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Triggering mechanisms and depositional rates of postglacial slope-movement processes in the Yosemite Valley, California

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Abstract

We examined information collected from 395 reports of slope-movement events during about the past 150 years in Yosemite National Park, central Sierra Nevada, California, to identify the most prevalent types of slope movements and their triggering mechanisms. Rock slides and rock falls have been more numerous than debris slides, debris flows, and miscellaneous slumps. Rock falls have produced the largest cumulative volume of deposits. About half of slope movements had unreported or unrecognized triggering events. Earthquakes and rain storms individually accounted for the greatest cumulative volumes of deposits from recognized triggers of all types of historical slope movements; snowmelt, human activities and freeze–thaw conditions accounted for only a small proportion of the volumes from reported triggers. A comparison of the historical and postglacial average annual rates of deposition from slope-movement processes in a portion of the Yosemite Valley indicates that, during the period 1851–1992, slope-movement processes have been producing about half the average rate of deposits than during the past 15,000 years.

1. Introduction

Using reports of 395 historical slope-movement events from Yosemite National Park (Wieczorek et al., 1992), we set out to quantitatively evaluate the relative frequency of occurrence of different kinds of slope movements and to study the association between historical slope movements and reported triggers. Prehistoric deposits of rocky debris also are prevalent throughout the valley. In the upper part of the Yosemite Valley we compared historical (1851–1992) with postglacial (post-15,000 yr BP) rates of deposition from slope-movement processes.

The relative importance of storms and earthquakes in triggering slope movements and in producing deposits in Yosemite and throughout the Sierra Nevada, California, has been discussed (Whitney, 1868; Matthes, 1930; Muir, 1962; and Rempel, 1983), but never evaluated quantitatively. Quantitative studies of slope movements and their relationships with triggering events are rare (e.g. Jäckli, 1957; Rapp, 1960; Keefer, 1994). An increased incidence of landsliding in Europe has been documented during periods of wetter and colder climate during the Holocene (Starkel, 1966; Grove, 1972). Earthquakes can trigger abundant slope movements in mountainous areas; the 1980 Mammoth Lakes, California, earthquake sequence in the central Sierra Nevada triggered more than 5000 rock slides and rock falls having an estimated total volume of deposits exceeding 10^9 m^3 (Keefer and Wilson, 1989).

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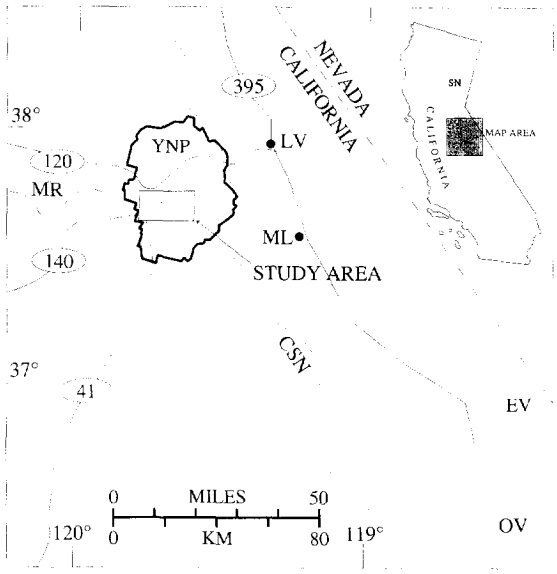


Fig. 1. Location map of the Yosemite Valley study area in California. Abbreviations for localities mentioned in text are as follows: SN, Sierra Nevada; YNP, Yosemite National Park; MR, Merced River; CSN, Crest of Sierra Nevada; LV, Lee Vining; ML, Mammoth Lakes; OV, Owens Valley; and EV, Eureka Valley.

1.1. Physical setting

Yosemite Valley within Yosemite National Park lies in the central part of the Sierra Nevada (Fig. 1), a strongly asymmetric mountain range having a broad western slope and an abrupt eastern escarpment. Beginning during late Cenozoic time, uplift along the faults of the eastern escarpment tilted the western slope into a broad upland surface of moderate relief into which westward flowing streams have incised narrow, steep canyons. Yosemite Valley is in the headward segment of the canyon of the Merced River, which was deepened by glacial erosion. The present valley floor is underlain by up to 600 m of deltaic and lacustrine deposits overlying bedrock (Gutenberg et al., 1956). The valley has very steep rock cliffs, 1000 m high or more, as well as moderately steep slopes mantled with deposits of colluvial soils and rocky talus. Alluvial fans extend on flatter slopes below the talus-mantled slopes toward the Merced River, which meanders along the valley floor on a broad flood plain before exiting the valley through the steep Merced Gorge (Fig. 2).

1.2. Climate

The climate of the Yosemite Valley can be classified as strongly seasonal with respect to both precipitation and temperature, according to seasonality indices of Bull (1991). During January, the mean temperature in the Yosemite Valley is 3°C; during July, it reaches 22°C (NOAA, 1992). Summer in the Sierra Nevada resembles a Mediterranean summer; it is characterized by a warm, dry period interrupted by convective storms that

