Sierra Nevada Earthquake History From Lichens on Rockfall Blocks

William B. Bull Emeritus Professor of Geosciences, University of Arizona
Bill@ActiveTectonics.com

Part 3--Earthquake Generated Rockfalls

We measured the sizes of lichens on rockfall blocks below Middle Brother in Yosemite Valley. This granitic monolith rises 800 to a 1000 m above the valley floor and has a well-deserved reputation for being unstable. Wieczorek and Snyder (2003) note that 23 rockfalls have been recorded at Middle Brother, so this would seem to be a good site for testing the hypothesis that distant earthquakes cause landslides in the Sierra Nevada. The histogram of Figure 9 was constructed by stacking up overlapping bell-shaped Gaussians representing each measurement. Then computer modeling identified the principal peaks in the overall distribution of lichen sizes. Two large rockfall events appeared to have impacted the fairly small part of the talus slope that we studied. Their lichenometry ages are about 1860 and 1812 A. D. These rockfall events may

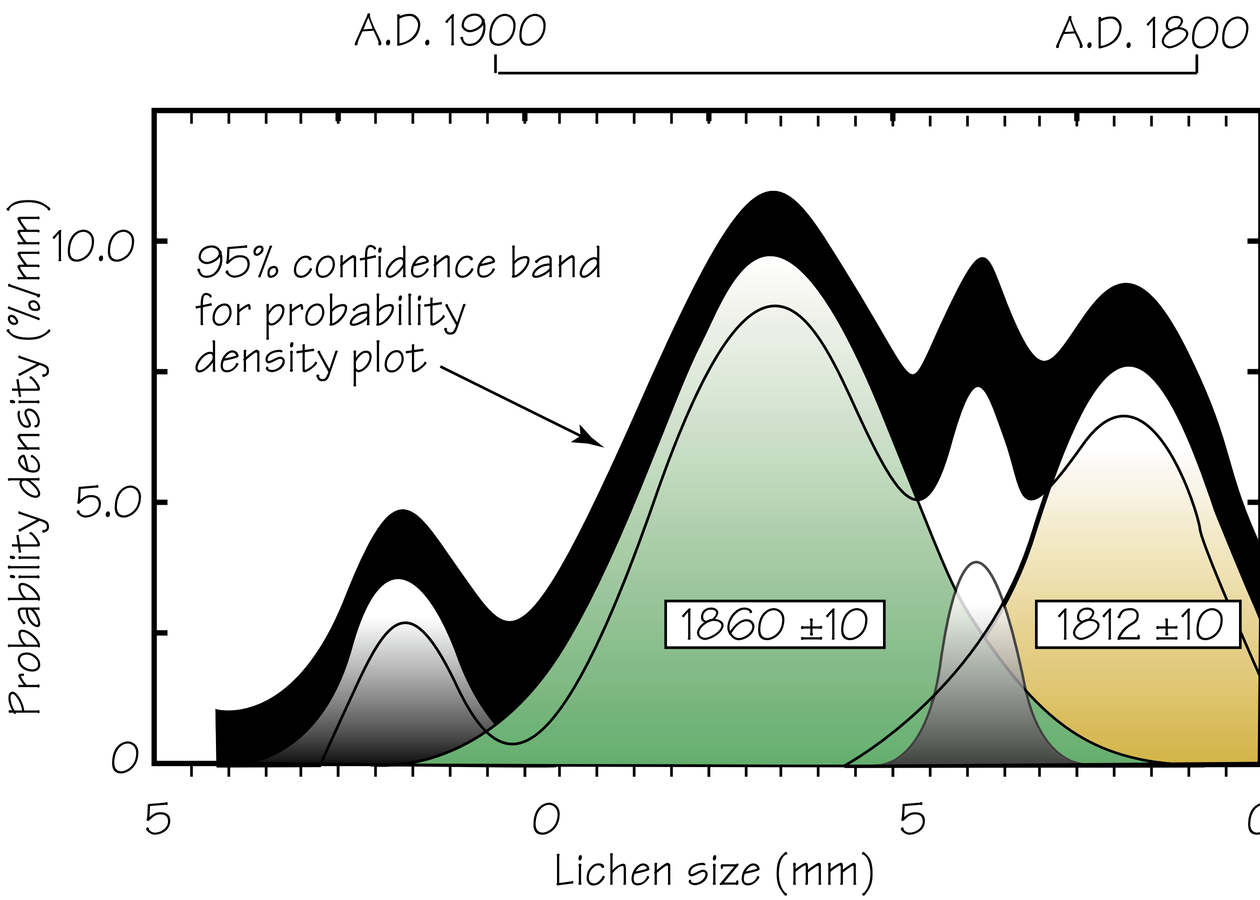

Figure 9 Modeling of lichen-size peaks on rockfall blocks at Middle Brother site reveals two large subpopulations close to the times of the 1857 and 1812 earthquakes on southern San Andreas fault.

have been generated by strong ground motions emanating from distant San Andreas fault earthquakes (Ellsworth, 1990) of 1857 (330 km) and 1812 (420 km). An 1857 cliff collapse on the opposite side of the valley is part of the Wieczorek and Snyder (2003) landslide inventory.

