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

J. J. Clague

Geological Survey of Canada, 100 West Pender Street, Vancouver, B.C., Canada V6B 1R8

Received 19 December 1975
Revision accepted for publication 1 March 1976

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.

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, and Cowichan Head Formation (Table I). Older sediment units have been recognized at a few localities (Fyles 1963; Armstrong 1975), but their age and correlation are not well

[Cit. par le journal]

[Traduit par le journal]
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.

Drift deposited during the Fraser Glaciation 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-beded, 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 glacio-marine 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 overridden 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
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.
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 (Krisnley and Donahue 1968; Krinsley and Doornkamp 1973; Whalley and Krisnley 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 Summeron 1971; Setlow and Karpovich 1972; Margolis and Krisnley 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 (Krisnley 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

2This 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 (L-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
Can. J. Earth Sci. Downloaded from www.nrcresearchpress.com by Vancouver Island University on 11/06/12
For personal use only.

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 overridden 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

<table>
<thead>
<tr>
<th>Site no., Fig.1</th>
<th>Laboratory dating no.*</th>
<th>Date list**</th>
<th>Date (+2σ)</th>
<th>Location</th>
<th>Material</th>
<th>Stratigraphic unit†</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GSC-210</td>
<td>7(36)</td>
<td>19 150±250</td>
<td>48°47'</td>
<td>123°54'</td>
<td>Organic silt</td>
</tr>
<tr>
<td>2</td>
<td>GSC-195</td>
<td>7(36)</td>
<td>21 070±290</td>
<td>48°46'</td>
<td>123°57'</td>
<td>Wood</td>
</tr>
<tr>
<td>3</td>
<td>GSC-2203</td>
<td>7(36)</td>
<td>21 600±200</td>
<td>49°20'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>4</td>
<td>GSC-317</td>
<td>8(111)</td>
<td>21 730±230</td>
<td>48°47'</td>
<td>123°54'</td>
<td>Wood</td>
</tr>
<tr>
<td>5</td>
<td>GSC-84</td>
<td>5(50)</td>
<td>22 600±340</td>
<td>48°30'</td>
<td>123°19'</td>
<td>Wood</td>
</tr>
<tr>
<td>6</td>
<td>GSC-518</td>
<td>9(173)</td>
<td>23 840±300</td>
<td>48°37'</td>
<td>123°31'</td>
<td>Wood</td>
</tr>
<tr>
<td>7</td>
<td>GSC-59</td>
<td>5(51)</td>
<td>23 920±420</td>
<td>48°39'</td>
<td>123°20'</td>
<td>Wood</td>
</tr>
<tr>
<td>8</td>
<td>L-502</td>
<td>3(148)</td>
<td>24 400±900</td>
<td>49°17'</td>
<td>123°13'</td>
<td>Wood</td>
</tr>
<tr>
<td>9</td>
<td>GSC-108</td>
<td>5(47)</td>
<td>24 500±500</td>
<td>48°45'</td>
<td>123°13'</td>
<td>Wood</td>
</tr>
<tr>
<td>10</td>
<td>GSC-317</td>
<td>8(111)</td>
<td>24 680±350</td>
<td>49°16'</td>
<td>123°31'</td>
<td>Wood</td>
</tr>
<tr>
<td>11</td>
<td>GSC-84</td>
<td>5(50)</td>
<td>25 100±600</td>
<td>49°51'</td>
<td>125°37'</td>
<td>Wood</td>
</tr>
<tr>
<td>12</td>
<td>GSC-1635</td>
<td>21</td>
<td>26 100±320</td>
<td>49°16'</td>
<td>123°15'</td>
<td>Wood</td>
</tr>
<tr>
<td>13</td>
<td>GSC-53</td>
<td>5(49)</td>
