Sierra Nevada Earthquake History From Lichens on Rockfall Blocks

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Abstract

Strong seismic shaking from nearby and distant earthquakes causes rocks to shift downhill and fall from cliffs. Lichens colonize bare rock and largest lichen sizes date times when blocks fell. Lichen-size measurements cluster in peaks that record earthquake-induced and nonseismic landslides. Same-age lichen-size peaks throughout the Sierra Nevada record regional seismic shaking events. Peak sizes are larger nearer earthquake epicenters, so are used to make maps describing seismic shaking intensity for historic and prehistoric earthquakes, and to study sensitivity of landforms to earthquakes.

Introduction

It was a gorgeous Sierra Nevada morning in the South Fork. I looked up at the cliffs towering above the Roaring River parking lot, massive cliffs that rival those of the fabled Yosemite. Rather monotonous gray lichens coat the surface of the jointed, granitic rocks. Then I noticed several small light gray to whitish patches on the cliff face (Fig. 1). Could these be where rock, weakened by expanding joints and fractures had fallen away from the cliff so recently that the rock surface had yet to be re-colonized by the gray lichens?

Luckily, I had the right tools to discern if a rockfall type of landslide had occurred recently. I had digital calipers, and I know how fast several genera of crustose lichens grow. Careful measurements of lichen sizes, with digital calipers that read to 0.01 mm, can provide insight about when the surfaces of fallen rock-fall blocks were first exposed to be colonized anew by lichens.

Figure 1. View of north-facng cliffs above the talus slope next to the Roaring River parking lot, South Fork Kings River. Whitish splotches on granitic outcrop are where masses of rock detached along exfoliation joints, in one or several events, and fell to add another increment(s) to the talus accumulating at the edge of the valley floor. The rest of the cliff has been stable for sufficiently long to become coated with gray lichens that like the cool, wet microclimate.

Different lichens start to grow on rock-fall blocks after they arrive on the sunny, dry talus slope at the base of the cliffs. I know how fast bright yellow, brown, and speckled yellow-green lichens grow, which allows me to estimate their ages to within just a few years. Using calipers, I go from block to block, and for each block I have the same question; "when did you come tumbling down the hill". I prefer nearly circular lichens with clearly defined margins growing as a symbiotic algae-fungi crust on smooth rock surfaces. I measure the longest axis of the largest lichen on each rockfall block, assuming that this single measurement records the time when the first lichen colonized the freshly exposed rock surface of this block after a landslide. I don't trust a single lichen-size measurement. It is better to measure many lichens because one does not know how far a single lichen size might vary from the norm. I collect enough measurements to define the range of lichen sizes for a specific rockfall event—we call this a lichen-size peak. The big piles of rocks in the Sierra Nevada are the result of many small rockfalls and larger landslides too.

Although different lichens grow at different rates, all crustose lichens pass through three stages of growth. First is the time it takes the first lichen to colonize a freshly exposed rock surface. This varies from about 8 to 40 years for my three lichen genera. Colonization is followed by rapid growth that gradually becomes slower. This great-growth phase may continue for more than 60 years. Then uniform growth begins at about the time that lichen fruiting structures form. Constant expansion of lichen size continues for many centuries for the crustose lichens growing on the rocks of the Sierra Nevada. Some lichens at the Roaring River site are more than 1,000 years old.

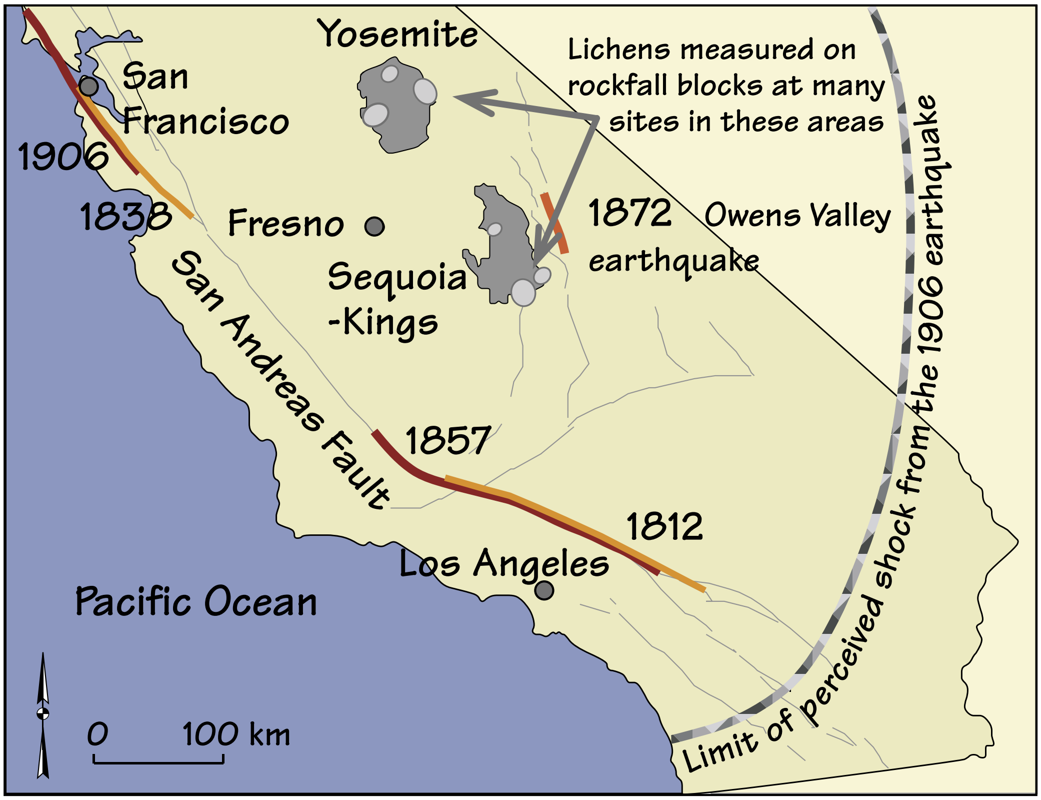

Figure 2. California location map showing locations of groups of lichenometry sites in the Sierra Nevada. Extents of historic magnitude Mw ~7.5 San Andreas fault earthquakes are shown by orange and reddish brown lines and the Owens Valley Mw 7.6 earthquake of 1872 with a red line. Limit of 1906 perceived shock is from Ellsworth (1990). Figure 1 from Bull (2003a).

So geologists with digital calipers can assess the history of landslides in the Sierra Nevada in order to answer several questions. How often do landslides occur? What causes them? Are they a hazard to visitors in the National Parks or hikers in the back country? The author is a tectonic geomorphologist and paleoseismologist so you can expect him to focus on landslides caused by earthquakes. I will conclude that the Sierra Nevada landscape records seismic shaking from distant earthquakes, including those noted in Figure 2.

Purpose and Scope

The purpose of this note is to see how distant or local earthquakes cause landslides in the Sierra Nevada and how we can use lichens to study such co-seismic landslides. The theme is that regional seismic shaking causes a regional rockfall event with larger and more abundant landslides closer to the earthquake epicenter. These mass movements range from a trickle of small rocks to huge, smothering rock avalanches. It is the intermediate size, very common, rockfall event that is most useful for my purposes. The glaciated valley sides make the Sierra Nevada a nice sounding board for earthquakes, even those generated by slip on the distant San Andreas fault. I test the idea that more rocks are shaken loose nearer an earthquake epicenter by mapping areal variations in the abundance of rockfalls for historic and prehistoric earthquakes. Such studies provide clues as to the sensitivity of different landforms and rock types to seismic shaking. Comparison of Sierra Nevada regional rockfall events with known ages of the much studied prehistorical San Andreas fault earthquakes is a good way to assess the validity of lichenometric dating of earthquakes and to find out how far back in time the method can be used. I use metric units of measurement, in part to get us Americans familiar with the way the rest of the world describes sizes.

