Evolution of Cheekye fan, Squamish, British Columbia: Holocene sedimentation and implications for hazard assessment

Pierre A. Friele, C. Ekes, and E.J. Hickin

Abstract: Cheekye fan, a large (~25 km²) fan located at the head of Howe Sound, southwestern British Columbia, has its origins in the collapse of the western flank of Mount Garibaldi onto a waning Late Pleistocene glacier, followed by post-glacial redistribution of colluvial–glacial sediments. Reconstruction of internal fan architecture allowed characterization of the rapid decline in sediment delivery to the lower fan through the paraglacial period, a result holding important implications for hazard assessment. A ground penetrating radar profile on lower Cheekye fan has reflectors with a steep (25°), westerly dip lying between 48 and 26 m above sea level, which are interpreted as foreset beds. Radiocarbon ages from marine deltaic deposits at the head of Howe Sound indicate that the sea stood at about 45 m above sea level at 10 200 BP. Together, the data indicate that the head of Howe Sound was deglaciated by 10 200 BP, that the fan had prograded 2.5 km into the fjord by this time, and continued to prograde as relative sea level fell. Reflectors at –10 m above sea level with a steep southerly dip along the southern edge of the lower fan, and radiocarbon ages in this vicinity, indicate it had reached close to its modern extent by 8000–9000 BP. Calculation of the volume of sediment stored in the lower fan indicates that at least 90% of the material was deposited before 6000 BP. This indicates that the Cheekye fan is largely a relict feature, putting its large size into context for future hazard assessments.

Résumé: Le cône alluvial de Cheekye, un grand cône (~25 km²) à pente douce localisé à la tête du bras de mer Howe, dans le sud-ouest de la Colombie-Britannique, doit son origine à l’affaissement, au Pléistocène tardif, du flanc occidental du mont Garibaldi sur un glacier en décrétitude, suivi de la redistribution postglaciaire des sédiments colluviaux–glaciaires. La reconstitution de l’architecture interne du cône permet de préciser le déclin rapide de l’approvisionnement en sédiment du cône inférieur durant le paraglaciaire, un résultat qui procure des enseignements importants pour évaluer un tel risque naturel. Une image radar du profil de terrain du cône inférieur de Cheekye montre des horizons réflecteurs avec inclinaison abrupte (25°) vers l’ouest, apparaissant entre 48 et 26 m au-dessus du niveau marin, interprétés comme étant des lits de progradation inclinés. Les âges au radiocarbone des dépôts deltaïques marins à la tête du bras de mer Howe indiquent, qu’il y a 10 200 ans avant le Présent, la mer se trouvait à environ 45 m au-dessus du niveau marin actuel. Ensemble, ces données révèlent qu’il y a 10 200 ans avant le Présent, le glacier était déjà retraité de la tête du bras de mer Howe, et qu’à cette période le cône avait pénétré 2.5 km dans le fjord, et que sa progradation continuait au fur et à mesure que s’abaissait le niveau marin. Les réflecteurs à –10 m au-dessus du niveau marin, avec une forte inclinaison vers le sud qui longent la bordure méridionale du cône inférieur, couplés aux âges radiocarbone des sédiments des environs, indiquent que le cône alluvial avait presque atteint sa position actuelle vers 8000–9000 ans avant le Présent. Le calcul du volume de sédiment stocké dans le cône inférieur indique qu’au moins 90% du matériel avait déjà été déposé 6000 ans avant le Présent. Ce qui indique que la portion principale du cône de Cheekye représente un phénomène relictuel, et que sa grande taille peut servir d’exemple dans un contexte analogique pour estimer les risques naturels futurs.