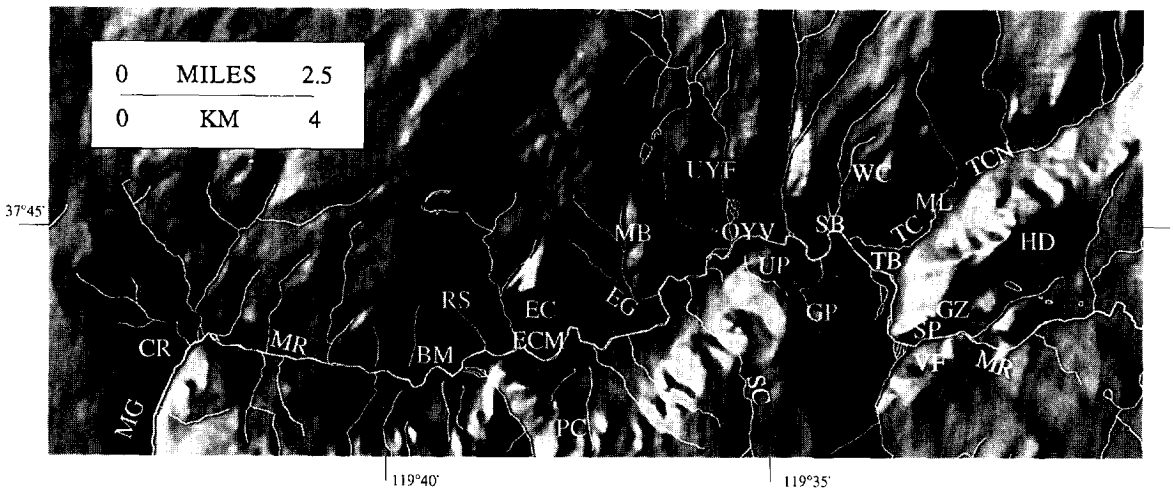


Fig. 2. Shaded-relief map from the U.S. Geological Survey's digital elevation model (DEM) of the Yosemite Valley study area. Abbreviations for localities mentioned in text are as follows: BM, Bridalveil Meadow; CR, Coulterville Road; EC, El Capitan; ECM, El Capitan Meadow; EG, Eagle Creek; GP, Glacier Point; GZ, Grizzly Peak; HD, Half Dome; MB, Middle Brother; MG, Merced Gorge; ML, Mirror Lake; MR, Merced River; OYV, Old Yosemite Village; PC, Profile Cliff; RS, Rockslides; SB, Sugarpine Bridge; SC, Sentinel Creek; SP, Sierra Point; TB, Tenaya Bridge; TC, Tenaya Creek; TCN, Tenaya Canyon; UP, Union Point; UYF, Upper Yosemite Fall; VF, Vernal Fall; WC, Washington Column.

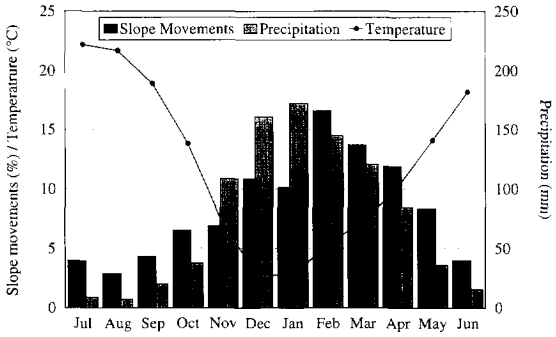


Fig. 3. Monthly temperature, precipitation and percentage of slope movements for the Yosemite Valley. Monthly average temperature (°C) and monthly average precipitation (mm) reported by the National Weather Service at Yosemite National Park Headquarters, Yosemite Valley, California (NOAA, 1992). Monthly percentages of slope movements exclude those triggered by earthquakes and those not attributable to any specific month (reduced sample size of 277). The highest frequency of slope movements occurred during the colder and wetter part of the season from November through April.

can produce short bursts of intense rainfall. The winter can bring large regional storms from the Pacific Ocean with prolonged rain and snow. During the generally colder part of the year between November and April, most of the average annual precipitation of 916 mm falls as rain in the Yosemite Valley (Fig. 3); at higher elevations surrounding the valley, a snowpack usually develops.

Reported slope movements (1851–1992) in Yosemite National Park, excluding those caused by earthquakes, reflect the strongly seasonal climate; the majority (70%) having occurred during the wetter and colder six months of the season between November and April (Fig. 3). A similar seasonal correlation between low monthly temperature, high precipitation, and increased monthly rock falls was noted during the period 1933–1970 in the Fraser Canyon, British Columbia (Piteau, 1977).

1.3. Geology

The Sierra Nevada batholith consists chiefly of Cretaceous granitic rock. In the Yosemite Valley, the most prominent geologic units are the diorite of the Rockslides, El Capitan Granite, Taft Granite, Sentinel Granodiorite, and Half Dome Granodiorite (Calkins, 1985). Jointing has influenced the landforms on both regional and local scales. Huber (1987) illustrated stream courses north of the Yosemite Valley influenced by orientation of major regional joints. On an individual outcrop scale, jointing influences the orientation of cliff faces and the size and shape of blocks, and it thus contributes to their tendency to fall or slide. Mineralogic composition and texture of the rock control the spacing of the joints. Generally, the more siliceous rocks, granite and granodiorite, have more widely spaced joints than the less siliceous rocks. Very steep cliffs composed of granite and granodiorite, such as El Capitan and Half Dome, are largely unjointed and have relatively small talus deposits at their bases. In contrast, the moderately steep area of the Rockslides, composed of fine-grained diorite, is closely jointed, is subject to frequent rock slides, and has accumulated large talus deposits.

1.4. Glaciation record

As in most parts of the Sierra Nevada, the record of glaciation in the Yosemite Valley is incompletely preserved. Only for the last two major glaciations, referred to as the Tioga and the Tahoe, can the extent of ice be reconstructed with confidence; glaciations older than the Tahoe are collectively referred to as pre-Tahoe. Neither the Tahoe nor the Tioga glaciation completely filled the valley; the valley has not been filled with ice for at least 750,000 years (Huber, 1987; Huber et al., 1989). Matthes (1930) mapped the levels of the Tioga glacier on the valley walls and a terminal moraine at Bridalveil Meadow marking the farthest advance of the Tioga glacier. The Tioga glacier in the Yosemite Valley probably had a maximum thickness of about 460 m between Glacier Point and Washington Column (Fig. 2).

The Tioga glaciation peaked between 28,000 and 17,000 yr BP (Bursik and Gillespie, 1993) and evidence suggests that the Tioga ice melted rapidly (Clark, 1976) with deglaciation between 19,000 and 13,200 yr BP (Dorn et al., 1987; Smith and Anderson, 1992). At a relatively low elevation, most of the Yosemite Valley was probably free of glacial ice by about 15,000 yr BP. After the retreat of Tioga ice from the valley, glacial Lake Yosemite formed behind a recessional moraine at the western edge of El Capitan Meadow and extended far up the valley (Matthes, 1930). Slope-movement deposits have been accumulating on the relatively flat valley floor during the past 15,000 years and probably

interfinger with and lie on top of the deltaic and lacustrine sediment that filled glacial Lake Yosemite. Historical retreat of small, high elevation glaciers since the 1870's in Yosemite (Huber, 1987) has corresponded to a warmer and drier climate in the Sierra Nevada (Curry, 1969).

2. Inventory of slope movements

An inventory of slope movements was assembled from 395 accounts of historical slope-movement events (1851–1992) from throughout Yosemite National Park. The inventory includes information on date, location, size-volume, trigger and type of slope movement, as well as types of damage, narrative description, reference(s), and an evaluation of the data quality in some categories. About 250 of these events occurred within the Yosemite Valley and most others were in close proximity, for example, along the Merced Gorge.

