Geological Society of America
Reviews in Engineering Geology, Volume XV
2002

Catastrophic rockfalls and rockslides in the Sierra Nevada, USA

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ABSTRACT

Despite having a low recorded historical incidence of landsliding, the Sierra Nevada has undergone large prehistoric and historical rockfalls and rockslides that could be potentially catastrophic if they occurred today in the more densely populated parts of the region. Several large documented rockfall and rockslides have been triggered either by strong seismic shaking or long periods of unusually wet weather; however, in several instances no obvious triggering event can be identified. The glaciated topography of the higher elevations of the Sierra Nevada has produced many relatively small falls and slides within relatively hard, massively jointed, granitic rocks; however, where exposed to weathering for long periods after glaciation, the oversteepened rock slopes are prone to uncommonly large falls and slides. At lower elevations on the nonglaciated slopes of the Sierra Nevada, rockslides commonly occur within more weathered granitic rocks, where the strength of the rock mass is typically affected by joint weathering and alteration of the intact rock to saprolite. Historical large rockfalls and rockslides in the Sierra Nevada have created additional secondary natural hazards, including debris flows and floods from the breaching of landslide dams that can be as hazardous as the initial rockfalls and rockslides.

INTRODUCTION

The Sierra Nevada of California (and Nevada) is a strongly asymmetric mountain range with a gentle western slope and a steep eastern escarpment that extends for more than 645 km from the Mojave Desert on the south to the Cascade Range on the north (Fig. 1). The Sierra Nevada is bordered on the east by the Basin and Range province and on the west by the Great Valley province (Norris and Webb, 1976). The Sierra Nevada is 80–130 km wide, and has a broad western slope and an abrupt eastern escarpment. Mount Whitney, in the southern part of the range, achieves an elevation of 4419 m; the crest of the range is a glaciated region characterized by numerous lakes and by peaks higher than 3960 m.

The core of the Sierra Nevada is a complex granitic batholith of Mesozoic age. The range is bordered on the west by sedimentary rocks of the Great Valley and on the north by volcanic rocks from the Cascade Range. In the northern half of the range the batholith is flanked by a metamorphic belt of strongly deformed, but weakly metamorphosed, sedimentary and volcanic rocks of Paleozoic and Mesozoic age. Volcanic materials cap large areas in the northern part of the range. In the eastern part of the range Cenozoic volcanic rocks are prominent (Bateman and Wahrhaftig, 1966). 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. During the Quaternary, glaciers sculpted the terrain at higher elevations of the Sierra Nevada.

The Sierra Nevada is a formidable physical barrier to the eastward-bearing moisture fronts that sweep off the Pacific Ocean. During the winter, polar fronts drop most of their moisture as snow as they pass over the Sierra Nevada; some areas receive as much as 2030 mm of precipitation per year. At the higher elevations, forests shade the heavy accumulations of snow that persist well into the spring. There is little moisture left in these fronts after passage over the crest of the Sierra Nevada; consequently, the eastern side of the Sierra Nevada has a much drier climate. Summer in the Sierra Nevada resembles a Mediterranean summer; it is characterized by a warm, dry period

Wieczorek, G.F., 2002, Catastrophic rockfalls and rockslides in the Sierra Nevada, USA, in Evans, S.G., and DeGraff, J.V., eds., Catastrophic landslides: Effects, occurrence, and mechanisms: Boulder, Colorado, Geological Society of America Reviews in Engineering Geology, v. XV, p. XX–XX.

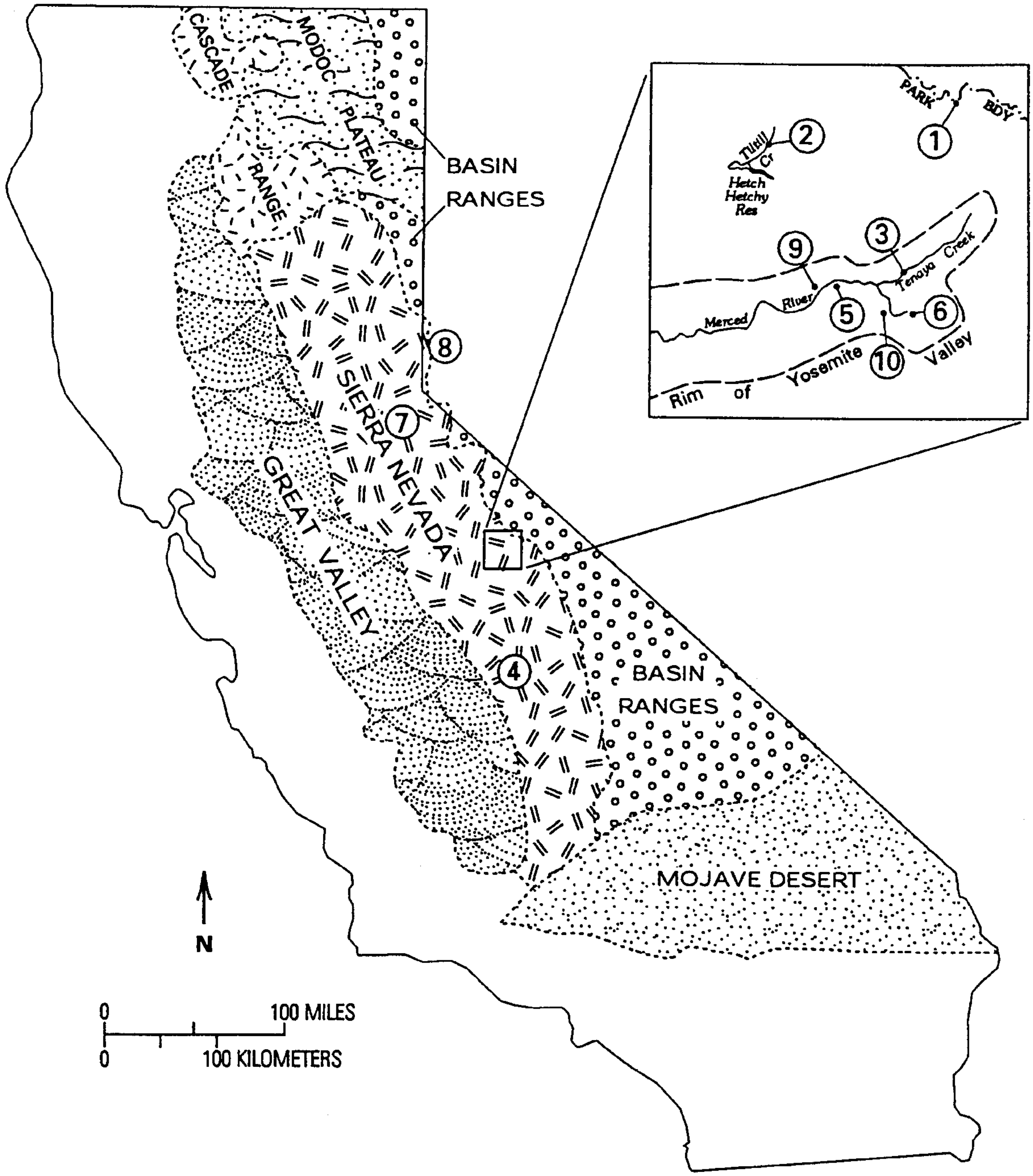


Figure 1. Map of California showing location of Sierra Nevada in California (along its eastern boundary, range extends slightly into Nevada), physiographic regions of California (from Norris and Webb, 1976), and locations of rockfall and rockslide sites described in text (inset shows rockfalls and rockslides within Yosemite National Park).

interrupted by convective storms that can produce short bursts of intense rainfall.

Seismic activity in the Sierra Nevada is primarily concentrated along the eastern side of the range. The largest historic earthquake in the Sierra Nevada occurred on March 26, 1872, with an estimated Richter surface-wave magnitude (M_s) of 7.6–8.0 (Goter et al., 1994) and an epicenter located in the Owens Valley of the southern Sierra Nevada. The May 25–27, 1980, Mammoth Lakes earthquake sequence, with four earthquakes measuring M_s = 6.0-6.2, was centered in the east-central Sierra Nevada.

The granitic rocks composing the majority of the Sierra Nevada are generally considered as firm and hard with a relatively low incidence of landsliding; large rockfalls and rockslides are uncommon (Radbruch and Crowther, 1973). Historically low reported incidence of rockfalls and rockslides may be due to the sparse population of the Sierra Nevada. However, a few early observers, including John Muir (1912) and Mark Twain (1872), described rockfalls and rockslides as frequently occurring in the Sierra Nevada. Mark Twain (1872) remarked the following in *Roughing It*:

The mountains are very high and steep about Carson, Eagle, and Washoe Valleysævery high and very steep, and so when the snow gets to melting off fast in the Spring and the warm surface earth begins to moisten and soften, the disastrous landslides commence. The reader cannot know what a landslide is, unless he has lived in that country and seen the whole side of a mountain taken off some fine morning and deposited down in the valley, leaving a vast, treeless, unsightly scar upon the mountain's front to keep the circumstance fresh in his memory all the years that he may go on living within seventy miles of the place.

Under strong seismic shaking caused by earthquakes and during periods of extremely wet conditions from storms or snowmelt, rockfalls and rockslides have been noted in the Sierra Nevada. The 1980 Mammoth Lakes earthquake sequence triggered several thousand rockfalls and slides (Fig. 2) in the eastern Sierra Nevada (Harp et al., 1984). During the unusually wet winters of 1982 and 1983, DeGraff et al. (1984) estimated $1.3 million damage from landslides, including a reactivated rockslide along a 23 km section of Stump Springs Road, a major timber-haul route in the Sierra National Forest. Some large rockfalls occur without apparent triggering events, such as the July 10, 1996, rockfall at Happy Isles, Yosemite National Park, that killed one person and seriously injured several others (Snyder, 1996; Wieczorek et al., 2000). With fluvial and glacial downcutting of the Yosemite and other valleys of the Sierra Nevada, the lack of lateral confinement may initiate the release of horizontal residual stress in the oversteepened valley slopes. This release of stress may be responsible for the formation of exfoliation sheets, the dilation of joints, and the occurrence of some rockfalls without recognized triggering events (Wieczorek et al., 1995).

This chapter describes 10 sites of prehistoric and historic large rockfall and rockslides in the Sierra Nevada and their

Figure 2. Photograph of rockfalls and rockslides triggered by 1980 Mammoth Lakes earthquake sequence, Mount Baldwin, eastern-central Sierra Nevada (Photograph by David Keefer, U.S. Geological Survey, 1980).

geologic settings and, if known, triggering events. Although these events caused neither large loss of life nor widespread destruction of property, a recurrence of large, rapidly moving rockfalls and rockslides in the currently more populated parts of the Sierra Nevada could be potentially catastrophic by causing significant loss of life and property damage.

