Dating San Andreas fault earthquakes with lichenometry

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ABSTRACT

Regional rockfall events in the Sierra Nevada of California are caused by distant earthquakes on the northern and southern San Andreas fault as well as by local earthquakes. Lichenometric dating of synchronous pulses of rockfalls that are presumed to be caused by five historical earthquakes suggests an accuracy of 2.2–3.5 yr (95% confidence level) for dating young events. Comparison of lichenometric ages for prehistorical rockfalls with precise radiocarbon ages of surface-rupture times at the Pallett Creek and Wrightwood paleoseismology sites indicates that earthquakes on the southern San Andreas fault caused rockfalls 200 to 400 km to the north. A major rockfall event at about A.D. 1690 supports the Fumal et al. (1993) model for a San Andreas fault earthquake that was not detected at Pallett Creek. The A.D. 1690 event in the chronology indicates that the earthquake recurrence interval was shorter and that the degree of clustering of times of earthquakes was less on the Mojave segment of the San Andreas fault than previously thought.

INTRODUCTION

Radiocarbon dating of materials from trenches across fault scarps has greatly improved our perception of the times of earthquakes on the more obvious faults in western North America. Blind thrusts and subduction zone thrusts, however, lack easily accessible fault scarps, and so fewer paleoseismic evaluations have been made for these common sources of earthquakes. However, seismic shaking emanating from these structures can cause landslides, including rockfalls. Earthquakes greater than magnitude 7 can trigger rockfalls at distances of 200 to 400 km from their epicenters (Keefer, 1984). In a departure from the current emphasis on radiocarbon dating of earthquakes, I use lichenometry to date rockfalls.

Rockfalls are sensitive to strong ground motion resulting from earthquakes on either obvious or hidden fault zones. Assessing times of synchronous rockfalls at many sites in a mountainous region may allow one to (1) estimate earthquake recurrence intervals and elapsed times for specific faults, (2) locate the fault responsible for a prehistorical earthquake by selecting lichenometry sites that respond mainly to local, strong ground motion, and (3) describe regional patterns of abundance for earthquake-generated rockfalls by selecting sites that record distant as well as local ground motion (Bull, 1996).

The purpose of this paper is to illustrate how lichenometric dating can provide new insights for paleoseismology studies and to present new paleoseismic information relevant to the earthquake potential of the southern San Andreas fault. I summarize evidence for historical coseismic (earthquake-generated) rockfalls caused by local and distant earthquakes in the Sierra Nevada of California (Fig. 1). Then I assess the completeness of the earthquake record by comparing times of prehistorical rockfall events estimated by lichenometry with surface-rupture ages for southern San Andreas fault earthquakes estimated by precise radiocarbon dating.

METHOD

The coseismic rockfall lichenometry model was developed initially in New Zealand after the discovery that lichens growing on rocky hillslopes recorded synchronous pulses of rockfalls generated by historical earthquakes. Consecutive rockfall events add increments of lichen-free blocks to hillside benches and stream terraces that serve as repositories of the coseismic and nonseismic rockfall record. A coseismic rockfall event is distinctive because (1) it typically causes collapse of outcrops or downslope block movements at many sites throughout a region and (2) landslide volumes increase toward the earthquake epicenter.

Times when blocks tumbled down hills during earthquakes, or for other reasons, were estimated by measuring sizes of lichens (*Rhizocarpon* subgenus *Rhizocarpon* unless otherwise noted). Most lichenometric age estimates in the prior literature have been based on the largest lichen, or the mean of the five largest lichens, per surface to be dated (Locke et al., 1979; Porter, 1981; Innes, 1984, 1985). Lichenometry has been used to date rockfall hazards (Porter, and Orombelli, 1981) and earthquakes (Smirnova and Nikonov, 1990). The method used here measures the maximum diameter of the largest lichen on tens to hundreds of unit areas approximated by rockfall blocks or outcrop joint faces. All lichen size measurements are used, including those for lichens that may have grown at different rates and those on unrecognized but anomalous inherited blocks that predate the geomorphic event of interest. Measurements at multiple sites test the hypothesis that large earthquakes generate synchronous pulses of rockfalls throughout a region.