Historical reports of slope-movement events are frequently fragmentary or inconsistent, most often the reports concentrate on events that damaged trails and roads, and consequently underestimated the actual number of events. Early accounts by occasional visitors to Yosemite described primarily the larger slope-movement events; more systematic recording of both small and large events began after 1911 with the monthly National Park Service (NPS) Superintendent's Reports that were occasionally supplemented by reports from trail and road maintenance crews. The monthly Superintendent's Reports ended in 1963; subsequent information on slope-movement events was compiled by Jim Snyder, NPS trail foreman. The few eyewitness accounts provided detailed information for some categories; however, other accounts mentioned the occurrence of slope movements without specific details. Because the descriptions of slope-movement events in these accounts varied widely in detail and quality, interpretations were necessary to complete the categorizations. A representative sample of data from the inventory is included in Table 1.

2.1. Types of slope movement

Types of slope movement were classified using the system of Varnes (1978) based on the type of material involved in movement — soil, rock, or debris — and

Table 1
Sample of inventory of slope-movement data from Yosemite National Park (modified from Wieczorek et al., 1992)

Date	Location	Type	Volume (m^3)	Q_{size}	Trigger
1/12/1980	Castle Cliffs	rock fall	2000	2	rain
1/12/1980	Castle Cliffs	debris flows	200	2	rain
1/12–13/1980	Sentinel Rock	rock slide	200	2	rain
5/25/1980	Sierra Point	rock fall	200	2	earthquake
5/25/1980	Cathedral Spires	rock fall	200	3	earthquake
5/27/1980	Glacier Point	rock fall	20	3	earthquake
5/27/1980	Clark Point	rock fall	2	2	earthquake
5/27/1980	Sentinel Creek	rock slide	2000	2	earthquake
5/27/1980	Castle Cliffs	rock fall	8	1	earthquake
5/25–27/1980	North Dome	rock slide	200	3	earthquake
Spring 1980	Half Dome	rock slide	2	3	unreported
10/4/1980	Clark Point	rock fall	200	2	unrecognized
10/6/1980	Yosemite Fall	rock fall	1	1	unrecognized
10/7/1980	Royal Arches	rock slide	20	3	unreported
11/16/1980	Yosemite Falls	rock fall	1500	1	freeze–thaw
Winter 1980–81	Elephant Rock	rock slide	24,000	2	rain
5/??/1981	Glacier Point	rock slide	2	2	unreported
6/10/1982	Yosemite Falls	rock fall	1	0	unreported
10/25/1982	Yosemite Falls	rock fall	38	0	rain
10/26/1982	Yosemite Falls	rock fall	249	1	rain
Winter 1982–83	West Quarter Dome	rock slide	200	3	unreported
Winter 1982–83	Clark Point	rock fall	1	1	unreported
5/20/1983	Sentinel Creek	debris slide	2000	2	unreported
5/1/1984	Glacier Point	rock slide	20	3	unreported

Table 2
Volume characteristics of historical reported slope-movement deposits in Yosemite National Park

	Rock falls	Rock slides	Debris slides	Debris flows	All types of slope movement
Mean volume (m^3)	19,800	1383	525	658	5170
Median volume (m^3)	104	20	200	200	83
Volume range (m^3)	1–600,000	1–100,000	20–2000	20–4500	1–600,000
Sample number	84	247	24	35	395[a]

[a]Sample number of all slope-movement events includes five miscellaneous slumps not separately characterized in this table.

Table 3
Rating of the quality of volume data on slope-movement deposits and estimates of the associated error

Q_{size}	Volume information	Possible error (+ / −)
0	Volume or weight reported	5%
1	Some dimensions reported	25%
2	Vague indication of size	50%
3	No size information given	75%

the dominant type of movement — sliding, flowing, falling, toppling, or a combination thereof. Most accounts either identified the type of slope movement or were sufficiently descriptive so that the type of slope movement could be interpreted based on examination of the form and character of source or deposits. Rock slides (62%) and rock falls (22%) were the most numerous kinds of slope movement recorded in Yosemite National Park; debris flows (9%), debris slides (6%), and earth, debris or rock slumps (1%) were much less common.

Some accounts included volume estimates; for others, the volumes were estimated by Jim Snyder, who as trail foreman, directed the removal of rocky debris that blocked trails. The range, mean, and median of volume for each type of slope movement are listed in Table 2. The system used to evaluate the quality of the reported volume data, Q_{size}, is summarized in Table 3. The distribution of volumes of historical slope-movement deposits (Fig. 4) is influenced by a few exceptionally large events (> 50,000 m^3), as indicated by a relatively low median value of 83 m^3 and a high mean of 5200 m^3. Comparing the percentage of the total cumulative volume of deposits from each type of slope movement, rock falls constituted the majority by volume (82%), with rock slides contributing a relatively minor amount (17%); debris slides, debris flows and miscellaneous slumps, together accounted for only 1% of the total cumulative volume.

Relatively small rock slides consisting of either one or several loose rocks or largely intact blocks of rock are frequent from the steeper cliffs of more closely jointed, weathered rock, such as the diorite of the Rockslides. Rock falls involving transport mostly by falling, with some bouncing or rolling of individual rocks, may account for a few exceptionally large isolated boulders that have travelled beyond the talus slopes and onto the valley floor. Many of the larger rock falls are probably complex rock falls/rock slides, in which the initial rock-fall movement transformed into a rock slide as additional rocky debris was mobilized upon impact by the falling mass.

Rapidly moving debris flows observed following periods of intense rain or rapid snowmelt involved a mixture of water, granitic materials, ranging from boulders and cobbles to sand-sized particles, and occasional organic items, including parts of trees. In the Yosemite Valley, debris flows have left characteristic deposits including bouldery lateral levees and distal snouts.

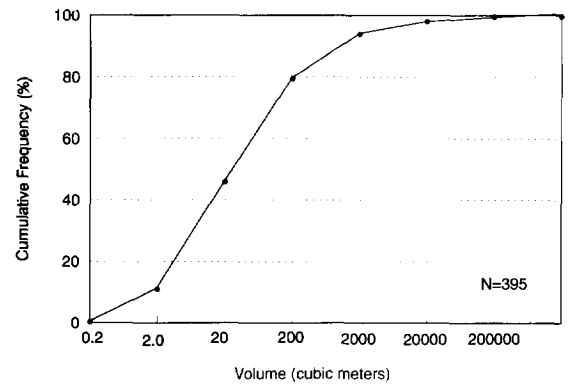


Fig. 4. Frequency distribution of the volume of historical slope-movement deposits. The volumes of most slope-movement events ranged from 2 to 2000 m^3, the median volume of all reported slope-movement deposits was 83 m^3.