PREHISTORIC ROCKFALLS

Slide Mountain, Yosemite National Park, California

The large Slide Mountain rockslide of 1.9×10^6 m^3 rock occurred in a remote part of northern Yosemite National Park within the drainage of Piute Creek, a glaciated valley near the crest of the Sierra Nevada (Bronson and Watters, 1987) (Fig. 1, site 1). The locations of this and other rockfalls and rockslides in the Sierra Nevada discussed in this chapter are shown in Figure 1. The Slide Mountain rockslide was first described by McClure (1895, p. 175–176) during 1894 while exploring the canyons of the Tuolumne River in the northern part of Yosemite National Park.

After traveling three and one-half miles down the canyon, I came to the most wonderful natural object that I ever beheld. A vast granite cliff, two thousand feet in height, had literally tumbled from the bluff on the right-hand side of the stream with such force that it had not only made a mighty dam across the canyon, but many large stones had rolled up on the opposite side. As it fell it had evidently broken into blocks, which were now seen of almost every size, piled one upon another in the wildest confusion. The smaller particles had settled between the crevices, leaving great holes among the larger blocks, some which weighed many tons. To look at it, one might think that it had occurred but yesterday; but it was, in all probability, ages ago, as the ground just above the slide is two hundred feet or higher than just below, showing that earth has accumulated on the upper side for many years.

The scarp of the rockslide near the crest of Slide Mountain is 3230 m in elevation; glacial polish and striations indicate that Tioga (latest Pleistocene) glaciation filled Slide Canyon to the top of the scarp (Bronson and Watters, 1987). The slide descended to the floor of the valley, a drop of 430 m, and continued up the opposite valley slope another 37 m, indicating that the mass was moving extremely rapidly at 63 m/s when it crossed the floor of the valley (Huber et al., 2002) (Fig. 3). The deposit, which contains many blocks exceeding 6 m (Huber et al., 2002), blocked Piute Creek with a small landslide dam 12 m high (Fig. 4). The area upstream from the dam that probably became a small lake or pond has since formed into a marshy meadow (Huber et al., 2002). The unweathered appearance of the rocky deposit (Fig. 5), almost devoid of vegetation, makes it appear fresh, suggesting that the slide occurred relatively recently; however, dendrochronology of two samples of wood recovered from logs pinned beneath boulders within the deposit has pinpointed the event as occurring between A.D. 1739 and 1740 (Huber et al., 2002). However, because the date of this event cannot be associated with a known seismic or climatic event, its specific cause or trigger remains unknown (Huber et al., 2002).

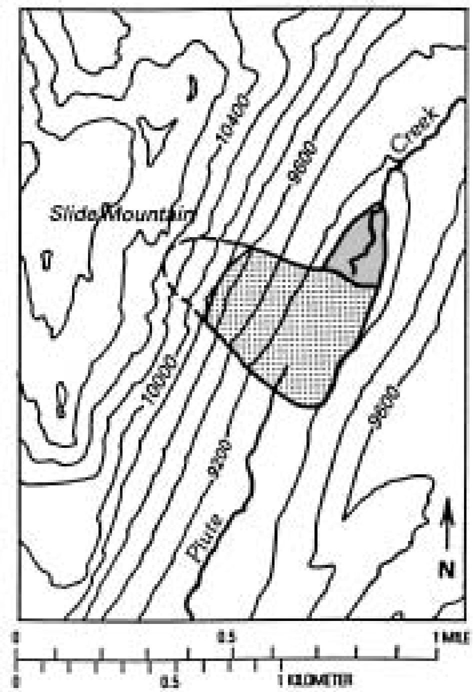


Figure 3. Map of Slide Mountain rockslide and deposit in Piute Canyon, Yosemite National Park (topographic base from U.S. Geological Survey 7.5′ Matterhorn quadrangle; contours in feet). Dashed lines indicate release area and path of travel; dotted pattern shows rock deposit; solid pattern represents lake backed up behind deposit.

The vicinity of the slide has been mapped as Cathedral Peak Granodiorite of Cretaceous age (Huber et al., 1989). The rock exposed in the scarps and deposits is predominantly a coarse quartz monzonite, although granite, granodiorite, and diorite are also found locally (Bronson and Watters, 1987). The structure of Slide Mountain is dominated by three prominent joint sets that break the rock mass into rectangular blocks. Bronson and Watters (1987) examined the terrain above the crown of the slide and found four prominent weathered linear zones with vertical to uphill-facing scarps that generally trend parallel to the ridge and coincide with a north-south-trending joint system. One of these lineaments coincides with the main scarp of the Slide Mountain slide. These lineaments with uphill-facing scarps suggest lateral spreading of Slide Mountain, a type of slow large-scale gravitational sliding (Varnes et al., 1989) that may have weakened the mountain and led to toppling and sliding that initiated the rapid rockslide (Bronson and Watters, 1987).

Tiltill Creek, Yosemite National Park, California

Another prehistoric rockslide slightly smaller in size than Slide Mountain described here is located in a remote section of

Figure 4. Photograph of Slide Mountain deposit blocking Piute Creek; slide movement was from left to right in photograph. Photograph was taken in 1988 by King Huber, U.S. Geological Survey.

Yosemite National Park along Tiltill Creek below Mount Gibson (Fig. 1, site 2; Fig. 6). The irregularly shaped scarp suggests that the slide released as two slumps from cliffs below the glacial trim line on Mount Gibson (Fig. 7). The rockslide, including some very large individual blocks, traveled down to and across Tiltill Canyon, damming Tiltill Creek and creating a small lake behind the rock deposit (Fig. 8). The slide may have overridden a low rocky ridge in crossing the canyon, because part of the slide deposit turns a little downstream. The lake is 15 m deep and now drains both around and through the deposit. The thickness of the deposit in the bottom of the canyon is difficult to estimate because of the irregular stepped topography in other parts of Tiltill Canyon; consequently, we did not attempt to estimate the volume of the rockslide deposit.

The relative age of the Tiltill rockslide can be inferred as older than the Slide Mountain event from the encroachment of the forest from all sides among the large rocks, development of soil among the vegetation, growth of lichens on presumably fresh rock surfaces at the time of the event, and the severe weathering of individual large rock blocks that can be pulled apart along once-intact joints. Kistler (1973) outlined the slide deposit and mapped the dark gray to black, coarse-grained rock of the slide area as the Quartz Diorite of Mount Gibson. J. Snyder (1996, written commun.) described the rock exposed at the release point as fractured, mostly brown, but sometimes gray, coarse- grained rock with occasional intrusions, this mixture of lithologies creating a natural weakness in the rock mass.

Mirror Lake, Yosemite National Park, California

A prehistoric rockfall from cliffs northeast of Washington Column in the northeastern part of the Yosemite Valley with an estimated volume of 11.4×10^6 m^3 blocked Tenaya Creek, forming Mirror Lake (Wieczorek and Jager, 1996) (Fig. 1, site 3). The largest portion of the Mirror Lake rockfall appears to have originated from an escarpment to the west of Washington Column and below North Dome (Fig. 9). Ice during the Tioga glaciation filled Tenaya Canyon to an elevation of 1680 m (Matthes, 1930), below the likely source for the rockfall. The rockfall occurred in a gray, medium-grained Half Dome Granodiorite of Cretaceous age (Calkins, 1985). Four major joint sets occur in Washington Column; however, because the joint spacing is fairly large, the rock masses are usually quite stable, resulting in prominent edifices, including North Dome, Half Dome, and Royal Arches.

Grading and sorting of the large boulder debris, as well as transverse troughs and ridges across the lower part of the deposit, suggest a single very large rockfall event. The rockfall spread, leaving a fan-shaped deposit that extended 520 m across the valley to block Tenaya Canyon. Tenaya Creek currently cuts through the deposit along the southeastern side of Tenaya Canyon. Along

Figure 5. Photograph of Slide Mountain rockslide deposit with mules (circled) in foreground for scale, Yosemite National Park. Photograph was taken in 1988 by James Snyder, National Park Service.

Tenaya Creek isolated individual boulders ranging to 250 m^3 are found among a matrix of sandy, gravelly material. The deposit was estimated to have a thickness of at least 28 m based on topographic data and exposures created by the downcutting of Tenaya Creek through the deposit; seismic profiling data (Gutenberg et al., 1956) suggest a maximum possible thickness of 100 m (Wieczorek and Jager, 1996).

The prehistoric Mirror Lake, which extended 2 km upstream, has now been almost completely transformed by sedimentation into a marshy meadow (Fig. 10). Matthes (1930) believed that the blockage of Tenaya Creek by prehistoric rockslides must have occurred recently in prehistoric time because of the noticeable rate at which the lake has been filling with sediment during historical time. Revegetation among the rocky deposit with thick pines (1.2 m diameter), large (7 cm diameter) individual lichens on the boulders, and evidence of Native American occupation of caves among the large interlocked

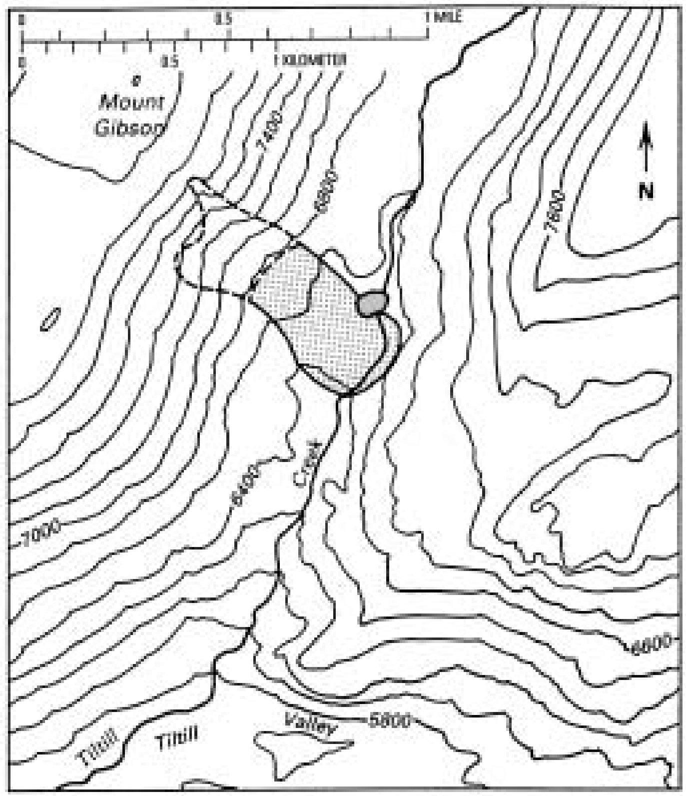


Figure 6. Map of Tiltill rockslide and lake behind deposit blocking Tiltill Creek (modified from James Snyder, 1996, written commun.) (base topography from U.S. Geological Survey 7.5′ Hetch Hetchy quadrangle; contours in feet. Dashed lines indicate release area and path of travel; dotted pattern shows rock deposit; solid pattern represents lake backed up behind deposit.

boulders of the toe of the deposit suggest an age of the deposit of at least 300-500 yr (Wieczorek et al, 1992; Bull, 1996).