Recent Rockfall Splash on Roaring River Talus Slope

I had a particular interest in trying to estimate the time, or times, of apparent recent cliff failure above the Roaring River parking lot. I was in the final stages of setting up a field-trip stop for a large group of geologists known as the ‘Friends of the Pleistocene’. Yes, they are especially keen to learn more about Sierra Nevada geology of the past 2 million years. Surely they would be curious as to when and why parts of the cliff failed. It would be better if I could be specific rather than make some shallow comment such as “a coating of gray lichens shows that these cliffs are fairly stable, but white patches suggest a recent rockfall event; most likely caused by the nearby Mw magnitude 7.6 earthquake of 1872”.

Having only 45 minutes before meeting a Park Ranger, I measured only a dozen lichens for each of the three genera for which I know rates of growth. I didn’t have time to measure hundreds of lichens—my preferred approach would require two or three long days work because large as well as small lichens would be measured. So I took a chance that 42 lichen-size measurements might reveal a consistent story about recent cliff failure, and that different genera would confirm a common story. Would there be a pattern of a few blocks breaking loose from the cliff face each frosty winter? (lichen sizes would be evenly spread

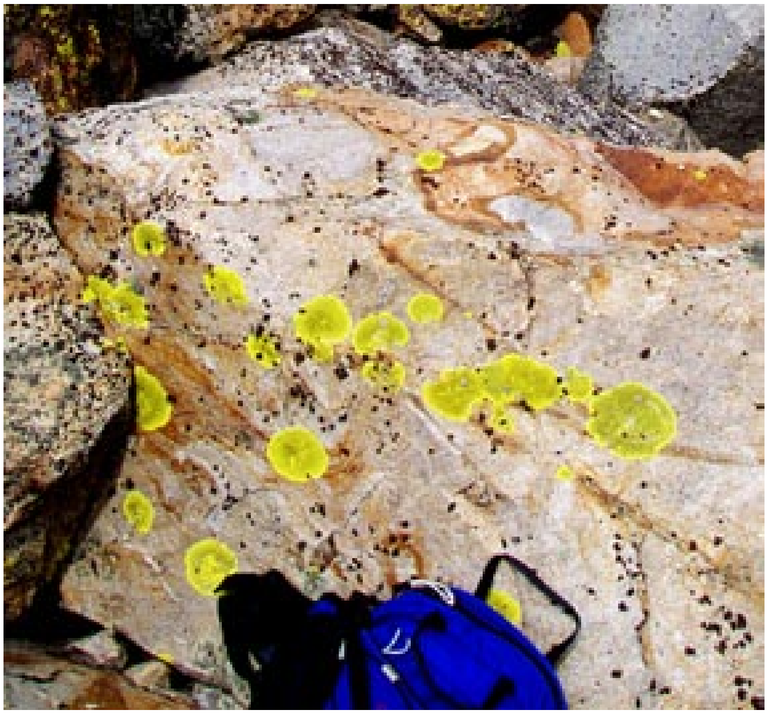

Figure 3 *Acarospora chlorophana* on Kings Canyon talus block. We examine each block for a potential largest lichen maximum diameter scrutinizing the largest thallus to see if it is indeed a single, not merged, thallus. Then determine if the two measuring points for the longest axis are sharp and well preserved. If in doubt, do not measure; just move on to the next block.

out in such a graph). Would all the lichen sizes clump together in one peak on a graph summarizing the results? (indicating that the cliff failed at only one time and was completely stable the rest of the time). The bright yellow crustose lichen, *Acarospora chlorophana* (Fig. 3), is one of my favorite lichens so I measured it at the start of my transect across that part of the talus slope where damaged oak trees also told me of recent rockfalls.

I use a histogram to see if my lichen sizes cluster, or are scattered. This simple graph consists of simply stacking one lichen size on top of another of the same size to see if peaks appear in the overall distribution of sizes. Two peaks are apparent even with only 14 measurements (Fig. 4A). This suggests that rocks have fallen from the cliff face as discrete events rather than as an annual trickle. Virtually nothing happens between the times of discrete rockfall events. Having a lichen-growth-calibration equation ready to use (Bull, 1996), I estimate the times of these two rockfall events to be approximately 1811 and 1741 A. D. I say approximately because lichenometry is not as precise as historical records, or tree-ring dating of landslides. But lichenometry is much better than the radiocarbon method for dating trees buried by a landslide. Importantly, it dates the event instead of wood that grew some time before the landslide event. Precision is excellent and the accuracy of lichenometric dating commonly is about 2 years from the true age. I recognize possible uncertainties of my calendric age estimates by adding a generous ± 10 years to the lichenometry dates of rockfall events.

Both *Acarospora chlorophana* age estimates suggest rockfalls during times of regional seismic shaking, because they are within 10 years of the known times of earthquakes. A big southern California earthquake occurred on the San Andreas fault in 1812, and tree ring dating suggests that the Honey Lake fault zone north-northwest of Reno, Nevada might be the source of earthquake-triggered regional seismic shaking during the winter of 1739-1740 A. D..