Table 4
Large rock falls within the Yosemite Valley. The largest rock falls are predominantly of prehistoric age. Triggering events identified for historical rock falls. Data from Wieczorek et al. (1992)

Location	Estimated volume ($\times 10^6$ m^3)	Date/Trigger
Mirror Lake	11.37	Prehistoric
El Capitan Meadow	3.76	Prehistoric
Old Yosemite Village	0.87	Prehistoric
Tenaya Bridge	0.63	Prehistoric
Middle Brother	0.60	3/10/1987; unrecognized
Middle Brother	0.50	Prehistoric
Sugarpine Bridge	0.43	Prehistoric
Profile Cliff	0.20	1857; unreported
Old Yosemite Village	0.20	3/26/1872; earthquake
Coulterville Road	0.10	4/3/1982; rain storm

Debris-flow deposits along the steep channels of ephemeral and permanent streams, e.g. Eagle and Sentinel Creeks, are prevalent below the cliffs and extend onto alluvial fans. Debris slides incorporate less water than debris flows and therefore are generally less mobile than debris flows. Although debris-slide deposits are common below the steep valley walls, they do not extend as far onto the alluvial fans as debris-flow and fluvial deposits.

In the Yosemite Valley, several large deposits of prehistoric slope movements (Table 4) have accumulated over the last 15,000 years, significantly larger than those deposits from historical events. A massive (11.4×10^6 m^3) prehistoric rock fall from cliffs behind Washington Column backed up Tenaya Creek to form Mirror Lake (Fig. 5).

2.2. Triggering events and mechanisms

A few slope movements were directly observed by eyewitnesses to be closely associated with storms or earthquakes; however, in many accounts, although the slope movement was not observed as it occurred, the triggering event was reported to be an associated coincident event, such as an earthquake, rain storm, period of rapid snowmelt, or period of extreme freeze–thaw conditions, which is inferred to be the triggering factor (Table 1). In many accounts no triggering event was reported. In a few cases, the slope movement was closely observed, but no trigger was recognized; these events with an unrecognized trigger, suggest that additional triggers exist, but are difficult to recognize. Gradual processes that contribute to weakening slopes, such as exfoliation, weathering of rock, and root penetration are mentioned in some descriptions of the conditions at sources of slope movements where no obvious trigger was apparent. The distinction between unreported

Fig. 5. Photograph of prehistoric rock-fall deposit (dashed line) from cliffs behind Washington Column (left) that blocked Tenaya Creek and formed Mirror Lake. The valley in the foreground is about 1.25 km across. Half Dome (partially visible on the right) is about 1000 m above the valley floor. View to the northeast toward Tenaya Canyon.

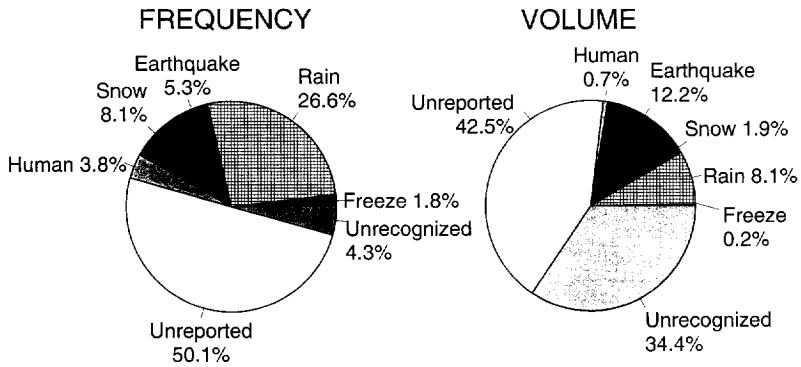


Fig. 6. Types of triggering mechanisms for slope movements by frequency of occurrence (%) and proportion (%) of cumulative total volume of all slope-movement deposits.

and unrecognized triggers made here was not included in the original inventory (Wieczorek et al., 1992), but is included in the sample of inventory data in Table 1.

The importance of different triggering events was examined by comparing both frequency and cumulative volume of slope movements from different triggers. Numerically about half (50.1%) of the accounts gave no reported triggering event, which accounted for slightly less than half (42.5%) of the cumulative volume of deposits from all slope movements (Fig. 6). Unrecognized triggers accounted for a minor number of events (4.3%); however, the percentage of the cumulative volume for unrecognized triggers was notably greater (34.4%), skewed by the inclusion of one unusually large event. Of the recognized triggering events, rain storms (26.6%) and rapid snowmelt (8.1%) triggered more numerous slope movements than earthquakes (5.3%); however, earthquakes were responsible for a greater cumulative volume (12.2%) than these other two individual triggers. Freeze–thaw conditions accounted for only a very small proportion of volume (0.2%) of deposits from documented triggers.

Storms and rapid snowmelt

Infiltration from intense rain or from a rapidly melting snowpack can increase ground-water levels, which creates temporarily perched aquifers in slopes of colluvial or residual soils or raises cleft water pressures within jointed bedrock masses; infiltration and buildup of pore-water pressures is an important mechanism for triggering slope movements (Reid et al., 1988; Wilson and Dietrich, 1987; Mathewson et al., 1990). The role of cleft pressure in triggering slope movements was suggested at a rock-fall site along the trail to Vernal Fall. On March 6, 1986, inspection of the release point of rock falls that occurred on February 7, 1986 (104 m^3) and on February 13 (415 m^3) revealed a rock overhang, defined by intersecting joints and fresh semi-arcuate fractures. A 3 to 5 m long, fresh crack in rock was detected about 20 m upslope from the overhang. This crack, having about 0.5 cm of extensional opening, was parallel to a deeply weathered joint, 0.5–1.0 m wide, filled with gruss and pine needles. During an intense rain storm on March 8, which dropped 98 mm of rain within 24 hr, a rock mass of about 690 m^3, extending from the previous release point to the wide joint, broke loose and fell, covering about a 150 m stretch of the trail with rocky debris. An increase in cleft water pressure in the joint from local drainage was the most likely trigger for the rock fall.

