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Movement of a Large Landslide Block Dated by Tree-Ring Analysis, Tower Falls Area, Yellowstone National Park, Wyoming

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Chapter B *of*

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Contents

Figures

Table

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Abstract

Tree-ring analysis can be a valuable tool to date geomorphic events in regions lacking long historical records. In this study, the latest detectable movement of a section of a large landslide block in the Tower Falls area of Yellowstone National Park, Wyoming, is dated by tree-ring analysis of Douglas fir trees (*Pseudotsuga menziesii* var. *glauca*) damaged by the event. The movement tilted many of the trees and damaged their root systems. Thirteen old, tilted Douglas fir trees, at three sites, were sampled within the section of the landslide block that moved during the life of these trees. In addition, 10 young, upright, undisturbed Douglas firs were also sampled at the sites in order to establish a minimum age for the movement. The oldest of the 10 young, upright trees had an age of about 135 years, indicating that the latest movement of the landslide block occurred prior to 1865 A.D. The youngest of the 13 old, tilted trees dated to the early 1600s, providing a maximum age for this latest landslide movement. Analysis of the tree-ring record of the older, tilted Douglas firs revealed an abrupt reduction in annual-ring width beginning in 1694 A.D. As no other period in the tree-ring record between 1865 and 1600 A.D. revealed such an abrupt reduction in annual-ring width, the landslide movement is thought to have occurred sometime between the end of the 1693 A.D. growing season and before the end of the 1694 A.D. growing season. Because Yellowstone National Park is within the Intermountain seismic belt, a zone of pronounced seismic activity, movement of the landslide block may have been caused by an earthquake at that time.

Introduction

Because many tree species can live for several centuries or more (Brown, 1996), tree-ring analysis can be a valuable tool to date various geomorphic events, such as landslides, earthquakes, floods, and avalanches in regions lacking long historical records. For example, during a landslide a tree may suffer damage—such as topping, tilting, impact, or root breakage—from ground shaking, breakage, or movement. This damage is recorded in the annual-ring record, commonly as an abrupt reduction in tree-ring width. In addition, tree-ring analysis can date such an event to within a year, whereas radiocarbon ages within the last few centuries have relatively large error limits. The purpose of this study is to date, by tree-ring analysis, the latest movement of a section of a large landslide block near the Tower Falls area of Yellowstone National Park.

The small, seasonal community of Tower Falls is located in north-central Yellowstone National Park at an elevation of 1,960 m (fig. 1). A large landslide block is present immediately north of Tower Falls. This landslide block, about 5 km^2, is bounded on the northeast by the Yellowstone River, on the southeast by Tower Creek, on the northwest by Lost Creek, and on the southwest by an unnamed stream. Elevations range from about 1,830 m along the Yellowstone River to about 2,150 m at the highest point on the landslide block. Steep, step-like features on the block appear to be old scarps that separate individual blocks within the larger block. One prominent step is 20 to 30 m in height and dips 25°.

The landslide block is mantled by a thin covering of glacial deposits about 20,000 to 30,000 years old (Pierce, 1974). The glacial deposits are underlain by about 200 m of Lava Creek Tuff (Prostka and others, 1975) dated, by the $^{40}Ar/^{39}Ar$ method, at about 639,000 years old (Lanphere and others, 2002). Exposed along the Yellowstone River is a sequence of Pleistocene sediments underlying the Lava Creek Tuff (Pierce, 1974) that may contain the slip plane on which the landslide block moved. The initial age of the landslide block is presently unknown, but it may have initially formed in the late Pleistocene soon after deglaciation and has experienced recurrent movements since that time. A section of the road from Tower Falls north for about 0.5 km is presently subsiding (C.S. Dewey, oral commun., 2001). Understanding the history of this landslide block is important because Yellowstone National Park receives millions of

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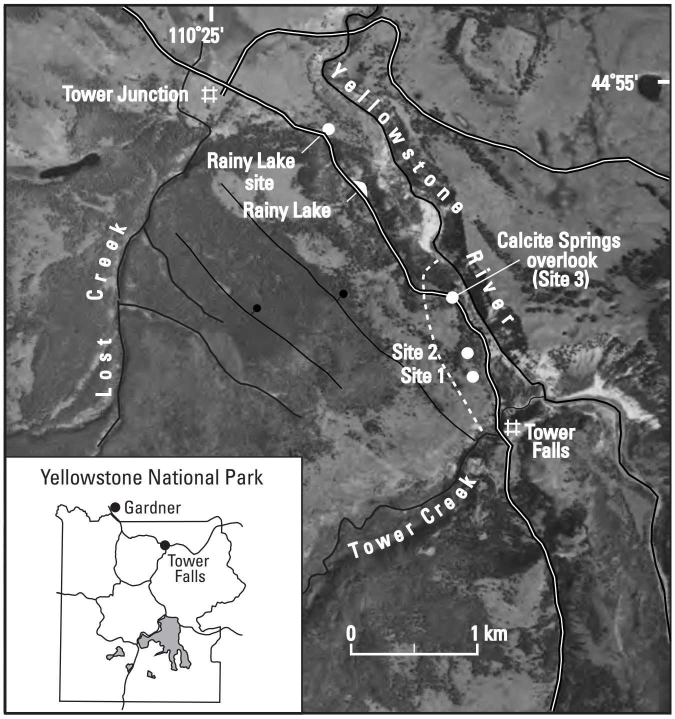

