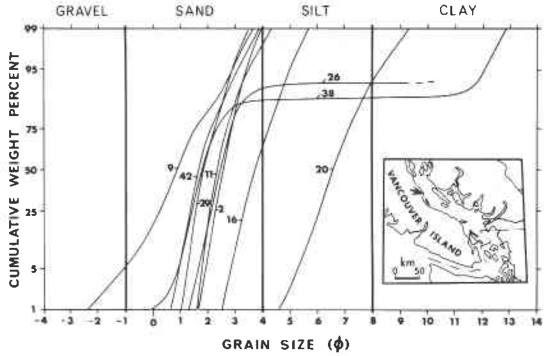

FIG. 4. Cumulative frequency curves for Quadra Sand at Comox. Numbers attached to the cumulative curves are elevations (in metres) of analyzed samples at the collection site (see Fig. 3C).

Nanaimo Lowland. At Vancouver (49°16′ N, 123°15′ W) the unit consists of sediment eroded in part from late Cenozoic volcanic rocks exposed about 70 km to the north; volcanic rock fragments (including glass), plagioclase, and orthopyroxene are especially common constituents (Clague 1975); oxyhornblende is an important accessory mineral (W. H. Mathews, University of British Columbia, personal communication 1976).

The surface textures of Quadra sand grains were studied in order to assess the transportational and depositional history of the unit (Porter 1962; Krinsley and Donahue 1968; Krinsley and Margolis 1971; Krinsley and Doornkamp 1973). Representative quartz sand grains, observed and photographed with a scanning electron microscope (Cambridge Stereoscan), are illustrated in Fig. 7. The following surface texture characteristics are common on most quartz grains from Quadra Sand: (1) conchoidal breakage patterns of a range of sizes; (2) very high relief; (3) semiparallel and arc-shaped steps. Other features observed on many grains include (4) parallel striations and (5) imbricate breakage blocks. These surface textural characteristics have been attributed to glacial transport (Krinsley and Donahue 1968; Krinsley and Doornkamp 1973; Whalley and Krinsley 1974). Recently, however, many surface features on quartz sand grains cited as indicative of the glacial environment have been shown to exist on grains from known nonglacial deposits (Fitzpatrick and Summerson 1971; Setlow and Karpovich 1972; Margolis and Krinsley 1974; Baker and Dott 1975). On the other hand, 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; Rehmer and Hepburn 1975). Nearly all Quadra sand grains, which were observed under the scanning electron microscope, have one or more 'glacial' surface characteristics, and it is concluded that these features were generated in a glacial environment. Fluvial transport did not modify significantly the grain surfaces and thus perhaps was relatively short.

Palynologic analyses were performed on organic-rich silt and peat from Quadra Sand by J. Terasmae (unpublished data). Terasmae found few, poorly preserved pollen and spores in most samples. The arboreal pollen is dominated by *Pinus* (largely *P. contorta*) and *Picea*. *Abies* and *Alnus* are abundant in some samples, and *Tsuga mertensiana* is present in most. Less common palynomorphs include *Tsuga heterophylla*, *Betula*, and *Salix*. Trees and shrubs represented in this assemblage all presently grow in the area, but as reported by Fyles (1963, p. 28), "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."

Age of Quadra Sand

Organic matter from Quadra Sand and the Cowichan Head Formation has provided radiocarbon dates from which a chronologic framework for late Pleistocene events in the Georgia Depression has been established. Finite radiocarbon dates obtained from these sediments in the Strait of Georgia region are summarized in Table 2 (see also Fulton 1971).

The dates indicate that Quadra Sand is progressively younger towards the south (Fig. 8). Wood, either at the base of the sand or 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 y BP (GSC-202).[2] About 50 km

[2]This radiocarbon date is from organic-rich silt exposed near sea level below thick sand. However, it is not known whether the dated material is within Quadra Sand or at the top of the underlying Cowichan Head Formation (see discussion in *Radiocarbon*, **3**, p. 147). If the material is part of the Cowichan Head Formation, sand deposition within the Georgia Depression began after 35 400 y BP, but before 28 800 y BP.