Rainfall intensity and duration affected the abundance of slope movements triggered by storms in Yosemite. On a plot of storm total and 1 day maximum rainfall (Fig. 7), four winter storms that triggered abundant (five or more reported) slope movements stand out from the cluster of almost all other storms that triggered less numerous slope movements, suggesting a rainfall threshold for triggering abundant slope movements. Each of these four large winter storms lasted several days, covered much of northern and/or central California, and included prolonged heavy rain with maximum 1-day rainfall exceeding 100 mm and storm rainfall totals of about 300 mm or greater. Short, locally intense convective storms, which are most common during the summer season, have triggered few slope movements. For example, in the late afternoon of July 14, 1992, a short downpour of 25 mm

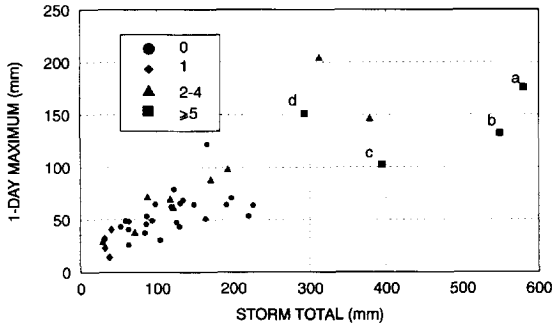


Fig. 7. Plot showing numbers of reported slope movements in the Yosemite Valley and vicinity in relation to storm total and 1-day maximum rainfall. Symbols representing number of reported slope movements depicted according to inset. Precipitation data from the Yosemite Valley covers period from 1903 to 1992. Four large winter storms that brought prolonged heavy rainfall which triggered abundant (5 or more reported) slope movements were: (a) December 12–19, 1955; (b) February 11–19, 1986; (c) January 9–18, 1980; and (d) December 9–12, 1937. Storm totals were compiled from consecutive days with rainfall exceeding 2.54 mm.

within one hour (36 mm one-day storm total) in the Yosemite Valley triggered only one reported debris flow from a recently burned area that partially buried two cars with gravelly sand in a parking lot near the Ahwahnee Hotel.

Earthquakes

Earthquakes felt in the Yosemite Valley usually have epicenters in western coastal California or along the eastern flank of the Sierra Nevada. Historically nine earthquakes (not including earthquake aftershocks) have been felt and reported in the Yosemite Valley; shaking has been strong enough to trigger rock falls and slides during four of these earthquakes and one aftershock (Table 5).

The March 26, 1872, Owens Valley (Inyo) earthquake, with an estimated Richter surface-wave magnitude (M_s) of 7.6–8.0 (Goter et al., 1992, 1994), triggered abundant rock falls and slides throughout much of the southern Sierra Nevada (Whitney, 1872a, Whitney, 1872b; Chalfant, 1933). In the Yosemite Valley, approximately 180 km northwest of the epicentral area in the Owens Valley, the earthquake triggered five reported rock falls; an aftershock triggered one additional rock slide. Muir (1962) felt the earthquake and witnessed a large rock fall from north of Union Point, which reached the valley floor behind Hutchings' Hotel in the Old Yosemite Village (Wieczorek et al., 1992).

The May 25–27, 1980, Mammoth Lakes earthquake sequence, with four earthquakes measuring $M_s = 6.0$–6.2, triggered several thousand rock slides and falls, mostly near the epicentral region on the eastern flank of the central Sierra Nevada (Harp et al., 1984). In the Yosemite Valley, the earthquakes triggered nine rock slides and falls; the farthest slope movement initiated from the rim of the Merced Gorge, approximately 71 km west of the epicenter. The May 25 shock sent a rock fall from the crest of the narrow ridge between Sierra

Table 5
Description of earthquake effects in the Yosemite Valley. Eyewitness descriptions are indicated by quotes

Earthquake Date[a]	Epicenter location (distance to Yosemite Valley, km)	Magnitude[b]	Earthquake effects	Volume deposits (m^3)
1. 3/26/1872	Owens Valley, CA (180)	7.6–8.0	5 rock falls; 1 rock slide[c]	242,000
2. 12/20/1932	Cedar Mountain, Nevada (177)	7.2	"rock slides"	2
3. 5/25–27/1980	Mammoth Lakes, CA (71)	6.0, 6.1, 6.1, 6.2	6 rock falls; 3 rock slides	2850
4. 5/2/1983	Coalinga, CA (202)	6.7	"felt very strongly"; no rock falls	none
5. 3/31/1986	Cienaga, CA (198)	5.7	"strongly felt" "buildings swayed"; no rock falls	none
6. 7/21/1986	Chalfant Valley, CA (103)	6.5	"felt very strongly"; no rock falls	none
7. 10/23/1990	Lee Vining, CA (46)	5.8	1 rock fall; 3 rock slides	578
8. 5/17/1993	Eureka Valley, CA (165)	6.0	"felt by some"; no rock falls	none
9. 9/12/1994	Gardnerville, Nevada (100)	6.3	"felt by nearly everyone"; no rock falls	none

[a]Date is given as mm/dd/yyyy. Earthquake numbers are used in Fig. 8.
[b]Magnitude is Richter surface-wave magnitude (M_s).
[c]Rock slide during aftershock of Owens Valley earthquake (3:30 am, 3/26/1872).

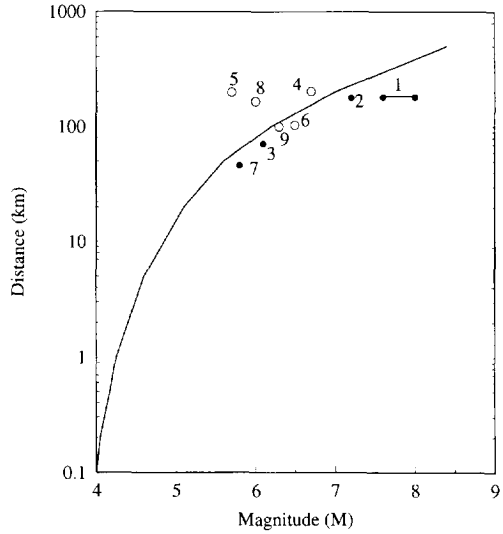


Fig. 8. Distances from the epicenters of earthquakes (1) to the farthest rock slides or falls triggered in Yosemite Valley (dots) or (2) to the center of Yosemite Valley for earthquakes felt in Yosemite Valley that did not trigger slides or falls there (circles). Numbers refer to earthquakes listed in Table 5. Solid curve is Keefer's (1984) upper bound from 40 historical worldwide earthquakes that triggered slides or falls.