HISTORIC ROCKFALLS AND ROCKSLIDES

1867 Kaweah River, Kings Canyon National Park, California

After prolonged heavy rainfall in late December 1867, a rock avalanche from the north side of Dennison Mountain dropped into the South Fork of the Kaweah River 68 km east of Visalia (Fry, 1933; Costa and Schuster, 1991) (Fig. 1, site 4). The rock avalanche blocked the Kaweah River and Garfield Creek with rocky debris forming a natural landslide dam (Fig. 11). The dam failed 25 h later, sending a torrent of thousands of tons of timber and rocky debris down the Kaweah River, past the small community of Three Rivers and farther into the small town of Visalia in the San Joaquin Valley.

A firsthand description of the event by Joseph Palmer, a homesteader who was the only person in the South Fork Canyon that evening, provides an interesting account of the setting and events (Fry, 1933, p. 119):

Figure 7. Photographs of rockslide deposits and release area of Tiltill rockslide. A: Revegetation has covered most of release point and is encroaching on rockslide deposits. More recent smaller rockfall deposits cover eastern edge of scarp (right). Person (circled) for scale. B: Looking across rockslide deposits at release point; size of individual rocks is indicated by person for scale. (Photographs are by James Snyder, National Park Service, 1993.)

Figure 8. Photograph of lake behind deposit of Tiltill rockslide with two people (circled) on crest of landslide dam for scale. Deposit is ~10 m thick above level of lake. Tiltill Creek drains from lake to left in this photograph. (Photograph is by James Snyder, National Park Service, 1993.)

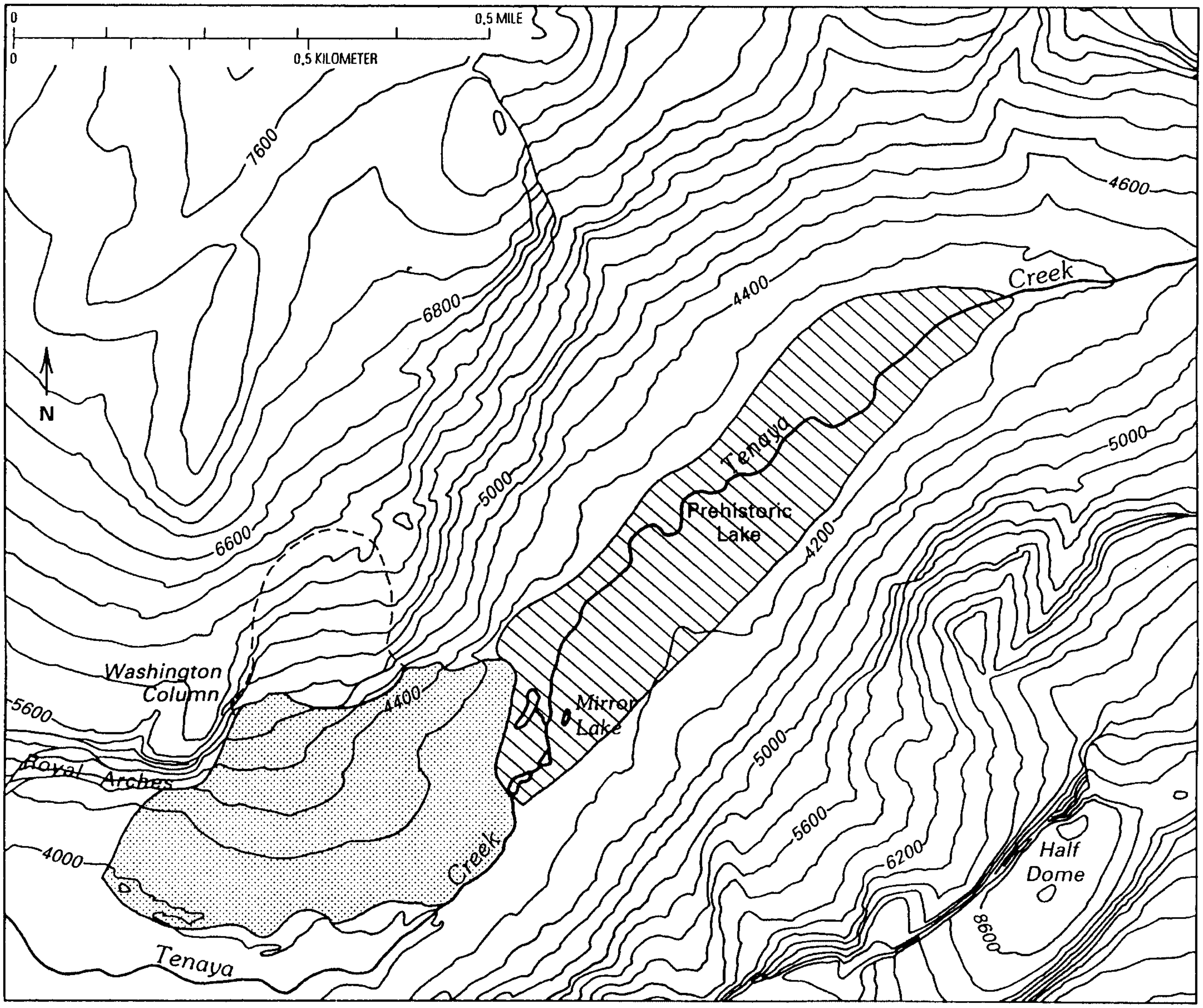


Figure 9. Map of Mirror Lake rockfall deposit in Yosemite Valley (base topography from U.S. Geological Survey 7.5′ Half Dome and Yosemite Falls quadrangles; contours in feet). Dashed lines indicate release area and path of travel; dotted pattern shows rock deposit; diagonal-striped pattern represents approximate boundary of prehistoric lake backed up behind deposit.

"It had been raining in the Three Rivers district almost steadily for 41 days and nights, with heavy snows above the 5000 foot level. All the rivers were very high. On the morning of December 20, the weather became warmer, and I went to bed that night, and a strong wind blew down the canyon. Just before midnight I was aroused by a heavy rumbling sound such as I had never heard before, and which lasted for an hour or more. Then a great calm set in, and even the roaring of the river ceased.

"On leaving my cabin in the morning, I found that despite the heavy rain the river was low. From this I knew that a great slide had blocked the canyon above and that later the dam would give way and cause a flood…About 1:30 a.m. (12/22) [my parentheses] I was aroused by a tremendous thundering and rumbling sound...I jumped out of bed, grabbed my clothing, and ran for safety up the mountain side some 200 yards from the river. In a few minutes the flood came along with a crest of water some 40 feet in depth that extended across the canon, carrying with it broken-up trees."

The rock avalanche started on a steep mountainside at an angle of about 45 degrees (Fry, 1931) near the crest of Dennison Ridge, at an elevation of 2286 m, and traveled 3.2 km to the South Fork of the Kaweah River (Fig. 11). The avalanche initiated in granitic bedrock overlain by sandy loam, ranging in depth from 1.5 to 3.7 m. The avalanche stripped the steep hillside of a thick forest of giant sequoia, pine, and fir in a path of devastation

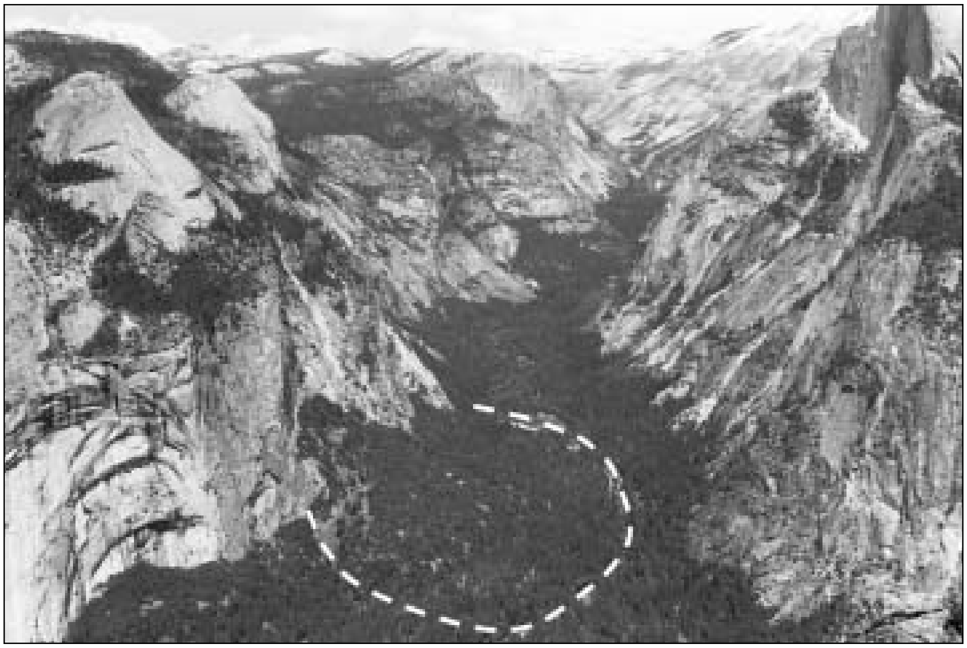


Figure 10. Photograph of prehistoric Mirror Lake rockfall deposit (dashed lines) from cliffs behind Washington Column and below North Dome. Deposit blocked Tenaya Creek and formed prehistoric lake that extended ~2 km upstream in Tenaya Canyon.

that ranged from 457 to 1220 m in width (Fry, 1933). The dam formed by the avalanche debris measured 350 m wide, 100 m long, and 13 m high (Costa and Schuster, 1991).