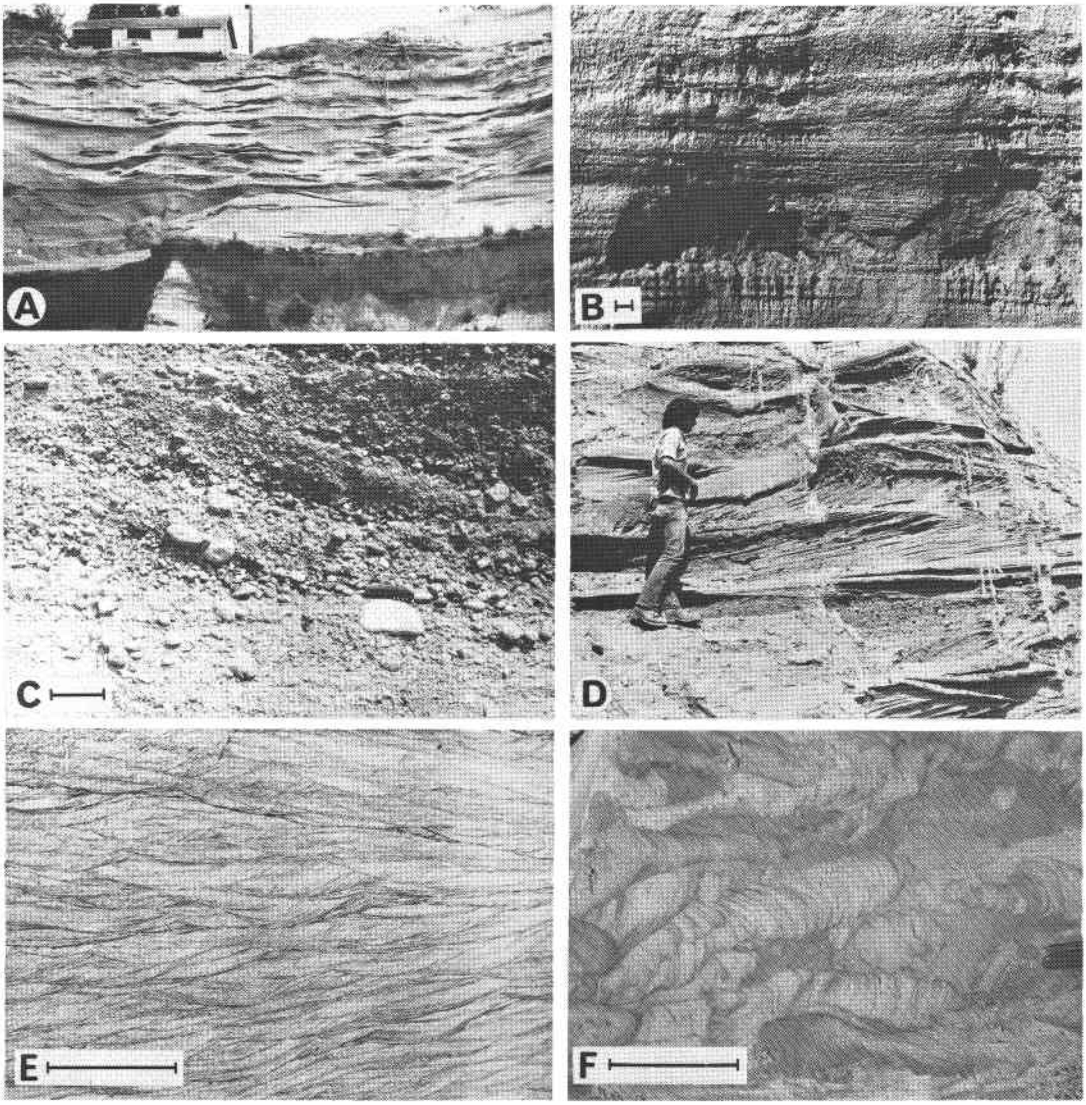

FIG. 5. Textures and sedimentary structures characteristic of Quadra Sand. A—cross-bedded sand, Comox (49°40′ N, 124°54′ W); B—interstratified silt and sand, Comox (49°40′ N, 124°54′ W); C—gravel, Parksville (49°18′ N, 124°22′ W); D—cross-bedded gravelly sand, Cowichan Head (48°34′ N, 123°22′ W); E—cross-bedded sand, Denman Island (49°36′ N, 124°49′ W; viewed perpendicular to bedding plane); F—cross-bedded sand, Parksville (49°17′ N, 124°15′ W; view of stratification surface). Scale bars in B, C, E, and F are 10 cm.

south of this site, wood from Quadra Sand dated 28 800 ± 740 y BP (GSC-95), whereas at the south end of the depression (48°30′ N, 123°19′ W), plant material in the unit dated 22 600 ± 300 y BP (GSC-84). Farther south in Puget Sound (48°06′ N, 122°43′ W) peat from Esperance Sand has been dated at 18 000 ± 400 y BP (I-2282). In the Seattle area (47°38′ N, 122°19′ W), clay yielding radiocarbon dates as young as 15 000 ± 400 y BP (W-1227) underlies Esperance Sand.

Deposition of the Cowichan Head Formation began before 40 500 y BP (GSC-2167) and continued to about 29 000 y BP at latitude 49°36′ N (L-424C) and to at least 15 000 y BP at latitude 47°38′ N (W-1227).

In addition to the diachronous nature of

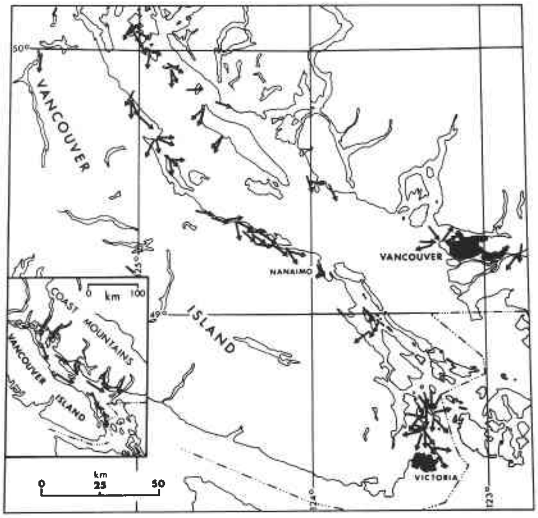

FIG. 6. Paleocurrent data, Quadra Sand. Arrows are vector resultants based upon the axial orientation of trough cross-beds. Inset map shows the regional flow pattern generalized from paleocurrent and mineralogic data.

