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# Analysis of rock falls in the Yosemite Valley, California[1]

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ABSTRACT: The volume-frequency distribution of rock falls and rock slides in the Yosemite Valley are well described by a simple power-law relationship, where log N(Vol) = 3.48 - 0.57(log Vol). This relationship, based on 214 documented rock-fall and rock-slide events that occurred from 1900 to 1992, allows determination of estimated return periods and probabilities for rock-fall events of different sizes. Based on this relationship, the largest prehistoric rock fall in the Yosemite Valley at Mirror Lake has an estimated return period of 325 years. On 10 March 1987 two massive rock falls from Middle Brother, with a combined volume of 600,000 $m^3$, spread across the talus cone and covered Northside Drive, blocking the primary exit from the Yosemite Valley. Brittle fracture indicated by rock popping noises and suggesting release of horizontal residual stress accompanied small (<50 $m^3$) rock falls that preceded these two massive rock falls from Middle Brother. Removal of "key blocks" by the smaller rock falls may have released the interlocked geometry of closely jointed and fissured rock of the face of Middle Brother and permitted the failure of the much larger rock mass. During the subsequent months the number of continuing small rock falls at Middle Brother exhibited an inverse power law decay with time.

## 1 INTRODUCTION

Approximately 400 rock falls and other forms of slope movement (as defined by Varnes, 1978) have been documented in the Yosemite Valley and vicinity since the 1850's (Wieczorek et al., 1992). The volume of individual rock falls has been noted, which provides volume- frequency data for analyzing the occurrence of infrequent, large rock falls. Many rock falls have been associated with triggering events, such as earthquakes, storms, and freeze-thaw cycles; however, the majority of the rock falls in Yosemite have occurred in the absence of a recognized trigger.

Beginning in March 1987, we documented an unusual sequence of rock falls from Middle Brother in Yosemite Valley (fig. 1). On March 10, two large rock falls with a cumulative volume of approximately 600,000 $m^3$ occurred, spread rapidly across the talus cone, and covered Northside Drive. This was the largest historical rock-fall in Yosemite Valley. The Middle Brother rock falls occurred without an apparent triggering event, such as an earthquake or storm, but they had been preceded for several days by smaller rock falls. Following the rock-fall events of March 10, numerous smaller rock falls continued at the site for several months. This sequence of rock falls at Middle Brother was unusual because of its several month long duration with smaller rock falls both preceding and following the larger events; unlike any other documented rock falls in Yosemite.

In this paper we examine the events and conditions associated with rock falls in Yosemite to better understand the behavior of large rock masses. The geologic setting of Yosemite is reviewed before describing the volume-frequency distribution of rock falls and rock slides in the Yosemite Valley and the sequence of rock falls at Middle Brother. We conclude by exploring several possible explanations for the spatial and temporal behavior of rock falls.

## 2 GEOLOGIC SETTING

The Sierra Nevada batholith consists chiefly of

[1]This paper is dedicated to Professor Richard Goodman, who stimulated the senior author's interest in the study of slope movements