Introduction

Cheekye fan is a large (25 km²), complex alluvial fan located at the head of Howe Sound in southwestern British Columbia (Fig. 1). The fan complex is composed of three units (Fig. 2): the upper two units have their origins in the collapse of supra-glacial volcanic debris from Mount Garibaldi, which had built up on waning Late Pleistocene ice occupying lower Cheakamus valley; while the lower Cheekye fan is the product of reworking of the upper and middle fan deposits, continued debris flow activity from the flanks of Mount Garibaldi, and fluvial processes. The neighbourhood of Brackendale (Fig. 2), within the District Municipality of Squamish, is situated on the lower fan and knowledge of fan history is of great importance in estimating debris flow and river avulsion hazards.

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More recently, Thurber Engineering – Golder Associates (1993) have conducted a detailed terrain hazard study of lower Cheekye fan. Using radiocarbon ages and stratigraphic data derived from shallow test pits, they produced a magnitude–frequency analysis of debris flow activity for the last 6000 years. However, the report was not able to place the late Holocene activity of the fan into the context of long-term paraglacial (sensu Church and Ryder 1972) sediment yield since no deep stratigraphic or early post-glacial chronologic control was available.

This study presents new data on the architecture and chronostratigraphy of lower Cheekye fan. Stratigraphic data from ground penetrating radar (GPR) surveys suggest subaerial and subaqueous facies consistent with fan-deltaic progradation into the fjord following deglaciation. New radiocarbon ages on early post-glacial marine deltaic deposits in upper Howe Sound provide chronologic control for early development of the lower fan. These data allow a description of fan evolution from deglaciation through the early Holocene Epoch.

Using a schematic cross-section of the lower fan constructed from GPR data, the volume of sediment deposited on the lower fan during the intervals 10 200 to 6000 BP and 6000 BP to present is calculated. This analysis shows that the lower Cheekye fan is largely a product of the geologic past, a point that land-use managers must consider before proceeding with highly restrictive zoning covenants.
Radiocarbon ages (Fig. 2; Table 1) from shallow test pits suggest that the fan was already well developed sometime between 6600 and 8700 BP.

**The formation of lower Cheekye fan**

GPR surveys were conducted along all roads crossing lower Cheekye fan. GPR penetration was to depths of 30 to 50 m below surface, providing deep, continuous profiles. The most obvious features visible are bedrock reflectors in the vicinity of existing bedrock outcrops and steeply dipping (15°–25° apparent slope) reflectors interpreted as foreset beds.

Since the front of the Squamish River delta was situated further upvalley in the early Holocene and did not reach the...
confluence of Squamish and Cheakamus rivers until about 3000 BP (Hickin 1989), the lower Cheekye fan was built out into the sea and did not prograde over existing Squamish River floodplain deposits. Thus, lower fan growth would have been intimately linked with post-glacial relative sea-level change, a significant point which allows correlation of fan stratigraphy with nearby marine deltaic deposits.

Foreset beds are revealed by GPR along the Squamish Valley road profile (SVR; Fig. 2), between 1300 and 1730 m south of Highway 99. On the SVR profile (Fig. 3), 1300 m south of the highway, the foreset–topset contact lies at about 48 m asl, but the elevation of the contact declines steadily south of Highway 99. The foreset–topset contact lies about 30 m below surface. It is reasonable to assume that, by 10 200 BP, Squamish Valley ice had retreated upstream beyond Cheakamus River confluence. The falling foreset–topset contact between 48 and 26 m asl (Fig. 3) is interpreted as evidence of fan progradation into Howe Sound during isostatic rebound following deglaciation. By 10 200 BP, the fan-delta extended about 2.5 km out into ancestral Howe Sound.

Along Highway 99, forest beds are revealed by GPR just off the southern edge of the fan, with the foreset–topset contact at about 10 m below present datum (Fig. 4). These foresets indicate that the lower fan continued to prograde as sea level fell, reaching close to its modern extent in the southern sector by about 8000–9000 BP, the time of the marine lowstand in the Lower Mainland (Clague et al. 1982). This is supported by radiocarbon ages (Table 1) of 7820 ± 95 BP (GX-17397) and 8715 ± 100 BP (GX-17890) from sediments in the southern sector (Fig. 2). Radiocarbon ages (Table 1) of 5975 ± 180 BP (GX-17893) and 6595 ± 90 BP (GX-17894) from sediments underlying the westernmost portion of the fan (Fig. 2) indicate that the fan had reached its modern extent by 6600 BP.