Quadra Sand, aggradation apparently occurred in a relatively short period of time at any one site. For example, at lat. 49°17′ N, sand about 50 m thick was deposited after 24 500 ± 500 y BP (GSC-108) but prior to glacial 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) was deposited after 18 000 ± 400 y BP (I-2282) but before the area was overriden by ice, less than 3000 years later.

Discussion

Quadra Sand formed subaerially by deposition from braided rivers and streams. Although the unit presently consists of relatively small, isolated sand bodies located around the Strait of Georgia and Puget Sound, 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. Strata on Savary Island (49°56′ N, 124°50′ W) probably correlate with strata 18 km distant on Harwood Island (49°51′ N, 124°38′ W; Clague 1975). It is thus probable that a flood plain existed across the entire northern Strait of Georgia during deposition of the unit. Because Quadra Sand is restricted to the margins of the central and southern Strait of Georgia, it is possible that a flood plain did not exist over the full width of the depression in these areas. However, paleocurrent (Fig. 6) and mineralogic data from Quadra Sand on southern Vancouver Island indicate flow south across the southern strait. This suggests that there was either a continuous flood plain across the strait or that glaciers located along the axis of the strait restricted sand deposition to lowland margins. The latter possibility is less likely, as the unit lacks features characteristic of kame terrace and other ice-contact deposits. The continuity and textural uniformity of individual beds and the absence of collapse and shear structures resulting from deposition against a shifting ice front argue against an ice-contact origin for much of the sand.