The Middle Brother data suggest that some landslides were coseismic, but we need to see if seismic shaking really has a pervasive influence on the Sierra Nevada rockfall process. The modeling done in Figure 10 is similar to that of Figure 9 and the large data set is a combination of 10 lichenometry sites in the central and southern Sierra Nevada. Indeed the lichen-size peaks have times that clearly match the times of historical local or distant earthquakes. When first published in 1996, the second largest peak that lichenometry dates to about 1837 A. D. was an enigma. All I could say about it was "the 1837 A. D. ± 10 years lichen-size peak records a regional rockfall event of unknown cause". Then Toppozada and Borchardt (1998) described a previously unregistered San Andreas fault earthquake that occurred near Hollister-San Francisco in 1838. The epicenter of this earthquake is directly opposite my Sierra Nevada study region (Fig. 2), which contributed to the large size of the lichen-size peak for that particular regional rockfall event. We now know that all of the lichen-size peaks of Figure 10 record regional seismic shaking events.

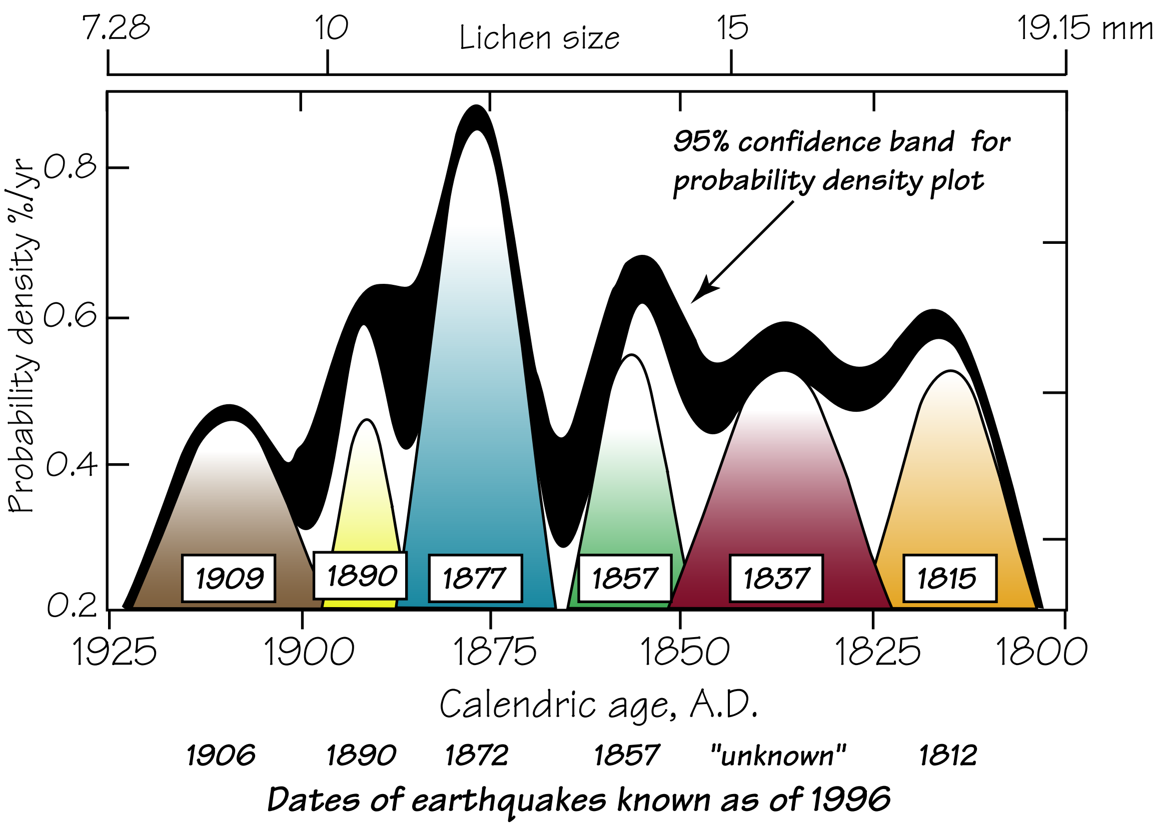

Figure 10 Modeled times of rockfalls for combined dataset of *Rhizocarpon* subgenus *Rhizocarpon* from 10 Sierra Nevada sites are clustered, which requires regional causes. 1872 and 1890 local earthquakes and 1812, 1857, and 1906 are San Andreas fault earthquakes. Five dates have an accuracy of 2.2 ± 3.5 yr. The A.D. 1837 ±10 yr lichen-size peak recorded a regional rockfall event of "unknown cause" in the opinion of Bull (1996), but it turned out to be caused by the San Andreas earthquake of 1838 that was discovered later by Toppozada and Borchardt (1998).