The assumptions for the coseismic rockfall lichenometry model are fairly straightforward. The longest axis of the largest lichen on each rockfall block is assumed to best represent the time since deposition by seismic or nonseismic processes, but this single lichen size

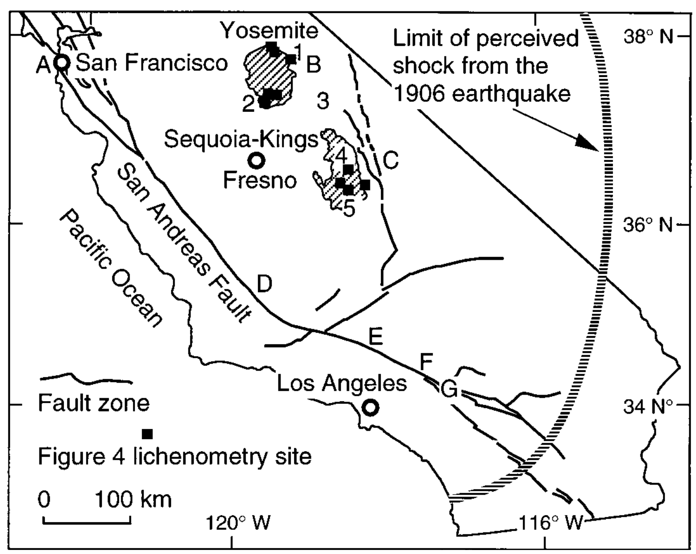

Figure 1. Map of central and southern California showing San Andreas fault system, and Yosemite and Sequoia–Kings Canyon National Parks in Sierra Nevada. North-to-south sequences for lichenometry sites (numbers) and earthquake epicenters and paleoseismology sites (letters) are 1—Tioga Pass, 2—Middle Brother, 3—Rock Creek, 4—Knapp's Rock, 5—Kern River Canyon and Laurel Creek site, A—1906 earthquake, B—1890 earthquake, C—1872 earthquake, D—1857 earthquake, E—Pallett Creek site, F—Wrightwood site and 1812 earthquake, and G—Pitman Canyon site. Limit of 1906 perceived shock is from Ellsworth (1990).

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measurement provides only a crude estimate of rockfall-event age. Maximum diameters of largest lichens growing on many rockfall blocks are assumed to provide the best estimate of rockfall-event age, which is tightly constrained by the mean and standard error of the mean for a large sample of blocks deposited at the same time. It is further assumed that rockfall abundance decreases with distance away from an earthquake epicenter and that coseismic rockfalls dominate Sierra Nevada lichen-size data sets for deposits created by many rockfalls. I also presume that many species of *Rhizocarpon* subgenus *Rhizocarpon* grow at virtually the same rate in the 600 to 3500 m altitude range of the Sierra Nevada study region.

Dating and locating prehistorical earthquakes with lichenometry require careful site selection. Rockfall sites sensitive to distant seismic shaking include steep bouldery hillslopes, glacial moraines, and landforms that intercept falling blocks (hillslope benches and footslopes, terrace treads, and alluvial fans). Low-sensitivity sites include fractured outcrops in the immediate vicinity of the fault believed responsible for a particular earthquake. Climatic as well as seismic events may add fresh blocks to hillslopes. Sites were selected carefully to minimize influence of snow avalanches and debris flows.

Accurate calibration of lichen growth rates is enhanced by precise measurements made with digital calipers and by substrate-exposure times known to the year. A new calibration of lichen growth is not necessary at every site in the study region because factors such as substrate lithology and smoothness, mean annual precipitation and temperature, and length of growing season appear to have a minimal affect on colonization times or lichen growth rates (Denton and Karlen, 1973; Bull et al., 1994). However, shelter from sun and wind promotes faster lichen growth (Benedict, 1967). I measured exposed lichens.

Growth-rate calibration for *Rhizocarpon* subgenus *Rhizocarpon* (Bull et al., 1994) is based on lichen-size measurements at two tree-ring–dated landslides and three historical sites. Regression of mean lichen size in millimetres, D, and calendric years, t, describes uniform lichen growth as

$$D = 190 - 0.095t; \quad (1)$$

n (number of control points) is 5 and r^2 (correlation coefficient) is 0.99.