Quadra Sand was deposited progressively from northwest to southeast down the Georgia Depression. It was derived in large part from the southern Coast Mountains, an area with the highest peaks (up to 4017 m in elevation) and the largest glaciers in southern and central British Columbia. Under existing conditions, sand-sized detritus produced by weathering of the Coast Crystalline Complex is deposited as alluvium along river courses and 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. Thus it is probable that the rate of sand production and hence environmental conditions during deposition of this unit differed from those of the present.

It is concluded that rapid aggradation of sand began during the climatic cooling associated with the change from nonglacial to glacial conditions 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 the increase in area affected by glacial scour and periglacial activity, but perhaps also to the loss of stabilizing vegetation cover. The erosion products would be transported into the valleys, but would be introduced into the Georgia Depression only 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 was then available for transport by the glaciers and meltwater, and would have been redeposited farther down the strait.

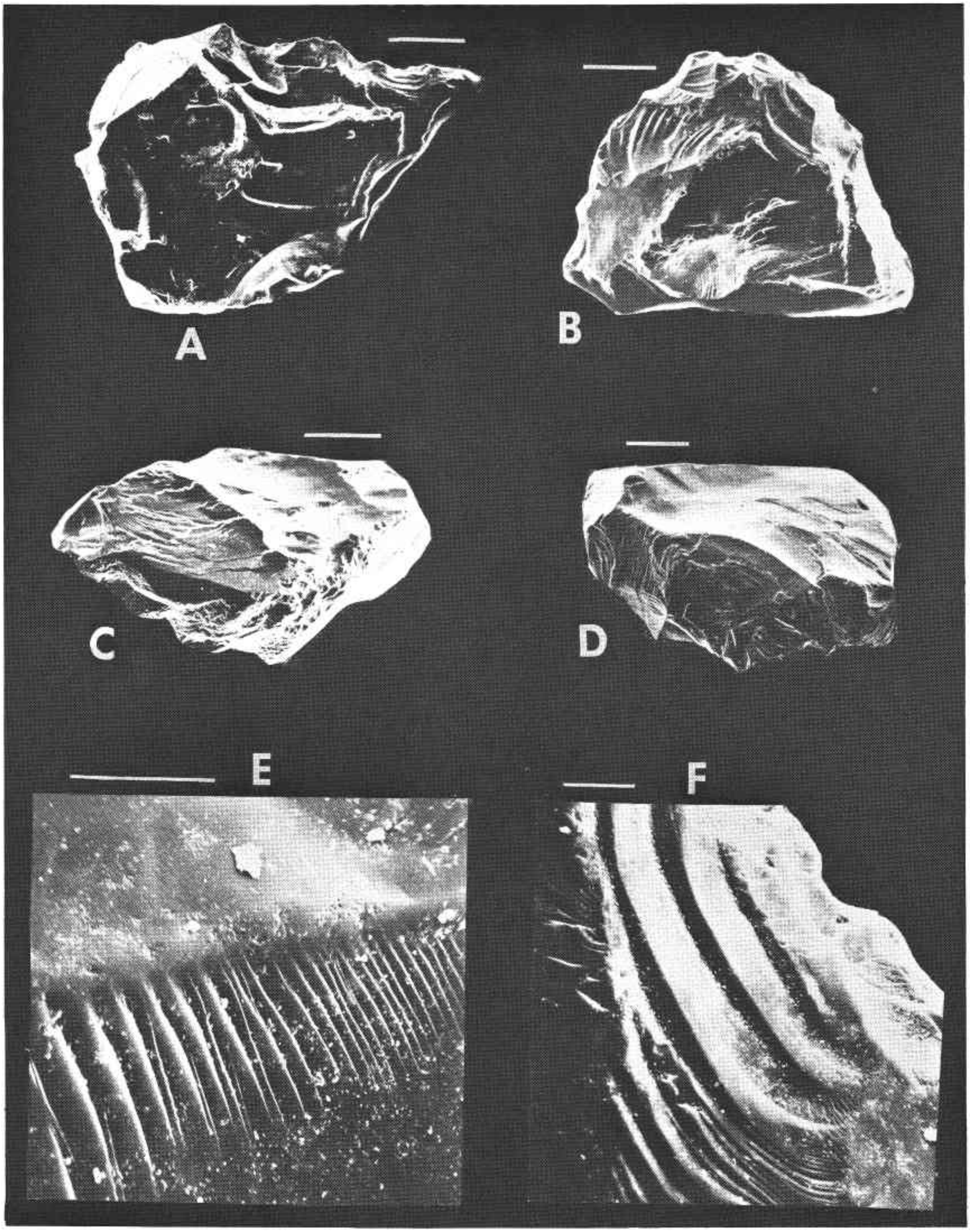

FIG. 7. Representative quartz grains from Quadra Sand, photographed with a scanning electron microscope. The grains exhibit glacial surface textures characterized by high relief, conchoidal breakage patterns, semiparallel and arc-shaped steps (*e.g.*, C and E), and imbricate breakage blocks (*e.g.*, F). Scale bars in A, B, C, and D are 100 μm; in E and F, 10 μm. Grains are from Quadra Sand at Comox (49°40′ N, 124°54′ W) and Quadra Island (50°00′ N, 125°10′ W).