Regional seismic shaking should decrease with increasing distance from the earthquake epicenter and so should the number of coseismic rockfall blocks. Making maps that show regional variations in seismic shaking index can test this hypothesis. This index is simply the percentage of lichen-size measurements contained within the lichen-size peak relative to the total measurements in a 6 mm wide band of lichen sizes--3 mm to each side of the peak that we are interested in. The results of two analyses are shown in Figures 11 and 14--one map is for the historic earthquake of 1812 A. D. in Southern California and the other map is for a prehistoric earthquake that I presume occurred in 1739 A.D. on the Honey Lake fault zone in northeastern California.

Rockfall abundance for the 1812 event decreases markedly from south to north. This overall pattern is just what one would expect from a large earthquake on the southern San Andreas fault.

Local details of the Figure 11 map are intriguing. The southern part of area varies from 10 to 20% response to seismic shaking to >50%. I attribute this to the different orientations of the rock-fall block source areas at lichenometry sites in the Kern River gorge. North-facing source areas may well be more sensitive than outcrops facing east or west (see Figures 4 and 12). Seismic energy from the south would tend to move partially detached blocks away from north-facing cliffs (Fig. 8).

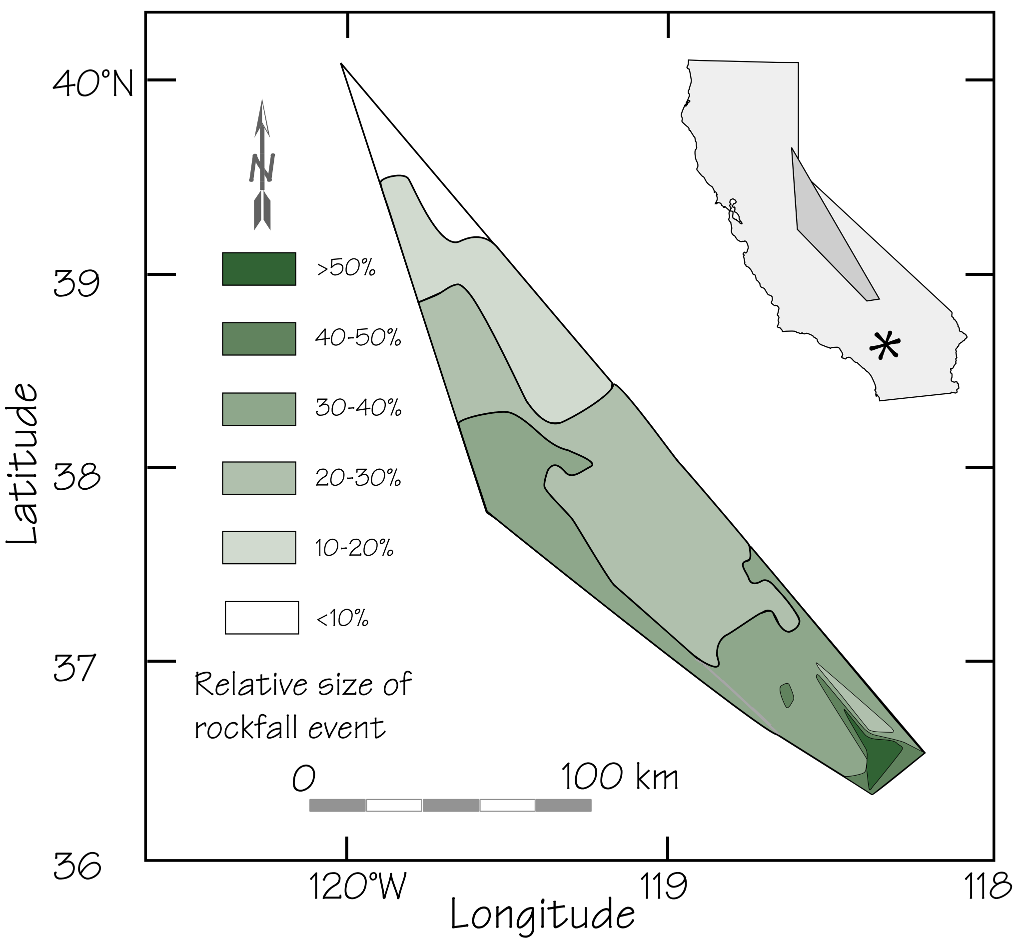

Figure 11 Variation in seismic shaking index for a historic regional rockfall event. The * symbol in the inset map approximates the epicenter of the earthquake of 1812 A. D. generated by the Mojave segment of the San Andreas fault in southern California.

