Two landslide-dammed lakes in the Cascade
Mountains, southwestern British Columbia

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Abstract: Two prehistoric landslides in the Cascade Mountains of southwestern British Columbia blocked streams and impounded lakes that contain remnants of a drowned forest. Radiocarbon ages on drowned trees indicate that Foley Lake formed less than 310 years ago, and Silver Lake formed, or grew greatly in size, 800-1000 years ago. Some trees growing on Foley Lake landslide debris are as much as 152 years old; thus the landslide was not triggered by the 1872 earthquake, which was the largest earthquake in this region in at least the last 200 years. Similarly, the Silver Lake landslide may be slightly younger than a very large earthquake, 1000-1100 years ago, that triggered a tsunami in Puget Sound and numerous landslides in the nearby Olympic Mountains of western Washington.

Résumé: Deux glissements de terrain préhistoriques dans la chaîne des Cascades dans le sud-ouest de la Colombie-Britannique ont obstrué des cours d'eau et formé des lacs contenant des vestiges d'une forêt submergée. La datation au radiocarbone d'arbres submergés indique que le lac Foley s'est formé il y a moins de 310 ans et que le lac Silver s'est formé ou s'est beaucoup agrandi il y a entre 800 et 1 000 ans. Certains arbres qui poussent sur les débris du glissement de terrain du lac Foley remontent jusqu'à 152 ans; le glissement n'a donc pas été déclenché par le séisme de 1872, qui a été le plus gros séisme dans cette région depuis au moins 200 ans. De même, le glissement de terrain du lac Silver pourrait être un peu plus récent qu'un très fort séisme qui s'est produit il y a entre 1 000 et 1 100 ans et qui a provoqué un tsunami dans le détroit de Puget et de nombreux glissements de terrain dans les monts Olympic voisins, dans l'ouest de l'État de Washington.

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INTRODUCTION

Many landslides in the Cordillera of western North America have blocked streams and impounded lakes (Evans, 1986; Costa and Schuster, 1988). At least 19 such damming events have occurred in British Columbia since 1880, mainly on the flanks of Plio-Pleistocene volcanoes and in valleys incised into thick Quaternary sediments (Evans, 1986). Lakes dammed by historic landslides commonly drained soon after they formed; consequently, little evidence of the events remains other than the breached dams.

In contrast, many, large, prehistoric, bedrock failures in British Columbia have dammed lakes that have persisted to the present (Evans, 1986). Two of these lakes (Foley and Silver), both in the Cascade Mountains of southwestern British Columbia (Fig. 1), are of particular interest because they contain drowned trees. Among other things, it is possible to determine the age of the landslides that formed these lakes by radiocarbon dating the outermost annual rings of the drowned trees. These two lakes and the landslides that formed them are the subject of this paper.

Historic landslides in British Columbia have been triggered by anomalous groundwater flow, high rainfall, freeze-thaw activity, and erosion of steep slopes by streams. Earthquakes were not involved in any of the 19 historic damming events. On the other hand, some of the large, prehistoric, landslide dams in this region may have formed during earthquakes. Certainly, this is common in other mountainous regions. For example, an earthquake in Calabria, Italy, in 1873 triggered landslides that impounded about 15 lakes (Cotecchia, 1978; R.L. Schuster, pers. commun., 1993), and the 1929 Buller earthquake in New Zealand created at least 16 landslide-dammed lakes (Adams, 1981; Perrin and Hancox, 1992; see also Costa and Schuster, 1991, for other examples).

Recently, evidence has been presented that several lakes in the Olympic Mountains of western Washington, similar to those described in this paper, were dammed by landslides 1000-1300 years ago (Schuster et al., 1992), probably as a result of a large earthquake centred near Seattle (Fig. 1; Atwater and Moore, 1992). Another large earthquake in Washington in 1872 triggered many landslides, including one

Figure 1. Locations of Foley and Silver lakes, as well as landslide-dammed lakes in the Olympic Mountains (darkened circles) that are discussed in the paper.
from Cheam Peak, only 10 km from Foley Lake, one of the lakes discussed in this paper (Chilliwack Progress, August 19, 1915). A major impetus for the present study was to determine whether or not Foley and Silver lakes formed during either of these earthquakes.

