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# Tectonic influences on geometry and kinematics of the 1998 Mission Peak Landslide, California

J. David Rogers<sup>1</sup> and Dan Wang<sup>1,2\*</sup>

## Abstract

The Mission Peak Landslide of March 22–28, 1998 represented a partial reactivation of a much larger prehistoric landslide complex that developed along the slopes of Mission Ridge during the Late Quaternary time. Its crown scarp is structurally controlled by the Mission Peak fault, and its toe is influenced by the Warm Springs Fault. The active slide encompassed an area of 0.346 km<sup>2</sup> (85.5 acres) and involved over 13 million m<sup>3</sup> (17 million yd<sup>3</sup>) of materials in an astonishing array of kinematic block reactions, which changed constantly during the first 6 days of movement. Most of the changes in surface morphology were influenced by the underlying geologic structure and stratification and the steep topography of the site, which rises from an elevation of 158.5 m to 562 m (520–1,845 ft) in just 1,255 m (4,120 ft). This paper summarizes evaluations of the areal extent of the slope movement and the various kinematic modes observed at the time, which were investigated during the following year through a program of surficial geologic mapping, subsurface exploration, sampling and testing, and analyses of collected data. A triangulated system comprising 43 benchmarks, 11 exploratory borings, 5 grouted slope inclinometers, and a telemetry network monitoring slope creep was established to allow near real-time monitoring from 1998 to 2008.

**Keywords** landslide; Mission Peak; slope stability; landslide mapping; kinematic models

## 1 Introduction

The Mission Peak Landslide of March 22–28, 1998, which is located in Fremont, California, contained more than 13 million m<sup>3</sup> (17 million yd<sup>3</sup>) of materials, making it the largest landslide to impact the San Francisco Bay Area during historic time [1]. This mass represented only a fraction of a much larger landslide complex that blanketed the slopes of Mission Ridge during Holocene and late Pleistocene time. This complex extends from just below the ridge crest down to the approximate position of Mission Boulevard (Fig. 1). The active slide occupies

an area of approximately 0.346 km<sup>2</sup> (85.5 acres). The slide extends upslope from the channel of Aliso Creek near elevation 158.5 m (520 ft) to the crest of Mission Ridge at elevation 562 m (1,845 ft), descending about 400 m over a flow distance of approximately 1.66 km.

There were several unique aspects associated with this landslide:

1. The slide was under careful observation for the first 6 days, beginning with a retrogressive slump complex approximately measuring area of about 244 m (800 ft) wide and up to 533 m (1,750 ft) long, which enlarged itself over the following week, exhibiting a remarkable array of kinematic reactions influenced by pre-existing structures that surprised most observers.
2. The slide occurred in an area that had exhibited considerable geomorphic evidence of recent activity, although this was the first confirmed movement since

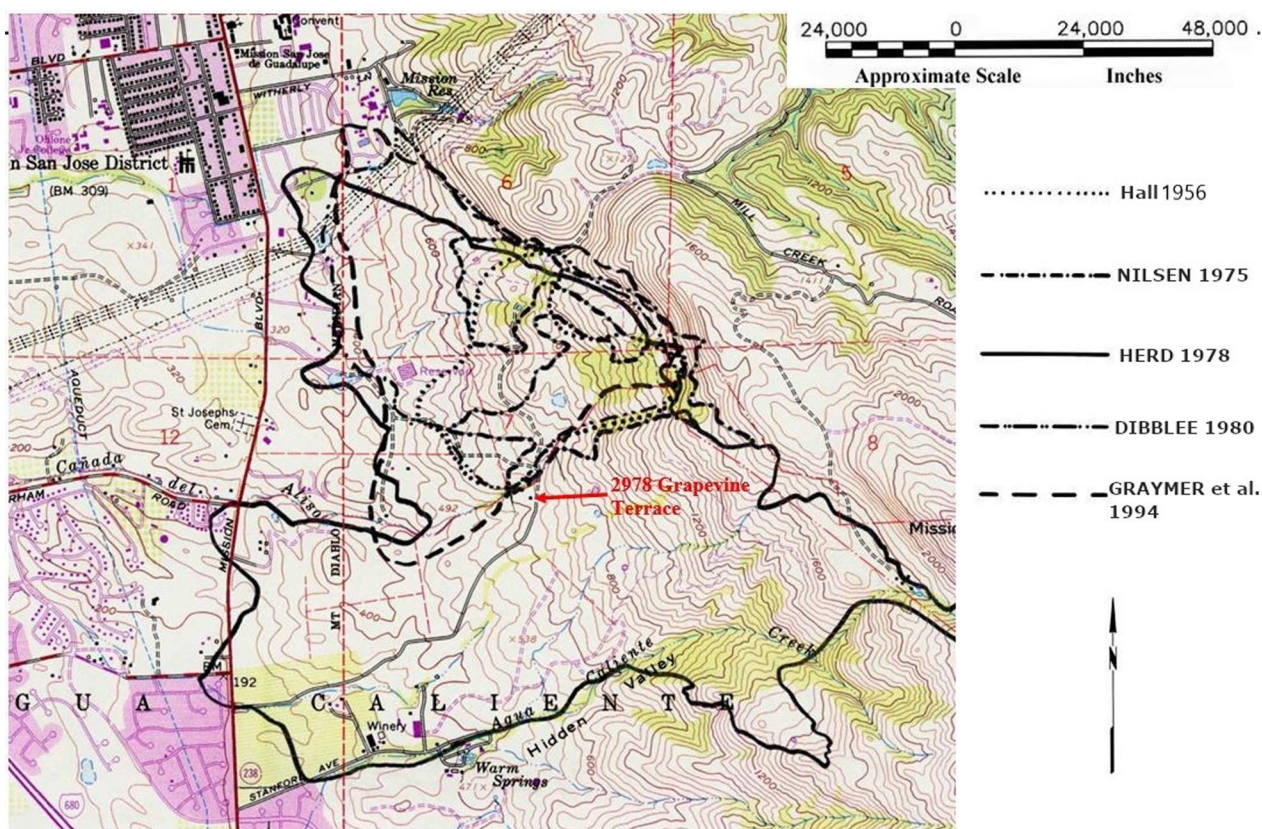
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**Fig. 1** Overlay of various interpretations of the coalescing landslide complex mapped by Hall [2], Nilsen [3], Herd [4], Dibblee [5], and Graymer et al. [6], before the 1998 landslide. Arrow points to 2978 Grapevine Terrace in Fremont, CA, immediately adjacent to the toe of the 1998 slide (base map Niles 7.5' Quadrangle in Alameda County, California, 1980).

- initial settlement of the Mission San Jose District in 1797.
3. The slide’s headscarp was structurally controlled by the Mission Fault, while the toes was controlled by the Warm Springs Fault. The Mission Fault was considered active by the California Geological Survey.
  4. The bedrock ridge above the slide reacted to the sudden loss of about 21 m (70 ft) of materials that dropped into the rapidly developed headscarp graben structure, hastening both a series of rockfalls from the exposed ridge above the headscarp and the appearance of some prominent tensile scarps between elevations 457 m (1,500 ft) and 533 m (1,750 ft).
  5. Two months later, the exposed slope above the headscarp began shedding approximately 46,000 m<sup>3</sup> of new sandstone onto the head of the landslide [7]. This creeping block involved about 185,000 m<sup>3</sup> of materials.
  6. A pair of extensometers were installed across an enlarging tension crack in late March 1998. This was tethered to a telemetry network using a cell phone in late April. This array recorded 0.71 m of movement

between late March 1998 and January 2000, with the average rate of creep diminishing to 2.5 mm/month in 1999. The block seemed to creep in proportion to precipitation, mostly during the wet winter months. In January 2000, the extensometer array was replaced by GPS receivers installed by the U.S. Geological Survey and monitored until 2008 [8–10].