TABLE 2. Finite radiocarbon dates from Quadra Sand and the Cowichan Head Formation

Site no., Fig.1	Laboratory dating no.*	Date list**	Date (±2σ)	Location		Material	Stratigraphic unit†
				lat. N	long. W		
1	GSC-210	7(36)	19 150±250	48°47′	123°54′	Organic silt	Q
2	GSC-195	7(36)	21 070±290	48°46′	123°57′	Wood	Q
3	GSC-2203		21 600±200	49°20′	122°47′	Wood	Q
1	GSC-317	8(111)	21 730±230	48°47′	123°54′	Wood	Q
4	GSC-84	5(50)	22 600±300	48°30′	123°19′	Plant fibers	Q
5	GSC-518	9(173)	23 840±300	48°37′	123°31′	Wood	CH
6	GSC-59	5(51)	23 920±420	48°39′	123°20′	Wood	Q
7	GSC-318	8(111)	24 060±300	48°45′	123°40′	Peat	CH
7	GSC-385	8(111)	24 380±350	48°45′	123°40′	Peat	CH
8	L-502	3(148)	24 400±900	49°17′	123°13′	Wood	Q
8	GSC-108	5(47)	24 500±500	49°17′	123°13′	Wood	Q
9	I-1225		24 560±800	48°45′	123°38′	Wood	CH
10	GSC-58	5(48)	25 000±400	49°57′	125°36′	Wood	Q
11	GSC-109	5(48)	25 100±600	49°16′	123°15′	Peat	Q
12	GSC-96	5(49)	25 190±470	49°51′	125°37′	Wood	Q
11	GSC-1635		26 100±320	49°16′	123°15′	Wood	Q
13	GSC-53	5(49)	26 100±400	49°40′	124°54′	Wood	Q
14	GSC-2191		26 200±320	49°14′	122°47′	Wood	CH
14	GSC-124	6(171)	26 450±520	49°14′	122°47′	Peaty silt	CH
14	GSC-2217		26 900±320	49°14′	122°47′	Wood	CH
14	GSC-536	9(173)	27 180±460	49°14′	122°47′	Wood	CH
14	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
14	GSC-2139		28 200±200	49°14′	122°47′	Wood	CH
13	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
14	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	48°34′	123°22′	Soil	CH
22	GSC-93	7(26)	36 200±500	49°21′	123°02′	Wood	CH
14	GSC-2137		40 200±400	49°14′	122°47′	Wood	CH
14	GSC-2167		40 500±1700	49°14′	122°47′	Wood	CH

*GSC—Geological Survey of Canada; I—Isotopes; L—Lamont Geological Observatory.
Radiocarbon: **volume (page); data also from Fulton (1971) and Armstrong (1975).
†CH—Cowichan Head Formation; Q—Quadra Sand.