**FOLEY LAKE**

Foley Lake (49°08'N, 121°35'W; 550 m asl) is located 110 km east of Vancouver in the valley of Foley Creek, a tributary of Chilliwack River (Fig. 1, 2A). The lake is 800 m

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**Figure 2.** A. Topographic map showing the scarp (line with arrow) and path (stippled) of the Foley Lake landslide. Contour interval = 40 m. B. Bathymetric map of Foley Lake compiled from an echo-sounding survey in October 1991. Contour interval = 2 m. Circle pattern shows approximate extent of drowned trees. Darkened circles are radiocarbon-dated trees (ages in radiocarbon years BP; see Table 1).
long, up to 200 m wide, and has a maximum depth of 18 m (Fig. 2B). It is dammed at its west end by debris emplaced by a rock avalanche from the south wall of Foley Creek valley. A conspicuous scarp extending from ca. 1050 m to 1300 m asl, just below the crest of the ridge that separates the valleys of Foley Creek and Chilliwack River, marks the source of the landslide. The failure occurred in Upper Paleozoic metapelitic rocks (mainly phyllite; Monger, 1970), mantled by colluvium and till. Several hundred thousand, to perhaps one million, cubic metres of rock became detached and moved down the 30° slope into the valley below. There, the debris came to rest as a hummocky lobe several hundred metres long and up to 200 m wide; the lobe extends beneath the western part of Foley Lake (Fig. 2B). Since the landslide occurred, a small gravelly delta has been built into the lake at its east end.

Large numbers of standing trees (mainly western red cedar and Douglas fir) are present in the eastern half of the lake (Fig. 2B, 3). Since the landslide, most of these have decayed to close to the lake surface or have been topped by logging operators; a few, however, still project far above the water.

The age of the landslide that impounded Foley Lake is constrained by two radiocarbon dates on drowned trees and by the ages of living trees on the landslide debris. Radiocarbon ages of $30 \pm 60$ BP and $150 \pm 50$ BP were obtained on the outermost preserved rings of two drowned trees (Table 1). The range of possible calendric ages, based on the calibration curves of Stuiver and Pearson (1986) and taking into account the 2σ error terms, is 50-310 years (Table 1). The landslide must be older than 152 years, however, because trees this old

![Figure 3. Drowned trees in Foley Lake, April 1991. The canoe in the upper photo provides scale.](image-url)
are growing on the debris lobe impounding the lake. The data thus indicate that the landslide occurred sometime between about 1680 and 1840 AD.

**SILVER LAKE**

Silver Lake (49°19'N, 121°25'W; 350 m asl) lies 8 km south of the town of Hope and 120 km east of Vancouver, in the valley of Silverhope Creek (Fig. 1). The lake is 1.5 km long and up to 400 m wide; its maximum depth is 12 m (Fig. 4). It is bordered on the south by the broad floodplain and delta of Silverhope Creek. In contrast, Silverhope Creek flows out of the lake in a narrow, steep, boulderly channel. This channel is constrained to the east by a colluvial apron and to the west by a bedrock hill occupying the centre of the valley. Rock slopes east and north of Silver Lake are steep (typically >40°) and culminate in peaks with elevations of 1500-1840 m. Gentler, till- and colluvium-mantled slopes rise southwest of the lake.

An echo-sounding survey in the fall of 1991 revealed the morphology of the lake floor (Fig. 4B). Much of the northern third of the lake has an irregular, hummocky bottom with relief of several metres (Fig. 5). This is interpreted to be rockfall or rock-avalanche debris derived from slopes to the northeast. Southward, the bottom gradually becomes flatter as the cover of silty and sandy sediments carried into the lake by Silverhope Creek thickens. Echo sounding indicates that the floor of the southern third of the lake is a bench that slopes gently upward from about 6-7 m at its north end to 4 m adjacent to the Silverhope delta (Fig. 5). A large number of in-situ tree stumps are present on this bench; many of these extend upward to the water surface. Similar submerged tree stumps also occur farther north near the eastern and western shores of the lake.

The large boulders and blocks that choke the outlet of Silver Lake (Fig. 6A) and cover part of the adjacent colluvial apron were deposited during a rockfall from cliffs northwest of the lake (Fig. 4B). One or more large masses of granodiorite or quartz diorite became detached from the cliff and cascaded down a ravine onto the colluvial apron below (Fig. 6B). Presumably, some of the debris on the lake floor near the outlet (Fig. 4B) also was deposited during this event. Farther south, however, blocky debris occurs on the lake floor outside the path of the landslide and is a substrate for several drowned trees. It thus seems likely that there has been more than one landslide into the Silver Lake basin.

The landslide either created Silver Lake or, more likely, raised its level 6-7 m (see below). The rising waters drowned a forest and began to overflow across the newly formed debris dam.

The age of this event is approximated by radiocarbon ages of 890 ±60 BP and 1010 ±100 BP on the outermost preserved rings of two drowned trees (Table 1). The range of possible calendric ages, again based on Stuiver and Pearson (1986), and taking into account 2σ error terms, is 770-1090 years; the two age determinations overlap between 830 and 960 years ago.

It is possible that this event did not actually create Silver Lake, but rather raised the level of a much smaller lake already present in the basin. The gently sloping bench that forms the floor of the southern third of the lake may be a remnant of a pre-830 year old floodplain or delta graded to a lake level 6-7 m lower than the present. If so, the rockslide 800-1000 years ago raised the level of the lake, as well as base level in Silverhope valley to the south. In response, Silverhope Creek prograded northward across the old delta-floodplain into the newly formed lake.