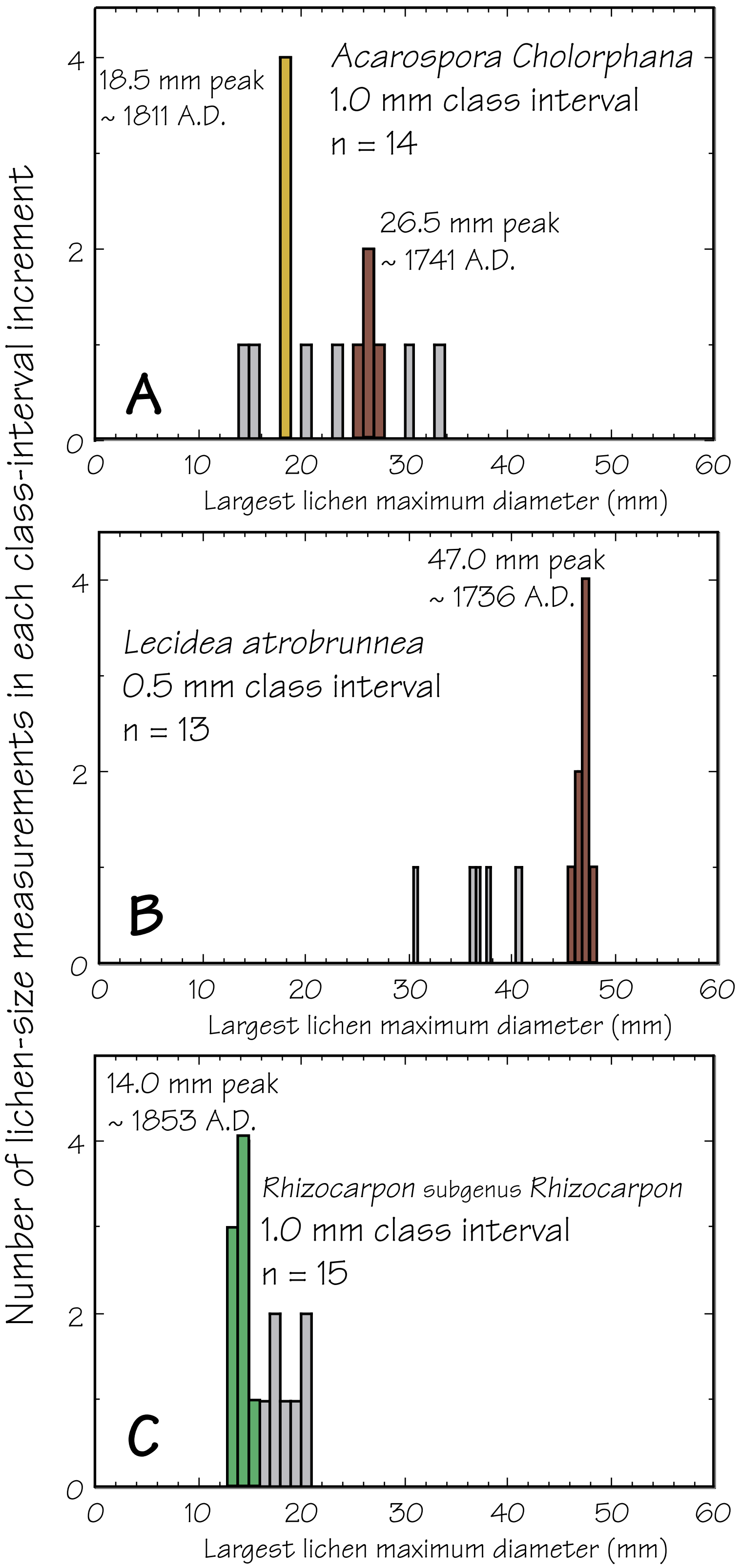

Figure 4 Simple histogram graphs for three common crustose lichens reveal clustering of lichen sizes. These lichen-size peaks date the times of the most recent rockfall events that splashed blocks and rock fragments onto a pre-existing talus slope at the Roaring River parking lot site, South Fork Kings River.

A. *Acarospora chlorophana*

B. *Lecidea atrobrunnea*

C. *Rhizocarpon subgenus Rhizocarpon*

Surprise! This cliff failed not once but twice, apparently from earthquakes whose epicenters were 300 km away. Both times are quite a bit older than I would have guessed by looking at the cliff. I say “apparently” to allow for the remote possibility that prolonged rain or snowmelt, or wedging by tree roots, might have caused rockfalls that just happened to coincide with the times of two earthquakes. I try to be careful, realizing that no one actually witnessed either

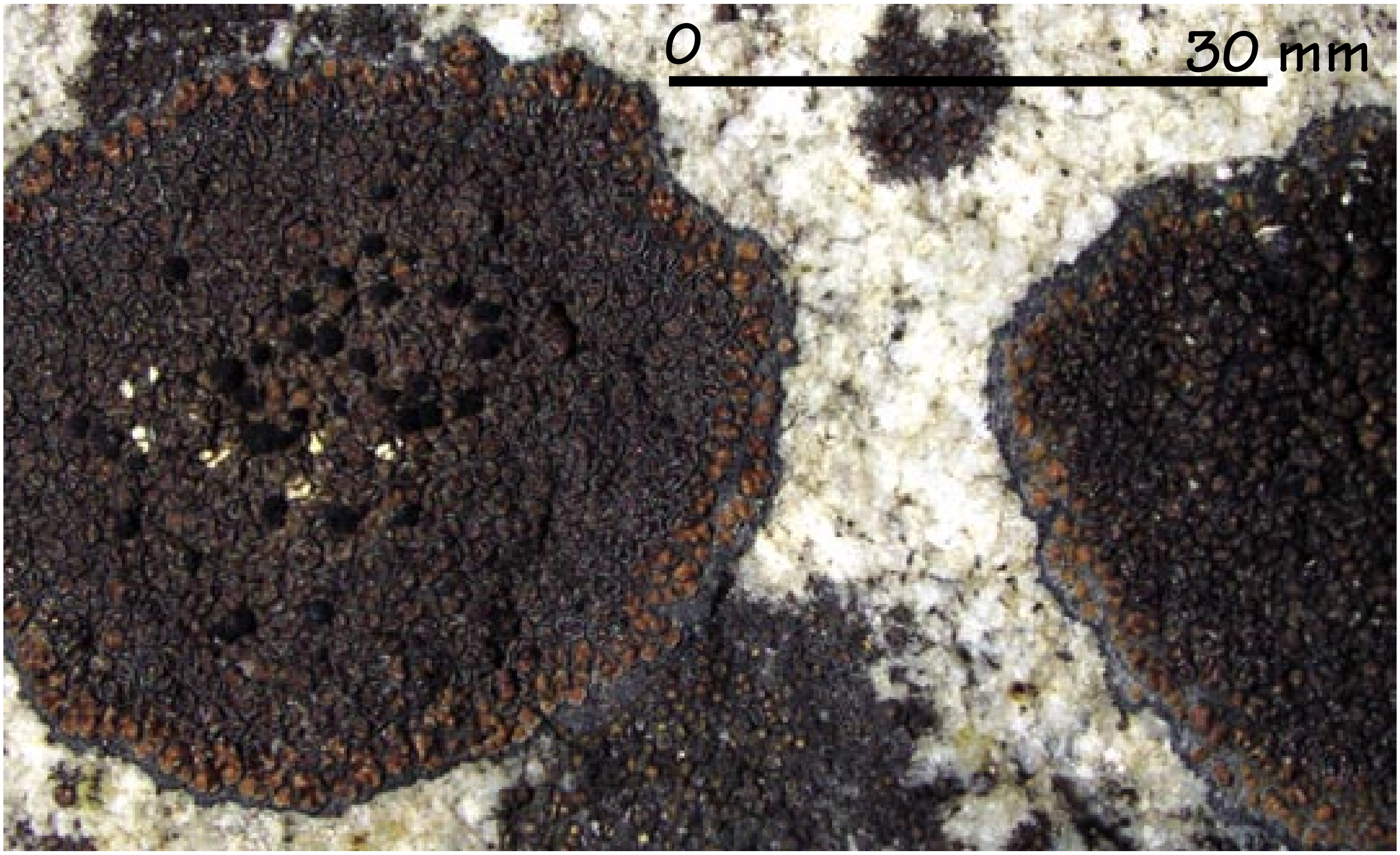

Figure 5 *Lecidea atrobrunnea* with typical large black apothecia and algal thallus rim. Broken areoles reveal whitish interior color.

cliff collapse. A good test of the earthquake hypothesis is to see if the same time of this rockfall event also occurs at high and low altitude lichenometry sites throughout the Sierra Nevada. Then, we can label the event as being regional instead of just being an unimportant local event. Yes, I'll do this for both the 1812 and 1739 events later on in this note. Fortunately, I know how fast two other lichen genera grow. What story do they have to tell me?

My initial results were crosschecked by graphing the sizes of another lichen genus in about the same part of the talus slope. This histogram is for the faster growing brown lichen *Lecidea atrobrunnea* (Fig. 5). Its uniform phase rate of growth is 23.1 mm each century as compared to 11.4 mm per century for *Acarospora chlorophana*. So, it is no surprise that the largest lichen on each rockfall block is bigger. This time, there is just one clumping of lichen sizes. It forms a single tall, symmetrical lichen-size peak (Fig. 4B) that dates to about 1736 A. D. Once again this is quite close to the known age of the regional seismic shaking event of 1739-1740 A. D..