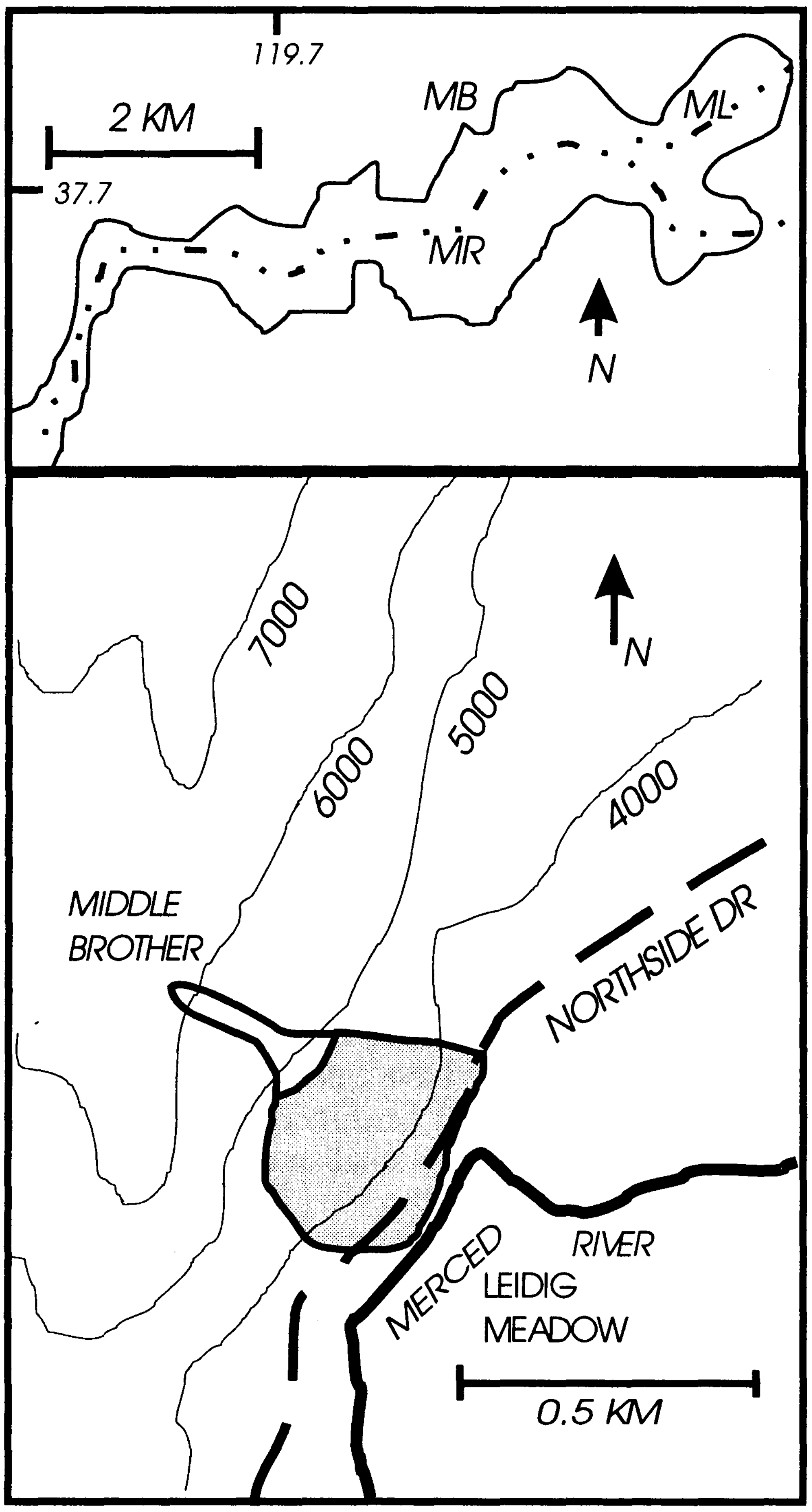


Figure 1. Map of Middle Brother rock fall and inset showing rim of the Yosemite Valley with MB, Middle Brother, ML, Mirror Lake, and dashed line indicating MR, Merced River. Rock-fall deposit is shaded with source and path outlined from near top of Middle Brother. Contour interval is 1000 ft.

Cretaceous granitic rock. At the end of the Cretaceous, about 65 million years ago, the granitic batholith was well exposed, and the region had been eroded to a low-relief landscape. Beginning about 25 million years ago, the region was uplifted and tilted to the southwest. With increased gradients, the streams draining the west flank of the Sierra Nevada incised deep canyons into the rising range before the onset of glaciation, possibly some 2 million years ago.

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 can the extent of ice be reconstructed with confidence; the valley has not been filled with ice for at least 750,000 years (Huber 1987). The depth of erosion in the valley is confirmed by seismic surveys that detected the bedrock surface beneath accumulated sediment that has a maximum thickness of over 600 m (Gutenberg et al. 1956).

## 2.1 *Volume-frequency distribution*

Figure 2 shows the cumulative volume-frequency distribution of 20th century rock falls and rock slides in the Yosemite Valley. A sample of 214 rock falls and slides with volumes characterized with the best quality ratings [$Q_{size}$], in order of decreasing accuracy, of 0,1, and 2 [0-volume or weight reported, 1-some dimensions reported, 2- vague indication of size] from Wieczorek et al. (1992) are plotted (fig. 2). The rolloff of data at the left hand side of the plot reflects the uncertainty of data including incomplete reporting of events with volumes less than about 100 $m^3$ (open circles).