### 1.1 Seismicity of the Mission Fault

The landslide lies in a tectonically active area, typified by fault-bordered blocks caught between the Hayward and Calaveras Faults. Hall was the first to recognize and name the Mission Fault [11], cutting across the base of Mission Peak and Mission Ridge, just missing old Mission San Jose (see Fig. 1 for different maps of the landslide area). The fault forms a boundary between the Briones Sandstone exposed on Mission Ridge and the younger Pliocene-age nonmarine sedimentary rocks known as the Orinda Formation within the overturned Tularcitos Syncline, intermittently exposed beneath the more gently inclined slope (Fig. 2). The Orinda beds



**Fig. 2** The upper image is an overview of the exposed headscarp on the north side of the landslide near elevation 1,440 ft. The lower image shows the conformable nature of contact between overturned Orinda Formation and Briones Sandstone. Hall [13] had mapped this buried contact as the Mission Fault.

are younger and less competent nonmarine sedimentary units, occupying a tightly folded prism extending southeasterly. Historic records kept by the Mission noted damaging earthquakes in 1812, 1822, and 1868 [12]. The Hayward Earthquake of October 21, 1868, completely destroyed the Mission, which was not rebuilt until the early 1980s.

By 1992, most seismologists conceded that the Mission Fault was part of what appeared to be a step-over feature between the Calaveras and Hayward Faults that was demonstrating seismogenic creep [11, 14–16]. Microseismic data suggests that the Mission Fault was near-vertical at depth where the earthquakes were occurring, exhibiting a strong right-lateral focal component.

Andrews *et al.* [11] prepared a detailed investigation of the Mission Fault. They believed that dip-slip movement may be occurring along buried faults within the Mission-Calaveras Fault step-over region. From a reconnaissance of the Monument Peak area, they deduced that a buried thrust or reverse fault underlies the area, dipping north-east. The prominent scarp below Mission Peak exhibits this same strike and sense of slip. They concluded that the Mission Fault zone must consist of two or more fault surfaces inclined at different dip angles.

Given the available data, aerial photo lineations, and fresh exposures in the slide's headscarp, it appears that the Mission Fault is bifurcated in two parallel segments, between 122 m and 244 m southwest of and parallel to the base of Mission Ridge [6]. Post-1969 microseismic data suggests that the Mission Fault is an active right-lateral Fault with near-vertical inclination below a depth of 3 km. Since the early 1990s, there has been a consensus of opinion that the Mission Fault likely represents a stress and seismicity transfer between the northern Calaveras and south Hayward Faults. Although the exact surface trace of the Mission Fault was not precisely determined, in February 1998, the California Geological Survey and International Conference of Building Officials redesignated the Mission Fault as part of the seismically active Hayward Fault, and required that its near-field effects be considered when designing structures within 15 km of the projected surface trace [17]. The Hayward Fault was recognized to have a slip rate of approximately 9 mm/year with a moment magnitude,  $M_L$  of 7.5.

### 1.2 Topography

Based on the topography shown in Fig. 1, between elevations 520 ft and 645 ft, the toe of the landslide is bound along its lower margins by the historic channel of Canada del Aliso Creek. Between elevations 520 ft and 555 ft, the channel was pushed about 3 m south of its pre-slide position in 1998. Near elevation 555 ft, the landslide moved about 5 m (16.5 ft) westward, constricting the channel and creating a narrow chasm, just a few meters wide. Upstream from this position, the channel was uplifted about 2 m (6.5 ft), then infilled with another 1–2 m (3–6.5 ft) of sediment, lifting the channel bed as much as 4 m (13 ft) between elevations 192 m and 198 m (630 ft and 650 ft), adjacent to the home at the uphill end of Grapevine Terrace.

Assessment of aerial photographs dating to 1939 revealed that the site has been under near-continuous use for open grazing during the previous six decades. Several unimproved access roads and stock ponds were graded by local ranchers between the late 1930s and mid-1950s, but none of these had any impact on the 1998 slide. The 1984–1986 photos revealed that two earthflows

had begun to mobilize just below the upper ranch road near elevation 1,300 ft. These dropped between 2 m and 3 m (6 ft and 10 ft), and remained dormant until March 1998. The reactivation of these earthflows between elevations 1,300 ft and 1,000 ft appear to have “triggered” the 1998 movement sequence, described in our conclusions.

A prominent strike-controlled bench exists across the 1998 slide area, between elevations 1,200 ft and 1,400 ft. This linear feature appeared to be an old landslide headscarp graben, extending from the Ohlone Trail (near elevation 925 ft) and natural saddle about 244 m (800 ft) southeast of the slide (near elevation 1,555 ft). This depression appeared to be filled with coarse detritus, which enhanced infiltration of local runoff.

### 1.3 Structural geology and stratigraphy

Dibblee showed the Mission Fault lying near the base of the Mission Ridge escarpment, crossing beneath the slide complex [5], which extends for over a mile, between Aliso Creek and Ohlone College. He also showed the Warm Springs Fault concealed beneath this same complex, near elevation 600 ft. Dibblee mapped Mission Ridge as overturned Tertiary Miocene-age marine sandstone (Briones Sandstone, [5], Fig. 2); while the area between the Mission and Warm Springs Faults was mapped as Tertiary Pliocene-age nonmarine sedimentary rocks (Tps: the Orinda Formation of [2, 13], Fig. 2). The Tps materials were folded into the Tularcitos Syncline, whose axial plane Hall projected to be dipping about 55° northeast [2]. Dibblee [5] projected the syncline through the upper slide area, near elevation 1,200 ft (Fig. 1). Hall [2, 13], Dibblee [5], and Crane [18] interpreted the Briones Sandstone comprising the Mission Ridge escarpment to be overturned, within the northeastern limb of the Tularcitos Syncline. The overturning of the syncline, in and of itself, placed older strata above younger, with both units being upslope of the synclinal axis.

Hall [2, 13] and Dibblee [5] showed the boundary between these units to be the concealed Mission Fault. The geomorphic evidence for faulting is considerable, and contrast in hardness is notable. Hall suggested that the Cierbo Sandstone and lenses of the Neroly Sandstone may lie between the Briones and Orinda beds, in near-conformability [13], but he believed them to be missing in this location. In 1998, the senior author trenched the landslide headscarp and found a thin wedge of green Cierbo Sandstone appeared to be conformable (but overturned) sequence between the Orinda and Briones beds across the base of the headscarp (Fig. 2). This bed appeared to be about 25 ft thick, and was laced with bedding plane shears dipping approximately 25° northeast, into the slope.