The one remaining plot is that for the yellow-green *Rhizocarpon* subgenus *Rhizocarpon* (Fig. 6), and it is still different. This is slow-growing lichen, has a uniform-phase growth rate of only 9.5 mm per century. Most of my few lichen-size measurements form a large peak at about 14 mm (Fig. 4C), which dates to about 1853 A. D. This result is clearly different than indicated by the other two lichen genera, but it too seems to have been earthquake generated. A major

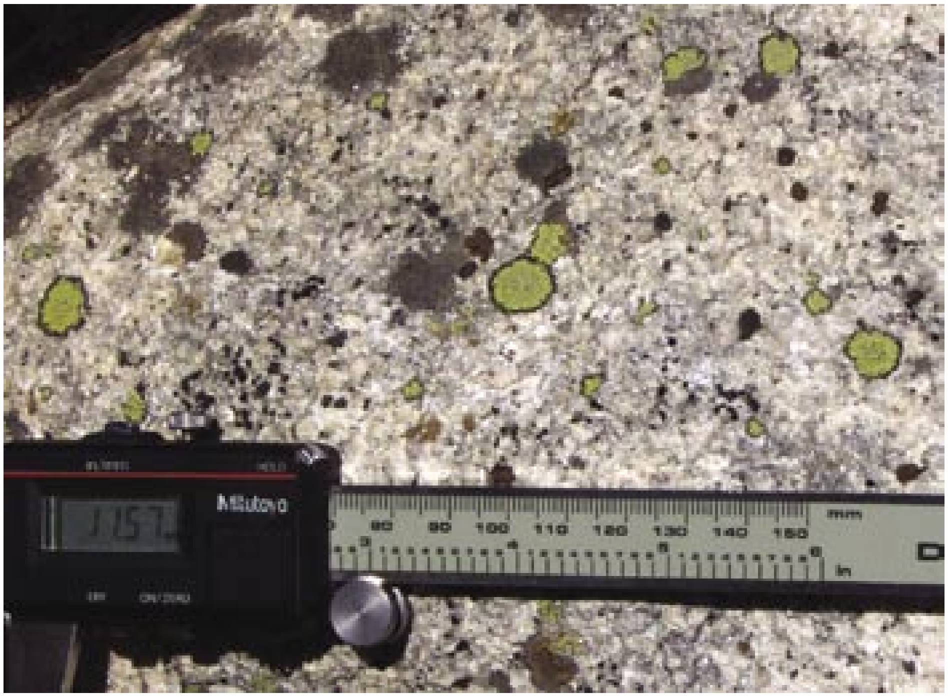

Figure 6 Small thalli of *Rhizocarpon* subgenus *Rhizocarpon*. A progression of lichen sizes that approach the favored largest lichen maximum diameter is much better than having only a single lichen to measure on a rock-fall block.

earthquake occurred on the southern San Andreas fault in 1857 A. D.. These yellow rhizocarpon measurements were collected at the end of my traverse, and the results clearly show that I had moved off of the 1739-1812 A. D. part of the rockfall accumulation into an area where the surface had been splashed more recently with chunks of rock during the 1857 A. D. earthquake.

So, measuring a few lichens changed my initial overall impression that the talus slope had been splashed by a single and fairly recent collapse of a small part of the overlying cliffs. Three earthquakes are recorded, and their epicenters lie either far to the north or to the south of the valley of the South Fork.

Where are the rockfalls that I expected from the Mw magnitude 7.6 Owens Valley earthquake of 1872 (Fig. 2) whose epicenter was only 50 km away to the east? Apparently the orientations of the joints and the overall east-west trend of the valley did not favor many blocks being shaken loose by seismic waves coming from the east. The east-west orientation of the joints in the cliff-face granitic rocks appears to be more conducive to blocks being pried loose by seismic waves coming in from the north or south. A given cliff face does not respond in the same manner to different earthquakes.

Of course not all cliffs disintegrate during an earthquake, only those parts that have reached the stage where a small amount of disruptive energy moves them across a stability threshold. The rest of the cliffy landscape remains unchanged by the seismic shaking. We can think of each hillslope, cliff, rubbly glacial moraine, steep talus slope as having its own sensitivity to seismic shaking.

Measuring lichens sizes as a way to study earthquakes strikes me as being a protective way of doing science in Yosemite or Sequoia-Kings Canyon National Parks. Nothing was dug up or sampled. I left with only photographs and lichen-size measurements. Best of all, you, or another tectonic geomorphologist can walk up to the same pile of rocks and collect a replicate set of measurements to check out my story. The Figure 4 story may strike you as being reasonable, but many geologists are skeptical. The precision of this new way of studying earthquakes just seems too good to be true. Besides they just might prefer to continue to study earthquakes using older methods that they feel more comfortable with.

Rockfall Processes in Glaciated Valleys

Cliff collapse commonly initiates a sequence of rockfall events over a time span of days to years. Wieczorek and Snyder (1999) nicely document three such events in 7 months above Curry Village in Yosemite valley (Fig. 7). None were earthquake induced. The first rock fall from the cliffs below Glacier Point was the largest, about 1576 metric tons and may have been triggered by seepage forces generated by ice that plugged the fractures to raise ground-water levels. The block(s) fell 30 to 45 m down a 75° cliff face to a ledge, breaking up against the cliff, then fell another 290 m before hitting the top of the talus. Block size and velocity was sufficient to remove large trees. Huge prehistoric rock-fall blocks partly determined the paths of bouncing blocks that crushed vegetation as they rumbled through the forest. Subsequent rockfall events followed the earlier routes. Some blocks traveled 500 m from the top of the talus, and small fly rocks may have been ballistic fragments that traveled much further from impact points high on the cliffs. A person measuring lichens a century from now would conclude that this sequence was a single event. This would influence her or his perception of landslide-event size. The measurements used to define the lichen-size peak would come from both sources; rock-fall blocks and chips, and from older blocks that had been smashed to create fresh surfaces to be recolonized by lichens (yes, one rock-fall block may record two events).

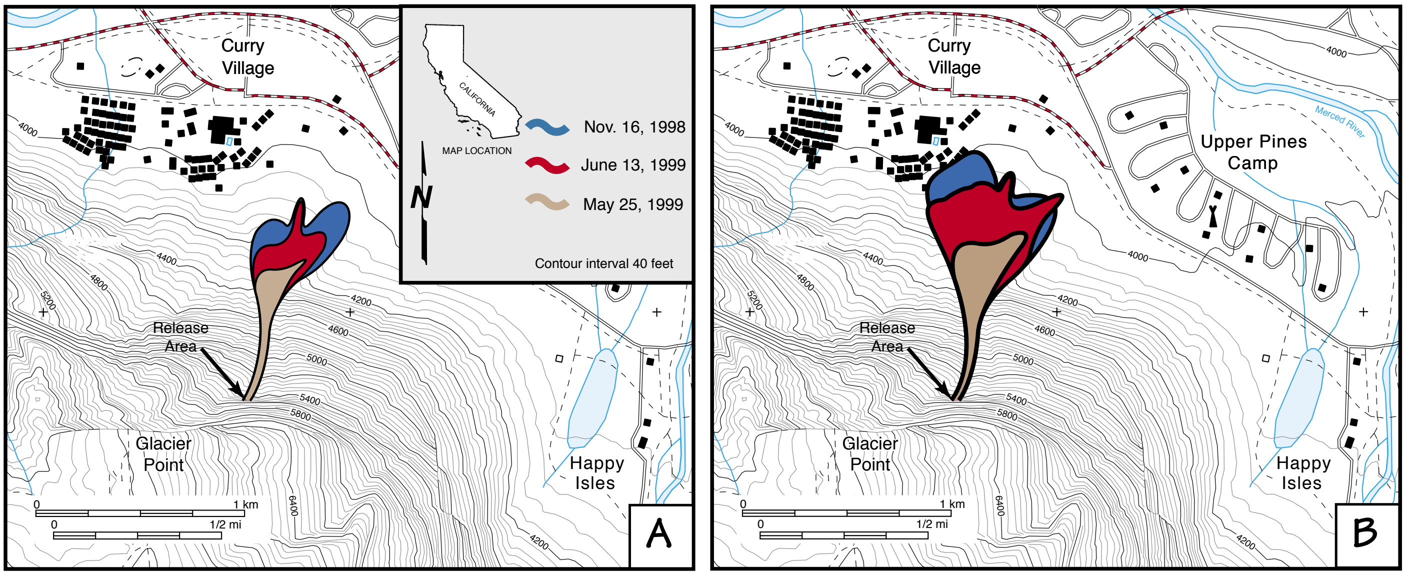

Figure 7 Series of three rockfall events in 6 months below the Glacier Point rock-fall release area near Camp Curry, Yosemite National Park. From Figure 2 of Wieczorek and Snyder, 1999.
A. Maps showing extents of the three rockfalls. Big blocks slid, bounced, and rolled shorter distances than fly rock chips and chunks.
B. Maps of areas splattered with flying 10-20 cm rock fragments produced when fast moving rocks were shattered upon impact with cliff projections or with other blocks.