Point and Grizzly Peak that severed the Sierra Point Trail in several places, snapping off trees at their bases, obliterating the trail in a mass of boulders and seriously injuring two hikers (Wieczorek et al., 1989).

Whether earthquakes trigger slope movements in the Yosemite Valley depends on earthquake magnitude and distance of epicenter from the valley, as well as local geologic site conditions. To examine the effect of earthquake magnitude and distance on triggering slope movements in Yosemite, we used the procedure of Keefer (1984), who developed curves representing the upper bound of the maximum distance to different types of landslides in historic worldwide earthquakes of different magnitudes. The solid curve on the plot of earthquake magnitude versus distance (Fig. 8) is Keefer's (1984) historical limit for disrupted slides or falls based on his compilation of data from 40 worldwide earthquakes. For earthquakes felt in the Yosemite Valley (Table 5), we plotted the earthquake magnitude and distance from epicenters to the Yosemite Valley. Earthquakes that triggered rock falls and slides (disrupted slides and falls, according to terminology used by Keefer (1984)) in the Yosemite Valley are shown as solid circles and earthquakes that did not are represented as open circles (Fig. 8). The distribution of Yosemite data agrees with Keefer's (1984) historical upper limit for disrupted slides or falls triggered by earthquakes from worldwide data. This agreement is valid despite the fact that two earthquakes plot below Keefer's (1984) curve, because the curve is an upper limit for earthquakes that triggered landslides and not a threshold separating earthquakes capable of triggering slope movements.

Freeze–thaw conditions

Repeated freezing and thawing of water in joints can progressively weaken a rock mass by small incremental movements that displace and destabilize blocks. Freezing of water in joints can also block drainage paths, resulting in build-up of cleft pressures and trigger slope movements (Lee et al., 1994). In the mountains of Scandinavia, Rapp (1960) observed that rock falls have a frequency maximum in May and June with thawing after frost cycles. In Norway (Bjerrum and Jorstad, 1968) and in Canada (Luckman, 1976), a high rock-fall frequency is attributed to triggering by freeze–thaw activity during spring and autumn, when the temperature fluctuates around the freezing point. The daily pattern and frequency of rock-fall activity varies markedly with slope aspect, and from site to site (Gardner, 1969, 1971; Luckman, 1976). In Yosemite, few reports suggest freeze–thaw as probable triggering events; however, the freeze–thaw process may weaken sites for subsequent failure by other triggering events, such as rain storms or earthquakes.

At 12:06 p.m. on November 16, 1980, a thin, tall 1500 m^3 flake of rock broke loose and fell from a southeast-facing rock wall above the trail to Upper Yosemite Fall where it switchbacks through a narrow, steep canyon. The 3 m thick flake that failed was defined by regular, closely spaced joints. The ensuing rock-fall avalanche destroyed about 800 m of trail, killed three hikers, and injured another seven. The minimum temperature during the three preceding days had fluctuated above and below freezing, and it had rained several days before. The rock pendent above the trail had been heard cracking the previous day, but the noise was mistaken for gunfire. Half an hour before the rock broke off, more apparent "shots" were heard by hikers. Subsequent inspection of the release point on the rock wall revealed patterns of roots previously behind the flake indicating that water probably had access through the jointed rock mass and that ice could have wedged

behind the flake. The freeze–thaw process is the most likely triggering event because the rock fall occurred after several days of rain and temperatures had fluctuated above and below freezing and there were no other apparent triggering events.

Unrecognized triggering events

Although numerous slope movements were reported without triggering events, on a few occasions, eyewitness observers watched slope movements occur but failed to recognize or identify a triggering event. On March 10, 1987, without an apparent triggering event, a large rock fall from the face of Middle Brother spread rapidly across the talus cone, covered Northside Drive, and sent a few boulders across the Merced River (Fig. 9). Another large rock fall occurred later that day. The combined volume of these two rock falls was an estimated 600,000 m^3, the largest reported historical event. Many smaller rock falls from Middle Brother had begun on March 8. During and a few days preceding March 8–10, the weather was dry and lacked extreme temperature variations that might otherwise be associated with freeze–thaw cycles or rapid snowmelt. Likewise, no earthquakes were detected during this period. The large size of this rock fall affected the distribution of the volume of deposits caused by different triggering events, to the extent that unrecognized triggering events accounted for a significant portion (34.4%) of the cumulative volume of slope-movement deposits.

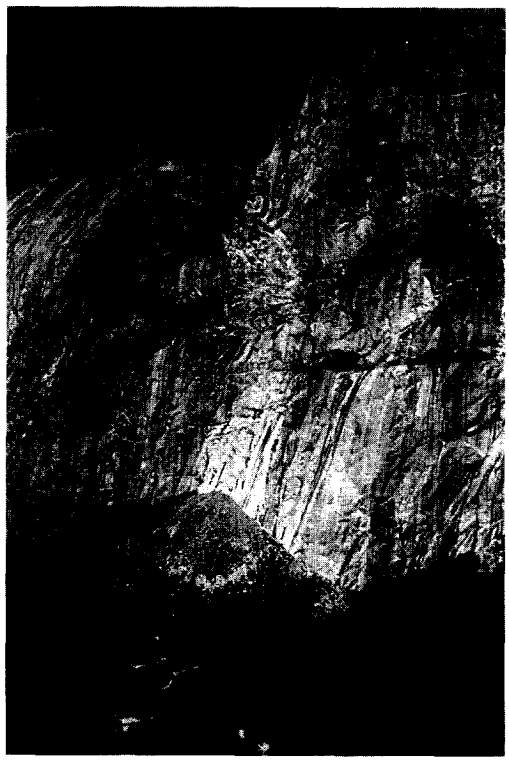


Fig. 9. Photograph of Middle Brother rock fall with talus cone extending to meander of the Merced River on the valley plain in foreground. The rock fall of March 10, 1987 covered a large portion of the talus cone approximately 500 m wide, blocked the Northside Drive, and reached the Merced River. The top of Middle Brother is about 900 m above the valley floor. Photograph taken May, 1994.

Several reasons may account for the abundance of unreported (and unrecognized) triggering events. The delayed effect of earthquake shaking in weakening rock masses and accelerating the rate of slope movements in the months, years, or decades following an earthquake could not be evaluated. Geologic processes including chemical weathering and exfoliation can gradually weaken a rock mass to the point of failure. Removal of lateral support following retreat of glacial ice could cause redistribution of internal stresses in the valley walls with consequent strain (Swolfs et al., 1974). Unloading of a rock mass can open joints or fractures weakening the rock mass. Because of the time dependent nature of glacial unloading (Nichols, 1980), the frequency of large rock falls could have been greater during and immediately following deglaciation in the Yosemite Valley, as proposed for the Canadian Rockies (Gardner, 1980) and in Scandinavia (Rapp, 1960).