Crane inserted blind thrusts, backthrusts, and overturned syncline and anticline axes, and utilized concepts of balanced structural cross sections [18]. He also mapped this landslide complex north of Aliso Creek, as did Dibblee, showing the Warm Springs Fault concealed beneath slide debris. Crane also suggested that the Briones Sandstone (Tmss) lies beneath the Orinda beds (Tps) between the Warm Springs Fault (elevation 580 ft) and elevation 700 ft, along Aliso Creek. He also showed the Orinda Formation to be tightly folded within the Tularcitos Syncline, with an overturned anticline located a short distance downslope. Crane also showed the Briones Sandstone forming Mission Ridge to be overturned, with the Mission Fault striking northwesterly, approximately 30–91 m (100–300 ft) downslope of the erosional escarpment [18].

The geologic map of Graymer *et al.* [6] reinterpreted many of the outcrop patterns mapped by previous workers in the area, using new fossil data, terrace age dates, and fault relationships, including recognition of several dozen thrust faults in the East Bay Hills. Graymer *et al.* [6] interpreted the Briones Sandstone beds of Mission Ridge to be right-side-up. They also noted that the surface trace of the Mission fault appeared as two steeply-dipping splays, which bound either side of Mission Ridge, lifting the Briones Sandstone more than 457 m (1,500 ft). A compressional environment is suggested by this arrangement. They projected the Mission and Warm Springs Faults beneath Dibblee's massive coalescing landslide complex, bound by Aliso Creek. Their trace of the Mission Fault was about 305 m (1,000 ft) downslope of Mission Ridge, somewhat downslope of the trace proposed by previous workers.

## 2 Materials and methods

### 2.1 Geologic mapping and site characterization

The investigation of the 1998 Mission Peak Landslide involved a comprehensive program of surficial geologic mapping and field reconnaissance conducted immediately following the failure. Field mapping focused on identifying the areal extent of slope movement, kinematic modes of failure, and the relationship between surficial geomorphology and underlying geologic structures. This work was supplemented by a review of regional geologic literature and maps to establish the stratigraphic and tectonic context of the Mission Ridge area. To define the structural boundaries of the slide, trenching was performed across the landslide headscarp to expose the contact between the Orinda Formation and Briones Sandstone, as described in the previous section.

### 2.2 Aerial photography analysis

To evaluate the history of slope instability at the site, we analyzed stereo-paired aerial photographs covering the period from 1950 through 2000. This photogrammetric review allowed for the identification of pre-existing geomorphic features, such as scarps and hummocky terrain, and the tracking of land use changes, including the grading of access roads and stock ponds between the late 1930s and mid-1950s.

### 2.3 Subsurface exploration

Subsurface conditions were investigated through a geotechnical exploration program that included:

- Exploratory borings: eleven exploratory borings were advanced to characterize the lithology and determine the depth of the slide mass.
- Instrumentation: five grouted slope inclinometers were installed to monitor the depth and rate of ongoing slope movement.
- Geophysical traverses: geophysical surveys were conducted to further delineate subsurface stratigraphy and rupture surfaces.
- Trenching: numerous trenches were excavated in exposed scarps to visualize shear surfaces and stratigraphy.

Data from these explorations were used to construct fifteen longitudinal geologic cross-sections and to estimate isopleths of the basal rupture surface, which will be discussed later.

### 2.4 Ground survey and monitoring

A precise ground survey network was established to monitor surface displacements and kinematic block reactions. A photogrammetric array capable of 5-mm resolution was established by Hammond-Jensen-Wallen Associates in mid-April 1998. This network utilized 41 GPS-surveyed control points distributed both on and off the active slide mass. The array was re-flown and orthorectified in mid-July 1998 to quantify block movements.

In addition to the photogrammetric array, a telemetry network was deployed to monitor slope creep in near real-time. This included a pair of extensometers installed across an enlarging tension crack in late March 1998 [8, 10]. In January 2000, this extensometer array was replaced by GPS receivers installed by the U.S. Geological Survey, which continued monitoring until 2008.

## 2.5 Hydrological data collection

To analyze the relationship between precipitation and slope failure, historical rainfall data were obtained from the Alameda County Water District (ACWD). Specific datasets included:

- ACWD Gage 1942: located on Agua Caliente Creek, approximately 1.1 km south of the slide.
- ACWD Gage 50: located near the mouth of Niles Canyon, approximately 8 km northwest of the slide, with records dating back to 1870.

These records were analyzed to calculate cumulative precipitation and recurrence intervals for the storm seasons preceding the 1998 failure.

## 3 Results and discussion

### 3.1 Geological and tectonic analysis

The geologic setting of the landslide appears to be dominated by active thrust faults with increasing sense of strike-slip motion, approaching the right-lateral sense Hayward Fault. During the 1998 field work, the senior author noted what appeared to be overturned crossbeds in the Briones Sandstone exposed on Mission Ridge. The nature of the contact between the marine Briones Sandstone and the younger nonmarine Orinda Formation appeared to be a conformable gradational contact. This suggests that the prominent break-in-slope at the base of Mission Ridge is stratigraphically controlled and not fault-bordered, as previously believed.

The rate of uplift along the eastern and western splays of the Mission Fault was likely in the range of 0.5–3 mm/year. The overturned Briones Sandstone appeared to be a resistant “plug” of material that was being squeezed upward between two reverse faults. As this resistant mass was pushed upward, it provided an ample supply of loose blocks that fell onto the coalescing landslide complex that mantles the base of Mission Ridge (Fig. 3).