The age for a specific size of lichen is the sum of colonization time, initial great-growth phase, and uniform-growth phase. The growth rate during the uniform-growth phase is about 9.5 mm per century. Thus lichens growing on substrates exposed in A.D. 1 would have a mean size of 190 mm. Similar calibration procedures were used for three other genera of lichens to verify the *Rhizocarpon* subgenus *Rhizocarpon* age estimates for rockfalls caused by San Andreas fault earthquakes.

The calibration equation for *Acarospora chlorophana* is

$$D = 225 - 0.114t; \quad (2)$$

n is 5 and r^2 is 1.0.

The calibration equation for *Lecidea atrobrunnea* is

$$D = 448 - 0.231t; \quad (3)$$

n is 6 and r^2 is 0.998.

The calibration equation for *Lecanora sierrae* is

$$D = 377 - 0.189t; \quad (4)$$

n is 7 and r^2 is 0.998.

Composite probability density plots, constructed by overlapping Gaussians that represent individual measurements, provide robust analyses of lichen size data sets. Decomposition of a plot into rockfall-event subpopulations (Fig. 2) provides means of peak ages and analytical uncertainties. Amplitude, or area, of a rockfall lichen size subpopulation describes relative abundance and is an index of seismic shaking for a coseismic rockfall event.

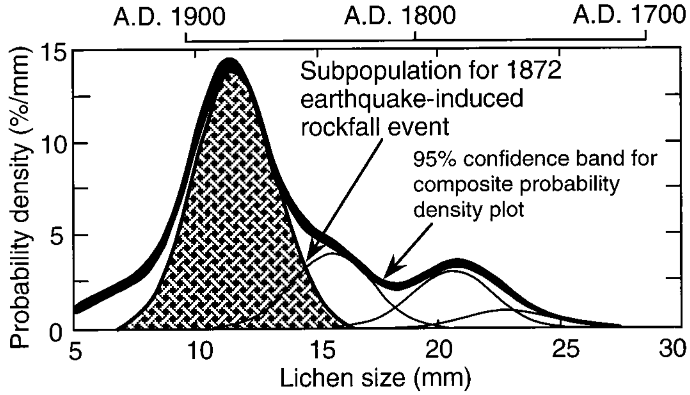

Figure 2. Probability density of lichen size measurements at Knapp's Rock rockfall site in Kings Canyon portrayed as composite plot with 95% confidence band. Amplitude (seismic-shaking index) of 12 mm peak reflects magnitude 7.6 earthquake of 1872 (Lubetkin and Clark, 1988); epicenter was only 50 km from Knapp's Rock.

SIERRA NEVADA REGIONAL ROCKFALL EVENTS

Lichens on talus deposits below cliffs may record regional rockfall events generated by earthquakes along Sierra Nevada fault zones or by distant earthquakes along the San Andreas fault. The Knapp's Rock site is representative of many Sierra Nevada lichenometry sites, being below glaciated cliffs of granitic rock with prominent pressure-relief joints parallel to the cliff face. Talus accumulates in an incremental fashion that records frequent coseismic and nonseismic rockfalls. Decomposition of the composite probability density plot suggests that most of the recent rockfalls occurred as four events: none appear to have been triggered by San Andreas fault earthquakes.

Middle Brother, a granitic monolith that rises 800 to 1000 m above Yosemite Valley, has a well-deserved reputation for being unstable. Lichen sizes were measured in two small adjacent areas by two workers (Bull et al., 1994, Fig. 7). Decomposition of the composite probability density plot for the combined data sets describes two large rockfall events (Fig. 3) estimated to have occurred in A.D. 1860 ± 10 yr and 1812 ± 10 yr. The 2σ uncertainties (95% confidence level) sum measurement, calibration, and modeling sources of error and are rounded up to the nearest decade. These rockfall events may have been generated by strong ground motion emanating from distant San Andreas fault earthquakes (Ellsworth, 1990) of 1857 (330 km) and 1812 (420 km). Cliff collapse in 1857 also occurred on the opposite side of Yosemite Valley (Wieczorek et al., 1992). Two minor subpopulations have lichenometry ages of A.D. 1914 ± 10 yr and 1833 ± 10 yr.

