Application of tree-ring analysis to paleoseismology: Two case studies

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ABSTRACT

Knowledge of earthquake probabilities is essential for planning earthquake hazard mitigation, and valid estimation of future probabilities requires precise information on past earthquake occurrences. Previous studies documented effects of earthquakes on trees and how these effects are recorded by tree rings. Tree-ring analysis can be combined with other disciplines to date and delineate earthquake-induced disturbance. Two case studies show the impact of the 1964 Alaska earthquake on shoreline trees and how a previously unknown southern San Andreas fault earthquake was recorded in tree rings.

INTRODUCTION

Seismological Background

In the past century North America has experienced several earthquakes that have been disastrous to life and property. Is a large ($M_W \geq 7.0$) (Sykes, 1971) earthquake likely in the near future? This question is especially germane in seismic gap areas, or fault segments with historic seismic activity but without a rupture for tens to hundreds of years (Sykes and Quittmeyer, 1981). Answers can help in selecting regions for intensive study (Kelleher et al., 1973) and also aid communities in earthquake preparedness planning.

Whereas short-term forecasting relies on recognition of earthquake precursors, long-range forecasting relies on the concept that earthquakes are cyclic relaxations in a continuous tectonic loading-release process (Scholz, 1985). Assuming uniform strain accumulation (Savage and Burford, 1973) and "characteristic" fault behavior (Schwartz et al., 1982), large earthquakes should occur nonrandomly along tectonic plate margins (Sykes, 1971). Knowledge of repeat time (period between large ruptures of a fault segment [Sykes and Quittmeyer, 1981]) is crucial for assessing seismic potential—the chance that a seismic gap will experience a large earthquake in the next few decades (Kelleher et al., 1973). Additionally, because repeat time is related to segment length (and displacement), delineation of ruptures would facilitate application of time-predictable models (Sykes and Quittmeyer, 1981).

Information about large earthquakes of the past few centuries or millenia has been gleaned from archival records (Louderback, 1947; Agnew and Sieh, 1978; Toppozada et al., 1981) and from ^{14}C dating of structural features in recent sedimentary layers along fault zones (Sieh, 1978a, 1978b, 1984; Davis, 1983; Sieh and Jahns, 1984). Unfortunately, precision of some stratigraphic ^{14}C dates can be poor relative to average recurrence intervals (Sieh, 1984). Given uncertainty about rupture dates and lengths and interval uniformity, Sykes and Nishenko (1984) urged focusing of attention on better dating and definition of prehistoric ruptures.

Dendroseismological Background

Many North American tree-ring records extend back 500 yr (Drew, 1972, 1975; Stokes et al., 1973; Dewitt and Ames, 1978; Stahle et al., 1985; our own collections), and therefore may potentially extend precisely dated records of major earthquakes beyond cultural records. Tree-ring analysis can reveal the year, or even season within a year (Page, 1970), of growth disturbance. Alestalo (1971) defined dendrogeomorphology as the application of plant ecology and tree-ring dating to geomorphological research. Shroder (1980) introduced the event-response concept, recognizing that many geomorphic processes cause various tree-growth responses (Table 1).

Fuller (1912) noted accounts of trees splitting apart during the 1811 New Madrid, Missouri, earthquake. Louderback (1947) quoted a witness of an "1839" California earthquake that redwoods "rocked like lake-side reeds"; Louderback determined this event to be the 1838 San Francisco Bay area earthquake. Louderback quoted a geologist: "limbs snapped off, trees uprooted, and the forest looked as though a swath had been cut through it two hundred feet in width" in the 1906 San Francisco quake. Lawson (1908) also described trees swaying violently, snapping off limbs and tops, or becoming uprooted and thrown to the ground in 1906. Effects of shaking of trees are criteria of the modified Mercalli intensity scale (Wood and Neumann, 1931): trees are shaken lightly at intensity V, moderately at VI, and strongly at VII. Branches and trunks may be broken off during intensity VIII+ quakes.

Direct Response of Trees to Large Earthquakes. Intermittent fault slippage can generate a variety of surface structural features, including displacement along a distinct fault trace, a zone of distributed shear, fresh scarp faces, offset streams or other linear features, sag ponds, and mole tracks (Bolt, 1978). Trees located within these features could be directly disturbed by large earthquakes and subsequently show growth change.