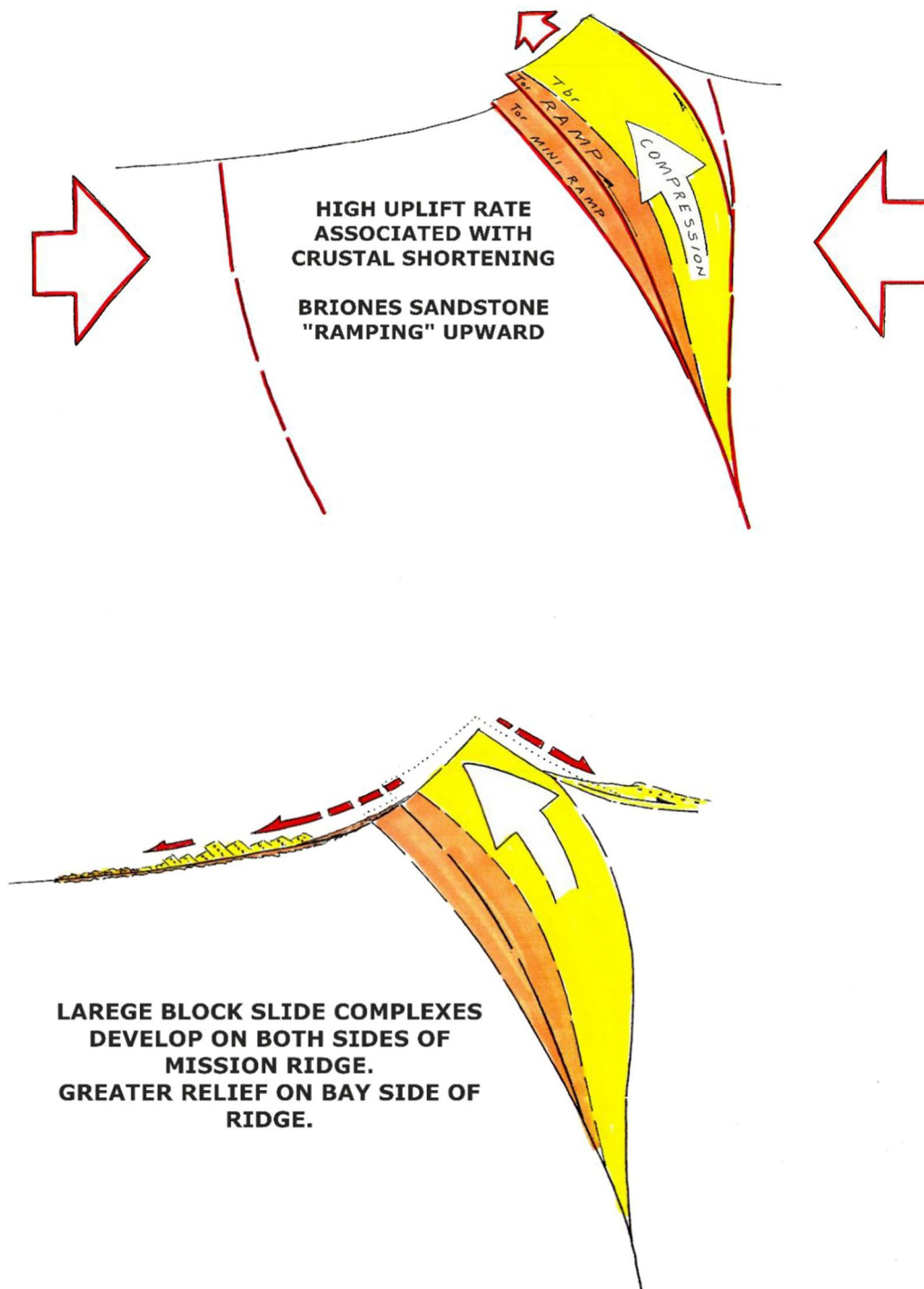
Seismicity recorded along the Mission Fault prior to the slide (1969–1991) suggested that vertically inclined strike-slip motion was occurring at depth of > 3 km. The dip likely lessened with shallowing depth, approaching the ground surface, due to diminishing confinement and creep of the steep escarpment. The observed dip of the lower Orinda beds near their contact with the Briones/Cierbo beds (near elevation 1,400 ft) appeared to be about 25° NE. The nonmarine Orinda beds were clearly exposed in much of the crown scarp (between elevations 1,475 ft and 1,375 ft) and in the secondary scarp (between elevations 1,275 ft and 1,050 ft). The dip of the Orinda beds was also likely influenced by gravitational creep,

due to their position and low competence (high plasticity). The dip of these strata likely increased with depth, as observed in the stiffer Briones beds, just upslope. The Orinda beds appeared to be tightly confined within the overturned Tularcitos Syncline of Hall [13].

The slope between Hunter Lane and Mission (Peak) Ridge appeared to be blanketed with late Pleistocene and Holocene age landslides, comprised of Briones Sandstone and weathered Orinda Formation materials. Displaced blocks of weathered Briones Sandstone formed many of the resistant knobs that typified the area, as well as conglomerate lenses of the Orinda Formation. Many of the displaced blocks of the Briones exhibited distinctive shell-rich beds observed on the main ridge. These blocks appeared to have been brought downslope in retrogressive slides, one upon another, sliding on fault gouge and weathered Orinda sediments, as shown schematically in Fig. 4.

The thrust feature mapped by JHA Geotechnical Consultants [19] near the Warm Springs Fault (Fig. 4) may be the toe thrust of deep-seated slope movements, as they suggested. Very little of the original structure can be discerned from outcrops in the lower slopes, where abundant fragments of Briones Sandstone abound within a matrix of clayey debris. Efforts to locate the surface trace of the west Mission Fault near the location shown by Hall [13] proved futile. Considerable microseismic and geomorphic evidence suggest that the Mission Fault was active. This included the strong linear expression of a strike-controlled depression between Ohlone Trail (elevation 925 ft) and the ridge valley south of Mission Peak (which extended up to elevation 2,300 ft). This depression appeared to be a massive landslide headscarp graben between elevation 925 ft and 1,555 ft, crossing the subject slide between elevations 1,350 ft and 1,450 ft (Fig. 5). There is considerable physical evidence suggesting that the Mission Fault splits along either side of Mission Ridge, as hypothesized by Oppenheimer *et al.* [15], as shown by Crane [18], and as confirmed by Graymer *et al.* [6]. This bifurcation could create a situation wherein the more resistant “plug” of Briones Sandstone would be squeezed upward to relieve compressive pressure, as sketched in Fig. 3.

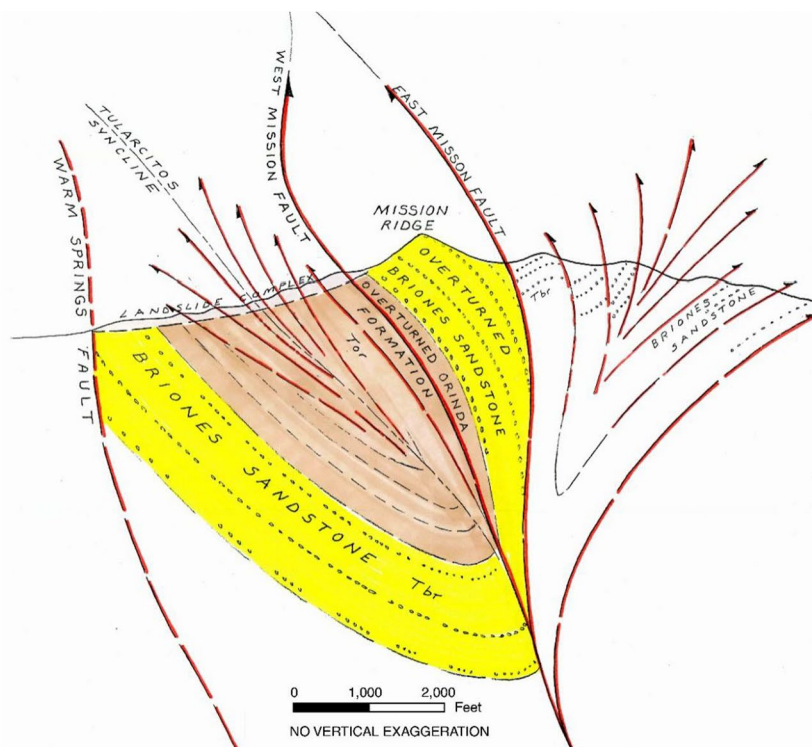
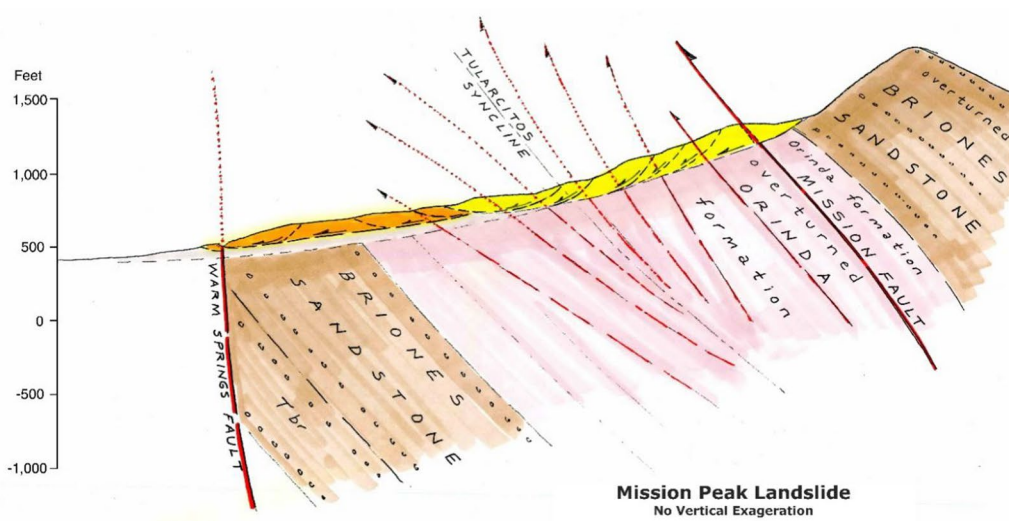
Our estimate of the underlying geologic structure in vicinity of the subject landslide is presented in Fig. 4. Based on the available data, we believe that the west trace of the Mission Fault lied somewhat downslope of the base of Mission Ridge, as suggested by Graymer *et al.* [6]. Ongoing uplift along the Mission Fault may be assisting in “lifting” the upslope side of the prominent landslide graben block, accounting for the apparent change-in-dip of the basal landslide slip surface, sketched in Fig. 4.