Figure 1. Aerial photograph of the Tower Falls area showing landslide block. Dashed white line shows area of trees affected by latest movement. Lines with black circles represent down-to-the-northeast faults on the geologic map of Prostka and others (1975) and are interpreted in this report as landslide scarps.

visitors each year, and its roads are heavily used. It is the area near this section of subsiding road and to the west that is the focus of this study.

In the study area, Douglas fir (*Pseudotsuga menziesii* var. *glauca*) is the dominant tree species. The trees can be divided into three age groups. The first group consists of smaller, younger, upright Douglas firs, established after the latest movement of the landslide block. These trees range between 15 and 50 cm in diameter, and 5 to 20 m in height. The second group consists of large, older Douglas firs that are tilted (fig. 2) as a consequence of the latest landslide movement. The trunks of these trees are tilted for a height of 5 to 10 m, whereas the upper parts of many of these trees are vertical. These tilted trees range between 60 and 130 cm in diameter, and about 15 to 30 m in height; angles of tilt ranged from 8° to 47°. The third group consists of standing dead trees that are tilted throughout their entire length as a result of the landslide movement. These trees range between 60 and 110 cm in diameter, and about 15 to 30 m in height; angles of tilt range from 10° to 27°. An excellent example of these large, tilted trees (groups 2 and 3) can be seen at the Calcite Springs overlook (fig. 3). These large, old, tilted Douglas firs, both alive and dead, contrast markedly with the smaller, younger, upright trees.

Figure 2. Photograph of a group of tilted Douglas fir trees, at site 1, on the Tower Falls landslide block. Tree on left is approximately 28 m in height.

Previous Work

Tree-ring analysis has been used to date various geomorphic events, such as landslides, earthquakes, and snow avalanches, in several ways. On the simplest level, the ages of the trees themselves supply important information. For instance, the oldest undisturbed tree on a landslide provides a minimum age of landslide movement (McGee, 1893; Fuller, 1912; Jibson and Keefer, 1988; Logan and Schuster, 1991).

One of the first investigators to use tree-ring analysis to date landslides was McGee (1893). On landslides near Reelfoot Lake, Tennessee, caused by the New Madrid earthquakes of 1811 and 1812, McGee (1893) noted trees "...frequently thrown out of the vertical." McGee (1893) observed that the trunks of trees 200 or more years old were inclined from base to top. The trunks of trees 100 to 150 years old were inclined, and the upper parts of the trees were vertical. Finally, undisturbed, vertical trees, 70 or 75 years in age, established a minimum age for the landslide movement. In 1904, Fuller (1912) studied the ages of upright and tilted trees on landslides caused by the New Madrid earthquakes along the bluffs of the Mississippi River. He determined that "...the greater part of the upright growth on the disturbed surfaces [landslides] is fairly uniform and a little less than 100 years of age, trees of greater age being in general tilted and partly overthrown."

A more complex analysis of landslide movement involves the interpretation of the tree rings in disturbed trees. Shroder (1978) was able to use tree-ring analysis to date recurrent movement on a rock-glacier-like deposit on the Table Cliffs Plateau in Utah. Reeder (1979) used tree-ring analysis to date movement of landslides in the Anchorage, Alaska, area and was able to correlate these movements with earthquakes in the region. Jensen (1983) was able to date episodic landslide movement in the upper Gros Ventre landslide of Wyoming by tree-ring analysis. Hupp and others (1987) used tree-ring analysis to determine the magnitude and frequency of debris flows in many of the drainages of Mount Shasta, California. Williams and others (1992) investigated four landslides in the Seattle area—using tree-ring analysis, they were able to demonstrate that the four landslides were probably of the same age and, hence, were seismically induced. Fleming and Johnson (1994) used the tree-ring record of several trees on a landslide in the Cincinnati, Ohio, area to date movement to 1958, following near-record precipitation in 1957.

In the above-cited studies, several kinds of tree-ring anomalies were observed. The most common anomaly observed was an abrupt reduction in annual-ring width either for several years or an extended period (fig. 4). Other anomalies include, (1) discontinuous or missing rings due to severe damage, (2) the formation of reaction wood on the underside of tilted conifers, (3) scars, formed by the impact of the tree by an object, such as a dislodged boulder or falling tree, and (4) an abrupt increase in annual-ring width due to an improvement in environment, such as an increase in sunlight because surrounding trees were felled by landslide movement.