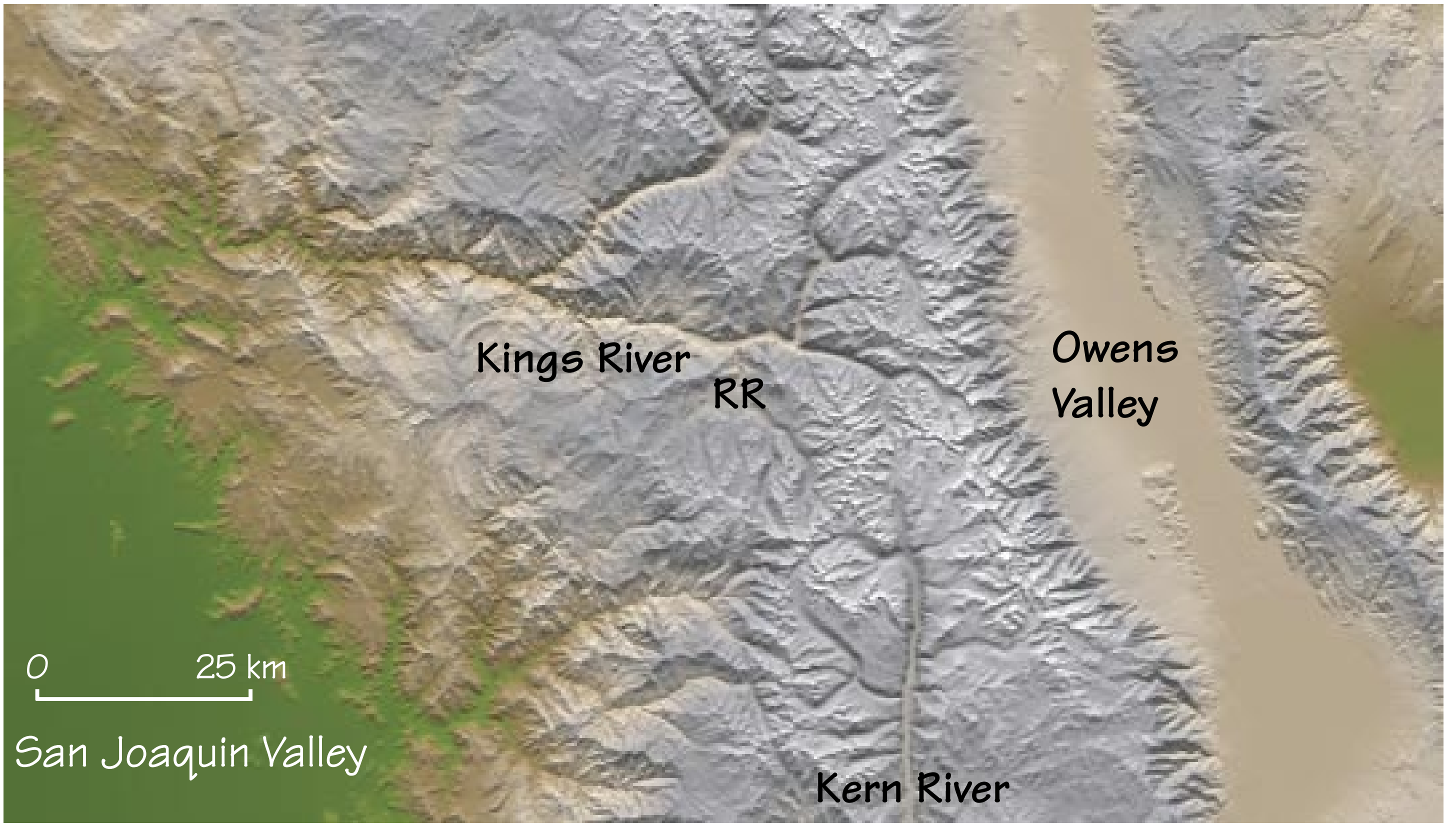

Figure 12 Digital image of the south-central Sierra Nevada. RR is near the mouth of the Roaring River tributary to the South Fork of the Kings River. The different orientations of the cliffs flanking the gorges of the Kern and Kings Rivers may influence rock-fall responses to seismic shaking being transmitted north-south as compared to east-west.