**Fig. 3** The upper section presents a schematic view of overturned Briones Sandstone forming Mission Ridge. This unit appears to be squeezing upward between reverse faults on either side of the ridge. As this resistant mass is elevated, it sheds loose blocks that spill onto the coalescing landslide complex that mantles the base of Mission Ridge (as shown in the lower view).

This deformation would also aid in breaking up the slide blocks and assisting in their translation downslope, as suggested by the steep subsidiary slip faces observed below elevation 1300 ft in the 1998 slide.

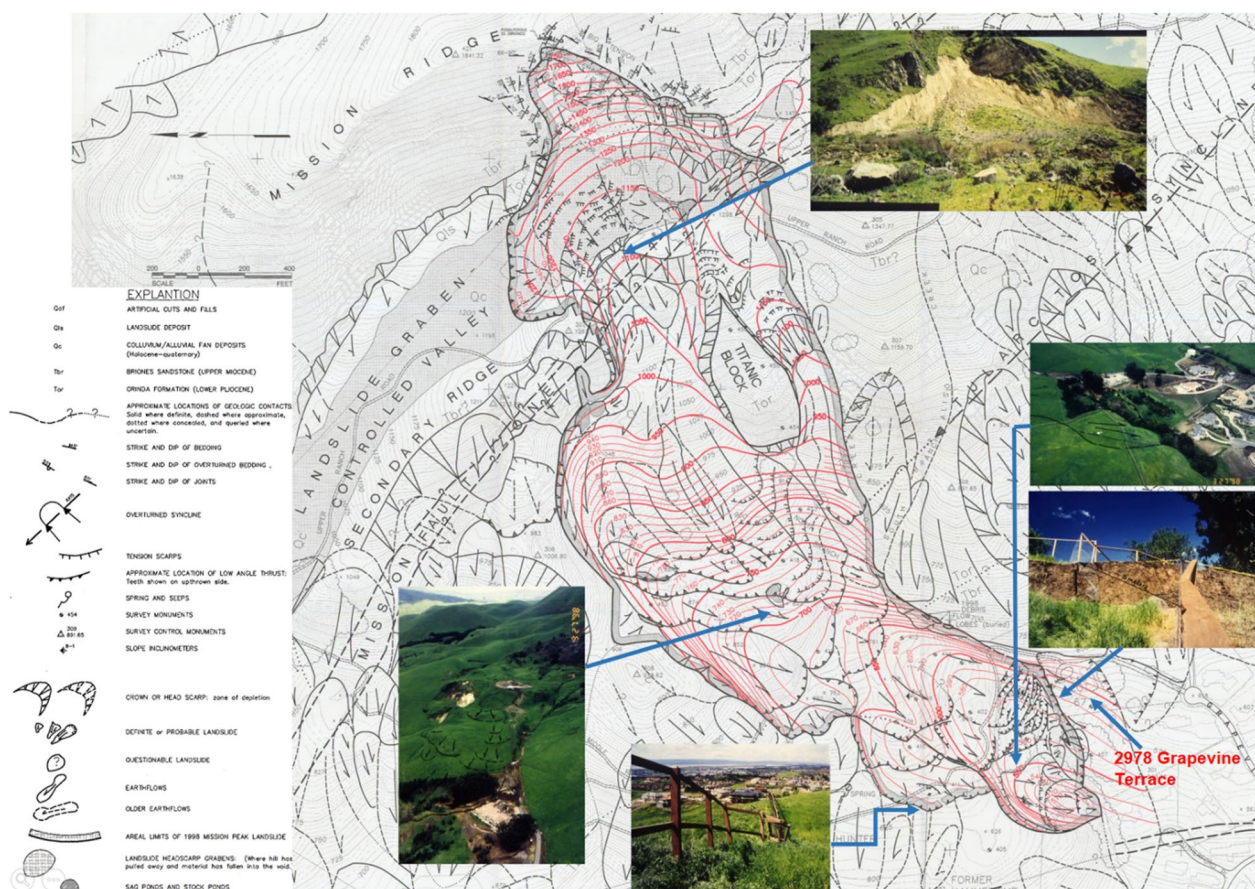
If the physical situation is similar to those conditions described in Figs. 3 and 4, this would account for the apparent elusiveness of the (west) Mission Fault, caught within the chaotic infill of a large headscarp graben. Up



**Fig. 4** The upper image is a schematic section showing how various slide blocks appear to have been brought downslope as retrogressive slides, one upon another, sliding on fault gouge and weathered Orinda sediments. A general picture of the underlying structure based upon mapping of exposures in the headscarp is shown in the lower figure.

until that time, little attempt had been made to explore the surface trace of the “eastern strand of the Mission Fault”. Landslide blocks on the northeast-facing slopes of Mission Ridge were almost as impressive as those on the

southwest side, except that the slope height was much less. The slide blocks on the northeast-facing slope were enormous, suggestive of translational features slipping on inclined bedding planes east of the ridge crest (Fig. 3



**Fig. 5** Isoleths of the basal rupture surface are shown as red contours (in ft). These were estimated by contouring subsurface data gleaned from borings and geophysical traverses, in conjunction with balanced structural cross sections. Photos illustrate some of the morphologic features within the 1998 landslide complex.

lower). Few of these features exhibit evidence of late Holocene movement.