**Architecture of lower Cheekye fan**

Fan architecture was interpreted from GPR profiles, sea-level data, and test-pit data. This information was plotted on a long profile of the lower fan to produce a schematic chronostratigraphic profile (Fig. 5). The proto-delta front position 10 200 BP is marked by the 45 m asl foreset–topset contact beneath the Squamish Valley road (Fig. 3), which lies about 30 m below surface. It is reasonable to assume that by 10 200 BP, the early fan was graded to this delta-front position, defining the 10 200 BP chronostratigraphic boundary (Fig. 5). Below this line, materials consist of early fan deposits overlaying an irregular topographic surface of bedrock and glacial drift. The shape of this underlying surface is unknown, but, near the apex, bedrock was located in one water well at 30 m depth (WW-15; well logs compiled by Thurber Engineering – Golder Associates 1993). GPR penetration deeper than 30 m below surface south of Highway 99 indicates a deeper alluvial sediment package as one moves away from the apex. Sediments deposited after 10 200 BP lie above this line and downfan (seaward) of the 10 200 BP delta-front position.

In Fig. 5, sediments younger than 10 200 BP are divided into three main chronostratigraphic units: (1) subaerial sediments younger than 6000 BP; (2) subaerial sediments between 10 200 and 6000 BP; and (3) subaqueous sediments.
Fig. 3. GPR profile and interpretation from beneath Squamish Valley road. Location shown in Fig. 2.
between 10,200 and 6000 BP. Using test-pit data (Fig. 2; Table 1), Thurber Engineering – Golder Associates (1993) estimated that $35 \times 10^6$ m$^3$ of sediment were stored on the lower fan in the last 6000 years. With a modern fan area of 7 km$^2$ (excluding the area of upland hummocks), this implies an average of 5 m deposition over the entire fan and places the 6000 BP chronozone at 5 m below surface; sea level at the time was within one metre of present datum (Clague et al. 1982). The projection of the 5 m chronozone to the mean sea-level datum approximately defines the

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**Fig. 4.** GPR profile and interpretation from beneath Highway 99 on the southern edge of the Cheekye fan. Location shown in Fig. 2.

**Fig. 5.** Schematic chronostratigraphic profile along a southwesterly trend from the apex to the Squamish floodplain. Location shown in Fig. 2.
Sediment delivery to lower Cheekye fan

Fan chronostratigraphy defined in Fig. 5 can be used to estimate the sediment volume stored in lower Cheekye fan during the time periods 10 200–6000 BP and 6000 BP to present. This allows a characterization of the decline in sediment yield from the Cheekye basin through the Holocene. To do this, depths were simply multiplied by appropriate fan areas; to reconstruct fan areas at 10 200 and 6000 BP, the estimated delta-front positions from Fig. 5 were rotated about the apex, clockwise from the south. First, for the south sector, the full radii (10 200 and 6000 BP positions) from the main apex at 190 m asl were rotated to a southwesterly alignment; then, for the northern sector, shorter radii from 120 m asl, a secondary apex, were rotated through the rest of the fan. The total fan area to the 6000 BP chronozone is 13.4 km² (upland hummocks excluded).

An average of 30 m of alluvial sediment lie above the 10 200 BP chronozone: with 5 m of aggradation occurring in the last 6000 BP, 25 m occurred between 10 200 and 6000 BP. However, since well-log data (WW-11, WW-12; well logs compiled by Thurber Engineering – Golder Associates 1993) suggest that only 10 m of alluvial sediment overlies till at the mouth of the Cheakamus Valley, only 5 m of aggradation could have occurred in this area in the early period. With an area of 3.5 km² occupied by the mouth of the Cheakamus Valley, the total subaerial deposition between 10 200 and 6000 BP equals (9.9 km² × 25 m) + (3.5 km² × 5 m), or about 2.7 × 10⁶ m³ (Table 2). After 6000 BP, 5 m of sediment accumulated over the entire fan (13.4 km²), yielding about 0.7 × 10⁸ m³ of subaerial deposition for the latter time period (Table 2).