TABLE 1. TREES AS INDICATORS OF PHYSICAL SITE DAMAGE

Change in trees*	Physical change	Possible cause
Tree growth initiated (date of first ring)	barren surface stabilized or newly available	uplift, change in base level, landslide, or other catastophic event
Tree growth terminated (date of terminal ring)	surface covered	rapid sedimentation, landslide, or other catastrophic event
	surface inundated	subsidence, tsunami
Physical damage (narrow rings)	top, major limb, trunk, or root system broken	violent shaking and/or local earth movement
Growth rate change		
Increase (wider rings)	improved growth environment, nutrient supply, or site hydrology	change of site into more favorable or protected zone
Decrease (narrower rings)	poorer growth environment, nutrient supply, or site hydrology	change of site into less favorable or more exposed zone
Onset of reaction wood†	ground surface tilted or tree pushed over	landslide, fault-block tilting
Chemical changes		
Minor elements	changes in site hydrology, nutrient supply, exotic contaminants	modification of water table or shift of site with respect to chemical regime
Stable isotopes	change in proportion of ground water to surface water	change in water table due to earth movement

* Some of these changes can be caused by biological, climatic, or other factors that must be considered when making interpretations. Accurate dating and sampling from a number of appropriate locations are the means to confirm interpretations.

† Reaction wood is defined here to mean the geotropic (gravity-growth controlled) response by an inclined tree to regain its vertical stance and strengthen its lower trunk (Low, 1964; Scurfield, 1973; Shroder, 1980).

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There may also be coseismic landsliding, slumping, or other surficial or shallow subsurficial disturbances that directly affect trees.

Meisling and Sieh (1980) reported conifers located on the southern San Andreas fault that lost their crowns during the January 1857 Ft. Tejon quake; ring widths were reduced beginning in 1857 and took many years to return to pre-earthquake growth rates. Wallace and LaMarche (1979) found coast redwoods (*Sequoia sempervirens* [D. Don] Endl.) and Douglas-firs (*Pseudotsuga menziesii* [Mirb.] Franco) that were tilted by the 1906 quake and responded with reaction wood beginning in 1907. Page (1970) noted tilting, felling, and topping of trees (one of which showed decreased growth beginning in 1959) resulting from the July 1958 Fairweather, Alaska, rupture.

Indirect Response of Trees to Large Earthquakes. Trees may also respond indirectly to coseismic environmental changes, with a possible one- or two-year delay due to biological factors. Fuller (1912) noted trees that died from flooding caused by general topographic reversals resulting from the New Madrid earthquake. Page (1970) reported increased growth in western hemlocks (*Tsuga heterophylla* [Raf.] Sarg.) growing near the swath of damaged trees on the Fairweather fault. These hemlocks responded favorably to increased light resulting from felling of on-fault trees. Jacoby and Ulan (1983) showed Sitka spruces (*Picea sitchensis* [Bong.] Carr.) with increased growth after the September 1899 Alaska earthquakes. These spruces were growing close to a wave-cut shoreline prior to 1899, but coseismic uplifting moved the shoreline away from them. In their new position (less exposed to wind, salt spray, and root-zone erosion), they gradually responded with increased growth.

APPLYING TREE-RING ANALYSIS TO PALEOSEISMOLOGY

The principle is to analyze growth rings from geomorphically disturbed trees as well as from nearby undisturbed trees (Alestalo, 1971). The concept of a control, to which disturbed trees are compared, is paramount. Dating a specific geomorphic event requires eliminating all other causal factors (Page, 1970). For example, even though tree rings document the 1857 Ft. Tejon earthquake (Meisling and Sieh, 1980), San Diego meteorological data and other tree-ring evidence (Drew, 1972; Meko et al., 1980) indicate an extreme drought that same year throughout southern California. In such cases the earthquake response (an extended period of recovery) must be differentiated from the drought response (narrow rings for only the drought years).

Only trees whose growth is clearly affected by a specific event should be considered as event-response trees (Shroder and Butler, 1987). Trees are sampled on the basis of age, size, and topographic and geologic setting, all indicating likelihood of seismic disturbance (Butler et al., 1987). Proximity to a fault is crucial: whereas dip-slip faulting results in wide disturbance zones, strike-slip faulting disturbance is restricted to a few metres from the fault (Bolt, 1978). Nondestructive increment cores are taken from each tree with hand-driven (Phipps, 1985) or power-driven corers (Johanson, 1987). Multiple cores are essential because of circuit nonuniformity of tree-ring growth and possible differential response around the stem. If allowable, cross sections provide the most ring-width information.