The 25 May 1999 event was much smaller (112 metric tons), but the 13 June 1999 event was of intermediate size (600 metric tons). The rock-fall block ballistic splatter pattern was similar to the previous events, and had almost the same extent as the 16 November 1998 event.

The type of landslide damage is much different when huge blocks remain coherent until impacting the valley floor talus. This contrast is underscored by the 1996 rock fall at nearby (Fig. 7) Happy Isles (Wieczorek, et al., 2000). An arch of exfoliating rock, 150 m long, 10 to 40 m high, and 6 and 9 m thick detached from the cliffs below Glacier point as two large blocks. Both blocks accelerated while sliding quickly down a 47° cliff and then fell in a ballistic trajectory about 500 m to a talus slope. The two impacts were 13 seconds apart and created an airblast that uprooted and snapped a thousand trees. Then a cloud of pulverized rock descended from the impact site, abrading remnants of trees and depositing gravelly coarse sand.

Rockfalls Caused by Seismic Shaking

Rockfalls and other landslides have been studied carefully in Yosemite National Park and a detailed inventory of 519 of them has been compiled (Wieczorek, et al., 1992; Wieczorek and Snyder, 2003). Three million people visit the park each year and rockfalls have killed 12 and injured 62 of them. Wieczorek and Jäger (1996) conclude that earthquakes do not trigger most of these rockfall events, but that earthquakes are responsible for most of the landslide volume that now resides in talus accumulations at the base of cliffs. Landslides generated by the 1872 earthquake resulted from strong seismic shaking that emanated from Owens Valley adjacent to the eastern flank of the Sierra Nevada (Figs. 2, 12). Truly spectacular debris slides and rock avalanches were witnessed in the park.

But do sources of earthquake energy that are more than 200 km away disrupt small parts of this granitic landscape that appears so strong? The great San Francisco earthquake of 1906 apparently did not produce rockfalls in Yosemite valley worthy enough to catch the attention of people there. Distant seismic shaking events may generate just a few blocks, which can fall at locations out of view of humans. The crash of falling ice during a winter night sounds very much like falling rocks, making recognition of rockfall events complex.

Some distant earthquakes do indeed cause landslides in the Sierra Nevada. A recent example is the San Simeon Mw magnitude 6.5 earthquake of 21 December 2003, which occurred 270 km southwest of Yosemite valley. This moderate earthquake was felt in Yosemite and even more surprising is that a magnitude 4.1 aftershock on the next day was also felt. Gerald F. Wieczorek (written communication, 26 February 2004) notes that the aftershock coincided with the timing of a debris slide from the upper part of Sentinel Creek in Yosemite Valley. Of course this might have been a delayed response to the main shock of the previous day. In either case an apparently miniscule amount of seismic energy was sufficient to cause part of the landscape to cross a stability threshold—a crossing that was recorded by a landslide.

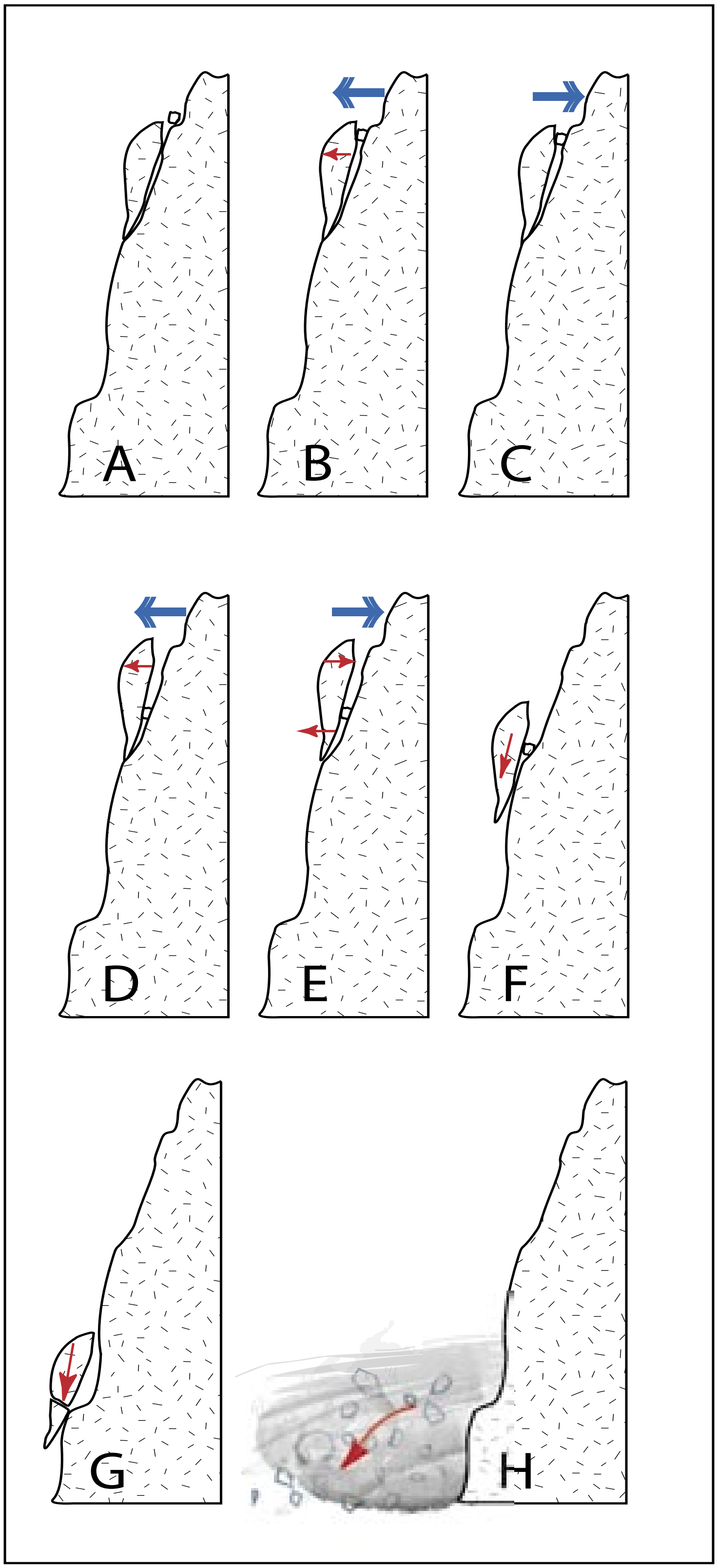

Figure 8 "Seismic rachet" process of generating landslides in an 800 m high glaciated granodiorite cliff with exfoliation joints. Large blue arrows show directions of oscillating seismic wave forces during an earthquake. Small red arrows show directions of movement for a potential landslide block. Concept courtesy of John Tinsley, U. S. Geological Survey.

A. Cliff-face parallel fractures open gradually over a long time span.

B. Seismic rarefaction wave from the right rotates top of block around a basal pivot point and allows blocks and rubble to fall into crack widened by seismic shaking.