<td>26 100±400</td>
<td>49°40'</td>
<td>124°54'</td>
<td>Wood</td>
</tr>
<tr>
<td>14</td>
<td>GSC-2191</td>
<td>21</td>
<td>26 200±320</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>15</td>
<td>GSC-124</td>
<td>6(171)</td>
<td>26 450±520</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Peaty silt</td>
</tr>
<tr>
<td>16</td>
<td>GSC-2217</td>
<td>21</td>
<td>26 900±320</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>17</td>
<td>GSC-535</td>
<td>9(173)</td>
<td>27 180±460</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>18</td>
<td>GSC-210</td>
<td>7(36)</td>
<td>27 400±420</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>19</td>
<td>GSC-263</td>
<td>7(37)</td>
<td>27 670±410</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>20</td>
<td>GSC-232</td>
<td>7(37)</td>
<td>27 960±420</td>
<td>49°30'</td>
<td>124°00'</td>
<td>Wood</td>
</tr>
<tr>
<td>21</td>
<td>GSC-2139</td>
<td>21</td>
<td>28 200±300</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>22</td>
<td>GSC-95</td>
<td>5(49)</td>
<td>28 850±740</td>
<td>49°40'</td>
<td>124°54'</td>
<td>Wood</td>
</tr>
<tr>
<td>23</td>
<td>L-424 C</td>
<td>1(10)</td>
<td>29 300±1400</td>
<td>49°36'</td>
<td>124°49'</td>
<td>Wood</td>
</tr>
<tr>
<td>24</td>
<td>GSC-2140</td>
<td>21</td>
<td>29 600±700</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Peaty silt</td>
</tr>
<tr>
<td>25</td>
<td>GSC-124</td>
<td>6(171)</td>
<td>30 100±320</td>
<td>49°36'</td>
<td>124°49'</td>
<td>Wood</td>
</tr>
<tr>
<td>26</td>
<td>GSC-424B</td>
<td>1(10)</td>
<td>30 200±1300</td>
<td>49°36'</td>
<td>124°49'</td>
<td>Peaty silt</td>
</tr>
<tr>
<td>27</td>
<td>GSC-535</td>
<td>9(173)</td>
<td>32 200±3300</td>
<td>49°19'</td>
<td>123°03'</td>
<td>Peaty silt</td>
</tr>
<tr>
<td>28</td>
<td>GSC-221</td>
<td>7(35)</td>
<td>32 580±720</td>
<td>49°15'</td>
<td>123°11'</td>
<td>Wood</td>
</tr>
<tr>
<td>29</td>
<td>GSC-2050</td>
<td>5(49)</td>
<td>32 600±550</td>
<td>49°22'</td>
<td>124°32'</td>
<td>Wood</td>
</tr>
<tr>
<td>30</td>
<td>L-455 B</td>
<td>3(147)</td>
<td>35 400±2200</td>
<td>50°05'</td>
<td>125°02'</td>
<td>Wood</td>
</tr>
<tr>
<td>31</td>
<td>GSC-202</td>
<td>7(26)</td>
<td>35 400±400</td>
<td>50°05'</td>
<td>125°02'</td>
<td>Wood</td>
</tr>
<tr>
<td>32</td>
<td>GSC-200</td>
<td>7(26)</td>
<td>35 600±300</td>
<td>48°34'</td>
<td>123°22'</td>
<td>Soil</td>
</tr>
<tr>
<td>33</td>
<td>GSC-93</td>
<td>7(26)</td>
<td>36 200±500</td>
<td>49°21'</td>
<td>123°02'</td>
<td>Wood</td>
</tr>
<tr>
<td>34</td>
<td>GSC-2137</td>
<td>21</td>
<td>40 200±400</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
<tr>
<td>35</td>
<td>GSC-2167</td>
<td>40</td>
<td>40 500±1700</td>
<td>49°14'</td>
<td>122°47'</td>
<td>Wood</td>
</tr>
</tbody>
</table>


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 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 low 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 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, 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.

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 Pleistocene sediments of southwest British Columbia. Many of the ideas presented in this paper were originally proposed by them. Much of the paleocurrent data was supplied by Fyles. R. J. Fulton reviewed a draft of the paper. This work is part of a larger study of the Quaternary geology of the Georgia Depression being made by the Geological Survey of Canada.