1872 Old Yosemite Village, Yosemite National Park

The March 26, 1872, Owens Valley earthquake (M_s = 7.6-8.0) triggered abundant rockfalls and rockslides throughout the southern Sierra Nevada and even a few in the Yosemite Valley, 180 km northwest of the epicentral area in the Owens Valley (Wieczorek and Jager, 1996) (Fig. 1, site 5). A rockfall behind the Hutchings Hotel in the Old Yosemite Village (Fig. 12) (Wieczorek et al., 1992) was observed and described by John Muir (1912):

> At half past two o'clock of a moonlit morning in March, I was awakened by a tremendous earthquake… and I ran out of my cabin, both glad and frightened, shouting, 'A noble earthquake! A noble earthquake!' feeling sure I was going to learn something. The shocks were so violent and varied, and succeeded one another so closely, that I had to balance myself carefully in walking as if on the deck of a ship among waves, and it seemed impossible that the high cliffs of the Valley could escape being shattered. In particular, I feared that the sheer-fronted Sentinel Rock, towering above my cabin, would be shaken down, and I took shelter back of a large yellow pine, hoping that it might protect me from at least the smaller outbounding boulders…

> It was a calm moonlight night, and no sound was heard for the first minute or so, save low, muffled, underground, bubbling rumblings, and the whispering and rustling of the agitated trees, as if Nature were holding her breath. Then suddenly, out of the strange silence and strange motion there came a tremendous roar. The Eagle Rock on the south wall, about half a mile up the Valley, gave way and I saw it falling in thousands of the great boulders I had so long been studying, pouring to the Valley floor in a free curve luminous from friction, making a terribly sublime spectacle—an arc of glowing, passionate fire, fifteen hundred feet span…

> The first severe shocks were soon over, and eager to examine the new-born talus I ran up the Valley in the moonlight and climbed upon it before the huge blocks, after their fiery flight, had come to complete rest. They were slowly settling into their places, chafing, grating against one another, groaning, and whispering; but no motion was visible except in a stream of small fragments pattering down the face of the cliff. A cloud of dust particles, lighted by the moon, floated out across the whole breadth of the Valley, forming a ceiling that lasted until after sunrise, and the air was filled with the odor of crushed Douglas spruces from a grove that had been mowed down and mashed like weeds.

Although the location of the release point cannot be precisely relocated, the rockfall probably originated from between Union Point and Moran Point (Fig. 12). The release point at an elevation of 1616 m was probably just above the level of glacial ice during the most recent Tioga glaciation (Matthes, 1930). In this vicinity the medium-grained granodiorite mapped as Sentinel Granodiorite of Cretaceous age (Calkins, 1985) is closely jointed and the rock has weathered preferentially along the joints, leaving spires or pinnacles (Fig. 13) that might resemble a bird with its wings outstretched; hence the descriptive names, Eagle Rock and Pelican Peak, by which Muir (1912) and Clark (1872) referred to the release point of the rockfall.

Below the release point of the rockfall, the rocks slid and bounced, breaking into many pieces, before being spouted down a steep narrow chute behind the Old Yosemite Village. The majority of the rocks spread about in a fan-shaped deposit that extends 150 m from the steep chute. Many of the boulders are large, to

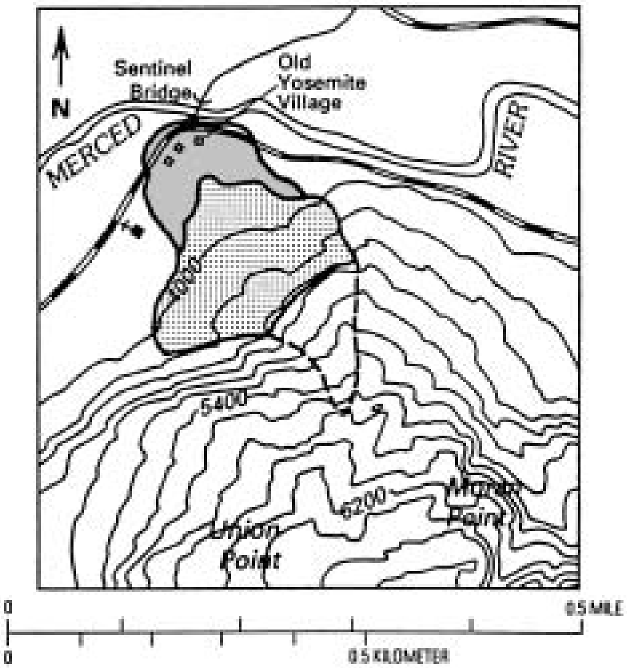


Figure 12. Map of rockfall behind Old Yosemite Village triggered by 1872 earthquake. Extent of larger prehistoric rockfall at this site is also shown (topographic base from U.S. Geological Survey 7.5′ Half Dome quadrangle; contours in feet. Dashed lines indicate release area and path of travel; dotted pattern shows rock deposit; solid pattern represents prehistoric rockfall deposit within area of Old Yosemite Village.

10 m in maximum dimension, and are perched upon one another; the deposit has remained largely unrevegetated. The 1872 deposit is roughly estimated to be 20 000 m^3 (revised from Wieczorek et al., 1992). An even larger prehistoric rockfall deposit extends another 150 m north beyond the boundary of the 1872 deposit. The site of the Old Yosemite Village was built among the boulders of this prehistoric rockfall, northeast of the present location of the chapel.

1872 Liberty Cap, Yosemite National Park, California

The 1872 Owens Valley earthquake also triggered a rockfall at Liberty Cap near the head of the Little Yosemite Valley (Fig. 14) (Fig. 1, site 6). Clark (1872, p. 1) gave the following account.

> The most remarkable results of the shake occurred at Snows, between the Vernal [and] Nevada Falls. Mr. Snow, on hearing the terrible rumbling noise preceding the shake, rushed out of his house somewhat alarmed. The night was very light and he being in plain view of the Nevada Falls, distinctly saw that the water ceased to flow over the falls for at least half a minute. A large mass of rocks, which would weigh thousands of tons fell from the west side of the 'Cap of Liberty' about a thousand feet above its base...
>
> When this great mass of rocks struck the earth Mr. Snow says he was instantaneously thrown prostrate to the ground. The house which stands on the solid bed rock which has an incline of about twenty degrees to the eastward towards the Cap of Liberty and Nevada Falls, has moved two inches to the east. An addition to the house, which was built last Fall, was so badly wrecked and shattered as to have to be taken down and rebuilt. The earth around Snow's place is still completely covered with dust from the pulverized rocks.

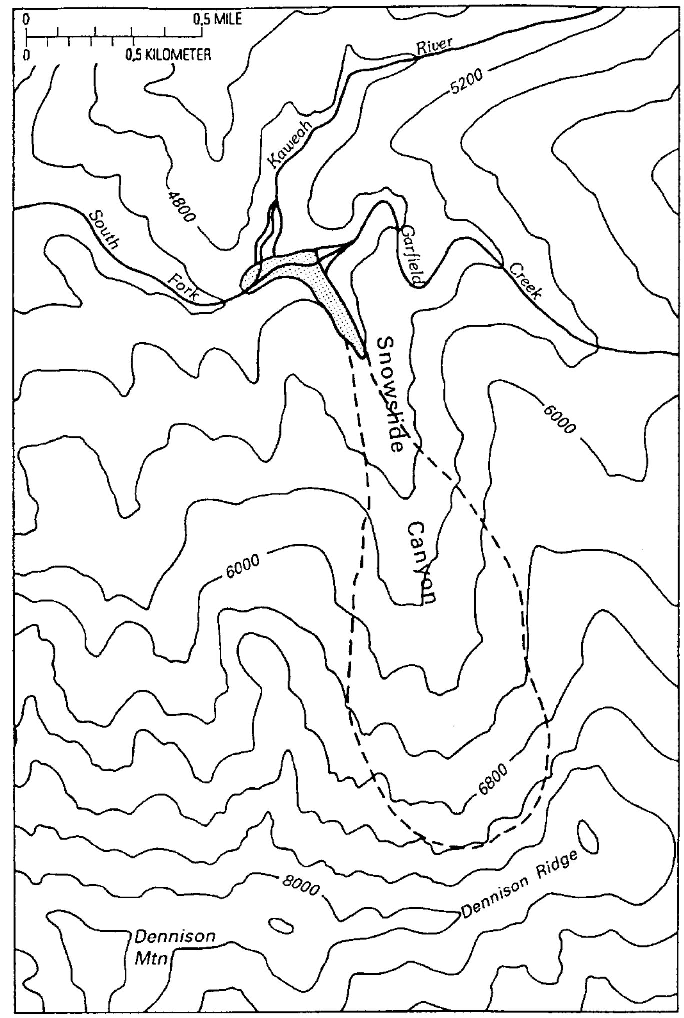


Figure 11. Map of South Fork of Kaweah River, Kings Canyon National Park rockslide, and landslide dam (base topography from U.S. Geological Survey 7.5′ Mineral King, S.W. quadrangle; contours in feet; modified from Robert Schuster, U.S. Geological Survey, 1990, written commun.). Dashed lines indicate release area and path of travel; dotted pattern shows rock deposit; solid pattern represents lake backed up behind deposit.

Liberty Cap, a monolith of massively jointed granodiorite (Half Dome Granodiorite), rises 350 m at the head of Little Yosemite Valley. During Tioga and earlier glaciations, ice overtopped Liberty Cap (Matthes, 1930). The rockfall scar (Fig. 15), about midway up the nearly vertical southwestern face of Liberty Cap, is geometrically controlled by four joint sets. Although the

Figure 13. Photograph of open joints in closely jointed rock mass along Glacier Point trail between Union Point and Moran Point.