Data for 10 sites (Fig. 1) in the central and southern Sierra Nevada were analyzed in the manner illustrated for the Knapp's Rock and Middle Brother data sets. Calendric ages for 58 mean lichen sizes of young lichen size subpopulations were estimated by using equation 1 (Fig. 4). Times of rockfalls in the central and southern Sierra Nevada are clustered, which requires regional causes. Five of the six regional rockfall events of Figure 4[1] are presumed to have resulted from two local earthquakes (1872 and 1890) and three San Andreas fault earthquakes (1812, 1857, and 1906). The peak

[1]Data Repository item 9606, data used to construct Figure 4, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

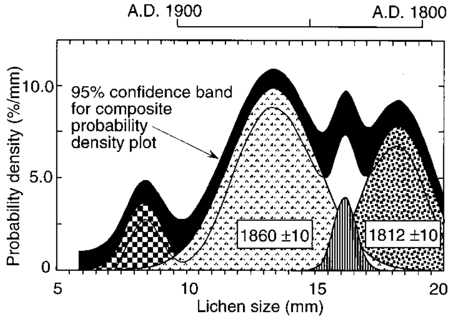

Figure 3. Probability density plot of lichen size measurements on rockfall blocks at Middle Brother site reveals two large subpopulations at times of earthquakes on southern San Andreas fault.

TABLE 1. COMPARISONS OF LICHENOMETRY AGES FOR SIERRA NEVADA REGIONAL ROCKFALL EVENTS WITH DATES OF HISTORICAL EARTHQUAKES AND WITH RADIOCARBON AGES FOR SURFACE-RUPTURE EVENTS ON THE MOJAVE SEGMENT OF THE SAN ANDREAS FAULT

Calendric ^{14}C earthquake ages	Kern River *Acarospora chlorophana*	Kern River *Rhizocarpon* subgenus *Rhizocarpon*	Rock Creek *Lecanora sierrae*	Rock Creek *Acarospora chlorophana*	Yosemite V. *Rhizocarpon* subgenus *Rhizocarpon*	Tioga Pass *Lecidea atrobrunnea*	Mean lichenometry calendric age
[1906.30]		1905 ±3	1907 ±3		1906 ±3	1901 ±3	1904.8 ± 1.5
[1857.02]	1864 ±3	1860 ±3	1859 ±2	1858 ±3	1860 ±3	1849 ±2	1858.3 ± 1.1
[1812.95]	1816 ±5		1816 ±3	1811 ±5	1812 ±3	1810 ±3	1813.0 ± 1.7
1688 ±13 (1686 ± 8)	1690 ±6	1686 ±6	1699 ±4	1692 ±6	1697 ±6	1689 ±7	1692.2 ± 2.4
(1610+40-110)	Several strong regional rockfall events occurred in the Sierra Nevada during this 150-year time span.						
1480 ±15 (1470 ±20)	1488 ±9	1477 ±9	1485 ±7	1490 ±9		1489 ±10	1485.8 ± 4.4
1346 ±17	1344 ±10	1340 ±11	1351 ±8	1341 ±10			1344.0 ± 4.9
1100 ±65	1094 ±12			1091 ±12		1102 ±20	1095.7 ± 8.5
1048 ±33	1054 ±12	1041 ±16		1052 ±12			1049.0 ± 7.7
997 ±16	993 ±13					1000 ±21	996.5 ±12.0
797 ±22	797 ±16						797.0 ±16.0
734 ±13	745 ±17			745 ±17		736 ±26	742.0 ±11.5
Distance 0 km	230 km	250 km	340 km	340 km	400 km	410 km	

Note: Dates in brackets are historical; those in parentheses are for surface rupture events at Wrightwood (Fumal et al., 1993); others are for surface rupture events at Pallett Creek (Sieh et al., 1989). All uncertainties are 2σ (95%). Lichenometry uncertainties include errors for lichen size measurement, decomposition of composite probability density plots, smoothing function, and spread of regression 95% lines based on slope of regression. Average uncertainty for mean lichenometry age estimate is directly proportional to $N^{0.5}$, where N is the number of lichenometry age estimates.

with greatest amplitude appears to record the large, nearby Owens valley earthquake of 1872. The two smallest peaks may record the small, local Mono Lakes earthquake of 1890 and the large but distant San Francisco earthquake of 1906. The A.D. 1837 ± 10 yr lichen size peak records a regional rockfall event (or events) of unknown cause. Age estimates for the modeled peaks of Figure 4 differ from the five historical earthquake dates by −0.4 to +4.8 yr; this difference averages 2.2 ± 3.5 yr (2σ). Thus, the precise coseismic rockfall lichenometry model appears to be accurate for dating young events.