3. Depositional rates

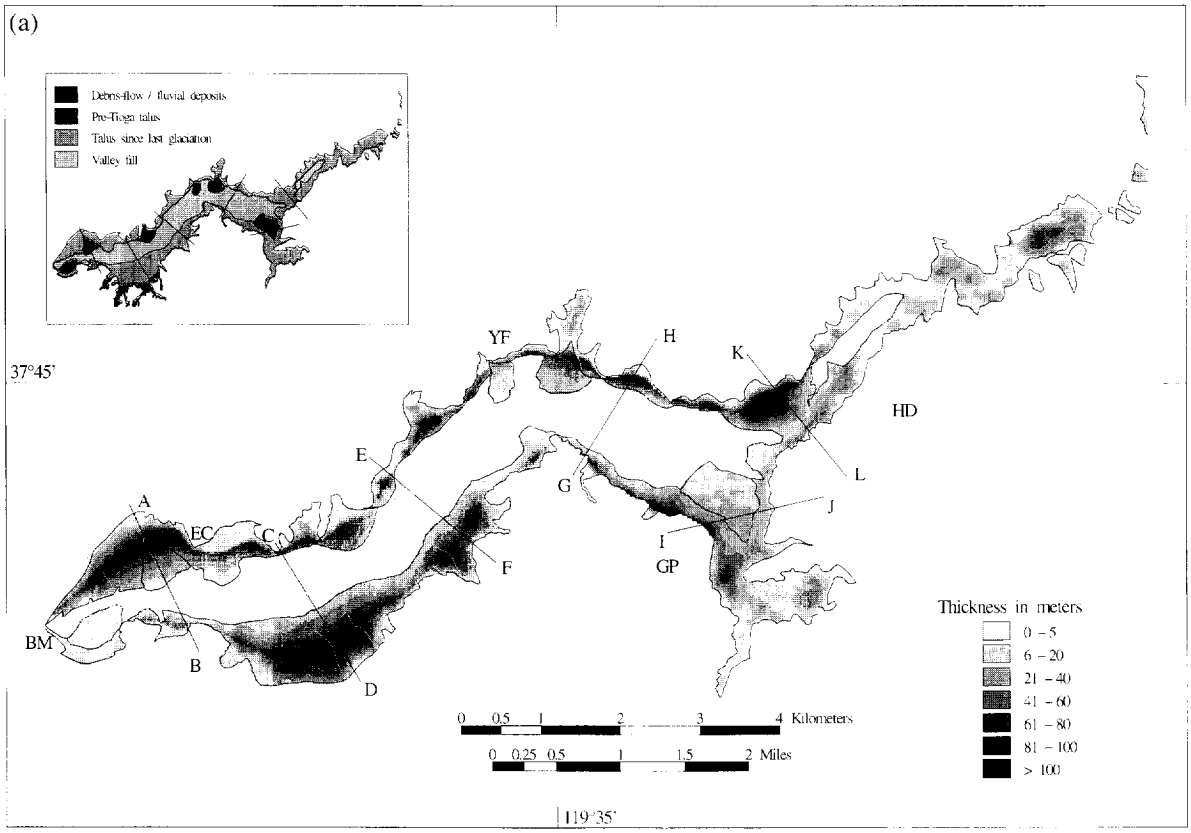
3.1. Postglacial rate for the last 15,000 years

We developed methods to assess postglacial and historical rates of deposition from slope movements in a portion of the Yosemite Valley. A geographic information system (GIS) was used to help estimate the volume of postglacial deposition from slope movements in the upper part of Yosemite valley, from Bridalveil Meadow to the eastern end of Tenaya Canyon. Matthes (1930, plate 29) mapped "rock waste shed from cliffs" in addition to "coarse rock waste, produced by torrent action"; however, the problem remained to evaluate the thickness and volume of these deposits. Deposition from slope movements over the valley floor has occurred during approximately the last

15,000 years since glacial retreat and infilling of glacial Lake Yosemite. The volume of these deposits removed from the Yosemite Valley by stream erosion was assumed to be negligible because of the relatively flat gradient of the Merced River in the upper part of the valley.

For calculating the volume of slope-movement deposits, three digital elevation models (DEMs) were needed: one of the present topography, a second depicting the underlying bedrock topography, and a third representing the hypothetical datum of a flat valley level soon after filling of glacial Lake Yosemite. The present topography was available from a U.S. Geological Survey Level 3 DEM with 30-m spacing. The bedrock topography was gridded using a minimum tension algorithm of Earthvision (a GIS software program marketed by Dynamic Graphics) based on the elevation values of the digitized seismic contours of bedrock (Gutenberg et al., 1956) and the present topography of bedrock above the level of deposits mapped by Matthes (1930). The valley-level datum was represented by a DEM that was interpolated based on the elevation values of the valley plain. Map calculation procedures available in GRASS (a public domain GIS software program developed by the U.S. Corps of Engineers) were used to subtract the gridded surfaces, resulting in a representation of the thickness of slope-movement deposits (Fig. 10a). The total volume of deposits resulted from multiplying the thickness by the size and number of grid cells. No volume corrections were made to account for void ratios of deposits.

The thickness of slope-movement deposits in the Yosemite Valley is depicted in several cross sections (Fig. 10b); deposits from some large individual prehistoric slope movements exceed 100 m in thickness. The combined volume from all slope-movement deposits was 2.83×10^8 m^3, including both "rock waste from cliffs" (2.57×10^8 m^3) associated with rock falls, rock slides, and debris slides and a lessor amount to debris "torrents" (0.26×10^8 m^3) corresponding principally