### 3.2 Hydrological factors

#### 3.2.1 Rainfall patterns

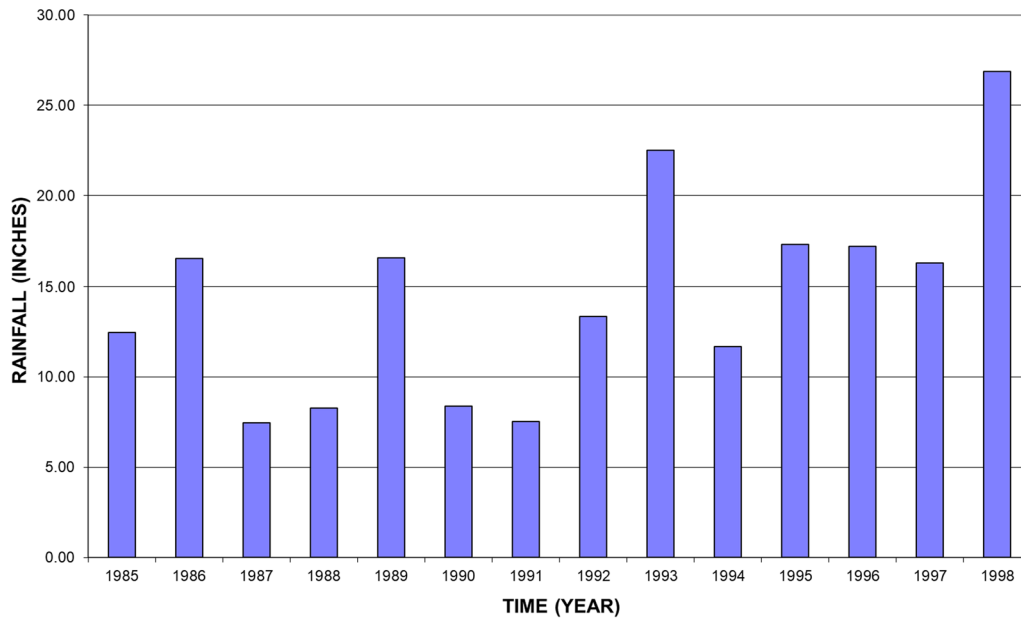
The mean annual precipitation for the area between 1867 and 1998 was between 457 mm and 559 mm (18 inches and 22 inches), from base to crest-of-slope [20]. Grunsky reported near-identical values for the same area [21], based on data collected from 1867 to 1903. The mean annual rainfall was recognized to increase from about 381 mm (15 inches) in the middle of the Santa Clara Valley (San Jose) to just above 787 mm (31 inches) at Mt. Hamilton (at elevation 1,283.5 m). The crest of Mission Ridge lied at 568 m (1,864 ft), increasing to 767 m (2,517 ft) at Mission Peak, about 800 m southeast. The actual rainfall felt on the ridge was likely 20%–25% greater than that reported by the ACWD gages, which are located in low areas at the base of the ridge. During the 1997–1998 storm season, 696 mm (27.4 inches) were recorded by the

nearest dipping gage station, ACWD Gage 1942 (Fig. 6). This value was about 150% of the average annual rainfall. ACWD Gage 50 recorded 894 mm (35.2 inches) of rain during the 1997–1998 storm season, the second-highest total on record (Fig. 7). The 2-, 3-, 4-, 5-, 6-, and 7-year running sums of rainfall in the 1990s were the highest cumulative totals recorded at Niles since 1870, coming on the heels of the most severe multi-year drought ever recorded between 1986 and 1993. These data suggest that record levels of cumulative precipitation likely precipitated the March 1998 landslide.

#### 3.2.2 Runoff hydrology

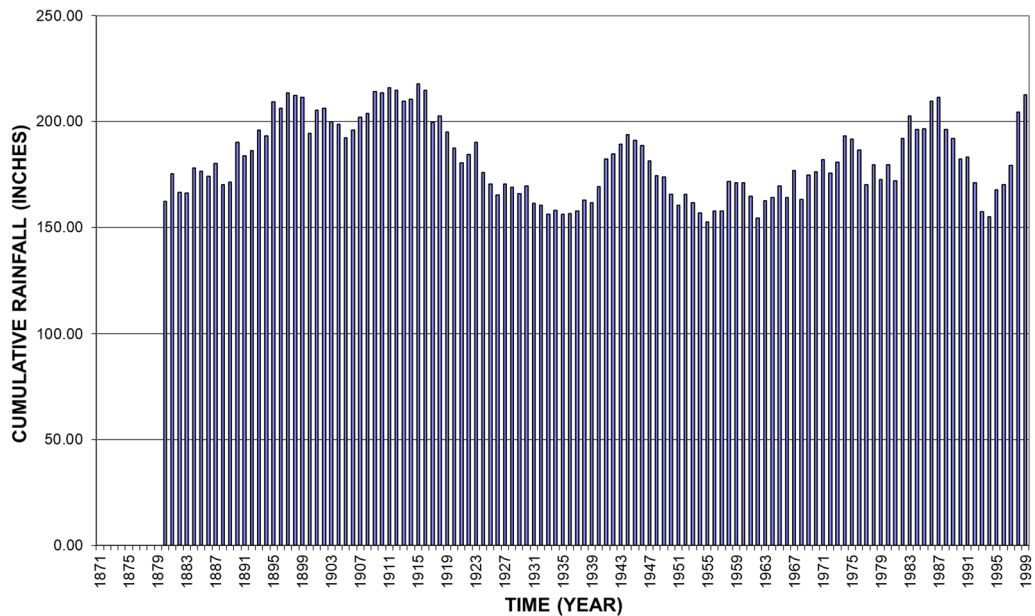
The pre-1998 slide area was once drained by three different streams—Aliso Creek, the next adjacent stream to the north (which fed onto what is now Hunter Highlands), and a third watercourse which ran down the landslide graben-controlled valley—towards Ohlone Community College. The watershed of Aliso Creek above elevation 640 ft appeared to have enlarged from 0.19 km<sup>2</sup> (48

### RAINFALL RECORDED AT GAGE 1942 PRECIPITATION RECORD, 12 MONTH RUNNING SUMS



**Fig. 6** Twelve-month running sums for precipitation recorded from 1985 to 1998 by Alameda County Water District's (ACWD) Gage 1942 on Agua Caliente Creek, only 1.126 km south of the slide. In 1998, the cumulative total was about 150% of the average annual rainfall.

### RAINFALL RECORDED AT NILES, CA PRECIPITATION RECORD, 120 MONTH RUNNING SUMS



**Fig. 7** ACWD's gage 50 has been recording rainfall since 1870, about 8 km northwest of the slide. It recorded 894 mm (35.2 inches) of rain during the 1997–1998 storm season, the second highest total in 128 years.

acres) to as much as 0.51 km<sup>2</sup> (125 acres) due to piracy of the upper reaches of the two adjacent streams by the 1998 slide. The expected range in flow along Aliso Creek near elevation 640 ft was estimated to be in the range of 0.88–1.19 m<sup>3</sup>/s (31–42 ft<sup>3</sup>/s) for a 2.5-year recurrence frequency storm, and 1.61–2.10 m<sup>3</sup>/s (57–74 ft<sup>3</sup>/s) for a 10-year recurrence frequency storm [22].