Sand aggradation began first at the northern end of the Strait of Georgia sometime between 29 000 and 36 000 y BP. By 28 800 y BP (GSC-95), deposition was occurring at 49°40′ N, and by 26 100 y BP (GSC-1635) at 49°16′ N. Aggradation was still in progress 26 100 y BP (GSC-53) at 49°40′ N, at the same time as sand was being deposited at 49°16′ N.

During or after deposition of Quadra Sand near Vancouver, sand deposition commenced in the Upper Campbell Lake area on Vancouver Island (Fig. 1, location 10). At Upper Campbell Lake, Quadra Sand is present at several hundred metres above sea level and apparently was laid down as outwash in an ice-marginal environment sometime after 25 000 y BP (GSC-58; 49°57′ N, 125°36′ W). It was deposited by flow up the Campbell Lake valley from the Strait of Georgia (Fig. 6). 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 Upper 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

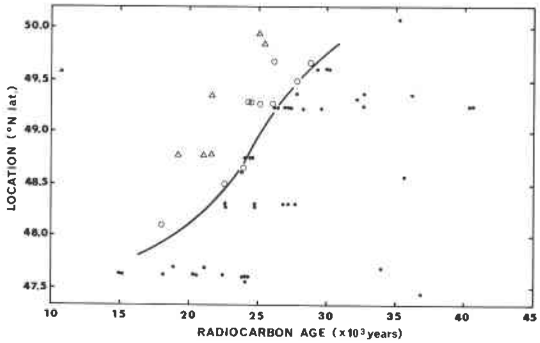

FIG. 8. Age relation of Cowichan Head Formation and Quadra Sand. Radiocarbon dates from Cowichan Head Formation (Olympia nonglacial sediments in Washington) are shown by dots; those from Quadra–Esperance Sand in lowland areas, by circles; and those from Quadra Sand in upland valleys adjacent to the Georgia Depression, by triangles. The curve marks the transition from fluvial to glaciofluvial sedimentation. Radiocarbon dates from the Georgia Depression are listed in Table 2. Dates from the Puget Lowland are summarized by Mullineaux *et al.* (1965), Easterbrook (1969), and Hansen and Easterbrook (1974).

contact between the two units occurs at an elevation of 330 m, which is also the elevation of the lowest drainage divided bordering the valley. Thus it is probable that ice in the Strait of Georgia blocked the valley and 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 also being deposited in the southern Strait of Georgia, perhaps from outwash reworked by the advancing trunk glacier to the north. If so, a sand blanket over the entire Strait of Georgia probably did not exist 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 a point source, systematic areal grain-size gradations might be expected. But such gradations do not exist; indeed, some of the finest Quadra sediments are the northernmost, and thus nearest the ultimate source area.

The above evidence indicates that Quadra Sand formed as outwash in front of, and perhaps along the margins of, glaciers advancing into the