Methods

Thirteen live, tilted Douglas fir trees were sampled at three sites near Tower Falls at the southeastern end of the landslide block (fig. 1) near the section of road known to be subsiding (C.S. Dewey, oral commun., 2001). Sites 1 and 2 are in the area above the “Overhanging Cliff,” site 3 is at the Calcite Springs overlook. Because all these trees are tilted, landslide movement likely occurred within the lifetime of the trees. In addition, attempts were made to sample several of the standing, tilted dead trees at the sites with the goal of obtaining a longer record. However, the interiors of these trees were rotten, and no cores were recovered. In order to establish a minimum age for the landslide movement, 10 young, upright, undisturbed Douglas fir trees were also sampled near sites 1 and 2. Finally, three Douglas firs were sampled northwest of Rainy Lake, about 2 km northwest of the section of subsiding road and that section of the landslide near Tower Falls thought to have been subjected to the latest movement (fig. 1).

Many of the Douglas firs were sampled in July 1999, with a 40-cm-long, 5-mm-diameter increment borer (an increment borer is a hand tool with a hollow drill bit that is screwed into a tree and allows the removal of a thin cylinder of wood from the tree with minimal damage). Because of the large diameters of some of the trees, the 40-cm bit did not penetrate the tree deep enough to include the pith. Therefore, several trees were cored again in August 2000 with a 50-cm-long increment borer. For the larger tilted trees, two cores were taken, one on the upper side of the tree, the other on the lower side. For smaller, younger, upright Douglas firs, two opposing radii were collected.

Figure 3. Photograph of tilted Douglas fir trees at the Calcite Springs overlook (site 3). Tree on right is about 16 m in height.

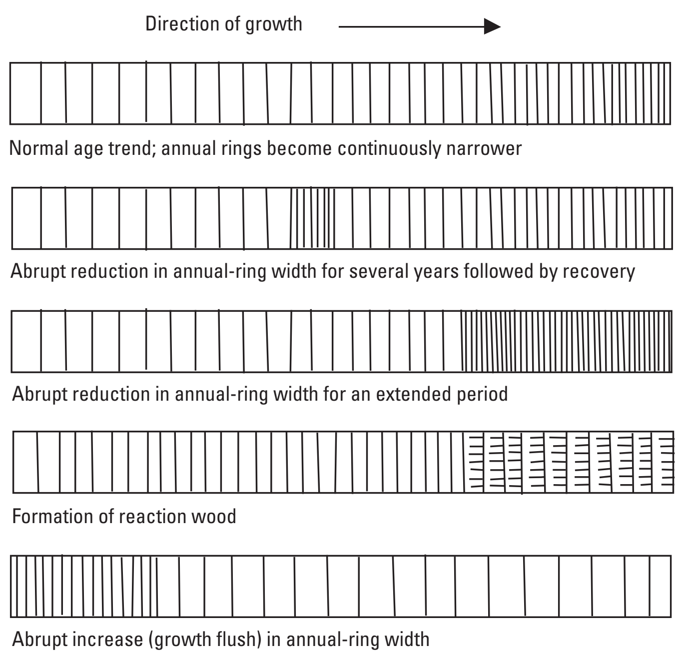

Figure 4. Drawing showing the type of reactions in the tree-ring record to physical damage (after Kienast and Schweingruber, 1986).

Table 1. Response in tree-ring record of Douglas fir trees in the Tower Falls area of Yellowstone National Park to the proposed 1693 or 1694 A.D. landslide event.

[M, missing ring; NR, narrow ring(s), less than 50 percent the width of the 1693 A.D. annual ring; --- , tree-ring sequence in core does not extend back to 1694 A.D.]

	Tree no./ core / year collected	Innermost ring in core (A.D.)	Estimated year (A.D.) tree germinated	Diameter (cm)	Angle of tilt (degrees)	Response to 1693 or 1694 A.D. event
Site 1	1/A/99	1799	1500	130	8	---
	1/B/99	1732				---
	1/A/00	1717				---
	1/B/00	1648				NR 1694-1700
	2/A/99	1800?	1620	72	32	---
	2/B/99	1692				M 1694, NR 1695-1701
	2/N/00	1641				M 1694, NR 1695-1709
	3/A/99	1612	1590	89	47	M 1694, NR 1695-1701
	3/B/99	1760				---
	3/B/00	1684				M 1694, NR 1695-98
	4/N/99*	1875	?	81	25	---
Site 2	6/A/99	1663	1620	86	20	NR 1694-98
	6/B/99	1667				NR 1694-95
	7/A/99	1669	1630	95	20	NR 1694-97
	7/B/99	1676				NR 1694-97
	8/A/99	1776	1620	69	18	---
	8/B/99	1650				NR 1694-98
	8/N/00	1653				NR 1694-96
	9/A/99	1646	1610	84	14	NR 1694-97
	9/N/00	1663				NR 1694-98
Site 3	16/A/99	1641	1610	60	32	NR 1694-97
	16/B/99	1652				NR1694-98
	17/A/99	1636	1590	62	32	NR 1694-98
	17/B/99	1610				NR 1694-98
	24/N/00*	1780	?	61	25	---
	25/B/00	1696	1570	73	10	---
	25/E/00	1615				NR 1694-1701
	27/A/00	1625	1590	103	21	NR 1694-97
	27/B/00	1664				NR 1694-97
	27/S/00	1630				NR 1694-97

* Cores from trees 4 and 24 are only partial cores because these trees had heart rot.