Analysis begins by cross-dating, whereby ring-width patterns are matched across different trees and all rings are assigned exact year dates (Stokes and Smiley, 1968). Cross-dating is essential in order to account for growth anomalies (missing or false rings), which are common to many temperate-region tree species. For quality control, each cross-dated core is measured (nearest 0.01 mm) and then computer-checked with Program COFECHA (Holmes, 1983), which standardizes and cross-correlates each series with the average of all others. Correctly dated cores are confirmed by strong positive correlation.

After cross-dating and checking, ring-width patterns are examined for disturbance. To avoid an irrelevant event response, where a growth response is caused by something other than the hypothesized geomorphic process (Shroder, 1978), the response should occur synchronously in at least two separate trees. Ring-width series from undisturbed trees are combined into a site- and species-specific control chronology. Measured series are converted into series of dimensionless indices (Graybill, 1982; Cook, 1985), which are merged into a single mean-value time series. Ring-width plots from disturbed trees are then compared to the control chronology to determine events of severe growth change. Dendroclimatic analysis of the control chronology with pertinent meteorological data (Fritts, 1976) helps differentiate between climatic and seismic disturbance responses.

TWO CASE STUDIES

Cape Suckling, Alaska

Cape Suckling, Alaska (lat 60°00′N; long 143°54′W), is located 240 km from the March 1964 earthquake epicenter. In addition to seismic shaking, Cape Suckling was uplifted approximately 4 m (Plafker, 1972).

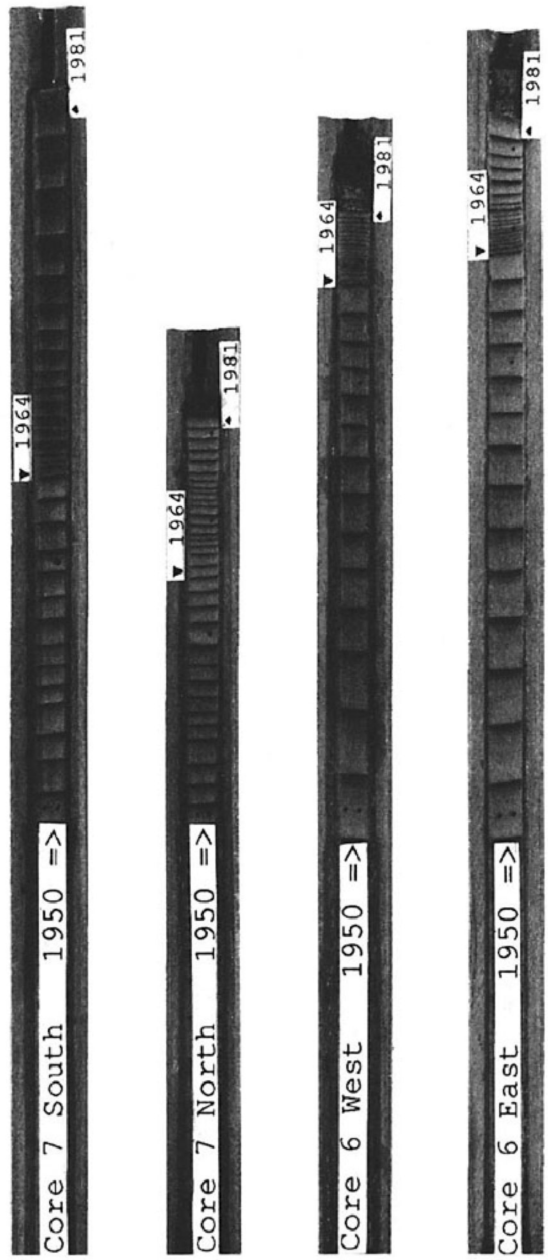

Figure 1. Cores from two disturbed trees from Cape Suckling. Notice sharp growth reduction in all but Core 7 North, plus reaction wood (darker rings) after 1964 in Core 7 South. North-facing cores showed some growth reduction in 1964, but much less than did south-facing cores.