C. Seismic compression wave does not close the crack because it is now wedged open by the rock(s).

D. Renewed seismic shaking, perhaps during a subsequent earthquake, further widens the crack and allows rocks to drop further into the fissure. The rock(s) is now below the center of gravity of the potential landslide block.

E. Reversal of seismic-wave energy rotates the landslide block, reducing its basal support.

F. The landslide slides down the cliff face, with underlying loose rocks acting as ball bearings, moving away from the cliff face as it strikes projecting outcrops. Rockfall block(s) becomes ballistic where it shoots over a steeper part of cliff.

G. The accelerating rock mass(es) disintegrate when they fall onto a projecting lower part of the cliff, crushing the brittle block into fragments that range in size from huge rock-fall blocks to sand grains the size of the minerals composing the granodiorite. Seismic-impact waves propagating back up the cliff may trigger additional rockfalls.

H. Landslide movement changes to mainly horizontal when it reaches the valley floor, where it buries trees. Lichens will begin to colonize the fresh rock surfaces after a few years.

Massive granitic cliffs (Huber, 1987) along the sides of glaciated valleys become progressively unstable because of the formation of exfoliation joints and other fractures. Exfoliation joints form roughly parallel to a cliff face when melting of glaciers removes lateral support of the valley walls and the surficial part of massive granitic rock becomes weaker as joints and fractures gradually open. The most recent glaciers of the Tioga glacial advance did not fill valleys with ice to the same level as earlier glacial advances, in part because previous glacial erosion had lowered the floor of Yosemite valley. So the higher parts of the cliffs have had more time to develop fractures and joints. This is where most of the rockfalls originate.

Seismic energy arrives in waves that move landscape elements back and forth, opening and closing cracks in the rock. Climbers scaling cliffs during the 1980 Mammoth Lakes and the 1989 Loma Prieta earthquakes saw rocks and rubble drop into fissures that opened and closed with the passage of seismic waves. This input of seismic energy can dislodge parts of cliffs by the 'seismic-ratchet' process described in Figure 8, causing slabs to fall. Characteristics of individual landslides vary greatly as a function of the height and mass of the landslide source, the steepness of the cliff, and the presence of projecting ledges that can convert big falling blocks into small fragments.

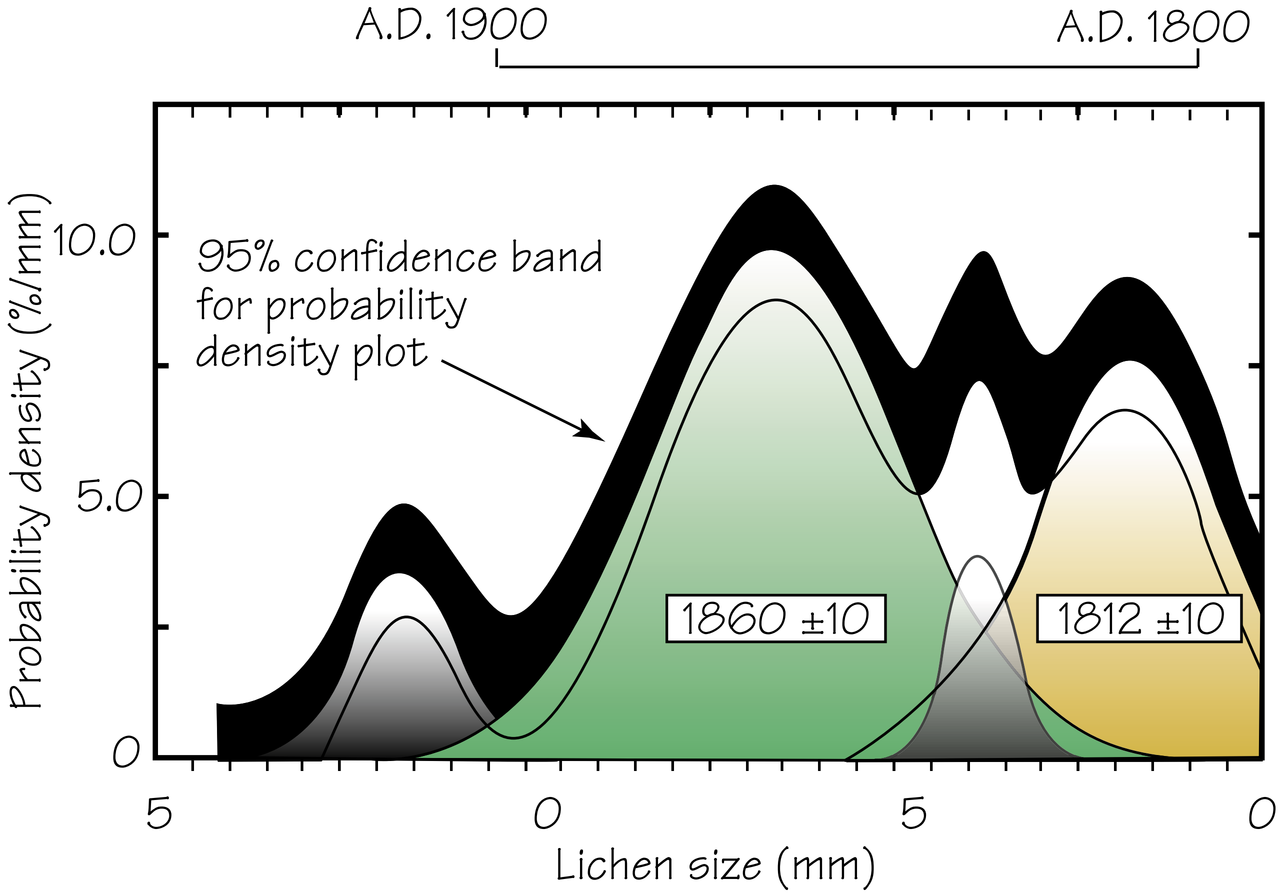

Figure 9 Modeling of lichen-size peaks on rockfall blocks at Middle Brother site reveals two large subpopulations close to the times of the 1857 and 1812 earthquakes on southern San Andreas fault.

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 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