The cores were prepared using standard procedures as discussed in Stokes and Smiley (1968). In the field, the cores were placed in soda straws. Upon return to the laboratory the cores were placed in grooved, redwood drying boxes that allow the cores to dry with minimal twisting and curling. The cores were left in these boxes for several weeks to dry completely. The cores were then glued into a semicircular groove in a small board and sanded with progressively finer grits to a fine finish (600 grit). Finally, the cores were rubbed to a high polish with fine steel wool.

The polished cores were then inspected under a binocular microscope (6, 12, and 25×) for signs of disturbance in their tree-ring records. One year was assigned to each ring counted. In temperate regions a tree will add (grow) one ring every year. The annual ring consists of two parts, earlywood and latewood. Earlywood is produced in the early part of the growing season and is characterized by large, porous, thin-walled cells. Latewood is produced in the latter part of the growing season and is characterized by small, thick-walled cells that commonly have a darker color than earlywood cells (Panshin and de Zeeuw, 1970). It is the sharp contrast between the last-formed latewood cells of one year and the first-formed earlywood cells of the following season that distinguishes the boundary of the annual ring.

False annual rings were also noted in several cores and result from a cold period during a growing season. False annual rings can be distinguished from true annual rings because cells composing the latewood in false annual rings grade to the inside and outside into more porous tissue. In true annual rings the transition from the latewood of one year to the earlywood of the next year is abrupt (Panshin and de Zeeuw, 1970).

Types of Disturbance in the Tower Falls Tree-Ring Record

In this study, two signs of disturbance in the tree-ring record were detected in the tilted trees that were sampled. Most commonly the trees displayed an abrupt reduction in annual-ring width for several years (fig. 4). In addition, at the time when the tree-ring record of most trees began an abrupt reduction in annual-ring width, two trees did not form an annual ring (missing ring). Reaction wood (commonly formed on the underside of tilted conifers) and scars (formed by the impact of an object, such as a dislodged boulder) are readily recognizable in cross sections, they are difficult to identify in cores. I looked for evidence of reaction wood and scars in the cores collected for this study, but none were detected. This is due in part because the core samples show only a very small part of each annual ring, as compared to cross sections, which display the entire circumference of each ring.

A reduction in annual-ring width for several years or more can be the result of injury due to a geomorphic event, such as a landslide or earthquake (Shroder, 1978; Meisling and Sieh, 1980). Damage to the root system, loss of a major limb, or topping can all result in an abrupt reduction in annual-ring width. Therefore, at the study sites, the initial year of decreased growth (table 1) provides an estimate of the date of landslide movement. Movement could have taken place between the end of the previous growing season and during the growing season of the year in which the first narrow ring is produced.

Missing annual rings can result when a tree is severely damaged by landslide movement (Shroder, 1978). These damaged trees may not form annual rings in a given year or period of years (Panshin and de Zeeuw, 1970). In this study, the presence of missing annual rings (table 1) was detected by cross-dating (recognition of commonly shared distinctive annual rings of known age) with nearby trees. Particularly distinctive narrow annual rings that were useful for cross-dating are: 1646, 1656, 1678, 1708, 1712, 1717–18, 1721–22, 1748, 1752, 1800, 1834, 1846, 1848, 1865, 1872, 1891, 1901, 1919, 1934, and 1936 A.D.

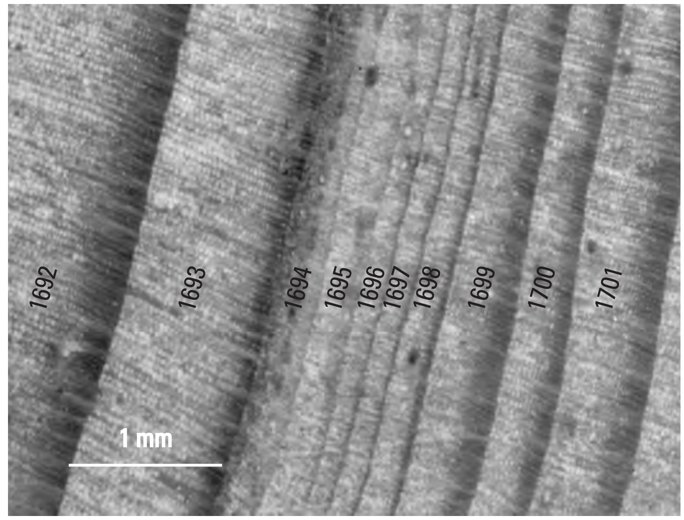

Figure 5. Photograph of core from tree 6 showing an abrupt reduction in annual-ring width beginning in 1694 A.D.