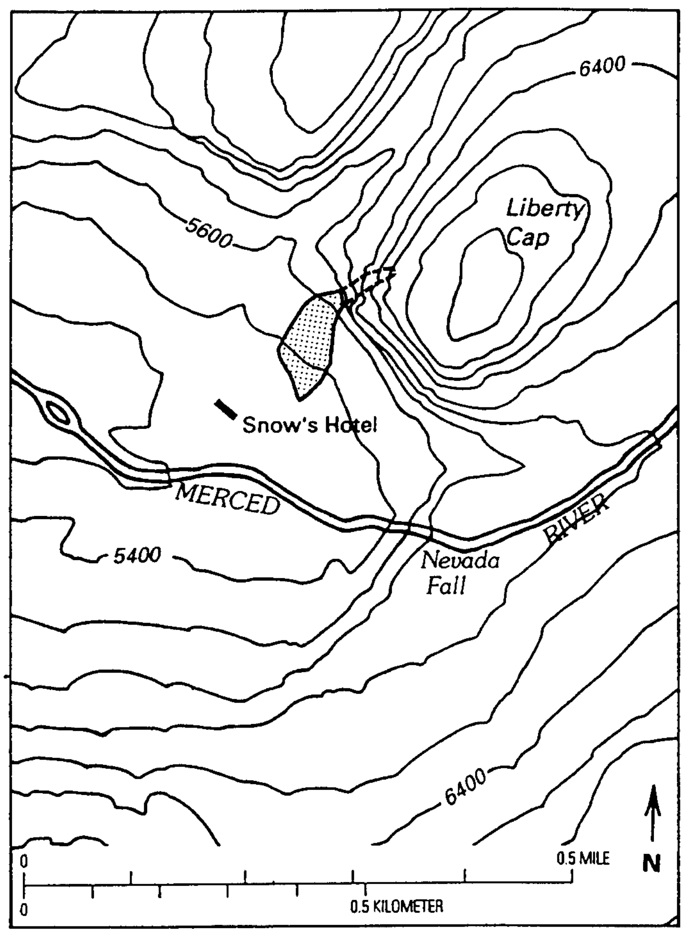


Figure 14. Map of Liberty Cap rockfall, Little Yosemite Valley (topographic base from U.S. Geological Survey 7.5′ Half Dome quadrangle; contours in feet). Dashed lines indicate release area and path of travel; dotted pattern shows rock deposit; position of Snow's Hotel is approximately located.

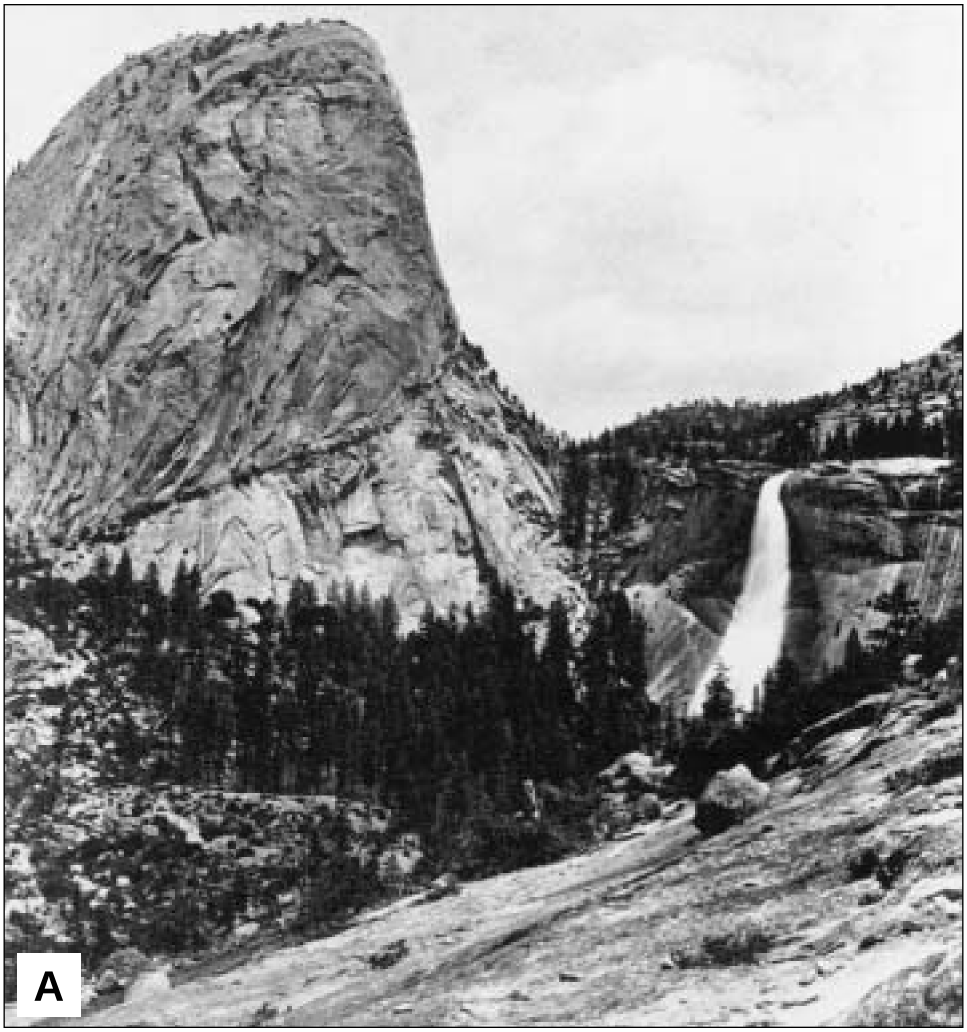


Figure 15. Photograph of Liberty Cap showing rockfall from southwest side triggered by 1872 Owen's Valley earthquake. A: Photograph of Nevada Falls and Liberty Cap by John Soule before construction of Snow's Hotel and 1872 earthquake (1870; Yosemite Research Library YRL-2700). B: Rockfall deposit (dotted lines) triggered by 1872 earthquake behind Snow's Hotel (photograph taken by Carleton Watkins (1878) (Yosemite Museum catalog 571). Release area is indicated by dashed lines. Both photographs published with permission of National Park Service, Yosemite Museum.

joints have wide spacing, they dip unfavorably in relation to the slope orientation along the southwestern face; rockfalls have repeatedly damaged the trail to Nevada Falls along this face (Wieczorek et al., 1992).

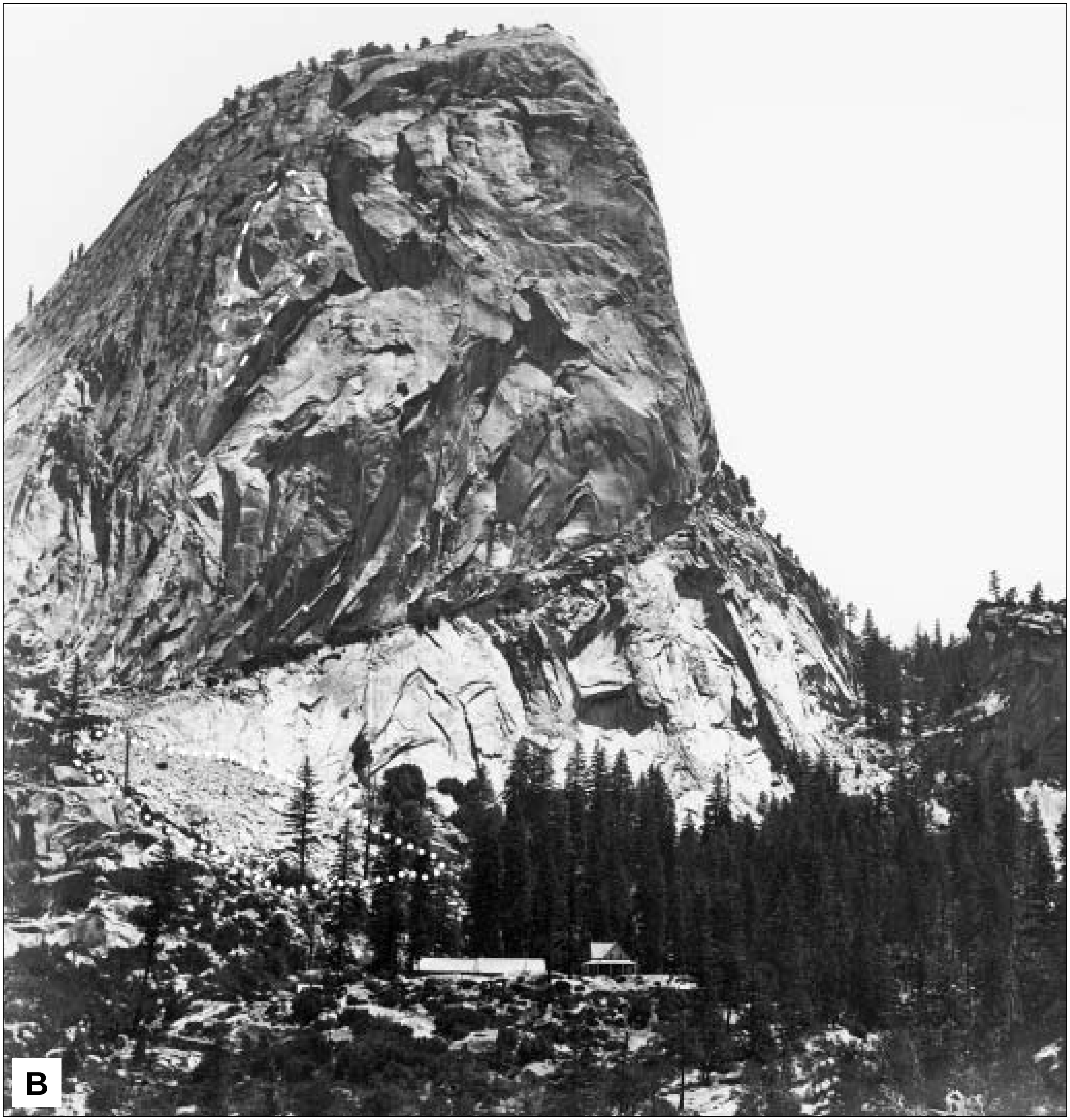
The falling rock mass hit the slope below Liberty Cap with great force. The impact is evidenced by a zone of shattered and split rock without revegetation that extends 20 m from the base of the steep slope. The deposit of large boulders, the largest of which are roughly equidimensional, 4 m in size, extends an additional 100 m from the impact zone to a boulder snout (Fig. 15). The deposit is 50 m wide, at least 5 m thick and has an estimated volume of 36 000 m^3. Several large trees within the depositional area survived, but lost their lower branches; other trees nearer the snout were knocked over and have resprouted new main shoots.

The air blast that knocked down Mr. Snow, moved Snow's hotel, and knocked down a small addition, was not a unique event in Yosemite. A rockfall that triggered an air blast that knocked over hundreds of trees over a wide area occurred near Happy Isles in July 1996 and is described herein.

1983 Highway 50, South Fork of American River, Whitehall, California (site #7 -fig. 1)

On April 9, 1983, a large slide of weathered granitic rock blocked the South Fork of the American River canyon between Whitehall and Kyburz, 100 km southeast of Sacramento (Fig. 1, site 7). At 5:10 a.m., a slide from the south side of the canyon measuring 245×400 m began to move toward the river (Fig. 16). For 15-20 min the river, flowing at a rate of 17 m^3/s, was able to remove the slide material as it entered the channel. The slide mass had an estimated volume of 765 000 m^3; it blocked the river at 5:30 a.m. and continued to move, covering U.S. Highway 50 on the north side of the canyon (Fig. 17). This slide moved a maximum of 75 m horizontally and 45 m vertically. In addition to closing the highway for 75 days, the landslide disrupted a canal that was used for domestic uses, irrigation, and electric power (Kuehn and Bedrossian, 1987).