The area of subaqueous deposition between 10 200 and 6000 BP occurred in the Squamish Valley west of the 45 m asl delta-front position, excluding the mouth of the Cheakamus Valley, and occupied an area of about 7.5 km². The volume of the subaqueous unit is calculated based on an estimate of the depth of the Squamish Valley fill. Water depths in upper Howe Sound average about 275 m, but are 150 m deep off the Squamish River delta (Thomson 1981). Using 150 m as a conservative (low) estimate of the depth of the early Holocene subaqueous component and an area of 7.5 km² gives a volume of 11.3 × 10⁸ m³ for subaqueous material stored in the lower fan (Table 2).

Since the fan had attained its present extent by at least 6000 BP, our method cannot capture the subaqueous component after this time. However, some of the material transported fluvially across the fan would have been deposited in the Squamish delta. Hickin (1989) estimated a modern annual sediment yield of 1.3 × 10⁶ m³ a⁻¹ for the entire Squamish River watershed. Using a unit area approach (the Cheekye basin occupies 1.4% of the Squamish watershed), about 1.1 × 10⁵ m³ of sediment was delivered to the Squamish delta from the Cheekye basin in the last 6000 years (Table 2).

The total volumes of sediment delivered from the Cheekye basin between the periods 10 200–6000 BP and 6000 to present were about 14 × 10⁸ m³ and 1.8 × 10⁸ m³, respectively, equating to average annual yields of about 33 × 10⁴ and 3 × 10⁴ m³ a⁻¹, respectively (Table 2). The estimates suggest that 90% of the fan volume was deposited before 6000 BP. However, the estimates of average annual yield underestimate the actual reduction of sediment yield through the paraglacial period. A best-fit curve through the average yields (Fig. 6) produces an exponential decline in sediment yield: the annual yield about 10 000 BP may have been as high as 60 × 10³ m³ a⁻¹ compared to a “normal” yield in the last few thousand years of about 2 × 10³ m³ a⁻¹, which would represent a 30-fold reduction through the Holocene.

The total volume of material delivered to the valley bottom and stored in the lower Cheekye fan or the Squamish River delta is about 16 × 10⁸ m³. Mathews (1952) estimated that about 30 × 10⁵ m³ of material was missing from the west flank of Mount Garibaldi. Since lower Cheekye fan is about 40–50% of the total area of the combined deposits of

<p>| Table 2. Estimated sediment volumes and yields delivered to the lower Cheekye Fan. |</p>
<table>
<thead>
<tr>
<th>Fan unit</th>
<th>Area (km²)</th>
<th>Depth (m)</th>
<th>Volume (× 10⁸ m³)</th>
<th>Average annual yield (× 10⁸ m³ a⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subareal 10 200–6000 BP</td>
<td>7.5</td>
<td>150</td>
<td>11.3</td>
<td>14</td>
</tr>
<tr>
<td>Apex, south and west sectors</td>
<td>9.9</td>
<td>25</td>
<td>2.5</td>
<td>33</td>
</tr>
<tr>
<td>Cheakamus Valley sector</td>
<td>3.5</td>
<td>5</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Subaqueous 10 200–6000 BP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area &lt;10 200 BP, excluding Cheakamus Valley mouth</td>
<td>7.5</td>
<td>150</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>Total 10 200–6000 BP</td>
<td>14</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subareal 6000 BP–present</td>
<td>13.4</td>
<td>5</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Subaqueous 6000 BP–present (after Hickin 1989)</td>
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<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Total 6000 BP–present</td>
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<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the upper, middle, and lower Cheekye fan, the calculations presented here appear to provide a reasonable estimate of post-glacial sediment production from Cheekye River basin.