For those rock slides and falls with volumes larger than 300 $m^3$ (solid circles) during the period 1900-1992, the cumulative number of events, N, with volumes greater than or equal to a particular volume, Vol, is well described by the power-law relation:

$$N(Vol)=2987(Vol)^{-0.57} \text{ or } \quad (1.1)$$

$$\log N(Vol) = 3.48 - 0.57(\log Vol) \quad (1.2).$$

This relation is similar to the Gutenberg-Richter frequency-magnitude relationship for earthquakes and is typical of the family of fractal or self-similar distributions found elsewhere in nature (Mandlebrot 1983; Scholz 1990).

Self-similar scaling behavior enables use of frequent smaller events to estimate of the rate of occur-

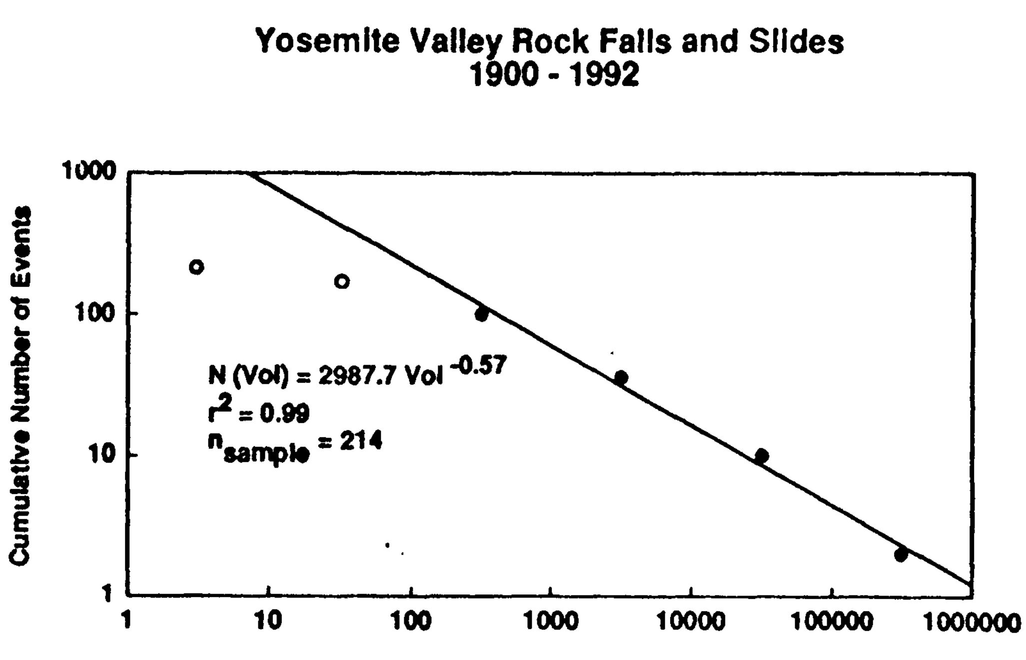


Figure 2. Volume-frequency distribution of rock falls and slides in the Yosemite Valley from 1900-1992.

rence of less frequent larger events. The largest recognized prehistoric rock falls in the Yosemite Valley occurred since the last deglaciation of the valley about 15,000 yr BP. The prehistoric rock fall which blocked Tenaya Creek forming Mirror Lake (est. volume $11.4 \times 10^6$ $m^3$), has an estimated return period of 325 years, based on the fit to the 92 years of 20th century data in Figure 2. Using this method, the return times and probabilities can be determined for other size rock-fall events. For example, the return period for events with volumes equal or greater than 10,000 $m^3$ is 6 years. The maximum size of these events are limited only by local geologic and topographic conditions, in particular, by the number of joint sets, their spacing, orientation, and length.

### 2.2 *Middle Brother rock falls*

Middle Brother is the second of three peaks of the Three Brothers on the northern rim of Yosemite Valley. The southeastern face of Middle Brother (fig. 3) has a history of rock falls (1873, 1921, 1923, 1962, and 1987) which occurred without apparent triggering events (Wieczorek et al. 1992). The sequence of rock falls in 1987 is the best documented of these events.