IMPLICATIONS FOR SOUTHERN SAN ANDREAS FAULT EARTHQUAKES

This new way of dating earthquakes should also be of considerable value in studies of prehistorical earthquakes. Both Sierra Nevada and distant earthquakes appear to be present in the coseismic-rockfall record of prehistorical earthquakes. Age estimates, based on lichen size measurements of four lichen genera (Table 1), identify synchronous times of widespread regional rockfall events in the central and southern Sierra Nevada. These events appear to be coseismic because their lichenometry ages are the same as radiocarbon age estimates for surface-rupture times at the Pallett Creek (Sieh et al., 1989) and Wrightwood (Fumal et al., 1993) seismogenic stratigraphy sites on the Mojave segment of the San Andreas fault (Fig. 1). Sieh's careful stratigraphic analyses have produced an excellent set of precise radiocarbon ages for San Andreas fault earthquakes, but young peat layers typically have several possible calendric radiocarbon ages. Sieh's event X may date as either A.D. 1785 (1753–1817) or 1688 (1675–1701). His preferred interpretation is that event X is the 1812 surface-rupture event (Sieh et al., 1989; Kerry Sieh, 1994, oral commun.). A weighted mean radiocarbon age of A.D. 1686 ± 8 yr for an earthquake at the Wrightwood site led Fumal et al. (1993) and Biasi and Weldon (1994) to favor the A.D. 1688 interpretation for the Pallett Creek event. The event at about A.D. 1690 also has been recognized at Pitman Canyon (Ray Weldon, 1995, personal commun.).

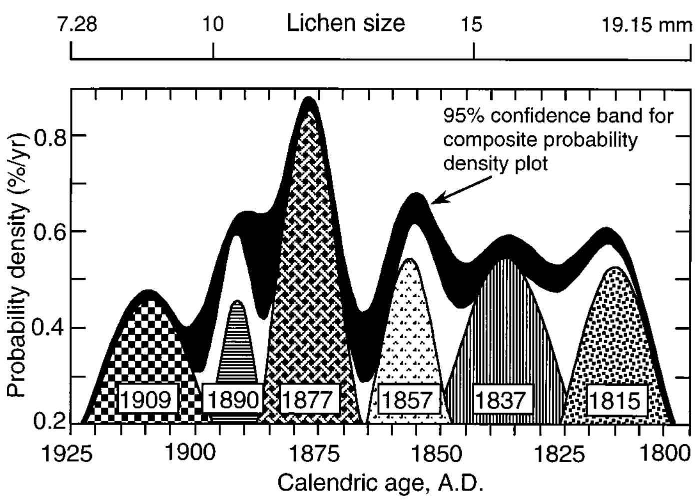

Figure 4. Times of regional rockfall events in central and southern Sierra Nevada. Historic Sierra Nevada earthquakes occurred in A.D. 1872 and 1890, and San Andreas fault earthquakes occurred in A.D. 1812, 1857, and 1906.

As noted by Fumal et al. (1993), inclusion of the 1688 event in the Pallett Creek earthquake chronology would have the effect of decreasing both the earthquake recurrence interval and the degree of clustering of earthquake ages postulated for the Mojave segment of the San Andreas fault. The data of Sieh, for historic and prehistorical earthquakes, but without an earthquake at about A.D. 1690, suggest a mean earthquake recurrence interval of 140 yr, and a large standard deviation of 109 yr is indicative of clustered times of earthquakes. In contrast, the Table 1 data set yields a mean earthquake recurrence interval of 124 yr. The standard deviation decreases to 79 yr, which suggests a lesser degree of clustering of times of earthquakes. Earthquake recurrence interval and standard deviation would be decreased still more if an event at about A.D. 1610 (1500–1640) described at the Wrightwood site was included in the chronology for southern San Andreas fault earthquakes. However, the radiocarbon age estimate lacks the precision (2σ uncertainty of +40, −110 yr) needed to assign it to a specific Sierra Nevada rockfall event, even though some sites record a rockfall event at about A.D. 1600 (Fig. 5 example is 1597 A.D. ± 10 yr). At present, we do not know which Figure 5 peaks are additional San Andreas fault earthquake-induced rockfall events.