The western edge of the seismic shaking index map reveals a slightly higher sensitivity—30 to 40% as compared to 20 to 30% in the adjacent area to the east. Landform sensitivity to seismic shaking may vary slightly in the study area. The eastern area lichenometry sites include glacial moraines, fractured cliffy mountainsides, and steep debris slopes whose blocks could be set in motion again with seismic shaking. Many of the sites in the western area are in deep glaciated valleys. The massive cliffs give the impression of being very strong, but they have pervasive exfoliation joints that parallel cliff faces. The Figure 11 map suggests that such joints are responsible for increased sensitivity to seismic shaking as compared to sites along the crest and east side of the mountain range. Middle Brother in Yosemite Valley (Fig. 9) is an example of very unstable cliff face that has both exfoliation joints parallel to the cliff face and numerous fractures oriented in other directions.

Recognition of a probable large earthquake in 1739 A. D. is the result of studies by many people. We knew of a large rock avalanche called "The Slide" in the headwaters of Piute Creek, a remote part of Yosemite National Park. Its age was unknown but seemed young enough to have potential for calibrating lichen growth rates. The rock avalanche damaged trees, which led Huber et al., (2002) to use dendrochronology to determine that the rock avalanche occurred after the growing season of 1739 A.D. and before the growing season began in 1740 A. D.. One speculation was that the landslide was a consequence of Little Ice

Age variations in snowpack and ground-water table. As such it would be a very large, but local, landslide event. Then, site by site, we gradually realized that lichen-size peaks dating to this time (Figs. 4A, B) were common throughout the Sierra Nevada. Then a lucky breakthrough happened. I pitched my tent near a volcanic neck in Fort Sage Mountains of the Basin and Range Province just east of the northern Sierra Nevada while on a Friends of the Pleistocene field trip in 2001. Measuring the sizes of *Acarospora chlorophana* the volcanic rocks revealed a dominant lichen size peak dating to about 1737 A. D. (Bull, 2003a, Figure 8-10). The volcanic neck is only 8 km from the Honey Lake fault zone, a major right-lateral strike-slip fault in the Walker Lane tectonic belt. It has ruptured Holocene age stream deposits at least four times and has an estimated slip rate of 2 m/1,000 years (Wills and Borchardt, 1993). I surmise that an earthquake here caused The Slide in Yosemite National Park.

Most of us, including me, had not heard of the Honey Lake fault zone. Did it really generate a surface rupture during the late Holocene? This is an opportunity to introduce you to a mainstay of paleoseismology—radiocarbon dated faulted stratigraphy.

First, the geologic setting. Pleistocene Lake Lahontan receded about 12,000 years ago. Then a stream alternated between depositing sandy layers on top of the lake clays, and cutting deep channels like the one that now exposes the prior sedimentary layers, soils, and faults shown in Figure 13. These intervals of non-deposition allowed weathering processes to create incipient soil profiles, each defines a former land surface.

General dating control is good. A volcanic ash spewed by Crater Lake volcano in Oregon (the former Mount Mazama stratovolcano) occurs as a layer below the Long Valley Creek stratigraphy, so all the layers and faults shown in

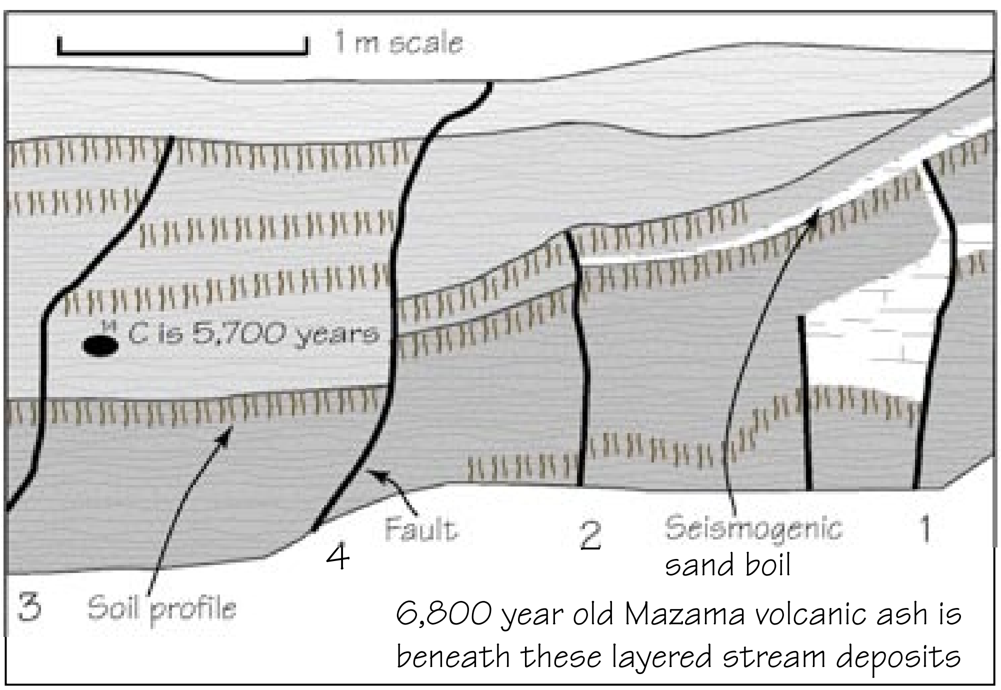

Figure 13 Cross section of a streambank of Long Valley Creek showing displacement of former land surfaces (soil porfiles) by four recent earthquakes on the Honey Lake fault zone in north-eastern California. From Figure 4 and text of Wills and Borchardt (1993).

