Sierra Nevada Earthquake History From Lichens on Rockfall Blocks

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Part 2--Rockfall Processes

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

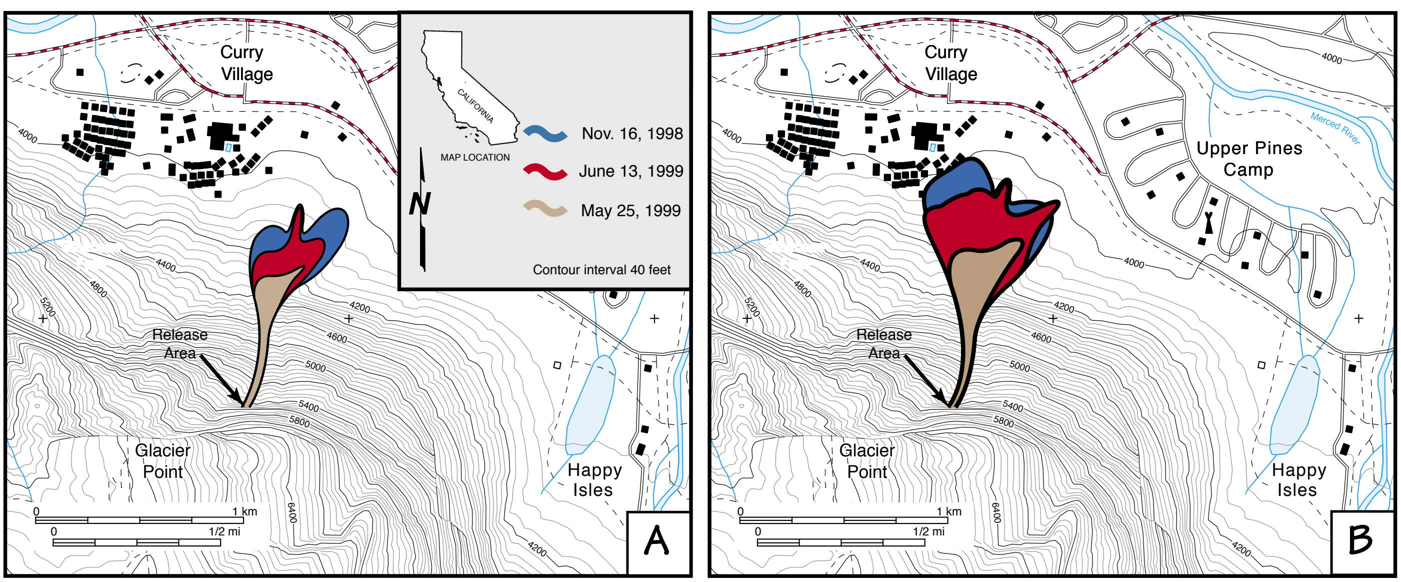

Figure 7 Series of three rockfall events in 6 months below the Glacier Point rock-fall release area near Camp Curry, Yosemite National Park. From Figure 2 of Wieczorek and Snyder, 1999.
A. Maps showing extents of the three rockfalls. Big blocks slid, bounced, and rolled shorter distances than fly rock 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.

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).

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 (Fig 1). 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

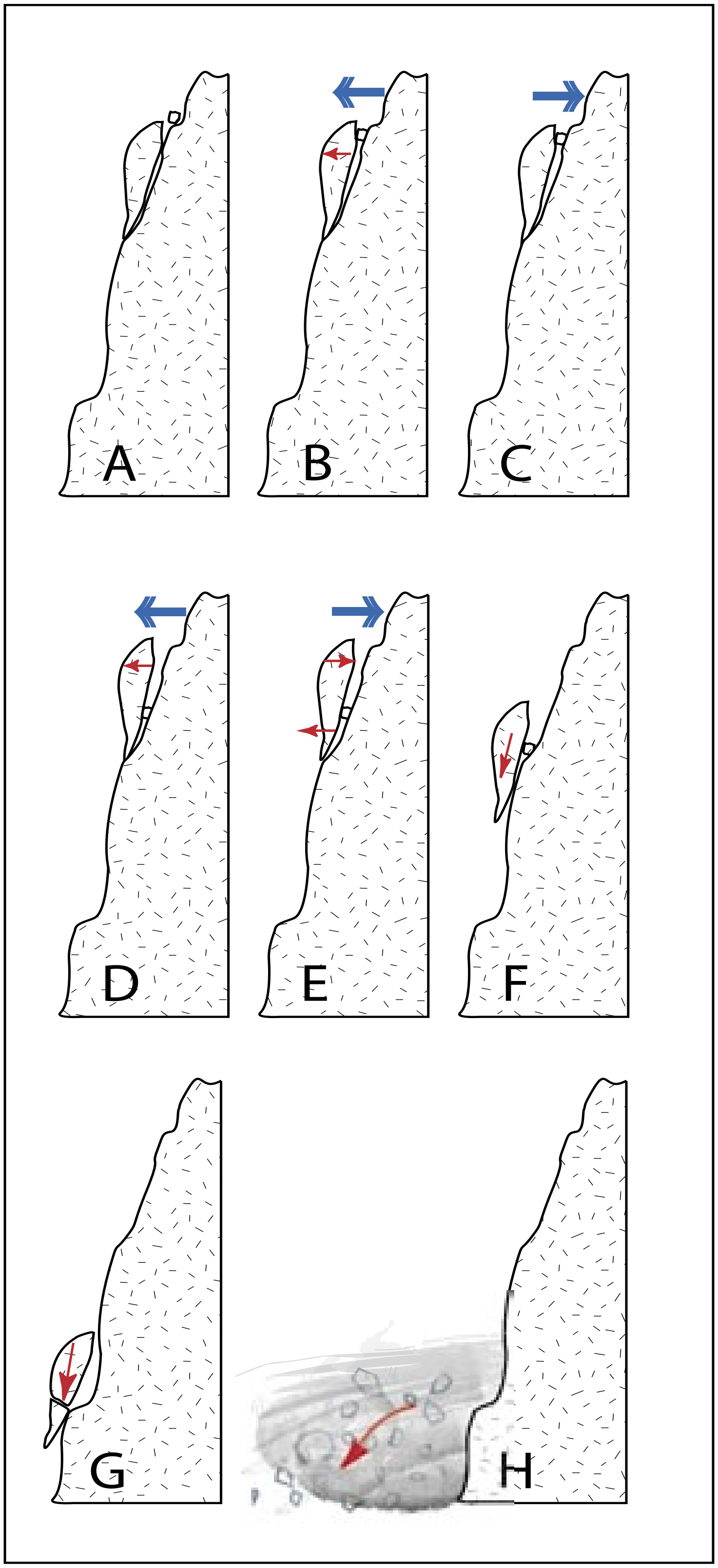

Figure 8 "Seismic rachet" process of generating landslides in an 800 m high glaciated granodiorite cliff with exfoliation joints. Large blue arrows show directions of oscillating seismic wave forces during an earthquake. Small red arrows show directions of movement for a potential landslide block. Concept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

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.

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.

End of Part 2

This story is continued in
Part 3--Earthquake Generated Rockfalls
The introduction is in Part 1

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