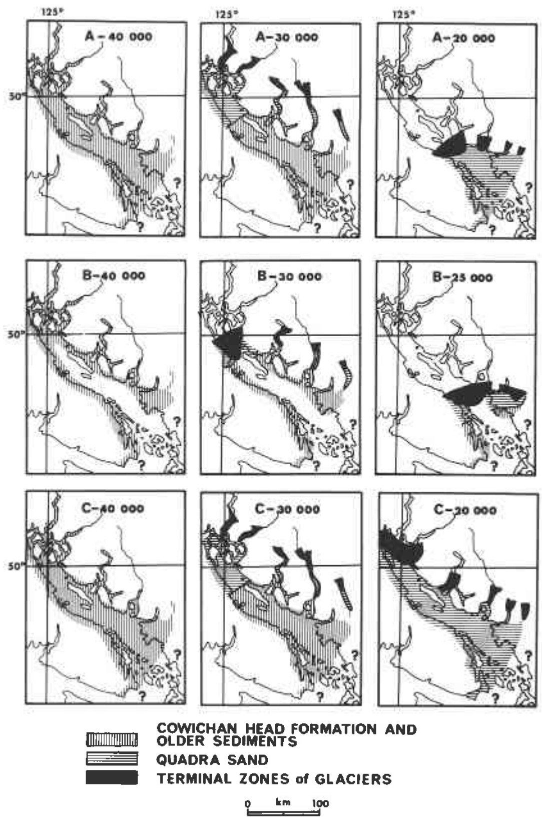

FIG. 9. Models for the formation of Quadra Sand. Three models (A, B, and C) are presented; for each, paleoenvironmental reconstructions are made at 40 000, 30 000, and 20 000 (or 25 000) y BP. The models are discussed in the text.

Georgia Depression during late Wisconsin time. Mullineaux *et al.* (1965) and Easterbrook (1969) reached the same conclusion regarding the origin of Esperance Sand in the Puget Lowland. The distance between successive positions of the glacier terminus and depositional site is unknown, but probably was variable. Much of the sand may have been deposited when ice was still confined to the fjords.

Figure 9 diagrammatically shows possible depositional models for Quadra Sand. The most likely model (Fig. 9A) shows Quadra Sand deposited as distal outwash on a platform of older sediments filling the Strait of Georgia. Part of the sand was repeatedly recycled as glaciers advanced down the depression. In a variation of this model (Fig. 9B), sand was deposited as proximal outwash along the lowland margins while ice occupied the adjacent axis of the basin. A third model (Fig. 9C) 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. The generation of large quantities of sand is thought to be due to intensified glacial and periglacial activity at the beginning of the Fraser Glaciation. The climatic change marking the change from nonglacial to glacial conditions resulted first in an expansion of glaciers in the high mountainous regions, which presently support glaciers. The largest such area in southern and central British Columbia is the Coast Mountains, north and northeast of the Georgia Depression. This area is the source of most Quadra sediments.

Because Quadra Sand and the Cowichan Head Formation have been extensively radiocarbon dated, it is possible to establish a time for the initial climatic deterioration at the inception of the Fraser Glaciation. This climatic change occurred before 28 800 y BP, perhaps as early as about 36 000 y BP. 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 a change from a nonglacial to a glacial climate occurred during this same time interval. However, this is substantially earlier than glacial occupation of the Interior Plateau of southern British Columbia. For example, the Fraser Glaciation ice advance in the Bessette Creek area (50°18′ N, 118°51′ W) of the southern Interior Plateau probably occurred about 19 100 y BP. (GSC-913; Fulton 1971). This indicates that many thousands of years may have intervened between the alpine and ice-sheet phases of the Fraser Glaciation.

Conclusions

Quadra Sand consists mainly of horizontally and cross-stratified, well sorted sand. Near Vancouver and Victoria, however, sand is overlain by gravel considered to be a coarse upper facies of the unit. Quadra Sand is underlain by sediments laid down during the Olympia nonglacial interval and is overlain by till deposited during the Fraser Glaciation. Most Quadra sediments are restricted to the Georgia Depression and Puget Lowland, where they occur from below sea level to an elevation of about 100 m asl, as remnants of formerly more extensive bodies.

Available stratigraphic, lithologic, and radiometric evidence indicates that Quadra Sand formed as distal outwash aprons on platforms of older Pleistocene sediments at sucessive 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, the entrained detritus being transported farther down the basin to sites where aggradation continued. Extensive erosion of the unit also occurred through glacial scour during the Fraser Glaciation.

Deposition of Quadra Sand transgresses time; radiocarbon dates show that the sand is older than 28 800 y BP at the north end of the Strait of Georgia, and is younger than 15 000 y BP 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 largely from the Coast Mountains and deposited by south- to southeast-flowing streams and rivers.

Quadra Sand is thus a body of sediment deposited in response to the climatic deterioration at the onset of the Fraser Glaciation and provides a minimum date for this climatic change.

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