Figure 13 are younger than 6,800 years. This was one of the worlds largest catastrophic eruptions in the last 10,000 years (Bacon, 1983). About 50 cubic kilometrers (12 cubic miles) of magma became pyroclastic detritus that spread across the west as a blanket of volcanic ash. A single radiocarbon date higher in the stratigraphic section is younger being about 5,700 years.

The nice work by Wills and Borchardt (1993) shows that faulting repeatedly broke through to surface, 1 through 4, oldest to youngest (Fig. 13). Seismic shaking by earthquake 1 liquified saturated sand and jetted it through a fissure to the surface where a fountain spread wet sand out as a low circular mound. This formerly level surface has been tilted by surface-rupture events 2, 3, and 4, which slid sideways much more than vertically. Deposition of the surficial sediments occurred just before modern stream-channel entrenchment and so recently that a soil profile has yet to form. Wills and Borchardt believe that event 4 occurred "within the past few hundred years". This strikes me as a good candidate for my postulated 1739 A. D. surface-rupture event. There may have been more than four events since the mid-Holocene on the Honey Lake fault zone if earthquakes occurred during times of non-deposition. A surface rupture tomorrow would rupture through to the same land surface as event 4, and both would appear in the future stratigraphic record as being the result of a single earthquake event.

Was the epicenter of the 1739 A. D. regional seismic shaking event really this far north? A seismic shaking index map is one way to test this hypothesis. The map shown in Figure 14 is the first map depicting areal variations in seismic shaking for a prehistoric earthquake in California. The intensity of seismic shaking decreases progressively towards the south, and makes a nice contrast with the pattern for the 1812 earthquake, which decreases progressively towards the north (Fig. 11).

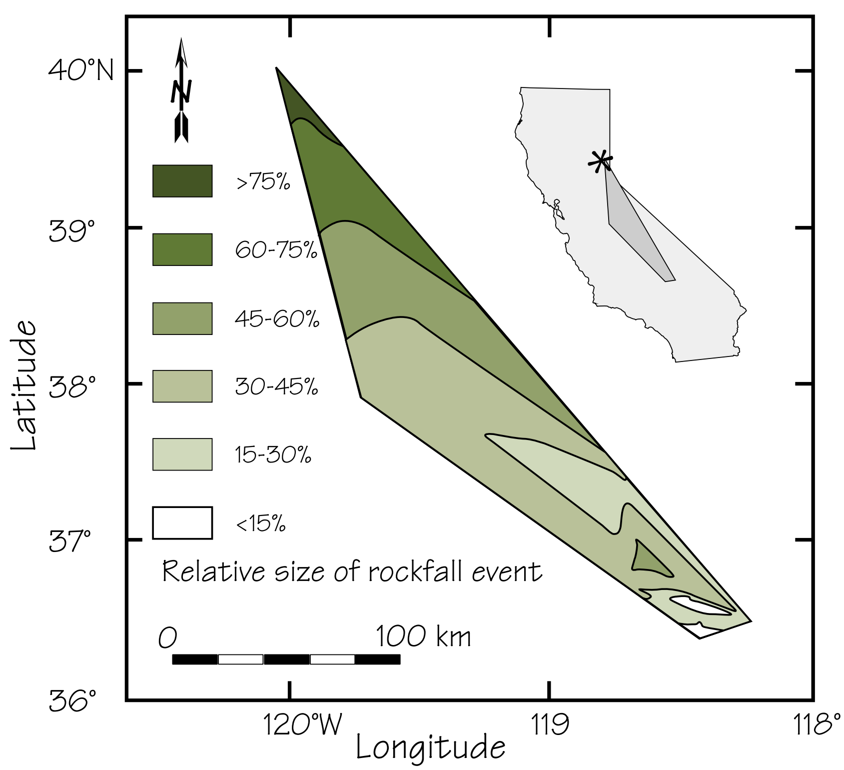

Figure 14 Variation in seismic shaking index for a prehistoric regional rockfall event. The * symbol in the inset map approximates the epicenter of the hypothesized earthquake of 1739 A. D., which may have been generated by the Honey Lake fault zone near the northern Sierra Nevada.