The Tower Falls Tree-Ring Record

Of the 10, upright, undisturbed trees cored in this study, the oldest had 120 annual rings and the pith was present in the core. Because the tree was cored at chest height (about 125 cm), an additional 15 years was added to the ring count to account for the years it took the tree to grow to this height. Thus, the age of the tree is estimated to be about 135 years. This age provides a minimum date for the latest movement of this section of the landslide, indicating that the movement occurred prior to 135 years ago (1865 A.D.). However, this age is probably a minimum by a number of years. The younger, upright, undisturbed trees were found in forested areas that are subject to occasional forest fires, such as those that swept through much of Yellowstone National Park during the summer of 1988. In contrast, the older, tilted trees were in more open areas with greater distances between trees and, hence, were less susceptible to forest fires.

The youngest of the 13 old, tilted trees is estimated to have germinated in the early 1600s (table 1). The years of germination of the tilted trees presented in table 1 are estimates for two reasons. First, because the pith was not present in the majority of cores collected, the number of missing annual rings between the end of the core and pith was estimated based on the curvature of the annual rings near the end of the core (Applequist, 1958). Secondly, because the trees were cored at chest height (about 125 cm), an additional 15 years was added to account for those years the tree took to grow to the sampling height. The youngest of the older, tilted trees date from the early 1600s—this establishes a maximum age for the landslide movement.

Inspection of the tree-ring record of the larger, older, tilted Douglas firs (13 trees) between 1600 and 1865 A.D. for which the recovered core included the late 1600s (11

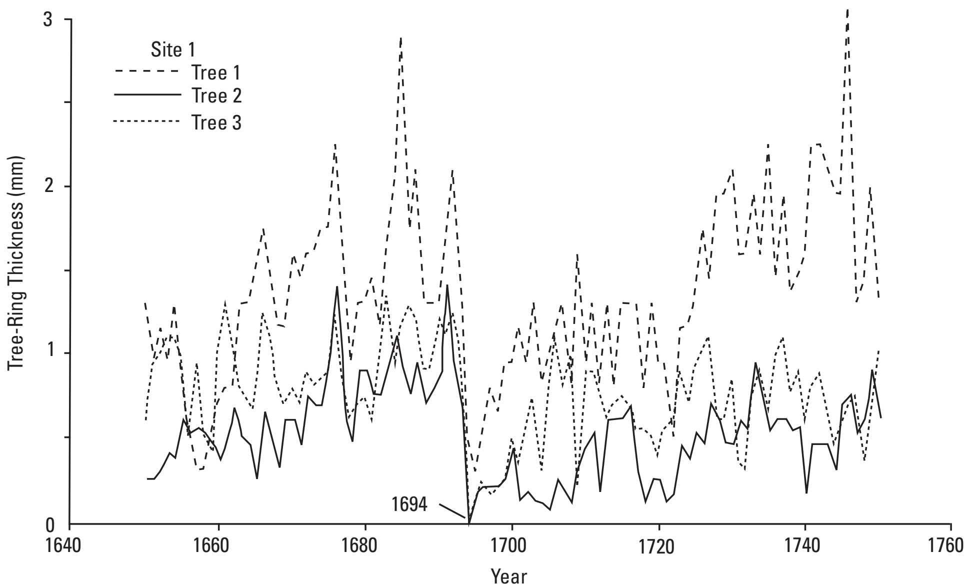

Figure 6*A*. Plot of tree-ring widths from 1650 to 1750 A.D. from trees at site 1, showing abrupt reduction in annual-ring width beginning in 1694 A.D.