Beginning on March 8, 1987, small rock falls began from near the top of Middle Brother, a 900-m high cliff of closely jointed dark gray, medium grained, granodiorite, onto a talus cone below. By 2:20 pm on March 10, the increasing frequency of small rock falls and audible rock popping noises had attracted the attention of the NPS, who closed Northside Drive and the surrounding area of Leidig Meadow.

At 2:47 pm on March 10, 1987, a large rock fall broke from the face of Middle Brother, spread rapidly across the talus cone, covered Northside Drive, and sent a few boulders across the Merced River. James Snyder of NPS observed the large rock fall initiate 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 (fig. 3). A second large rock fall from the face of Middle Brother occurred later that day at 5:10 pm.

Dozens of smaller rock falls continued during the next several days and consequently a monitoring program was initiated by NPS, consisting of daily observations of the number and timing of rock falls from Middle Brother. During the next several weeks, a large number of small rock falls 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.

Figure 3. Photograph of Middle Brother showing densely jointed and fractured rock. Release point of 10 March 1987 rock fall is visible as bright patch (center). Pine trees above and to left of release point provide approximate scale. Photo by Michael Dixon, National Park Service (NPS), March, 1987.

An extrapolation of the rock-fall data for the first 30 days (3/10-4/8/87) gave a preliminary indication that the average rate of rock falls would drop below one event per day by late April, perhaps permitting the opening of Northside Drive. Although the rate of rock falls continued to fluctuate, the average rate remained in the low range (<1 event per day) after late April. By late June the rock-fall frequency had dropped even lower and Northside Drive was re-opened in early July. A brief flareup of rock-fall activity in early August again required the temporary closing of Northside Drive, but rock-fall activity quickly diminished and the road was again opened without subsequent problems.

Figure 4 shows the rate of rock-fall activity following the two primary falls on 10 March 1987. The average number of events per day, based on discreet 10-day windowing of the field data, are plotted as a function of time (in days) since 10 March 1987. The overall decay in the average rate of daily rock-fall activity follows an inverse power law:

$$n(t)= 352\ t^{-1.58} \tag{1.3}$$

where n is the number of events and t is the time elapsed, in days since March 10.

The decay of rock-fall activity as a function of time in Figure 4 is similar to the Omori law (Utsu 1969) of earthquake aftershock sequences. Decay in aftershock activity represents the relaxation of stresses following the main shock (Scholz 1990). Following a large rock fall, small rock falls may represent a redistribution of stress in the rock mass with a descreasing rate approaching equilibrium. Note that in Figure 4, while the overall pattern of rock-fall activity decays as a function of time, there are significant variations and fluctuations in rock-fall activity which may be real or partially attributable to observational inconsistency.