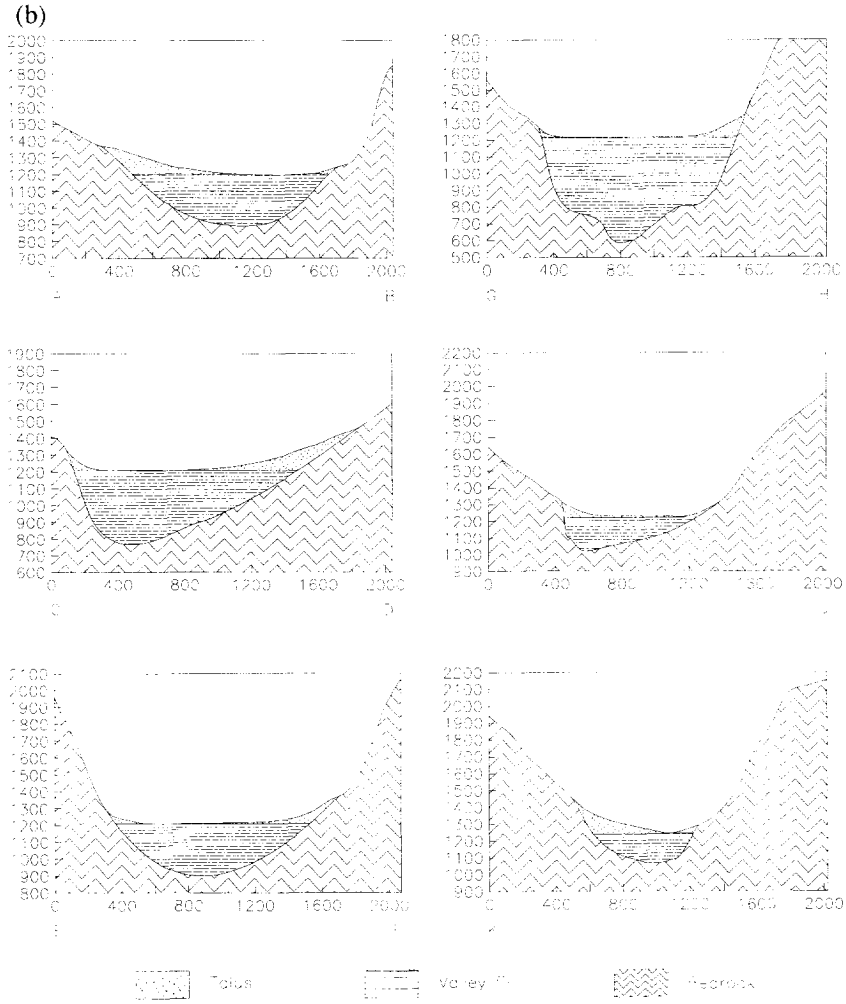


Fig. 10. Thickness of postglacial slope-movement deposits in the Yosemite Valley. Abbreviations for localities are as follows: BM, Bridalveil Meadow; EC, El Capitan; GP, Glacier Point; HD, Half Dome; YF, Yosemite Fall. a) map showing thickness of slope-movement deposits and locations of cross sections; inset map shows debris-flow/fluvial fan deposits, pre-Tioga talus, slope-movement deposits (talus) since last glaciation, and deltaic and lacustrine valley-fill sediments; and b) cross sections (with no vertical exaggeration) showing slope movement deposits (talus), valley fill sediments, and bedrock. Cross-section K–L located near Mirror Lake rock-fall deposit indicates a thickness of more than 100 m.

to debris flows. If as assumed these deposits accumulated on the valley floor during the post-Tioga glacial period of the last 15,000 years, then the average annual depositional rate is 1.89×10^4 m^3/yr.

The accuracy of estimating an average postglacial depositional rate depends on possible errors associated with both measuring the volume of deposits and with assessing the length of time that the valley has been free of ice. The accuracy of volume measurement depends upon (1) the seismic reflection technique employed to locate the bedrock beneath the deposits, (2) the DEMs used to represent the three topographic surfaces, and (3) the digitization of the geologic contacts used to distinguish the slope-movement deposits. The depth of the bedrock discontinuity varied by 20% possible error associated with the seismic reflection technique according to Gutenberg et al. (1956). The DEMs that were used have a mean error of 7 meters in elevation at any point which is not systematic from point to point within the grid. Although errors associated with DEMs do not easily provide a range of volummetric error, it is presumed to be small. Digitization

of the geologic contacts was done within an accuracy of 1 mm representing a precision of 24 m (horizontal); the volummetric error introduced by this potential error was calculated. The combined volummetric errors associated with (1) and (3) above resulted in volumes ranging from 2.53 to 3.25×10^8 m^3. If deglaciation of the Yosemite Valley occurred at either 19,000 or 13,200 yr BP, rather than at 15,000 yr BP, then the annual depositional rate could range from 1.33 to 2.46×10^4 m^3/yr.

3.2. Historical rate (1851–1992)

An average historical rate of deposition was calculated by summing the volumes of historical slope movements (1851–1992) within the same portion of the Yosemite Valley for which the postglacial rate was evaluated. An average annual depositional rate of 0.93×10^4 m^3/yr was determined for the last 142 years, about 50% lower than the average postglacial rate. If the possible errors (Table 3) associated with the reported volumes are considered, then the historical rate of deposition ranges from 0.57 to 1.28×10^4 m^3/yr.

Although several reasons could be suggested for the difference between the postglacial and historical rates, no definitive evidence is available to account for the different rates. There is no reason to believe that either rate has remained constant; the relatively short lower historical average rate may not be significantly different from the normal fluctuations of the prehistoric rate over the past 15,000 years. The prehistoric rate was possibly higher immediately following deglaciation because of glacial unloading and weakening of the valley walls. More than one large earthquake could have significantly influenced the postglacial rate, but no paleoseismic evidence is available for this region. The lower historical rate could possibly correlate with the generally warmer and drier climate that has been noted in the Sierra Nevada during the last 90 years.

4. Summary

In the Yosemite Valley, rock falls and rock slides have been historically more numerous and have larger cumulative volumes of deposits than debris slides, debris flows and other types of slope movement. Although in about half of the reports, the triggering event for slope movement was either unreported or unrecognized; when triggering events were identified, more slope movements were triggered by large winter rain storms, rapid snowmelt, and earthquakes than by freeze–thaw conditions or human activities.

Earthquakes accounted for the greatest cumulative volume of slope-movement deposits from reported triggering events. The historical record of seismically induced rock falls and slides from earthquakes in the Yosemite Valley fits within previously observed worldwide upper bounds of earthquake magnitude and distance for triggering similar types of slope movements. Large regional winter storms, with characteristically high daily rainfall and storm total, have the potential for triggering abundant slope movements.

In the Yosemite Valley, the largest individual prehistoric slope-movement deposits are significantly larger than most historical deposits. The historical average rate of deposition in the Yosemite Valley from 1851 to 1992 has been about half that of the average postglacial rate during the past 15,000 years. No definitive evidence is available to explain the difference in average postglacial and historical rates.

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