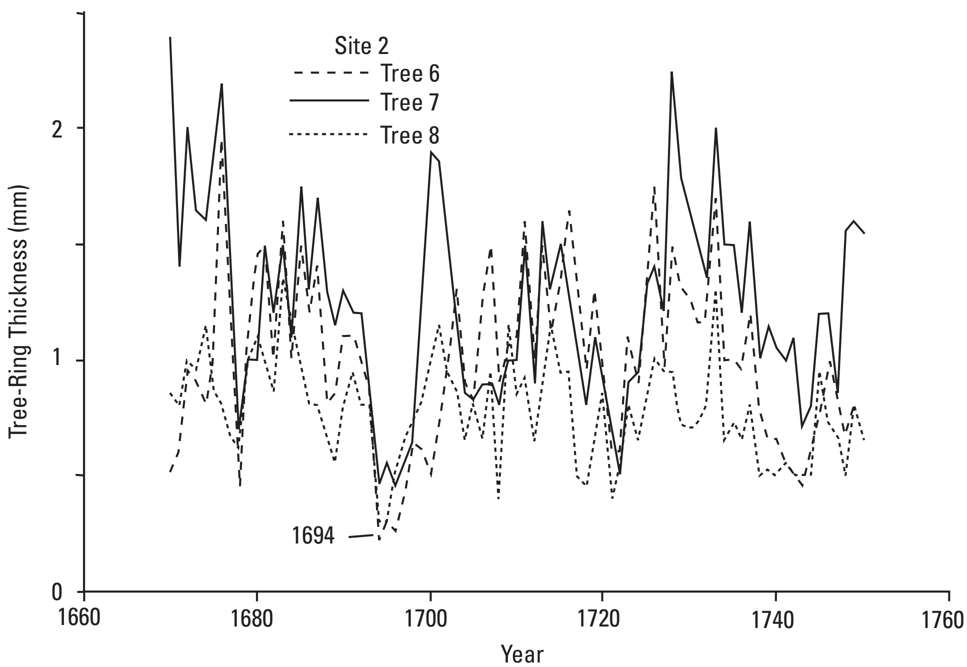

Figure 6*B*. Plot of tree-ring widths from 1650 to 1750 A.D. from trees at site 2, showing abrupt reduction in annual-ring width beginning in 1694 A.D.

trees), revealed an abrupt reduction (greater than 50 percent) in annual-ring width beginning in 1694 A.D (figs. 5, 6*A*, 6*B* and 6*C*; table 1). Because no other period in the tree-ring record revealed such a dramatic reduction in annual-ring width, the landslide movement is thought to have occurred after the growing season in 1693 or during the growing season of 1694 A.D.

The tree-ring response in nine of the sampled trees to the 1693 or 1694 A.D. event consisted of the formation of narrow annual rings beginning in 1694 A.D. and continuing for 2 to 8 years (table 1). However, the response of the trees was not necessarily uniform along opposing radii. Tree 6 produced narrow annual rings from 1694 to 1695 A.D. along one radius and narrow annual rings from 1694 to 1698 A.D. along the opposing radius.

Missing annual rings were noted in two trees (2 and 3) in which the 1694 A.D. annual ring was not formed (table 1). These trees began to form narrow annual rings in 1695 A.D. and continued to produce narrow annual rings for several years to as many as 15 years. For instance, in tree 2, two radii, whose record included the late 1690s, are missing the 1694 A.D. annual ring. Beginning in 1695, one radius formed a series of narrow annual rings until 1701 A.D., whereas the other radius produced a series of narrow annual rings until 1709 A.D. (table 1).

The abrupt reduction in annual-ring width in 1694 A.D. is thought to have been caused by landslide movement and not by climatic variations for several reasons. The reduction in annual-ring width beginning in 1694 A.D. displayed by the tilted Douglas firs sampled in this study is not reflected in a

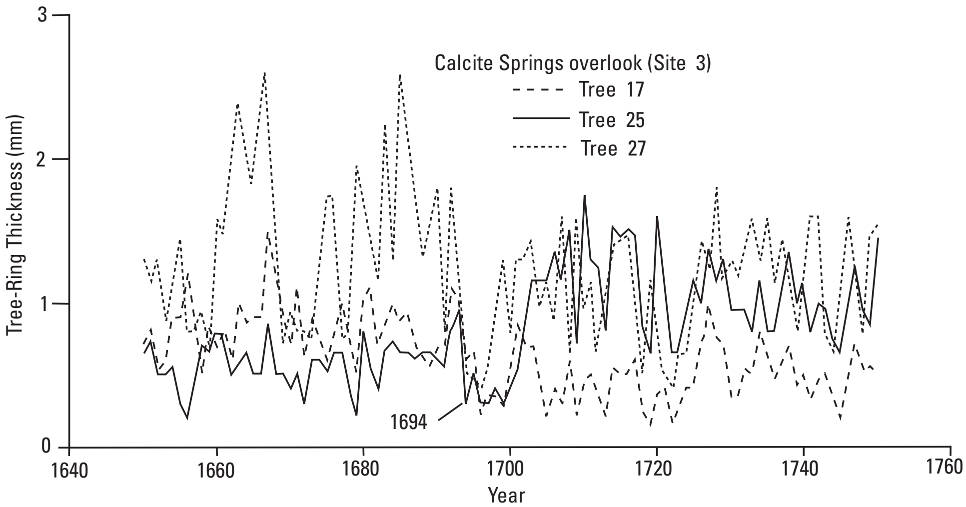

Figure 6*C*. Plot of tree-ring widths from 1650 to 1750 A.D. from trees at the Calcite Springs overlook (site 3), showing abrupt reduction in annual-ring width beginning in 1694 A.D.