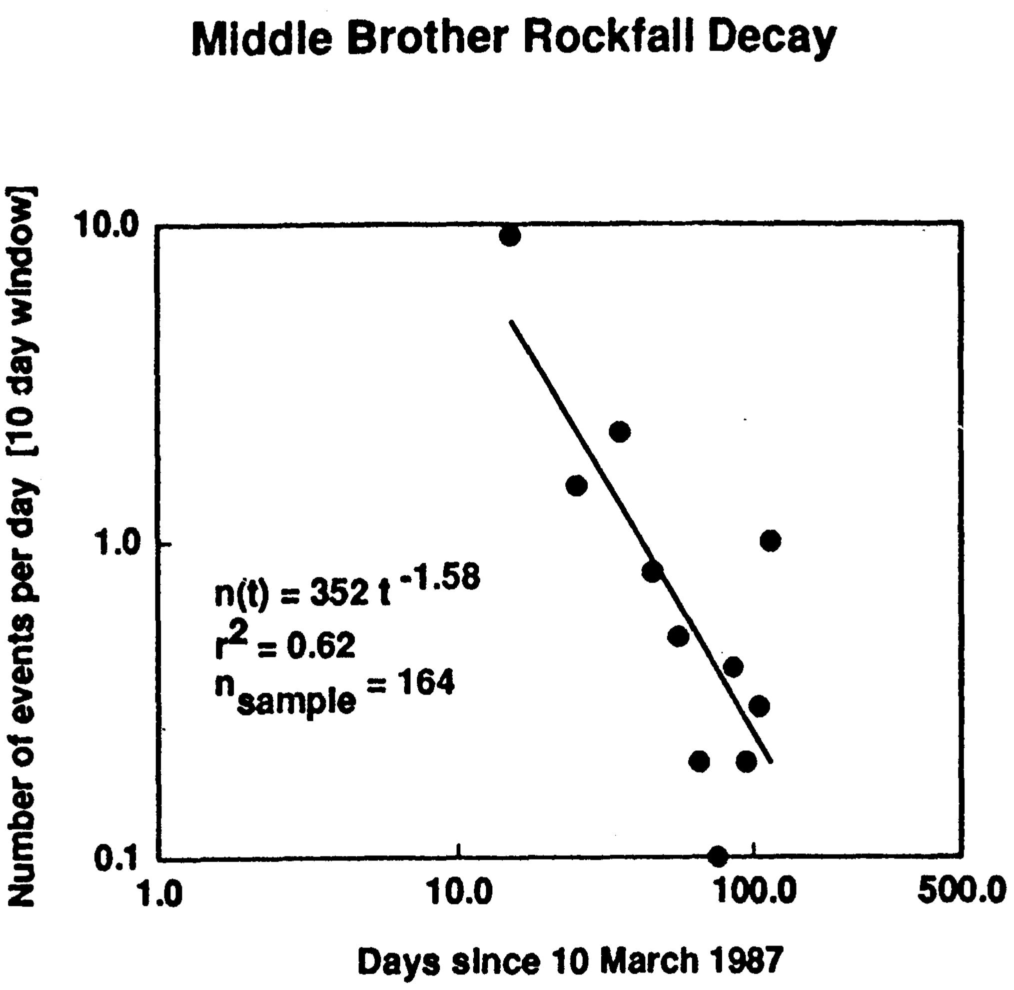


Figure 4. Frequency of rock falls from March 10 until June 13, 1987 at Middle Brother. Log scales are used for both axes in this plot.

## 3 DISCUSSION

Several reasons may explain the triggering and unusual long duration of rock falls at Middle Brother. The potential movement of one critical block may undermine neighboring blocks; these most dangerously located blocks are called "key blocks" (Goodman 1989). Brittle fracture indicated by rock noise and subsequent removal of "key blocks" by smaller rock falls beginning on March 8, 1987, may have released the interlocked geometry of the closely jointed and fissured rock of the face of Middle Brother and permitted the failure of the much larger rock masses. Because the locations of the initial small rock falls and discontinuities in relation to the larger rock masses that failed are unknown, block theory (Goodman and Shi, 1985) cannot be used to verify this hypothesis.

During and immediately preceding March 8-10, the weather was dry without extreme temperature variations that might be associated with freeze-thaw or snowmelt cycles. Weakening of the rock mass by water freezing in joints which exerts cleft pressures could have occurred during the preceding winter. No earthquakes occurred during this period that would account for this sudden onset of rock falls.

The granitic rocks of Yosemite crystallized at depth and by the end of the Cretaceous had been unloaded by uplift and erosion. At this stage the residual stress remaining in the crystalline structure of the rock was probably highly anisotropic with residual horizontal stresses several times greater than vertical stresses (Varnes 1970). With the consequent fluvial and glacial downcutting of the deep trough of the Yosemite Valley, the lack of lateral confinement may have initiated the release of these horizontal residual stresses. In the Yosemite Valley sudden stress release is evidenced by rock noises such as popping or gunshot sounds; gradual stress release may be responsible for the formation of exfoliation sheets, the dilation of joints, and the occurrence of some rock falls without triggering events.

This investigation has resulted in new guidelines for estimating the frequency of occurrence of large rock falls based on a power-law relationship of volume-size frequency. This information is being used to assess rock-fall hazards in Yosemite National Park. In addition, by using earthquake processes as analogs, we have been able to model some of the temporal behavior of rock falls and slides of Yosemite Valley. For the rock falls in 1987 at Middle Brother, extrapolation of the decaying rate of rock falls provided useful information for the reopening of Northside Drive.

## 4 ACKNOWLEDGMENTS

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