A Test of the Lichenometry Method

We need an independent test of the lichenometry story presented here. The traditional approach to paleoseismology is to dig a trench across a scarp created by an active fault, describe the ruptured layers, and constrain the times of surface ruptures by radiocarbon dating of organic matter that grew either before or after each surface-rupture event. The importance of this approach to paleoseismology was initiated by careful studies made by Kerry Sieh at Pallett Creek on the Mojave segment of the San Andreas fault in southern California (Sieh, et al., 1989). His studies at this site have become the hallmark for paleoseismology investigations, in part because of the precision (lengthy and low counting background) of his radiocarbon age estimates. The site is unusual in that many events are recorded far back in time and only one earthquake on this part of the San Andreas fault may have occurred during a time of non-deposition of marshy sediment.

Can we really record and date San Andreas fault earthquakes at many places in the Sierra Nevada? Are the lichenometry age estimates sufficiently accurate for us to believe them? A good way to appraise the quality of traditional stratigraphic paleoseismology work done at Pallett Creek is to check it against the much different geomorphic paleoseismology method, which uses lichenometry to date rockfall events. Table 1 shows a close match between the times of San Andreas fault earthquakes and lichenometry age estimates for rockfall events at seven sites. Cross checks include using four genera of lichens. I conclude that both the stratigraphic and geomorphic approaches to paleoseismology are robust.

By including four historical earthquakes we can ascertain the accuracy of lichenometric dating of earthquakes. The mean ages are within 0.2 to 1.5 years of the known ages, an accuracy that should please paleoseismologists. Table 1 also shows that every one of the Pallett Creek events is matched by a lichenometry determined time of regional seismic shaking in the Sierra Nevada. It also seems that the lichenometry approach has the capability of dating the times of exposure of rock surfaces that are more than 1000 years old, but only at those relatively few sites where the rockfall blocks have large lichens.

I conclude that lichenometry is a valuable tool for paleoseismologists. It precisely dates prehistoric earthquakes and describes their patterns of seismic shaking. Here is a tool for earth scientists that can be used to study how seismic energy interacts with landscapes and different rock types. All aspects of the field data collection, and analytical procedures can be tested against historical earthquakes, which increases our confidence about the results of lichenometry evaluations of prehistorical seismic shaking of alpine mountains.

Calendric ^{14}C earthquake ages, A. D.	Kern River	Kern River	Kings River	Rock Creek	Rock Creek	Yosemite	Tioga Pass	Mean lichenometry calendric age
	Acarospora chlorophana	*Rhizocarpon* subgenus *Rhizocarpon*	*Acarospora chlorophana*	*Lecanora sierrae*	*Acarospora chlorophana*	*Rhizocarpon* subgenus *Rhizocarpon*	*Lecidea atrobrunnea*	
[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**
[1838.47]		1839 ±3	1837 ±3	1841 ±3	1836 ±3	1838 ±3	1841 ±3	**1838.7 ±1.2**
[1812.95]	1816 ±5		1811 ±4	1816 ±3	1811 ±5	1812 ±3	1810 ±3	**1812.6 ±1.7**
1688 ±13	1690 ±6	1686 ±6	1697 ±8	1699 ±4	1692 ±6	1697 ±6	1689 ±7	**1693 ±2**
1480 ±15	1488 ±9	1477 ±9	1482 ±10	1485 ±7	1490 ±9		1489 ±10	**1485 ±4**
1346 ±17	1344 ±10	1340 ±11	1335 ±12	1351 ±8	1341 ±10			**1342 ±5**
1100 ±65	1094 ±12		1086 ±12		1091 ±12		1102 ±20	**1093 ±8**
1048 ±33	1054 ±12	1041 ±16	1037 ±14		1052 ±12			**1046 ±8**
997 ±16	993 ±13		997 ± 14				1000 ±21	**997 ±12**
797 ±22	797 ±16		781 ±18					**789 ±14**
734 ±13	745 ±17		741 ±20		745 ±17		736 ±26	**742 ±11**
671 ±13			654 ±22					**654 ±22**
Distance 0 km	**230 km**	**250 km**	**290 km**	**340 km**	**340 km**	**400 km**	**410 km**	

Table 1 Comparisons of lichenometry ages for Sierra Nevada regional rockfall events with dates of historical [ ] earthquakes, and with precise radiocarbon ages for surface-rupture events at Pallett Creek (Sieh, et al., 1989)on the Mojave segment of the San Andreas fault. All uncertainties are 2σ (95%). Lichenometry uncertainties include errors for lichen-size measurement, decomposition of 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.

References Cited and Further Reading

Bacon, C.R., 1983, Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, USA: Journal of Volcanology and Geothermal Research, v. 18, p. 57-118.