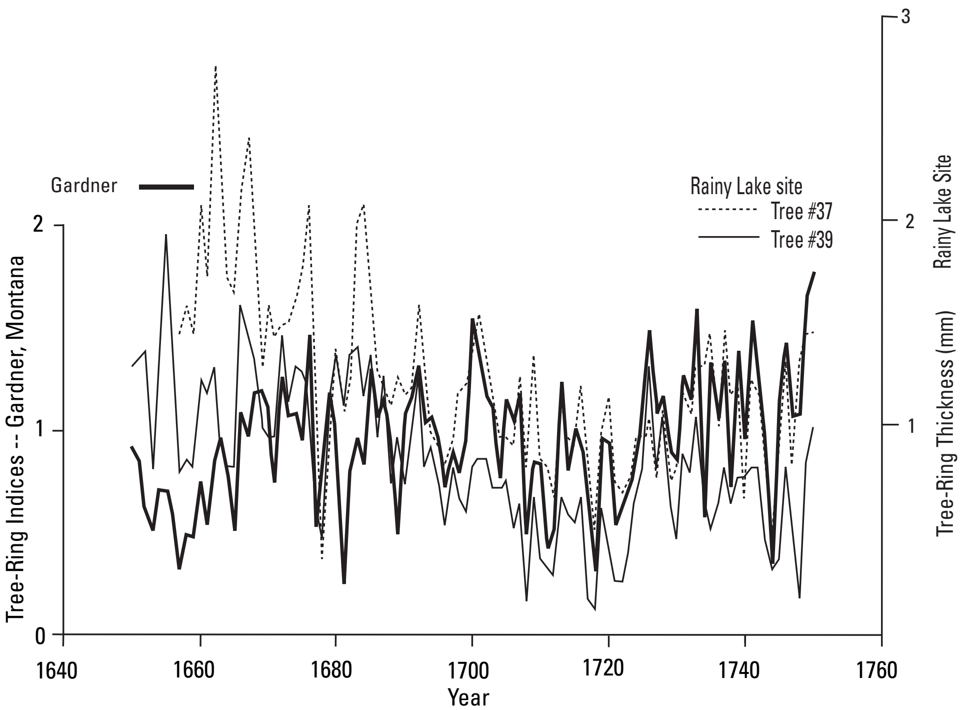

Figure 7. Plot of tree-ring indices of Douglas fir near Gardner, Mont. (after Drew, 1975), and plot of tree-ring widths from 1650 to 1750 A.D. from trees at the Rainy Lake site. Note the absence of narrow rings at 1694 A.D., as would be expected in trees unaffected by the landslide movement of 1693 or 1694 A.D.

500-year tree-ring chronology of Douglas firs at a site near Gardner, Mont. (fig. 7) (Drew, 1975), about 30 km northwest of the Tower Falls area, or in the ring widths of trees sampled at the Rainy Lake site (fig. 7), about 2 km north of the Calcite Springs overlook, or in whitebark pines (*Pinus albicaulis*) at a site near Dunraven Pass, approximately 10 km to the south of the study sites (John King, oral commun., 1999). If the 1694 A.D. response in the tree-ring record were climatically induced, it should be present over a broad area, including these other sites.

In addition, the response of the trees to the 1693 or 1694 A.D. event is typical of trees subject to physical damage and is not a typical climatic signature. Trees in a given area that exhibit a reduction in annual-ring widths caused by climatic factors have a more uniform response; hence, they generally recover at about the same year, and the climatic response is present over a broad region (Jacoby and others, 1988)—in this case, away from the landslide. Growth-rate reductions caused by physical damage may last from as little as 1 year to more than 20 years and may contain many missing rings (Shroder, 1978; Carrara, 1979). In this study, the tree-ring response to the 1693 or 1694 A.D. event lasted from as little as 2 years to as many as 16 years. In addition, prolonged growth suppression usually cannot be attributed to drought, which generally causes acute, diminished annual-ring growth for a single year (Jacoby and others, 1988).

The abrupt reduction in annual-ring width in 1694 A.D. could be caused by other factors, such as insect infestation or fire, but this seems unlikely. The sampled trees are clearly tilted, an effect not associated with either insect infestation or fire. Furthermore, the Douglas firs at the nearby Rainy Lake site do not display the marked reduction in annual-ring width beginning in 1694 A.D. (fig. 7). If the 1694 A.D. response in the tree-ring record were caused by an insect infestation, it should be present over a broader region, similar to a climatic effect and would include the Rainy Lake site. In addition, no evidence of charred wood or fire scars was found in the sampled trees. Finally, the fact that the tilted trees are growing on a landslide block is also strong evidence for landslide-induced damage.

Was the Landslide Movement Triggered by an Earthquake?

