are restricted to epicentral distances of a few kilometres (Fig. 55). Magnitude 6 earthquakes also cause liquefaction over relatively small areas (within about 50 km of the epicentre), and probably could not produce the large (0.3 m diameter) dykes and surface offsets found on the Fraser delta. It thus is likely that the Fraser delta-Serpentine River liquefaction features record one or more large (M7+) prehistoric earthquakes. This is in agreement with evidence at one site (no. 8) for coincident liquefaction and subsidence about 2000 14C years BP. Contemporaneous subsidence here and at other sites on both sides of the southern Strait of Georgia 2000 14C years ago (see section Late Holocene sea level change, southwestern British Columbia) could only result from a M7+ earthquake.

**LANDSLIDES**

Large earthquakes typically trigger many landslides both in bedrock and unconsolidated sediments (Keefer, 1984). Three pilot studies were conducted to assess the potential value of terrestrial and subaqueous landslides as archives of paleoseismic information in southwestern British Columbia. The results of these studies are reported here.

![Graph](image)

**Figure 55.** Relationship between earthquake moment magnitude (Mw) and distance of the farthest liquefaction feature from the earthquake epicentre (modified from Ambraseys, 1988).

**Terrestrial landslides and landslide-dammed lakes**

**J.J. Clague and W.W. Shilts**

Rock and soil falls and small slides may be triggered by relatively small earthquakes (M4 to M5), whereas more coherent, deeper-seated slides and slumps require stronger shaking (Keefer, 1984). Lateral spreads and flows require shaking that is stronger still, and large, highly disrupted rock and soil avalanches are only triggered by moderate to large earthquakes (M6+). There is also a general relationship between earthquake magnitude and the areal extent of landsliding (Keefer, 1984): the maximum area likely to be affected by landslides increases from 0 at M3 to M4 to 500 000 km² at M9.

These observations suggest that only large earthquakes can produce a suite of terrestrial landslides than can be recognized and interpreted hundreds or thousands of years after the event. The 1946 Vancouver Island earthquake triggered more than 300 landslides over an area of about 20 000 km² (Mathews, 1979), but few of them are clearly recognizable today 50 years after the event (Evans, 1989; VanDine and Evans, 1992).

The attribution of large, prehistoric, terrestrial landslides to earthquakes is problematic in that they can be triggered by many nonseismic processes, for example anomalous groundwater flow, high rainfall, and freeze-thaw activity. If, however, several large, widely separated landslides can be shown to be of the same age, a seismic trigger can be suspected. The only other reasonable explanation for contemporaneous widespread landsliding is a catastrophic rainfall event. Such storms, however, would more likely produce shallow slope failures (soil avalanches and debris flows) than large, deep-seated landslides.

Most dating techniques that are applicable to landslides do not have sufficient precision to allow contemporaneity to be established. Conventional and accelerator mass spectrometry radiocarbon ages, for example, have error terms of ± 50-100 14C years, which is a serious limitation when exact dating is required. With high-precision techniques, the quoted laboratory error can be reduced to 10-20 years (e.g., Atwater et al., 1991). Precision can also be improved by dating a succession of tree rings in fossil wood and by matching these ages with independently determined, tree-ring-calibrated 14C ages (e.g., Pearson and Stuiver, 1993; Stuiver and Pearson, 1993). Nevertheless, even with these refinements, there will always be some doubt as to whether two or more landslides are the same age and thus possibly the product of a single earthquake. This uncertainty is highlighted in the Foley Lake and Silver Lake case histories, described below.

One dating technique that has annual, and in some cases seasonal, precision is dendrochronology, the counting and characterization of annual rings in trees. Dendrochronology can be applied to living trees to determine when growth commenced or, in the case of trees that have been disturbed, when tilting or scarring occurred. It can also be applied to fossil wood. The ring patterns in fossil wood are matched with those of old living trees (a procedure termed crossdating) to determine the age of the former. An advantage of
dendrochronology is that high precision calendar ages can be obtained. A disadvantage is that the age of establishment or death of a tree may differ from that of the landslide with which the fossil wood is associated. This problem, however, is not unique to dendrochronology. Radiocarbon ages on fossil plant or animal material within or directly beneath landslide deposits do not actually date the landslide, but rather are maximum age estimates.

One group of prehistoric landslides, however, can be dated with a high level of accuracy, using either the radiocarbon method or dendrochronology. These are landslides that have blocked stream courses, impounded lakes, and thus drowned vegetation. Their age can be determined by dating the outermost rings of standing trees in the lake, the assumption being that the trees were killed within months to, at most, a couple of years of the landslide. The widespread use of this approach is limited by the relatively small number of landslide-dammed lakes containing in situ drowned trees in western Canada. Also, these landslides need not have been triggered by earthquakes. Earthquakes were not involved in any of the nineteen known historical damming events in British Columbia since 1880 (Evans, 1986; Clague and Evans, 1994a). It should be pointed out, however, that there have been few large earthquakes in British Columbia during this period, and that large historical earthquakes in other mountainous regions have generated many landslide-dammed lakes. For example, an earthquake in Calabria, Italy, in 1873 triggered landslides that impounded about 15 lakes (Cotecchia, 1978; R.L. Schuster, pers. comm., 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). The two case histories that follow illustrate the danger of attributing prehistoric landslides to earthquakes.