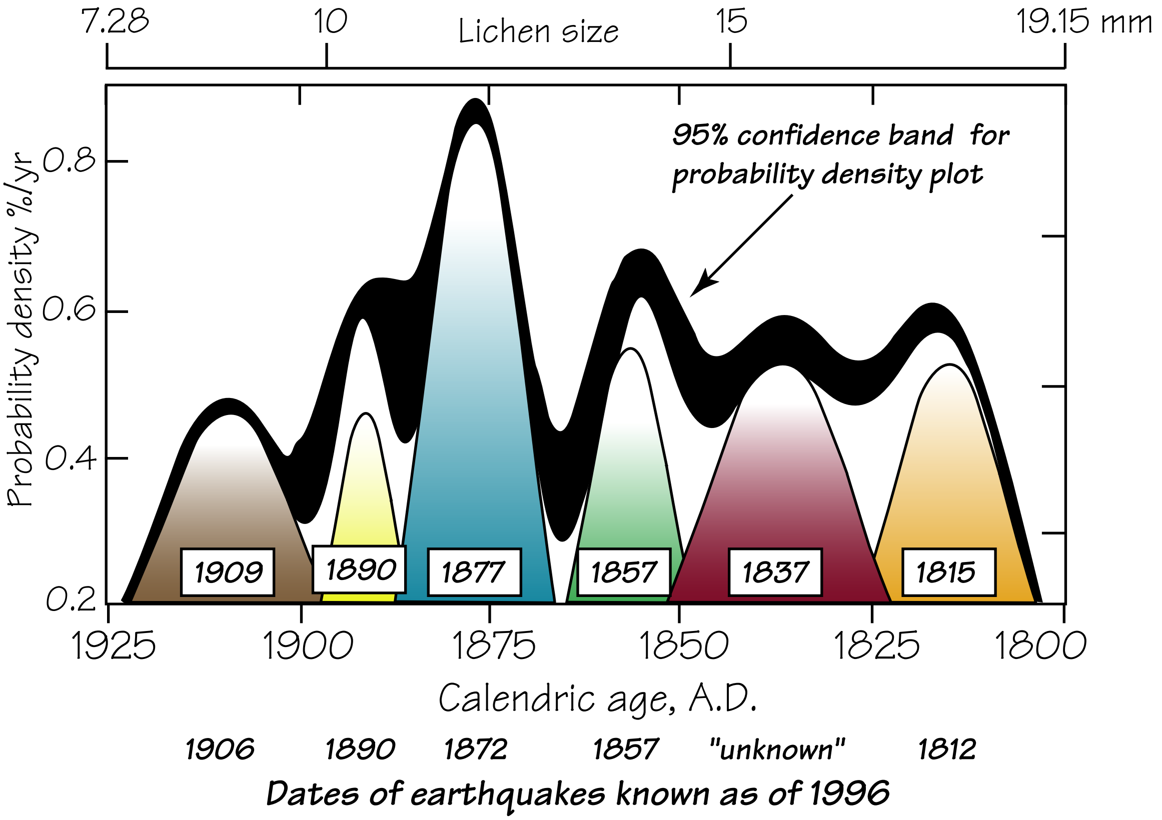

Figure 10 Modeled times of rockfalls for combined dataset of *Rhizocarpon* subgenus *Rhizocarpon* from 10 Sierra Nevada sites are clustered, which requires regional causes. 1872 and 1890 local earthquakes and 1812, 1857, and 1906 are San Andreas fault earthquakes. Five dates have an accuracy of 2.2 ± 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).

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.

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.

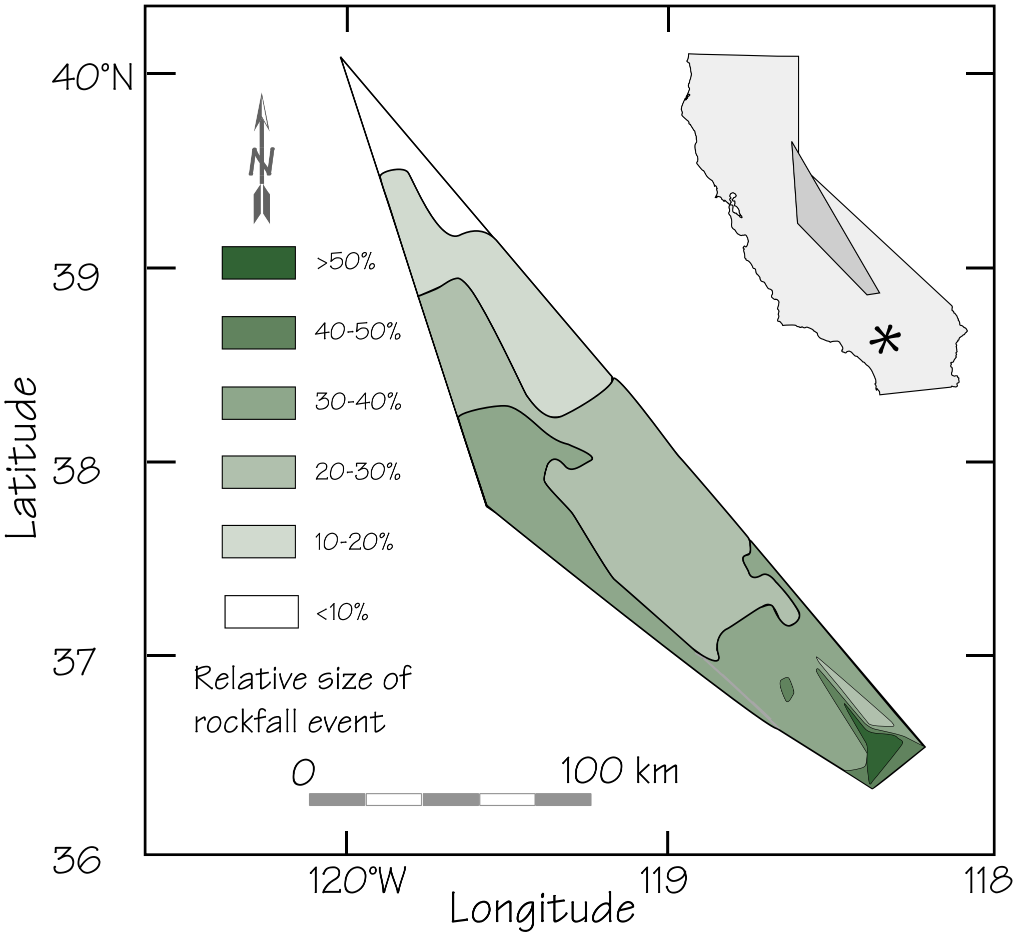

Figure 11 Variation in seismic shaking index for a historic regional rockfall event. The * symbol in the inset map approximates the epicenter of the earthquake of 1812 A. D. generated by the Mojave segment of the San Andreas fault in southern California.

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).

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.