### 3.3 Historic and seismic movement evidence

#### 3.3.1 Seismically induced movement

The slide area above 750 ft elevation exhibited considerable geomorphic expression of recent landslippage in aerial photos taken between 1939 and 1996. An active erosional scar had been developing above the slide’s headscarp since the earliest images. This led Radbruch-Hall [23] and Herd [4] to presume that the site was the scene of seismically induced ground fissures described by Andrew Lawson in Wood [24]. These fissures were thought to be associated with the M6.8 October 21, 1868 Hayward earthquake:

*“Immediately to the east of Mission San Jose, entirely within the hills, another crack opened with a strike of N. 18° to 20° W., which, converging upon the crack thus far traced, extended south as far as the County line.”*

Radbruch [25] attempted to tie this description to ground cracks surveyed in 1907 by A. A. Bullock. These cracks were shown on his planimetric map of property lines in Washington Township, which was prepared by George L. Nusbaumer, the Alameda County Surveyor described in Wood [24]. This map shows other 1868 quake related ground fissures, and is archived at the U.C. Berkeley Seismology Lab. Radbruch placed a fault along the alignment of the four ground fissures [25], shown on her 1974 hazard map [23]. This NW-trending lineament cuts across the subject landslide at an elevation of

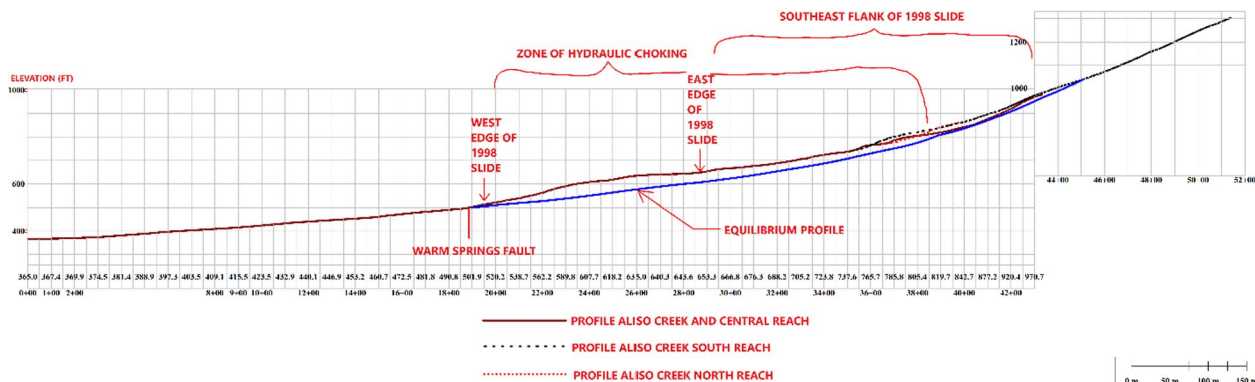
approximately 800 ft. An alternative possibility for the “1868 ground fissures” might be dynamic consolidation of loose infill within the landslide graben-controlled valley, which trends approximately N. 40° W., passing through the old Mission San Jose, established in 1797.

The Warm Springs Fault is the closest structure which approximates the trend and area of the reported 1868 ground fissures. The Warm Springs Fault was not recognized until the early 1960s. JHA Geotechnical Consultants [19] determined that they had located this feature in fault trenches excavated across the proposed Vineyard Heights subdivision in Fremont. Co-seismic movement (strain energy release) along the Warm Springs Fault or the toe thrusts associated with the large ancient slides might also have accounted for the linear character of the 1868 ground fissures.

It is unlikely that any reliable correlation can be drawn between the 1868 ground fissures and the 1998 landslide without additional information. Based on the related description, we would suspect that these ground fissures were associated with co-seismic stress relief along the Warm Springs Fault, or dynamic consolidation of the linear headscarp graben infill materials, depending on the location.

#### 3.3.2 Perturbed channel profile

The most powerful evidence of geologically recent landslippage is the perturbed thalweg profile of Aliso Creek, presented in Fig. 8. This profile suggests that Aliso Creek is out-of-equilibrium with respect to its hydraulic grade, between elevations 500 ft and 810 ft, due to choking of the channel by landslide debris. More debris has been produced than the channel has stream power available to transport, resulting in a convex-up profile [26, 27]. A channel with normal balance between runoff and sediment yield (in “equilibrium”) will tend to develop a



**Fig. 8** Thalweg profile of upper Aliso Creek along the toe and lower lateral boundary of the 1998 slides. This profile suggests that Aliso Creek is out-of-equilibrium with respect to its hydraulic grade between elevations 500 ft and about 810 ft, due to choking of the channel by landslide debris.

convex-up profile downstream, with slope decreasing as watershed area increases [28].

Field evidence for hydraulic choking is also abundant between elevations 500 ft and 520 ft, where the channel gradient increases markedly, in a series of small drops. Part of this change may be associated with vertical offset of the Warm Springs Fault, which crosses Aliso Creek between elevations 500 ft and 505 ft. But faulting cannot, of itself, account for the convex form of the channel profile between elevations 500 ft and 650 ft, which is suggestive of a large “plug” of sediment [29].

### 3.3.3 Recent channel offsets

JHA Geotechnical Consultants noted that Aliso Creek and the unnamed creek channels bordering the south side of the Vineyard Heights-Phase II subdivision exhibited sharp drops in their channel profiles [19], which ranged between 8 and 10 vertical feet. These drops appear coincident with the projected trace of the left-lateral Warm Springs Fault, as discussed previously.

During the March 1998 landslide, the channel of Aliso Creek was pushed about 2.7 m southward, between elevations 520 ft and 550 ft, where a bounding block was forced against the opposing creek bank. At an elevation of approximately 550 ft, the landslide toe underwent approximately 5 m of southwesterly movement into the channel of Aliso Creek, creating a hydraulic choke. This

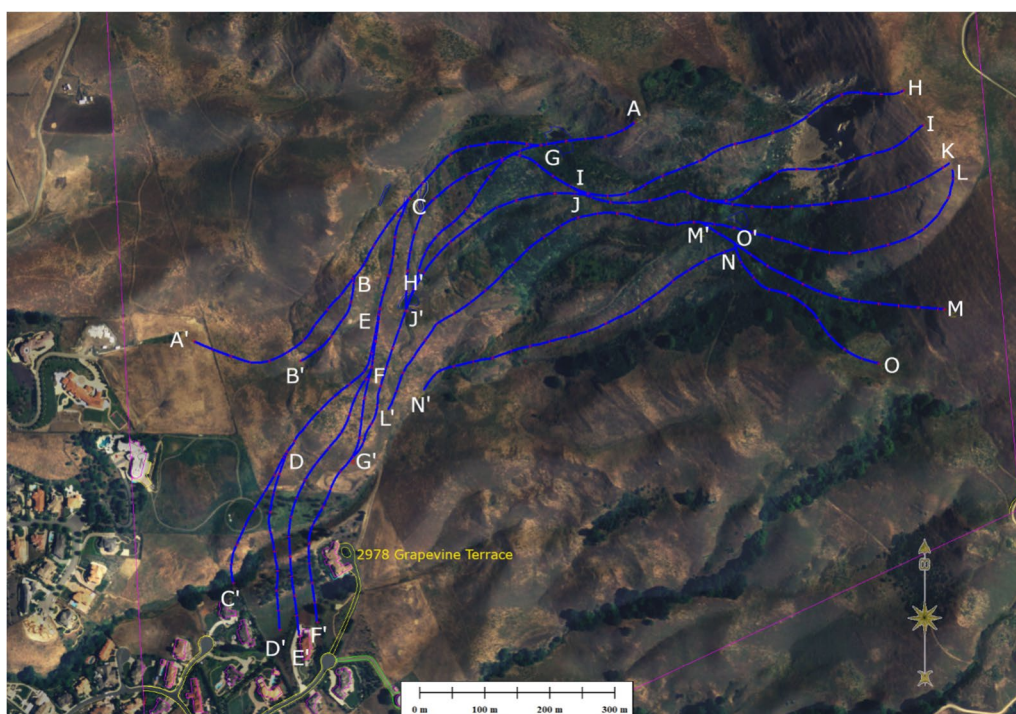
block was over 30 m high, and translated approximately 2 m upward and 3.5 m laterally, with a rake of approximately 30° (dipping northeast).