Foley Lake

Foley Lake is located 110 km east of Vancouver in the valley of Foley Creek, a tributary of Chilliwack River (Fig. 56, 57A). The lake is 800 m long, up to 200 m wide, and has a maximum

Figure 56. Map showing the locations of Foley and Silver lakes, as well as landslide-dammed lakes in the Olympic Mountains (darkened circles) that are discussed in the text (Clague and Shilts, 1993, Fig. 1).

Figure 57A. Topographic map showing the scarp (line with arrow) and path (stippled) of the Foley Lake landslide. Base map – 92H/4 (Chilliwack). Contour interval = 40 m.
depth of 18 m (Fig. 57B). It is dammed at its west end by debris emplaced by a rock avalanche from the south wall of the valley. A conspicuous scarp extending from about 1050 m to 1300 m a.s.l., 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), 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. 57B). 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. 58). 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 trees growing on the landslide debris. Radiocarbon ages of 150 ± 50 and 30 ± 60 years BP were obtained on the outermost preserved rings of two drowned trees (Table 6). The range of possible calendric ages, using the calibrations of Stuiver and Pearson (1993) and taking into account 2σ error terms, is 0-290 years BP (Table 6). The landslide must be older than 155 years, however, because trees this old are growing on the debris lobe impounding the lake. The data thus indicate that the landslide occurred sometime between about A.D. 1840 and A.D. 1660.

Silver Lake

Silver Lake is 8 km south of the town of Hope and 120 km east of Vancouver, in the valley of Silverhope Creek (Fig. 56). The lake is 1.5 km long and up to 400 m wide; its maximum depth is 12 m (Fig. 59). 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, bouldery
Table 6. Radiocarbon ages, Foley and Silver lakes.

<table>
<thead>
<tr>
<th>Location</th>
<th>Dated material</th>
<th>Location</th>
<th>Dated material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foley Lake</td>
<td></td>
<td>Silver Lake</td>
<td></td>
</tr>
<tr>
<td>30 ± 60</td>
<td>-26.1 (&lt;260)</td>
<td>Foley</td>
<td></td>
</tr>
<tr>
<td>150 ± 50</td>
<td>-27.7 (&lt;290)</td>
<td>Lake</td>
<td>Drowned tree¹</td>
</tr>
<tr>
<td></td>
<td>GSC-5239</td>
<td>890 ± 60</td>
<td>Drowned tree⁵</td>
</tr>
<tr>
<td></td>
<td>49°07.7' 112°34.3'</td>
<td>1019 ± 100</td>
<td>Drowned tree⁷</td>
</tr>
<tr>
<td></td>
<td>121°34.3'</td>
<td>670-930</td>
<td>Drowned tree⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td>700-1130</td>
<td>Drowned tree⁷</td>
</tr>
</tbody>
</table>

¹ Radiocarbon and calibrated ages are expressed in years before A.D. 1950. Laboratory-reported error terms are 2σ. Ages normalized to δ¹³C = -25.0% PDB.
² Determined from dendro-calibrated data of Stulver and Pearson (1993). The range represents the 95% confidence interval based on the 2σ error limits of the radiocarbon age (error multiplier = 2).
³ Geological Survey of Canada Radiocarbon Laboratory.
⁴ Outermost 20 rings of conifer; identified as *Abies* sp. by H. Jette (GSC Wood Identification Report 91.37).
⁵ Outermost 10 rings of conifer; identified as *Abies* sp. by H. Jette (GSC Wood Identification Report 91.44).
⁶ Outermost 18 rings of conifer; identified as *Pseudotsuga menziesii* by H. Jette (GSC Wood Identification Report 92.61).
⁷ Outermost 10 rings of conifer; identified as *Pseudotsuga menziesii* by H. Jette (GSC Wood Identification Report 90.53).

Figure 59. 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. Base map = 92H/6 (Hope). 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 ¹⁴C years BP; see Table 6). Also shown is the line of the profile reproduced in Figure 60 (Clague and Shilts, 1993, Fig. 4).
Figure 60. Echo-sounding profile of Silver Lake (see Fig. 59B 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 (Clague and Shilts, 1993, Fig. 5).