Sitka spruces growing on the seaward margin of the raised beach edge were tilted slightly southward, and a few had roots exposed; these were cored (mostly on the north-south axis) in order to ascertain an earthquake response. In addition, spruces from nearby Suckling Hills were cored for the control chronology.

All samples were cross-dated, measured, and checked, and a control chronology was constructed from undisturbed trees, to which ring-width plots of disturbed trees were compared. South-aspect cores (toward the beach) of disturbed trees showed sharp growth reductions in 1964 followed by reaction wood growth (Figs. 1 and 2). North-facing cores appeared less disturbed, illustrating differential response around the stem. One tree was sampled on the east-west axis and both cores recorded disturbance.

Trees on the seaward edge of the beach ridge were apparently shaken and tilted by the earthquake. After an initial growth reduction, they responded with wider rings of reaction wood on their south sides in order to regain upright positions. Control trees also showed a growth reduction in the late 1960s and early 1970s (Fig. 3, top), but this began in 1965. The chronology corresponds significantly (correlation $r = +0.595$, $\alpha = 0.004$ for the period 1945 to 1977) with current-year January-February temperatures, which were below average beginning in 1965 (National Weather Service meteorological data from Cordova, Alaska). Cropper and Fritts (1981) found a similar relation between winter temperature and tree growth in coastal Alaska.

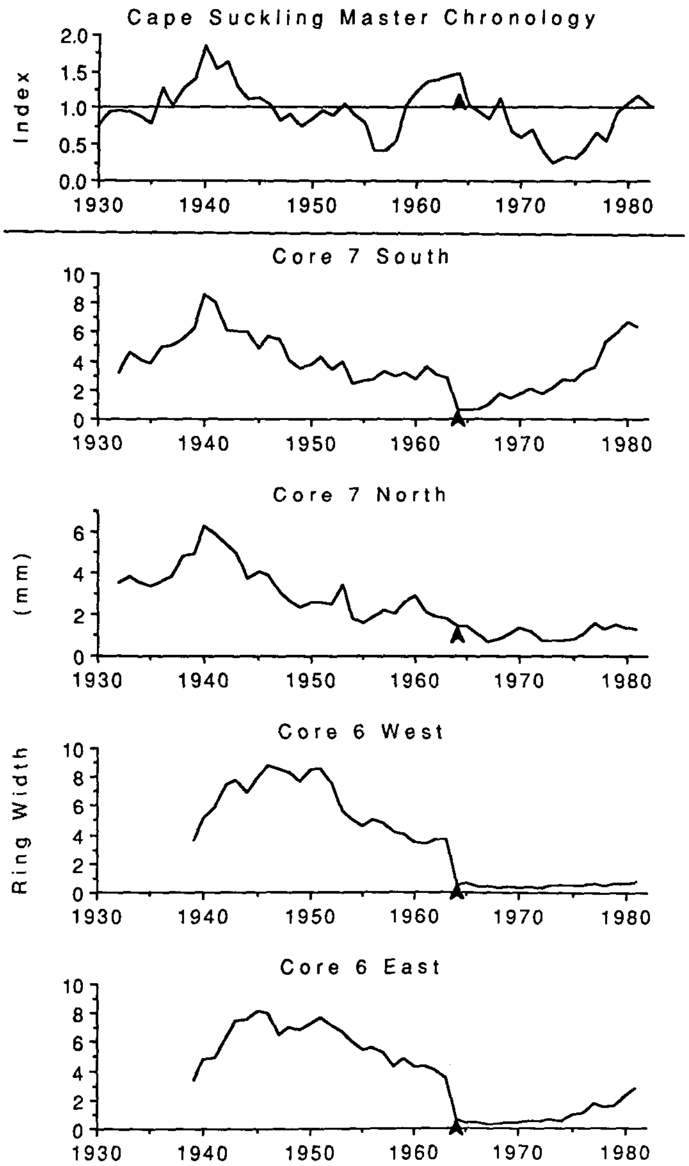

Figure 2. Time-series plots of Cape Suckling master chronology (top) and ring-width series from cores of Figure 2. Arrows point to 1964 values. Growth reduction apparent in chronology begins in 1965 and is attributable to below-average winter temperatures.