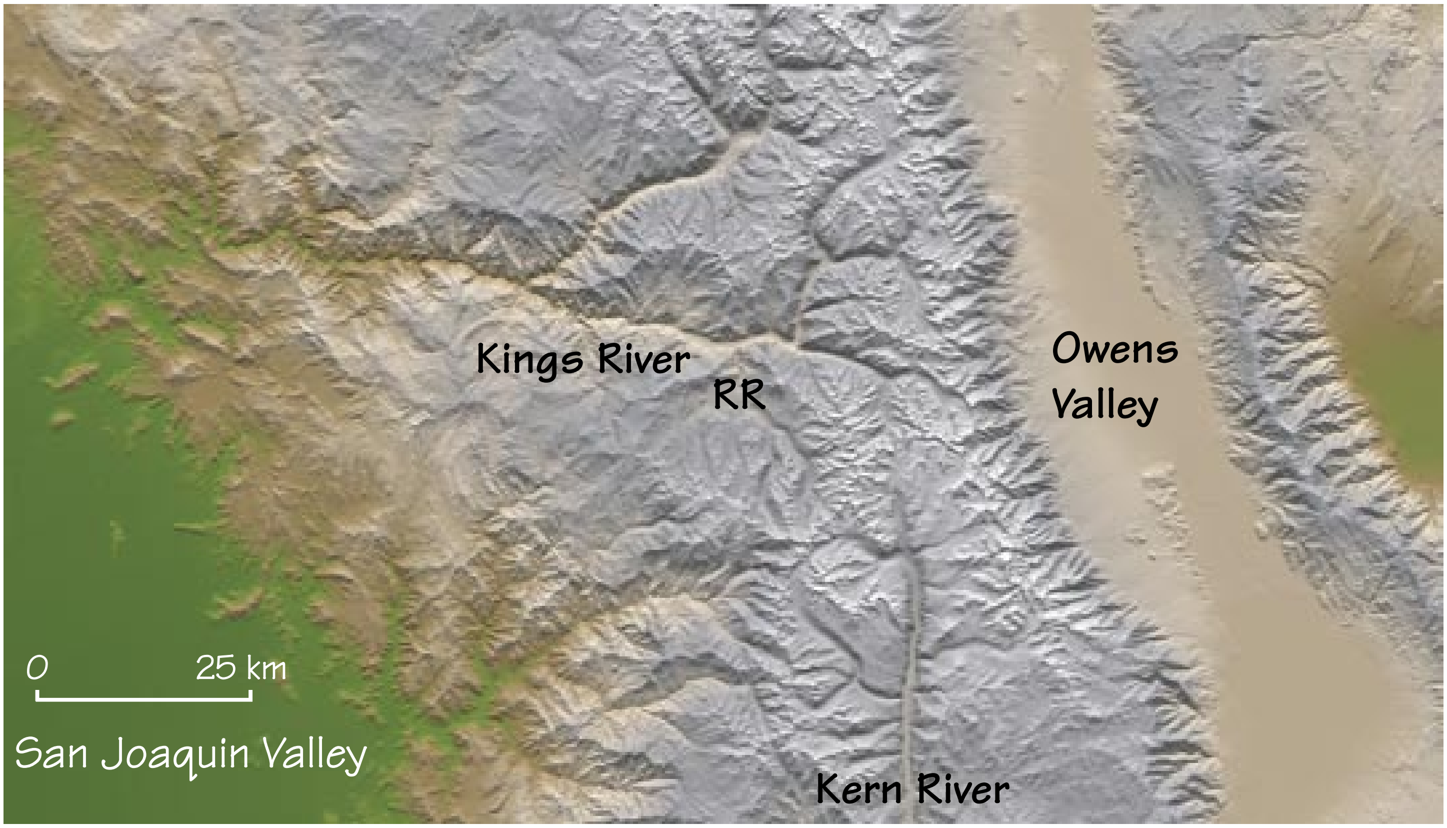

Figure 12 Digital image of the south-central Sierra Nevada. RR is near the mouth of the Roaring River tributary to the South Fork of the Kings River. The different orientations of the cliffs flanking the gorges of the Kern and Kings Rivers may influence rock-fall responses to seismic shaking being transmitted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

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 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.

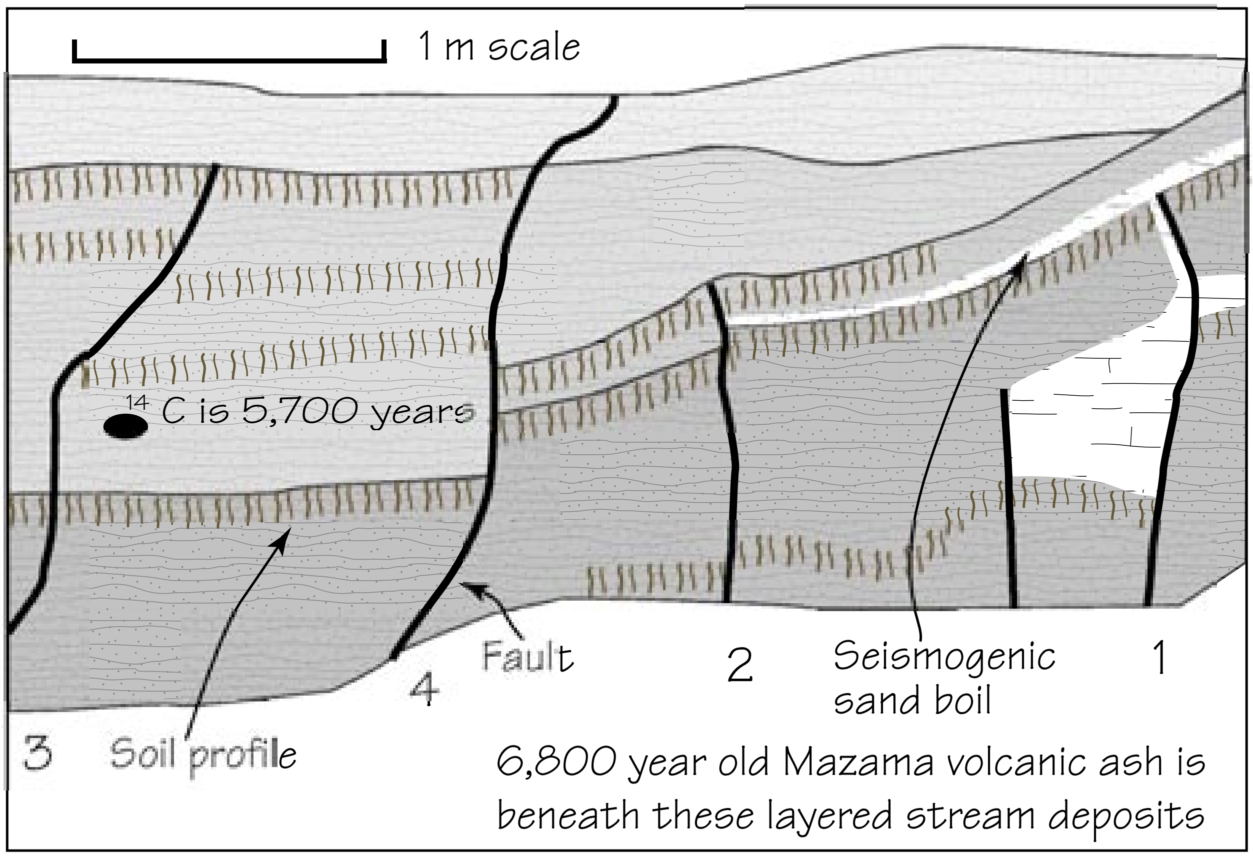

Figure 13 Cross section of a streambank of Long Valley Creek showing displacement of former land surfaces (soil porfiles) by four recent earthquakes on the Honey Lake fault zone in northeastern California. From Figure 4 and text of Wills and Borchardt (1993).

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).

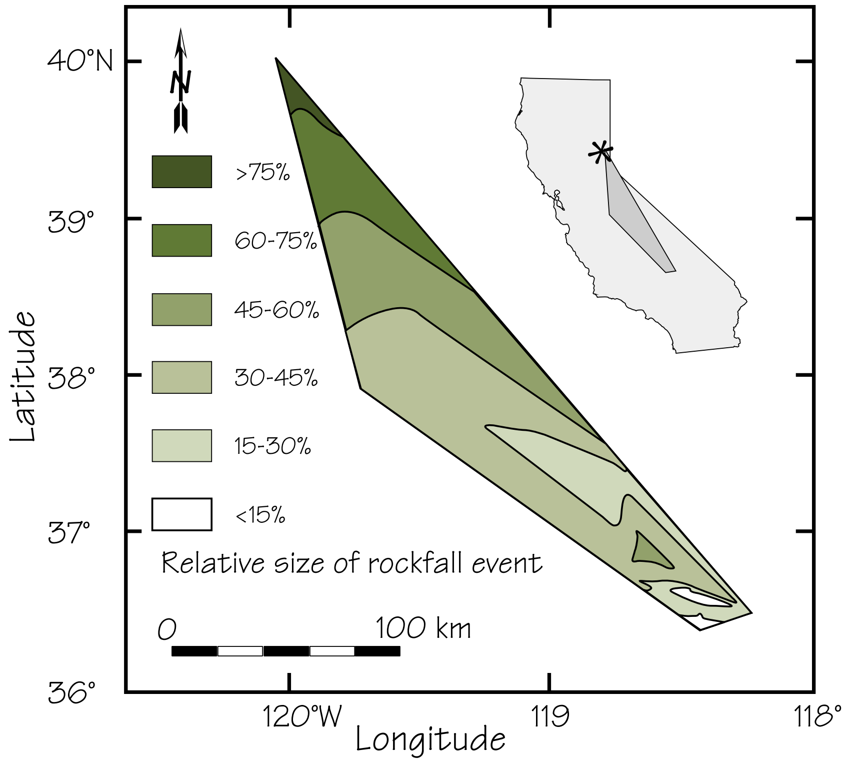

Figure 14 Variation in seismic shaking index for a prehistoric regional rockfall event. The * symbol in the inset map approximates the epicenter of the hypothesized earthquake of 1739 A. D., which may have been generated by the Honey Lake fault zone near the northern Sierra Nevada.

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.

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