Figure 61. A) Boulder-choked outlet of Silver Lake. GSC 1995-101P 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 the slope above Silver Lake. Photos by J.J. Clague (Clague and Shilts, 1993, Fig. 6). GSC 1995-101Q

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. 59B). Much of the northern third of the lake has an irregular, hummocky bottom with relief of several metres (Fig. 60). 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 depth at its north end to 4 m depth adjacent to the Silverhope delta (Fig. 60). 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. 61A) and cover part of the adjacent colluvial apron were deposited during a rockfall from cliffs northwest of the lake (Fig. 61B). 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. 61B). Presumably, some of the debris on the lake floor near the outlet (Fig. 59B) also was deposited during this event. The landslide either created Silver Lake or 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 1010 ± 100 and 890 ± 60 BP on the outermost preserved rings of two drowned trees (Table 6). The range of possible calendric ages, again based on Stuiver and Pearson (1993) and
taking into account \(2\sigma\) error terms, is 1130-670 years BP; the two age determinations overlap between 930 and 700 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-700-year-old floodplain or delta graded to a lake level 6-7 m lower than present. If so, the rockslide 900-700 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 expanded lake.

### Discussion

A large earthquake in Washington in 1872 triggered many landslides, including one from Cheam Peak, only 10 km from Foley Lake (Chilliwack Progress, August 19, 1915). This probably was the largest earthquake to affect the region in the last two centuries. In view of the youthful appearance of the drowned trees in Foley Lake, one might assume that the 1872 earthquake triggered the landslide that dams the lake. This clearly is not the case, however, because the landslide occurred before A.D. 1840. Radiocarbon dating indicates that the lake is no more than 335 years old and thus formed no more than 213 years before the 1872 earthquake, but the cause of the landslide remains unknown.

Another large earthquake in the Seattle area, 190 km south of Silver Lake (Fig. 56), produced surface deformation (uplift and subsidence), landslides, and a tsunami sometime between 1100 and 1000 cal years BP (Atwater and Moore, 1992; Bucknam et al., 1992; Jacoby et al., 1992; Karlin and Abella, 1992; Bucknam and Biasi, 1994). The earthquake may have triggered landslides that dammed lakes in the Olympic Mountains, 60-85 km west and southwest of Seattle (Fig. 56; Schuster et al., 1992). It is tempting to ascribe the Silver Lake rockfall to the same event, because the radiocarbon ages from Silver Lake are close to those in Washington State that date the earthquake. Close inspection, however, indicates that the former are younger, by 100-300 years, than the latter (Fig. 62). The older Silver Lake radiocarbon age does overlap many of the Washington State ages, if laboratory error terms are taken into account, but this is not true for the younger Silver Lake radiocarbon age. The available evidence thus suggests that the Silver Lake rockfall postdates, although not by much, a major earthquake that triggered numerous landslides farther south.

The two case histories described above show how difficult it is to determine the cause of a prehistoric landslide. In an area of high seismicity, it is tempting to conclude that most large prehistoric landslides have been triggered by earthquakes. This assumption, however, may not be correct; consider, for example, that the three largest historical landslides in Canada—Frank, Alberta, 1903; Hope, British Columbia, 1965; and Devastation Glacier, British Columbia, 1975—were not caused by earthquakes. Only by demonstrating that many large landslides occurred at the same time, or at the time of an independently dated earthquake, can a seismic trigger be reasonably inferred.

This problem is aggravated by the unavoidable imprecision in radiocarbon dating mentioned above; it is very difficult to prove that two landslides are contemporaneous on the basis of radiocarbon ages alone. This is clearly illustrated by the Foley Lake event: A.D. 1872 is within the range of calibrated ages corresponding to the Foley Lake radiocarbon ages; in other words, the earthquake and the landslide cannot be separated in time by radiocarbon dating.

### Subaqueous landslides and related disturbance

#### Vancouver Island lakes

J.J. Clague, R.H. Linden, and W.W. Shilts

The lakes of southwestern British Columbia offer opportunities for determining the intensity and character of recent tectonic activity in the region. Late Quaternary sediment fills in many of the lakes are likely to preserve a record of past earthquakes because they are saturated and fine grained, and thus susceptible to failure when shaken.

![Figure 62. Plot of Silver Lake calibrated radiocarbon ages and calibrated ages of a tsunami and landslides triggered by a large prehistoric earthquake near Seattle, Washington State (data from Atwater and Moore, 1992; Jacoby et al., 1992; Schuster et al., 1992). Radiocarbon ages were calibrated using the method and curves of Stuiver and Pearson (1993). Some of the mean radiocarbon ages correspond to two or more calendric ages; this is indicated by multiple symbols along one line. The horizontal lines represent the \(2\sigma\) age range, calculated using an error multiplier of 1.0. Relationship of dated sample to event: darkened circles and darkened triangles = minimum age; circle containing \(x\) = approximate age; all other symbols = maximum age (modified from Clague and Shilts, 1993, Fig. 7).](image.png)
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Cover illustration

View northeast of Port Alberni, British Columbia. The town was severely damaged by the tsunami of the great Alaska earthquake of March 27, 1964. This tsunami deposited a layer of sand in the marsh in the foreground. Sands and gravels of older, prehistoric tsunamis are also present beneath the marsh.

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