The landslide was a large rotational slide originating at the toe of a much larger ancient landslide complex. The slide had a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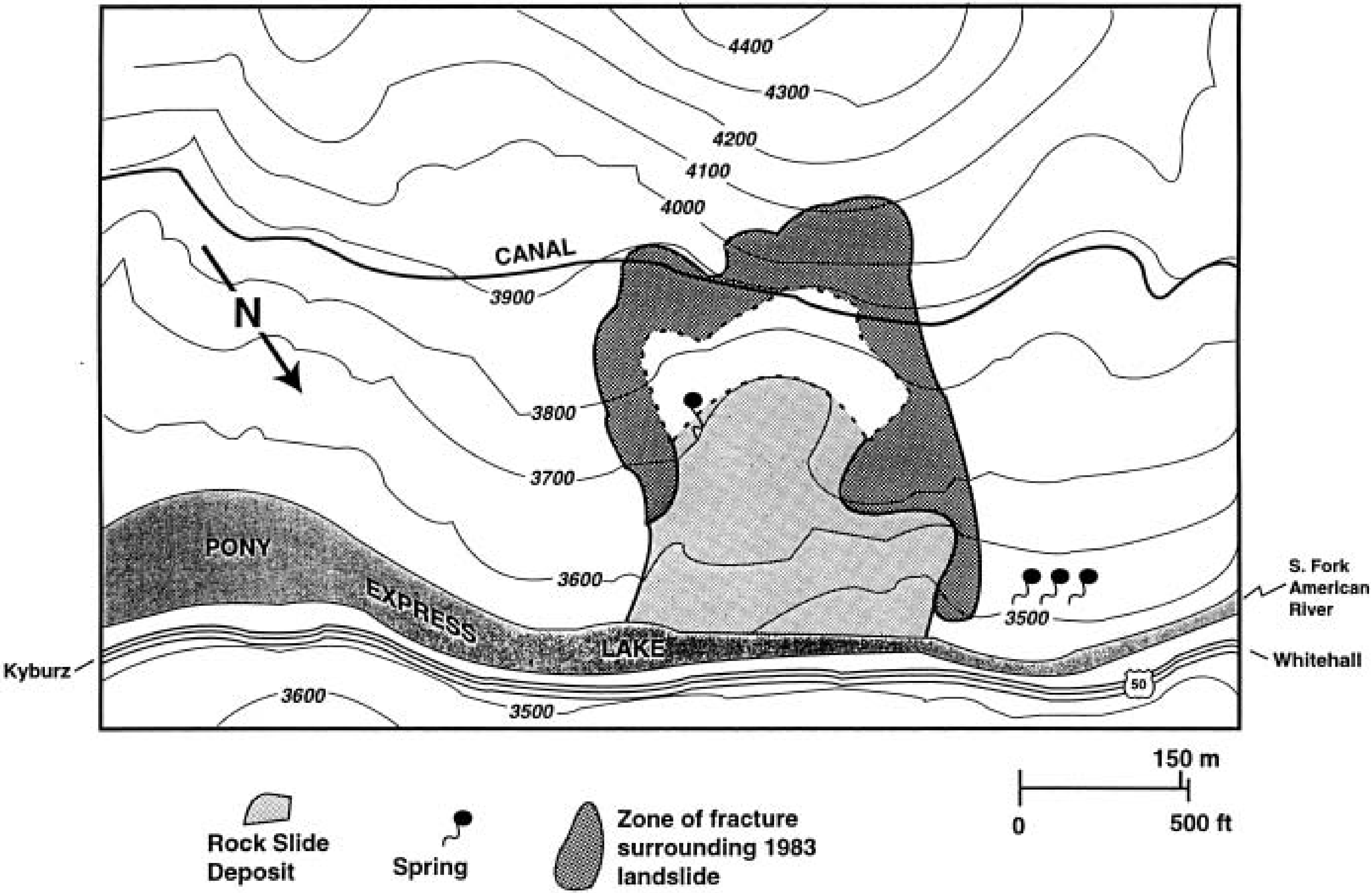

Figure 16. Map of Highway 50, South Fork of American River rockslide between Whitehall and Kyburz (modified from Kuehn and Bedrossian, 1987; contours in feet). Dashed lines indicate release area; dotted pattern shows rock deposit; solid pattern represents lake backed up behind deposit.

Figure 17. Photograph of rockslide covering Highway 50 and backing up Pony Express Lake. South Fork of American River is draining over breached landslide dam (published with permission of California Department of Transportation, photo C-9021-4).

depth of 50 m at the head scarp and occurred primarily within decomposed granitic rock, granite, and granodiorite of Mesozoic age (Kuehn and Bedrossian, 1987). Most of the slide material had been weathered to a disintegrated granite; however, a portion still involved rock with some boulders that measured more than 5 m in diameter.

In recent years prior to the slide the river had cut into the base of the slope, reducing the overall stability of the hillside. During the 1982 water year (October 1981-September 1982) 2310 mm of precipitation was measured 11 km west of the landslide. This value was 179% of normal, among the wettest years of the twentieth century. The combined water years of 1982 and 1983 were the wettest period since the beginning of records in the Sierra Nevada more than a century ago. High runoff during 1982 and early 1983 would have resulted in additional undercutting and removal of the toe of the landslide by the South Fork of the American River. The long period of heavy rainfall during the 1982 and 1983 water years probably raised groundwater levels and increased pore-water pressures within the hillside, and in combination with the removal of the base of the hill by river erosion acted together to trigger the landslide.

The formation of a landslide dam cut off the flow of the South Fork of the American River for 6 h and backed up a lake, referred to locally as Pony Express Lake. Overtopping of the lake began at 11:30 a.m. The lake reached a maximum elevation at 1 p.m. with a depth of 15 m. The lake inundated an 0.8 km section of U.S. Highway 50 and covered several houses. At 2 p.m. the river started to cut rapidly through the slide mass, but there were enough large boulders to prevent rapid breaching. During the following months, the outlet of the lake gradually lowered and the depth and size of the lake diminished; by June 1983, the area of the lake had decreased to roughly one-third its original size.

1983 Slide Mountain, Nevada

At about noon on May 30, 1983, a large complex rock and soil slide detached from the southeast face of Slide Mountain, Nevada (Fig. 1, site 8; Fig. 18). Slide Mountain has an elevation of 2956 m on the eastern edge of the Sierra Nevada, and overlooks the Washoe Valley to the east. As elsewhere in the western United States, the winter of 1982-1983 had been unusually wet, with a record snowpack (Wieczorek et al., 1989).

A sudden sustained warm period beginning in late May had greatly reduced the snowpack, produced high runoff, and promoted infiltration of water into the subsurface. The increase of moisture content would have increased local pore pressure in discontinuities and in the unconsolidated surficial deposits covering the bedrock, possibly leading to the slope failure. Several types of slope movement were involved, including rock slump, rockfall avalanche, and debris avalanche. The rock slump composed the largest part of the slide and was as thick as 30 m (Watters, 1983). The area of rock slumping consisted of numerous joint-controlled rotated blocks that were 90 m or more wide and several hundred meter long. Depending largely upon the estimated thickness of the slide, the total volume of the slide was estimated to range from 720 000 m^3 (Watters, 1983) to 1.07×10^6 m^3 (Glancy and Bell, 2000). For a detailed mapping of this complex slide, see Glancy and Bell (2000, p. 23).

The initial slope movement involved slumping in unweathered, jointed granodiorite of Cretaceous age. Two of the four major joint sets at Slide Mountain approximately parallel the preslide topography and possibly provided planes of weakness for slope movement. Parts of the rotational slump blocks were subsequently displaced or covered by material from the rockfall avalanche and debris avalanche. Displacement of treelines indicated maximum downslope movement of the rock slump to be about 75 m (Glancy and Bell, 2000).

Subsequently, along the northeastern margin of the rock-slump zone, a rapidly moving rockfall avalanche of large boulders and a debris avalanche of gravelly sand initiated and entered the northern end of Upper Price Lake, a small reservoir. As described by Glancy and Bell (2000) the material entering Upper