Bull, W.B., 1996, Dating San Andreas fault earthquakes with lichenometry: Geology, v. 24, p. 111-114.

Bull, W. B., 2003a, Guide to Sierra Nevada lichenometry: in Tectonics, Climate Change, and Landscape Evolution in the southern Sierra Nevada, California: Greg Stock, editor; 2003 Pacific Cell Friends of the Pleistocene field trip, Sequoia and Kings Canyon, Appendix 8, p. 100-121. This article can be downloaded from (http://activetectonics.com/downloads/BullFOPlichenometry.pdf)
or download the entire guidebook at (http://es.ucsc.edu/~gstock/fop2003/)

Bull, W.B., 2003b, Lichenometry dating of coseismic changes to a New Zealand landslide complex: Annals of Geophysics: v. 46, p. 1155-1167.

Bull, W. B., 2003c, Choices and calibration of lichens for dating geomorphic processes in the Sierra Nevada of California: 7 p. This unpublished article can be downloaded from (http://activetectonics.com/downloads/MeasuringSNlichens.pdf)

Bull, W.B., and Brandon, M. T., 1998, Lichen dating of earthquake-generated regional rockfall events, Southern Alps, New Zealand": Geological Society of America Bulletin. v. 110, p. 60-84.

Bull, W.B., King, J. Kong, F. Moutoux, T., and Phillips, W. M, 1994, Lichen dating of coseismic landslide hazards in alpine mountains: Geomorphology, v. 10, p. 253-264.

Huber, N.K., 1987, The geologic story of Yosemite National Park: U.S. Geological Survey Bulletin 1595, 64 p.

Huber, N.K., Phillips, W. M., and Bull, W. B., 2002, The Slide, Yosemite: Yosemite, v. 64, p. 2-4.

Sieh, K., Stuiver, M. and Brillinger, D., 1989, A more precise chronology of earthquakes produced by the San Andreas Fault in Southern California: Journal of Geophysical Research, v. 94, p. 603-623.

Toppozada, T. R., and Borchardt, G., 1998, Re-evaluation of the 1836 "Hayward Fault" and the 1838 San Andreas fault earthquakes: Bulletin of the Seismological Society of America, 1998 v 88, p. 140-159.

Wieczorek, G.F., and Jäger, Stefan, 1996, Triggering mechanisms and depositional rates of postglacial slope-movement processes in the Yosemite Valley, California, Geomorphology, v. 15, p. 17-31.

Wieczorek, G.F., Morrissey, M.M., Iovine, G., and Godt, J., 1998, Rock-fall hazards in the Yosemite Valley: U.S. Geological Survey Open-file Report 98-467, 1:12,000, 7 p. (http://pubs.usgs.gov/of/1998/ofr-98-0467/)

Wieczorek, G.F., Morrissey, M.M., Iovine, G., and Godt, J., 1999, Rock-fall potential in the Yosemite Valley, California: U.S. Geological Survey Open File Report 99-578, 1 plate 1:12.000, 7 p. (http://pubs.usgs.gov/of/1999/ofr-99-0578/)

Wieczorek, G.F., and Snyder, J.B., 1999, Rock falls from Glacier Point above Camp Curry, Yosemite National Park, California: U.S. Geological Survey Open-file Report 99-385, 13 p., 9 figs. (http://pubs.usgs.gov/of/1999/ofr-99-0385/)

Wieczorek, G. F., and Snyder, J. B., 2004, Historical rock falls in Yosemite National Park, California: U.S. Geological Survey Open-File Report 03-491. (http://pubs.usgs.gov/of/2003/of03-491/)

Wieczorek, G.F., Snyder, J.B., Alger, C.S., and Isaacson, K.A., 1992, Rock falls in Yosemite Valley, California: U.S. Geological Survey Open-File Report 92-387, 38 p., 2 appendixes, 4 plates.

Wieczorek, G.F., Snyder, J.B., Waitt, R.B., Morrissey, M. M., Uhrhammer, R., Harp, E. L., Norris, R. D., Bursik, M. I., and Finewood, L.G., 2000, The unusual air blast and dense sandy cloud triggered by the July 10, 1996, rock fall at Happy Isles, Yosemite National Park, California: Geological Society of America Bulletin, v. 112, n. 1, p. 75-85.

Wills, C.J. and Borchardt, G., 1993, Holocene slip rate and earthquake recurrence on the Honey Lake fault zone, northeastern California: Geology, v. 21, p. 853-856.

ACKNOWLEDGMENT

Gerald Wieczorek's pioneering studies encouraged me to study Sierra Nevada rockfalls. His suggestions for the text and illustrations of this note improved the coherence and completeness.

End of Part 3
The Introduction was in Part 1
Part 2 was about Rockfall Processes

Nature Notes Home