**Table 1. Radiocarbon ages from Foley and Silver lakes**

<table>
<thead>
<tr>
<th>Radiocarbon age (years BP)a</th>
<th>δ¹³C (‰)</th>
<th>Calibrated age (years)b</th>
<th>Laboratory no.</th>
<th>Site</th>
<th>Location</th>
<th>Dated material</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 ± 60</td>
<td>-26.1</td>
<td>110</td>
<td>GSC-5239</td>
<td>Foley Lk.</td>
<td>49°07.7' 121°34.3'</td>
<td>Drowned treec</td>
</tr>
<tr>
<td>150 ± 50</td>
<td>-27.7</td>
<td>50-310d</td>
<td>GSC-5260</td>
<td>Foley Lk.</td>
<td>49°07.7' 121°34.3'</td>
<td>Drowned treed</td>
</tr>
<tr>
<td>890 ± 60</td>
<td>-22.9</td>
<td>830 (770-960)</td>
<td>GSC-5444</td>
<td>Silver Lk.</td>
<td>49°18.6' 121°24.4'</td>
<td>Drowned treef</td>
</tr>
<tr>
<td>1010 ± 100</td>
<td>-26.2</td>
<td>970 (830-1090)</td>
<td>GSC-5204</td>
<td>Silver Lk.</td>
<td>49°18.8' 121°24.8'</td>
<td>Drowned treeg</td>
</tr>
</tbody>
</table>

aError terms are 2σ.
cOutermost 20 rings of conifer; identified as *Abies* sp. by H. Jetté (GSC Wood Identification Report No. 91.37).
dThere are four possible calendar ages corresponding to a radiocarbon age of 150 BP: 50, 190, 250, and 310 years. If the 2σ error term is taken into consideration, the possible range is 0-330 years.
eOutermost 10 rings of conifer; identified as *Abies* sp. by H. Jetté (GSC Wood Identification Report No. 91.44).
fOutermost 18 rings of conifer; identified as *Pseudotsuga menziesii* by H. Jetté (GSC Wood Identification Report No. 92.61).
gOutermost 10 rings of conifer; identified as *Pseudotsuga menziesii* by R.J. Mott (GSC Wood Identification Report No. 90.53).
Figure 4. A. Topographic map showing the path (stipple) of the Silver Lake landslide. Two possible source areas are marked by half circles, the northern area being the more likely of the two. Contour interval = 100 feet (30.5 m). B. Bathymetric map of Silver Lake compiled from an echo-sounding survey in October 1991. Contour interval = 2 m. Darkened circles are radiocarbon-dated trees (ages in radiocarbon years BP; see Table 1). Also shown is the line of the profile reproduced in Figure 5.

Figure 5. Echo-sounding profile of Silver Lake (see Fig. 4B for location). Note the hummocky bottom at the north end of the lake and the gently sloping bench at the south end (see text for discussion). Horizontal scale and vertical exaggeration (VE) are approximate.
DISCUSSION

At the beginning of this study, it was thought that the damming of Foley Lake might be related to the 1872 earthquake, centred in north-central Washington just south of the International Boundary. This is clearly not the case, however, because the landslide damming Foley Lake occurred before 1840 AD. Radiocarbon dating indicates that the lake is no more than 310 years old, but the cause of the landslide remains unknown.

A large earthquake in the Seattle area, 190 km south of Silver Lake (Fig. 1), produced surface deformation (uplift and subsidence), landslides, and a tsunami sometime between 1000 and 1100 years ago (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992). Three, or possibly four, landslide-dammed lakes in the Olympic Mountains, 60-85 km west and southwest of Seattle, contain trees that were drowned at this time, and it has been suggested that these lakes also are products of this earthquake (Schuster et al., 1992). It is tempting to ascribe the Silver Lake rockfall to this event, because the radiocarbon ages from Silver Lake are close to those in Washington that have been attributed to the earthquake. Close inspection, however, indicates that the former are slightly younger (ca. 100-200 years) than the latter (Fig. 7). The older Silver Lake radiocarbon age does overlap many of the Washington ages, if laboratory error terms are taken into account, but this is not true for the younger Silver

Figure 6. A. Boulder-choked outlet of Silver Lake. B. View of the source area of the Silver Lake landslide from the south end of the lake, June 1991. Two possible sources are indicated by arrows; the more likely of the two is to the left; note the colluvial apron on the lower part of slope above Silver Lake.
very difficult to prove that two events are contemporaneous on the basis of radiocarbon ages alone. This is illustrated by the Foley Lake event. The radiocarbon ages from Foley Lake indicate that the lake formed 50 to 310 years ago; one might conclude from this that the landslide that impounded the lake was triggered by the 1872 earthquake, which is probably the largest earthquake to affect this area in the last two centuries. In this case, however, other evidence proves that the landslide is older than 152 years and thus unrelated to the 1872 earthquake.

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