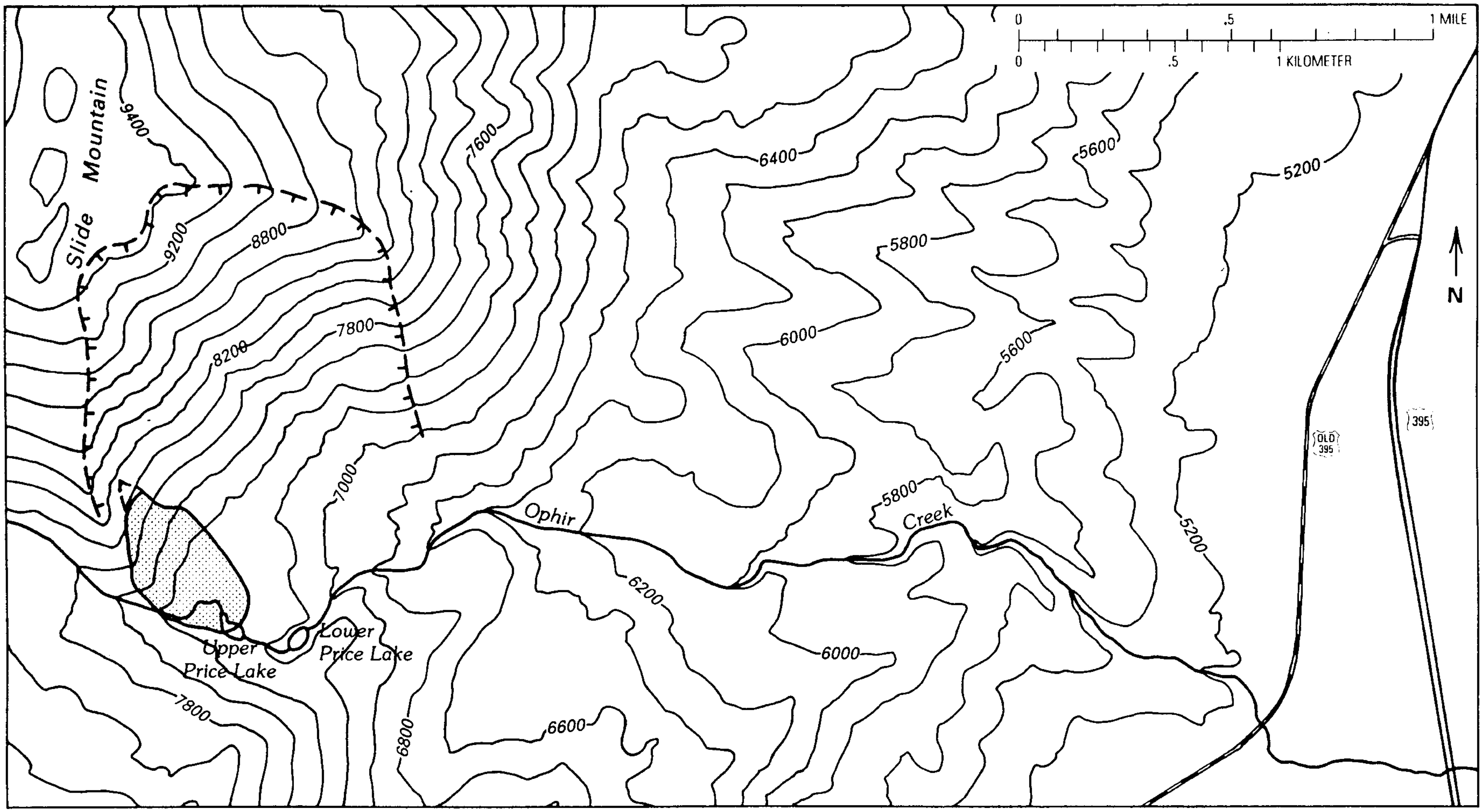

Figure 18. Map of Slide Mountain, Nevada, rockslide and associated events (topographic base from U.S. Geological Survey 7.5′ Mount Rose and Washoe City quadrangles; contours in feet). Hachured line indicates old slide boundary (Tabor and Ellen, 1975, p. 19); dashed line indicates main scarp of recent release area; dotted pattern shows rockslide deposit that moved into Upper Price Lake. A more detailed representation of the 1983 landslide features can be found in Clancy and Bell (2000, p. 23).

Price Lake, displaced most of the lake water, which overtopped and breached a low dam (Fig. 19). The water then breached the dam of Lower Price Lake and sent a torrent down the gorge of Ophir Creek. In the steep canyon the rapidly moving water picked up fine and coarse rocky debris. Emerging from the canyon 6 km downstream, the debris flow spread out and deposited over the alluvial fan of Ophir Creek in the Washoe Valley, destroying and damaging houses, causing one fatality, and covering old U.S. Highway 395 (Fig. 20).

1987 Middle Brother, Yosemite National Park, California

Beginning on March 8, 1987, small rockfalls began from near the top of Middle Brother, the second of three peaks of the

Figure 19. Photograph of Slide Mountain, Nevada, rockslide. Scarp at top right with person (circled) in foreground for scale (photograph by Steve Ellen, 1983).

Figure 20. Photographs of debris flow on Ophir Creek fan triggered by rockslide on Slide Mountain, Nevada. A: Debris-flow deposition on fan; recent rockslide scar on Slide Mountain is visible in distance (dashed line). B: House partially buried and bus overturned (right) by debris flow on fan of Ophir Creek (photographs by Steve Ellen, 1983).

Three Brothers on the northern rim of Yosemite Valley (Fig. 1, site 9). Middle Brother, a 900-m-high cliff of closely jointed, dark gray, medium-grained granodiorite, has a history of rockfalls (1873, 1921, 1923, and 1962) that occurred without apparent triggering events (Wieczorek et al., 1992). By 2:20 p.m. on March 10, the increasing frequency of small rockfalls and audible rock-popping noises had attracted the attention of the National Park Service, which closed Northside Drive and the surrounding part of Leidig Meadow below Middle Brother (Fig. 21).

At 2:47 p.m. Pacific Standard Time, March 10, 1987, a large rockfall broke from the face of Middle Brother, dropped 800 m, and spread rapidly across a talus cone, covered Northside Drive, and sent a few boulders across the Merced River (Fig. 22). James Snyder, historian of the National Park Service, observed that the

large rockfall initiated as an intact planar slab of rock that separated from the cliff face. As the slab fell, it appeared to shorten in a folding-like manner similar to the steps of an escalator, as might be expected from deformation of a closely jointed and highly fractured rock face. A second large rockfall from the face of Middle Brother occurred later that day at 5:10 p.m. The combined volume of these rockfall deposits totaled an estimated 600 000 m^3. Dozens of smaller rockfalls continued during the next several days. During the next several weeks, a large number of small rockfalls occurred, some of which could be attributed to runoff during storms dislodging the abundant loose rock that accumulated on the ledge beneath the face of Middle Brother. Based on the monitoring of the decreasing rate of rockfall activity, Northside Drive was reopened in early July 1987 (Wieczorek et al., 1995).

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

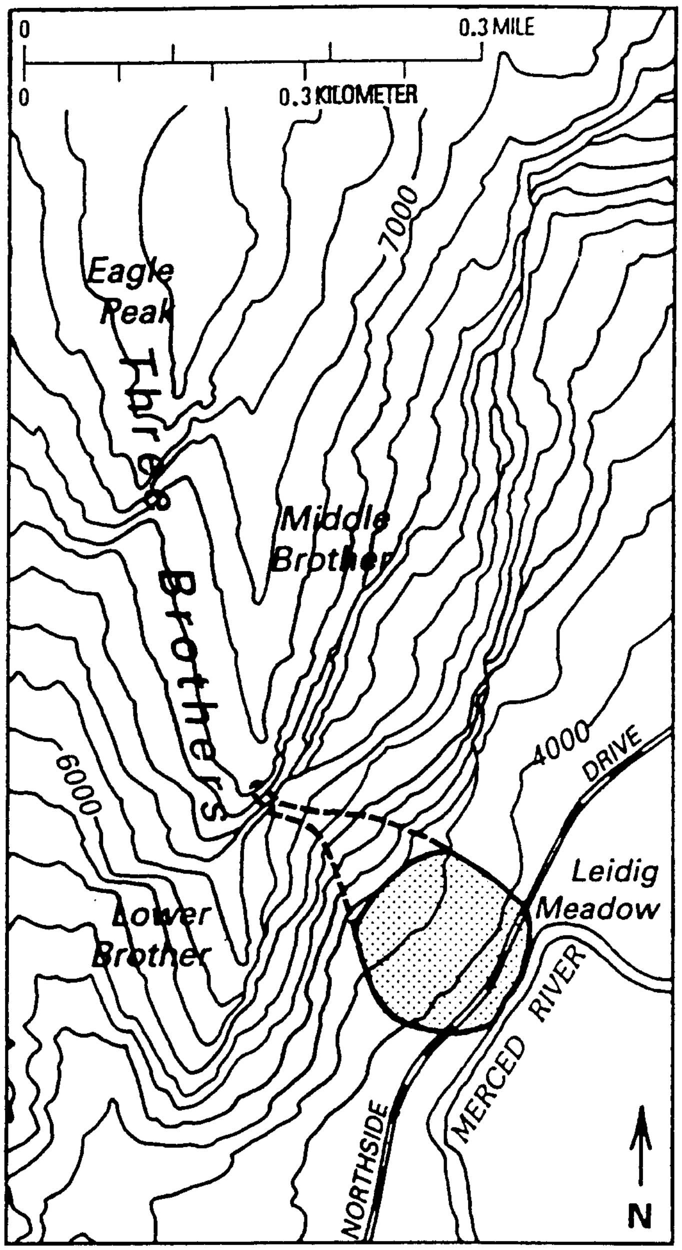

Figure 21. Map of Middle Brother rockfall, Yosemite Valley (topographic base from U.S. Geological Survey 7.5′ Half Dome quadrangle, contours in feet). Dashed lines indicate release area and path of travel; dotted pattern shows rockfall deposit.

snowmelt. Water freezing in joints, which exerts cleft pressures, could have weakened the rock mass during the preceding winter. No earthquakes were detected during this period that could account for this sudden onset of rockfalls. The release point of the rockfall was significantly above the level of Tioga glaciation on the valley walls. Calkins (1985) mapped Middle Brother as Sentinel Granodiorite (Cretaceous) close to contacts with the El Capitan Granite and Half Dome Granodiorite; the cliff face shows a highly sheared and jointed rock mass intruded by dikes, indicative of the geologic complexity of this juncture and inherent weakness of the site.

Several reasons may explain the triggering and unusual long duration of rockfalls at Middle Brother. The potential movement of one critical block may undermine neighboring key blocks (Goodman, 1989). Beginning on March 8, brittle fracture indicated by rock noise and subsequent removal of key blocks by smaller rockfalls may have released the interlocked geometry of the closely jointed and fissured rock face. The granitic rocks of Yosemite crystallized at depth and were unloaded by uplift and erosion. With fluvial and glacial downcutting of the deep trough of the Yosemite Valley, the lack of lateral confinement may have initiated the release of residual horizontal stresses. Sudden stress release is evidenced by rock noises, such as popping or gunshot-like sounds; gradual stress release may be responsible for the formation of exfoliation sheets, the dilation of joints, and the occurrence of some rockfalls without triggering events.

Happy Isles, Yosemite National Park, California (site #10—figure 1)

At 6:52 pm on July 10, 1996 two rockfalls only seconds apart occurred near Happy Isles in the Yosemite Valley (Fig. 1, site 10; Fig. 23) without any apparent triggering event. From a developing arch-like cliff between Washburn and Glacier Point several hundred meters above the Tioga glacial trim line, the rock masses started sliding along a steeply inclined plane. Traveling down this plane their horizontal velocity was sufficient to launch the falling masses, which cleared the base of the cliff and hit the talus 500 m below (Fig. 24). The first mass was estimated to be 15%-20% the size of the second; together the two masses amounted to a volume of between 23 and 38 $\times 10^3$ m^3 (Wieczorek et al, 2000). The two rockfalls hit the talus slope 13.6 s apart; their separate impacts were recorded by seismographic stations in western Nevada and central California (Uhrhammer, 1996, written commun.).

The impacts of these large, still largely intact rock masses on the talus slope generated an air blast that traveled well beyond the limit of fresh rock on the talus slope and knocked down or snapped 1000 trees that damaged the Happy Isles Nature Center, destroyed a snack bar, killed one person, and seriously injured several other people in the vicinity of Happy Isles (Morrissey et al., 1999; Wieczorek et al., 2000). Shortly following the air blast, a rapidly moving cloud including coarse sand and finer particles was generated from the impact that enveloped the area of the Nature Center and Happy Isles in a thick cloud of dust that for

Figure 22. Photographs of Middle Brother rockfall. A: Release point (dashed line) of March 10, 1987, rockfall. Pine trees above and to left of release point provide approximate scale. (National Park Service photo 92-013-28 taken February 19, 1992. B: Release point (dashed line) and rockfall deposit on talus at base of Middle Brother. (National Park Service photo 92-013-4 taken February 19, 1992. C: Talus from March 10, 1987, rockfall covering Northside Drive and reaching Merced River at left (National Park Service photo 87-004 taken March 11, 1987).