The Yellowstone region is within the Intermountain seismic belt, a zone of pronounced seismic activity, that extends north from southern Nevada through northwestern Arizona, Utah, eastern Idaho, western Wyoming, and northwestern Montana (Smith and Sbar, 1974; Stickney and Bartholomew, 1987). The largest historic earthquake (magnitude 7.5) ever recorded in the Intermountain seismic belt occurred in the Yellowstone region during the night of August 17, 1959 (Doser, 1985). This earthquake, centered in the Hebgen Lake area of southwestern Montana, about 70 km west of the study area, was felt throughout an area of 1,500,000 km^2 (Witkind and Stickney, 1987) and caused considerable damage. Near Hebgen Lake, it released a large rockslide that overran a campground and killed 26 people, burying them under 21 million m^3 of debris (Witkind and Stickney, 1987). Other landslides in the Yellowstone region could have been caused by large prehistoric earthquakes. Was initial failure of the large landslide block triggered by an earthquake, and was latest movement of the section in the Tower Falls area in 1693 or 1694 A.D. earthquake induced? Because of the pronounced seismic activity in this region one or both hypotheses are possible.

Limitations of Tree-Ring Analyses

Several limitations of the detection of landslide events by tree-ring analyses became apparent in this study. First, in order for the event to be recorded in the tree-ring record, the event must be large enough to damage the trees, such as by topping, tilting, impact, or root breakage.

Secondly, the age of the trees themselves may be a limitation. Although ages of Douglas firs can exceed 1,000 years (Brown, 1996), the oldest tree in this study (tree 17) had an innermost ring date of 1610, and only four trees had records extending back prior to 1640 (table 1). Hence, information concerning landslide movements could only be extended back to about 1650 A.D. However, it should be noted that no significant disturbance other than that of the 1693 or 1694 A.D. event is recorded in the tree-ring record of the Tower Falls Douglas firs at the three sites investigated in this study.

In addition, damage to trees by landslides and other events, such as earthquakes and snow avalanches, may cause an additional limitation on the age of the trees. Damaged trees may not recover at all or be so slow to recover that they may be at a competitive disadvantage with other nearby trees that sustained little or no damage. This disadvantage may in time lead to an earlier-than-normal death. Thus, several decades after an event, those trees that suffered the most damage—and hence have the best evidence of the event in their tree-ring record—are no longer alive.

At a site in the Gravelly Range, about 100 km west of the study area, 11 Douglas firs, including one standing dead tree, were sampled for information concerning the relation between landslide movement and earthquake events (O'Neill and others, 1994; Carrara and O'Neill, 2003). Only the dead tree showed significant tree-ring evidence of a 1926 landslide movement believed to be related to the 1925 Clarkson, Mont., earthquake (magnitude 6.75), about 175 km northwest of Tower Falls. None of the live trees showed any evidence of this event. The dead tree was heavily damaged and tilted by landslide movement and formed wide annual rings of reaction wood for several years before entering a period of reduced growth rate (narrow annual rings). The tree died in 1932 A.D., yet it remained standing for 60+ years before it was cross-sectioned for analysis. Hence, it may be worthwhile to sample dead trees at a given site and cross-date them with live trees at the same site.

Finally, another limitation of tree-ring analysis is that, while a tree is recovering from damage sustained by one landslide event and forming very narrow annual rings, it may be hard to detect a subsequent landslide event. For example, in this study, the response of tree 2 along one radius lasted from 1694 to 1709 A.D.; this tree is missing the annual ring for 1694 A.D. and shows a marked reduction in annual-ring width from 1695 to 1709 A.D. (table 1). Subsequent landslide events, if they had occurred during the 1694 to 1709 A.D. period, would not have been detectable in this tree-ring sequence because this tree was already forming very narrow annual rings.

Conclusions

The majority of the large, tilted Douglas fir sampled in this study on the section of landslide block near Tower Falls recorded an abrupt reduction in annual-ring width that began in 1694 A.D and lasted for 2 to 16 years. This reduction in annual-ring width is interpreted to indicate the latest movement of the landslide sometime between the end of the 1693 A.D. growing season and during the 1694 A.D. growing season. This interpretation is based on several factors.
(1) The age of the oldest upright, undisturbed tree indicates

that the latest landslide movement occurred prior to 1865 A.D. (2) The age of the youngest, tilted, disturbed tree indicates that this landslide movement occurred after the early 1600s. (3) The most severe and long-lasting reduction in annual-ring width between 1600 and 1865 A.D. began in 1694 A.D. (4) A tree-ring chronology of Douglas fir at a site near Gardner, Mont. (Drew, 1975), about 30 km northwest of the Tower Falls area, as well as trees at two other nearby sites, do not display any significant climate-related reduction in annual-ring width during the 1690s A.D. Because the Yellowstone region is in a seismically active zone, it is possible that an earthquake triggered this landslide movement.

Although the use of tree-ring analysis to date various geologic events or processes has its limitations, the method can be a valuable tool to date events in regions lacking long historical records. In this study, ages of the trees sampled provided information concerning possible landslide movement back to about 1650 A.D. No disturbance other than that of the 1693 or 1694 A.D. event is recorded in the tree-ring record of the Tower Falls Douglas firs. These results suggest that the approach used in this study could be applied to paleolandslide and paleoseismological investigations in forested regions throughout the Rocky Mountain region.

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