Discussion

Evidence of foreset beds between 40 and 55 m asl in the lower Cheekye fan indicate that ancestral Howe Sound was rapidly deglaciated after 10,700 BP and was inundated by higher sea levels before 10,200 BP. The downfan dip direction of the foresets indicate that the sediments were derived from Cheekye basin, confirming Hickin’s (1989) suggestion that Squamish delta stood farther upvalley during the Late Pleistocene and early Holocene. Rapid deglaciation probably resulted from calving of the ice margin once the Sumas Stade terminus, marked by the Porteau sill (Fig. 1), was breached by the sea sometime after 11,000 BP (Armstrong 1981; McCrumb and Swanson 1999). Deglaciation of tributary valleys was probably complete by 10,000 BP (Brooks 1994).

During the period of rapid deglaciation, between 10,700 and 10,200 BP, stagnant ice lay in the region of the middle fan. During this period, deposits on the upper fan were rapidly incised, and this reworked material, along with additional material derived from Cheekye basin, was deposited on the middle and lower fans. Since the shores of all lakes in the middle fan are irregular in shape, suggesting a melt-out origin, we argue that all alluvial deposits outside of the main channel area are Late Pleistocene in age and not Holocene. This differs from the interpretation of Thurber Engineering – Golder Associates (1993) who mapped a portion of the middle fan around Stump and Alice lakes as Holocene in age. This difference in interpretation has important implications with regard to hazard assessment, since extensive Holocene deposits in this area would imply a greater contemporary debris flow hazard both in Alice Lake Park and on the lower fan.

Our estimates of fan volume and deposition rates indicate that 90% of the material in the lower Cheekye fan was delivered prior to 6000 BP, representing a 30-fold reduction in annual sediment yield from deglaciation to the present. This suggests that the Cheekye fan is largely a product of the geologic past, that is, it is a paraglacial fan. Paraglacial fans (e.g., Ryder 1971; Kostachuk et al. 1987) formed rapidly following deglaciation, as unstable drift sediments were re-worked and redistributed largely by debris flow activity. Gradually, sediment availability declined and fan growth slowed toward an equilibrium condition, where sediment reaching the fan was transported across it, resulting in no net change in volume. However, the modern sediment supply to many paraglacial fans is so low that channel erosion dominates and their streams become entrenched in the fan. Incision also occurs commensurate with the lowering of base level if the trunk stream becomes incised into its floodplain (e.g., Jackson et al. 1982). In these cases, channel avulsion is restricted; debris flows may still affect the channel, but the frequency of debris flows reaching the fan surface may be low to nil. These fan surfaces are generally safe for development.

The modern channel of the Cheekye River is not appreciably incised, with banks along alluvial reaches varying from 2 to 7 m in height. Yet, the north and west edges of the fan have been truncated by the Cheakamus and Squamish Rivers, respectively, suggesting a low sediment supply and a tendency toward inactivity (Jackson 1987). The last debris flow to inundate the fan surface occurred about 1300 BP, covering an area of about 1 km² with a volume of about 3.5 × 10⁷ m³ (Baumann 1991). This large event did not cause a major channel avulsion. Thus, it is not clear whether the fan is in equilibrium condition or whether erosion dominates, with the channel tending toward incision and stability. The issue is interesting because fan growth has been intimately linked with relative sea-level change: following initial isostatic rebound, sea levels rose steadily from 8000 to 5000 BP (Clague et al. 1982) with perceptible rise through to 2500 BP (Williams and Roberts 1989). Base-level rise may have countered any tendency toward incision caused by a reduced sediment supply. Since the channel is presently graded to base level, further incision is unlikely, unless a large debris flow were to trigger an avulsion directing the channel off the western scarp. These issues confound interpretations regarding the fan’s contemporary level of activity and must be considered in future hazard analyses. The lower Cheekye fan and its linkage with relative sea level provides an interesting and unique example of paraglacial fan evolution.

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