Wrightwood, California

An important application of the time-predictable model is estimating the occurrence of the next great earthquake on the southern San Andreas fault (Sykes and Quittmeyer, 1981), which crosses forested areas. This seismic gap appears to be mature (Raleigh et al., 1982), and whether the average interval between great shocks is as short as 100 yr or as long as 200 to 300 yr affects earthquake hazard assessment (Sykes and Quittmeyer, 1981).

Conifer tree-ring samples were collected within or near Wrightwood, California (lat 34°23′N; long 117°26′W). The San Andreas trace was located by using a U.S. Geological Survey fault-zone map (Ross, 1969) and by identifying geomorphic fault features. Trees growing both on and away from the fault trace were sampled. All samples were cross-dated, measured, and checked, and undisturbed samples were merged into a control chronology, to which ring-width plots from disturbed trees were compared.

Two on-fault trees (located 5 km from each other) recorded drastic growth reductions beginning in 1813, and each took tens of years returning to predisturbance growth rates (Fig. 3); both trees lost their crowns at some point. In addition, seven other on-fault trees recorded growth reductions beginning in 1813 (Jacoby et al., 1988). Because nine synchronously disturbed trees were located on the fault, and because control trees showed no such prolonged disturbance, Jacoby et al. hypothesized that a large earthquake ruptured this segment between the 1812 and 1813 growing seasons. In conjunction with historic and stratigraphic evidence, they determined that event to be the December 1812 "San Juan Capistrano" earthquake ($M_w > 7.5$), and estimated its rupture length at about 170 km.

CONCLUSIONS

Applying tree-ring science to paleoseismology can increase understanding of recent seismicity in order to improve probability estimates of

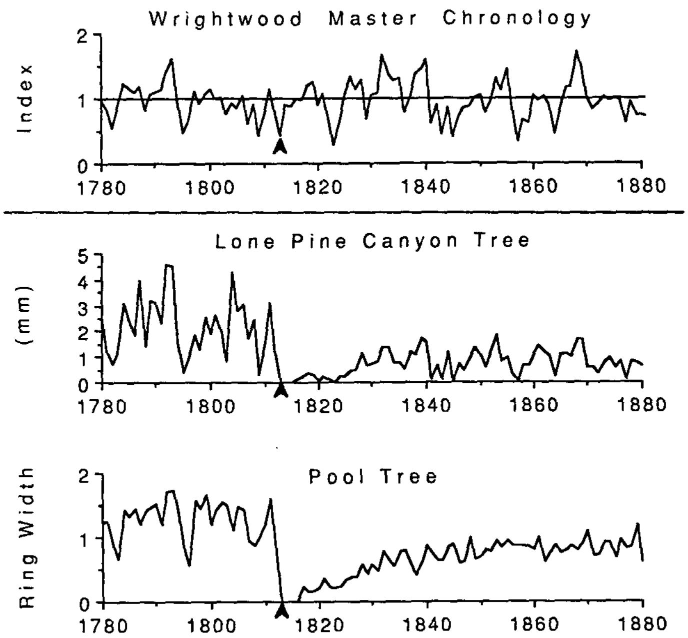

Figure 3. Time-series plots of Wrightwood master chronology (top) and of ring-width series from two disturbed trees. Arrows point to 1813 values.

future large earthquakes. Ring-width data revealed that the 1964 Alaska quake was recorded by trees and that a large earthquake ruptured the southern San Andreas fault in 1812. These two studies demonstrate how tree-ring analysis can complement geological and historical efforts to date and delineate large earthquakes.

The advantage of tree-ring analysis is that absolute year dates (or even seasons) of disturbance can be obtained. All tree-ring samples must be cross-dated to ensure accurate disturbance dates. Synchronous responses should be present in multiple trees located on or very near a fault or within geomorphic features indicating seismic activity. All other disturbance mechanisms must be ruled out before an earthquake is concluded. For this, a species-specific control chronology must be constructed from nearby, undisturbed trees.

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ACKNOWLEDGMENTS

Supported by Earth Science Division of National Science Foundation Grant EAR 85-19039 and U.S. Geological Survey contract 14-08-001-G1329. We thank L. Seeber, E. R. Cook, G. A. Carver, and J. F. Shroder for reviews, and D. Peteet for the core collection from Suckling Hills, Alaska. Lamont-Doherty Geological Observatory Contribution No. 4376.

Manuscript received July 8, 1988
Revised manuscript received October 24, 1988
Manuscript accepted November 9, 1988