Lichenometric dating of rockfall deposits may help clarify situations in which surface-rupture events occur during times of nondeposition at seismic stratigraphy sites. The lichenometry surface-

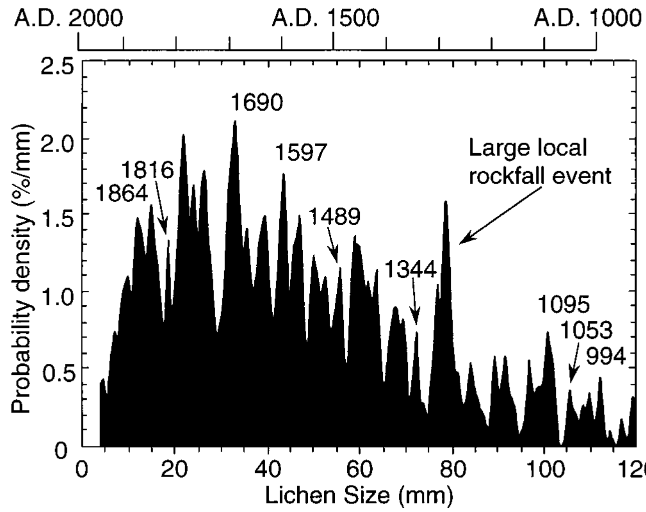

Figure 5. Probability density plot of lichen size measurements for *Acarospora chlorophana* at Laurel Creek rockfall site in Kern River canyon, southern Sierra Nevada. All earthquakes at Pallett Creek and Wrightwood sites (Table 1) appear to be recorded by rockfalls. Calendric ages for lichen size peaks of decomposed composite probability plot are from Kong (1994, Table 6a).

exposure dating method also avoids two other inherent problems with radiocarbon age estimates. Organic matter dated by radiocarbon analysis either predates or postdates the time of a landslide or disruption of stratigraphy, and atmospheric radiocarbon production rates may vary sufficiently to result in multiple possible radiocarbon ages for a single sample (Stuiver and Reimer, 1993).

This lichenometry study also suggests that southern San Andreas fault earthquakes may trigger rockfalls 400 km away; seven events appear to have been recorded at Tioga Pass (Table 1). Seismic shaking caused by the 1812 earthquake seems to have caused rockfalls to an extent approaching that of the major 1857 earthquake. Seven of the 12 sites used for the Figure 4 analysis—all more than 200 km from Pallett Creek—appear to record the 1812 event. This result suggests that the length of the 1812 surface rupture was longer than defined by Sieh et al. (1989).

CONCLUSIONS

Coseismic rockfall events of the past millennium can be precisely and accurately dated by lichenometry (±10 yr). Rockfall studies complement seismic stratigraphy dating of earthquakes by providing an independent way to date earthquakes and to assess potential for future earthquake hazard. Dating of Sierra Nevada coseismic rockfall events confirms age estimates for earthquakes made for the Pallett Creek and Wrightwood sites on the southern San Andreas fault. An implication of the Fumal et al. (1993) study, and this study, is that acquisition of new paleoseismic data tends to indicate both shorter recurrence intervals and a less clustered nature of times of San Andreas fault earthquakes.

Although fairly labor intensive, application of the coseismic rockfall model to paleoseismology problems is relatively inexpensive. Future lichenometric studies could (1) assess the distribution and types of historical mass movements in the Sierra Nevada that have been triggered by local and distant earthquakes, (2) evaluate rockfall abundance in different topographic and structural settings, in response to seismic waves generated by earthquakes east, south, and west of the mountain range, and (3) use seismic-shaking index maps to describe extent and intensity of regional rockfall events associated with historical earthquakes in order to estimate approximate sizes of prehistorical earthquakes.

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