A


B


C

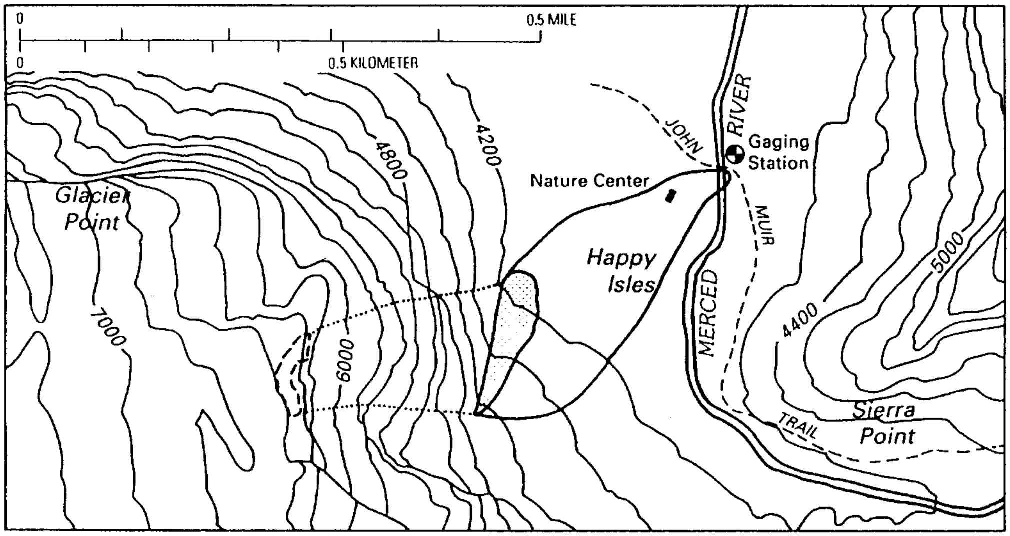

Figure 23. Map of rockfall and air blast area near Happy Isles, Yosemite National Park (topographic base from U.S. Geological Survey 7.5′ Half Dome quadrangle; contours in feet). Dashed lines indicate release area; dotted lines indicate path of free fall; dotted pattern shows rock deposit; pattern represents area of air blast caused by impact of rockfall.

several minutes blocked out the early evening sunlight. Later that evening and early the next morning two additional large pieces of rock from the southern section of the cliff broke loose and followed an alternate path down a chute that added to the upper southern part of the talus. Bouncing and breaking up along this path, these masses did not reach the talus as large intact pieces and there was no large air blast as with the two earlier rockfalls.

These falling rock masses originated from an arch structure 150 m long that had been gradually developing from a combination of weathering, erosion, exfoliation, and other previous rockfalls since last covered by glaciers more than 1 m.y. ago. The rock faces exposed after the event showed open joints with tree roots, soil, water seeps, and stains, as well as portions of brown weathered rock, all indications of the extensive weathering and gradual weakening of the rock mass. The release occurred at or very near the boundary between two plutons, the granodiorite of Glacier Point and the other of Half Dome Granodiorite (both of Cretaceous age)(Peck, 2002), possibly contributing to the long-term erosion processes (Snyder, 1996). On August 2, 1938, a rockfall occurred from this locale that added to the existing talus, created noise and dust, but caused no damage. Along with the previously described 1872 Liberty Cap rockfall, this 1996 rockfall was only the second rockfall to have triggered an air blast among more than 400 documented events in Yosemite National Park (Wieczorek et al., 1992). This rockfall demonstrates how the detailed topography of the release area and possible paths of descent play an integral roll in determining the consequences of individual rockfall events. If this rockfall had occurred some two hours earlier, the consequences may have been significantly different, because the Happy Isles vicinity is usually busy at that time with as many as several hundred people.

SUMMARY

The prehistoric, historic, and recent rockfalls and rockslides described in this chapter illustrate that rockfalls and rockslides are a long-term geomorphic process shaping the landscape in the Sierra Nevada. Despite having a low recorded historical incidence of landsliding, the Sierra Nevada has undergone large prehistoric and historic rockfalls and rockslides that could be potentially catastrophic if they occurred in currently more densely populated parts of the region. The glaciated topography of the high Sierra Nevada has produced many relatively small falls and slides within relatively hard, jointed, granitic rocks, such as from Liberty Cap in Yosemite National Park. Where the granitic rocks have been weakened by prolonged weathering after glaciation, e.g., above the level of Tioga glaciation in the Yosemite Valley, large rockfalls have occurred near Mirror Lake, Old Yosemite Village, Middle Brother, and Happy Isles. At lower elevations of the Sierra Nevada, rockslides occur within even more weathered granitic rocks, where strength of the rock mass is typically affected by joint weathering and alteration of the intact rock to saprolite, such as the rockslide along Highway 50 on the South Fork of the American River.

Strong shaking during earthquakes or abundant moisture from large regional winter storms has triggered large rockfalls and rockslides in the Sierra Nevada. Large, infrequent earthquakes along the eastern Sierra Nevada have caused historical rockfalls and rockslides; the paleoseismicity of the Sierra Nevada is not well understood, but the large piles of rocky talus in many places along the eastern Sierra Nevada may be attributable to large prehistoric earthquakes. Unusually heavy seasonal precipitation is also a trigger for large rockfalls and slides, particularly when warm rain falls on a thick winter snowpack and the melting

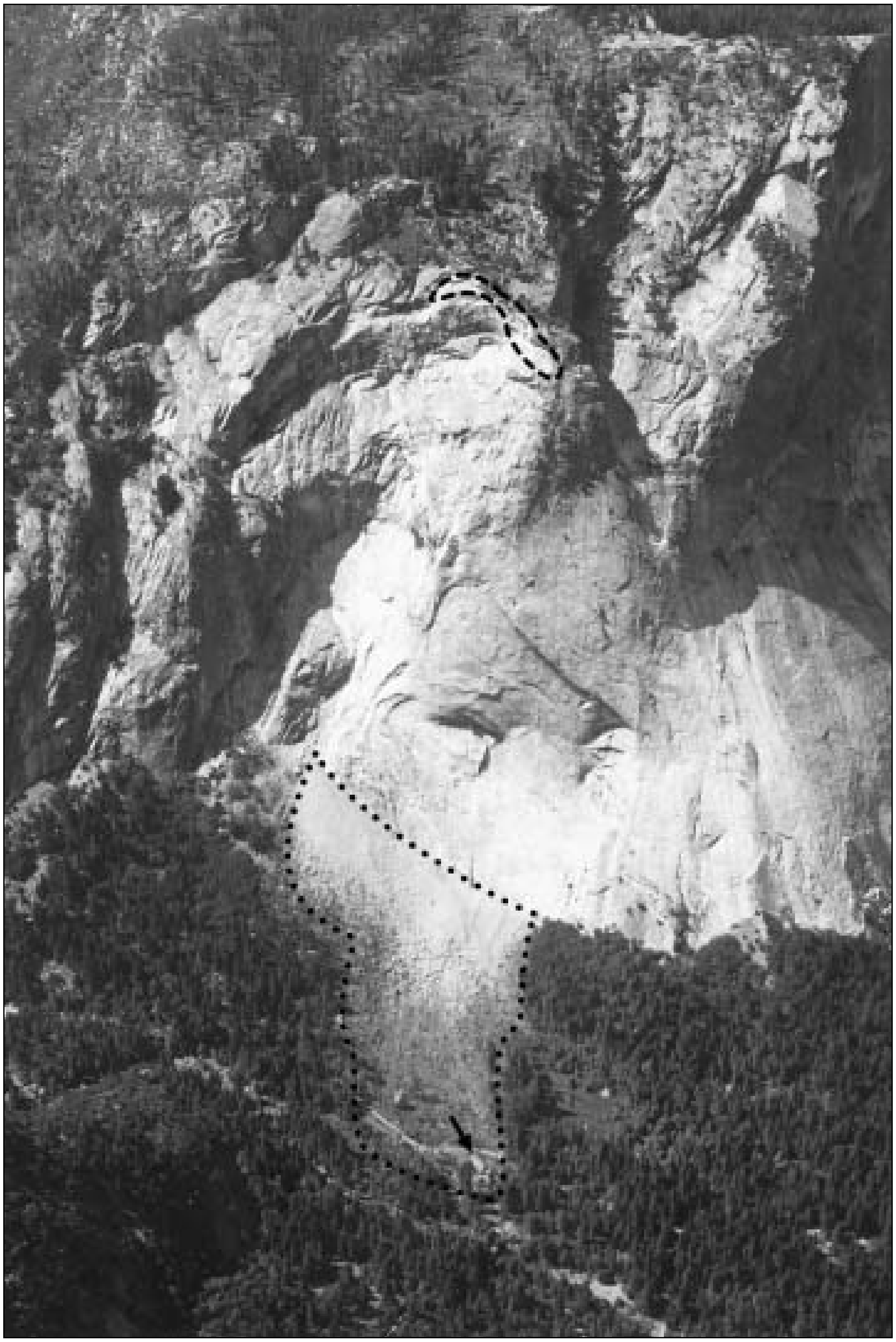

Figure 24. Photograph of rockfall and air blast near Happy Isles along Merced River. Release point (dashed line) below and southeast of Glacier Point (top right). Impact areas on talus and area affected by air blast (dotted line). Happy Isles Nature Center building (arrow), 30 m long, is shown for scale (courtesy of National Park Service; photograph by Pacific Aerial Surveys, September 1996)

provides an abundant source of moisture. Historically large rockfalls and rockslides in the Sierra Nevada have posed secondary hazards, including landslide dams, floods, and debris flows, that can be as hazardous as the initial rockfalls and rockslides.

ACKNOWLEDGMENTS

I am indebted to many people, especially James Snyder, Steve Ellen, King Huber, William Bull, and David Keefer, who provided descriptions and photographs of rockfalls and slides. James Snyder is also credited with supplying archival information and photographs from the National Park Service Yosemite Museum. The preliminary version of this manuscript benefited greatly from reviews by Robert Schuster and Jerry DeGraff.

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Manuscript Submitted May 21, 1996;
Accepted by the Society November 30, 2001.

Printed in the USA