The recurrence of this blockage through recent geologic time suggests geologically recent activity of the 1998 landslide complex. Given the sharpness of channel perturbations, the slide appears to have been dormant for 100–1000 years since its last episode of comparable magnitude to the 1998 event.

### 3.4 Geometry of the 1998 landslide complex

In order to estimate the likely depths of landslippage (Fig. 5) and volume of the slide mass, 15 longitudinal geologic cross sections were constructed across the 1998 landslide area and adjacent ground. The red isopleths in Fig. 5 show the inferred elevations of the basal rupture surface of the 1998 slide. These are based on data from our field investigation methods described in Section 2.3.

The locations of these cross sections are presented in Fig. 9. The isopleths were estimated by contouring subsurface data gleaned from borings and geophysical traverses, in conjunction with balanced structural cross sections [30]. We also drew upon physical relationships reported by others who had studied similar landslides [31], and the principles of block kinematics [32]. The purpose of reconstructing balanced cross sections was to estimate the likely depths of sliding, and to delineate



**Fig. 9** A total of 15 longitudinal geologic cross sections are constructed across the 1998 landslide area, following the curvilinear paths of the slide’s principal blocks, laid on a shaded digital elevation model. Most of the blocks were retrogressive slump-earthflows. These cross sections are included in Supplementary Figs. S1–S6.

those blocks of ground involved in the recent movements. These cross sections are presented in Supplementary Figs. S1–S6.

Cross Sections H–H', I–I', and L–L' (Supplementary Figs. S1–S3) present our estimate of the underlying conditions in the headscarp area of the 1998 slide, where the movements appeared to be the deepest. These cross sections suggest an initial headscarp graben width of approximately 122 m, with depths of 33.5–55 m (based on the methods advanced by previous studies [33–36]). Note how the deepest portions of the slide occurred in two areas: (1) at the upper end of the main headscarp graben, where the depth of rupture reached 55 m (175 ft) below existing grade; and (2) beneath the deepest earthflows between elevations 850 ft and 1,050 ft, where the plane of rupture was up to 55 m below ground surface.

As the upper slide block translated downslope, an extensive graben, or pull-apart structure, was formed. Headscarp grabens collected surface runoff and talus from the newly evacuated headscarp. As this headscarp depression filled with eroded material and water, the graben periodically extended, allowing the graben block to back-rotate and break into smaller pieces. These pieces are often described as “breccia zones” or “fanglomerate”, which can frustrate attempts to advance exploratory borings due to loss of fluid circulation. Pull-apart grabens typically support sag ponds like those observed near elevation 1,280 ft. Within a few years, these ponds gradually filled with sediment and coarse talus derived from the eroding headscarp.

During the summer of 1998, 6,116–9,175 m<sup>3</sup> of Briones Sandstone talus fell onto the headscarp graben, due to retrogression of the headscarp [22]. The reasons for this belated regression appeared to be related to the geometry of the regional systematic joints controlling the Briones formation. Many of these joint intersections were “daylighted” in the newly exposed landslide headscarp, following the March 1998 movement. This sudden loss of lateral restraint allowed increasingly larger blocks of Briones Sandstone to be brought down, increasing the load on the headscarp graben. Geomorphic evidence of past landslipping and headscarp erosion was abundantly displayed within the 1998 slide area. This situation does not appear nearly so acute at other locations along Mission Ridge, suggesting that this is the most active location of periodic slope instability.

As the slope above elevation 1,300 ft becomes increasingly loaded with blocky talus and absorbs more runoff, the slide mass could reactivate. It appears that this upper block had moved between 122 m and 200 m from its pre-slide position, because the exposed face (between elevations 1,125 ft and 1,275 ft) was comprised of Orinda beds. Additional movements are also

likely fostered by percolation of water into the headscarp sag ponds (near elevation 1,280 ft). The “Titanic” block shown in Fig. 5 (between elevations 925 ft and 1,215 ft) did not reactivate. It appears to be comprised of displaced Orinda beds, devoid of recognizable structure. This suggests a much older sequence of translational slippage at some unknown depth.

Below elevation 1,125 ft on the north side of the Titanic block, and elevation 1,150 ft on the south, were a series of deep-seated earth flows, which also mobilized in March 1998. Those on the north side of the block extended down to elevations 700–775 ft, while those on the south side only extended to elevation 855 ft. Cross Sections H–H' (Supplementary Fig. S1) and L–L' (Supplementary Fig. S3) suggest that the northern earthflows could extend to depths of 21–30 m, but this was never confirmed. Based on the 10 m height of the lateral scarp along the north side of the Titanic block, these estimates appear reasonable.

The massive earthflows along the north side of the middle slope area began to thrust upward around elevation 875 ft, and continued in a series of toe thrust “steps” down to elevation 700 ft. Some of these toe thrusts appeared to have lifted as much as 33.5 m, suggested in Cross Sections A–A' and B–B' (Supplementary Fig. S5).

Below elevation 775 ft, a series of ancient landslide blocks appear to have been loaded by the toe thrusts in 1998, and they reacted in passive compression along pre-existing slip surfaces (associated with prehistoric landslipping). Representative samples of these blocks are presented in Cross Sections C–C' (Supplementary Fig. S5) and E–E' (Supplementary Fig. S6). In this lower slope of the 1998 slide, we observed considerable evidence of passive compression, including multiple toe thrusts and back-thrusts, as shown on Fig. 5 and diagrammatically in Cross Sections D–D', E–E', and F–F' (Supplementary Fig. S6).

A peculiar aspect of the slide's toe is the thrusting that occurred adjacent to the residence at 2978 Grapevine Terrace. In this area, the landslide made a sudden 70° right-hand turn, about 15 m northeast of the residence, along a pre-existing plane of weakness with slickensides, likely a minor fault. Past landsliding appeared to have occurred along this boundary, sufficient to have uplifted a toe-thrusted hillock 26 m high, overlooking Aliso Creek (this was excavated during emergency earthwork to re-open the Aliso Creek channel in late 1998).

The toe of the 1998 landslide appeared to have moved close to 5 m, the majority of which occurred between March 22 and 29, 1998. Components of this movement were both vertical (2 m) and horizontal (3.5 m), for an upward rake (incline) of approximately 30° (dipping northeast). This movement shifted the afore-mentioned hillock 3.5 m towards Aliso Creek, constricting channel

flow by creating a landslide dam. The channel of Aliso Creek above elevation 550 ft was lifted 2–2.5 m.

### 3.5 Apparent offset of landslide by the Mission Fault

The noticeable bench developed along the landslide’s headscarp graben and the observed back-rotation of this block suggest the basal landslide slip surface flattens in the vicinity of the headscarp, as shown in Cross Sections H–H’ (Supplementary Fig. S1), I–I’ and K–K’ (Supplementary Fig. S2), and L–L’ (Supplementary Fig. S3). This change occurred just upslope of the prominent ridge that pervaded the area, between elevations 1,000 ft and 1,300 ft across the slide area (increasing in elevation toward the southeast). This ridge formed the western side of the landslide headscarp graben-controlled valley (Fig. 5).

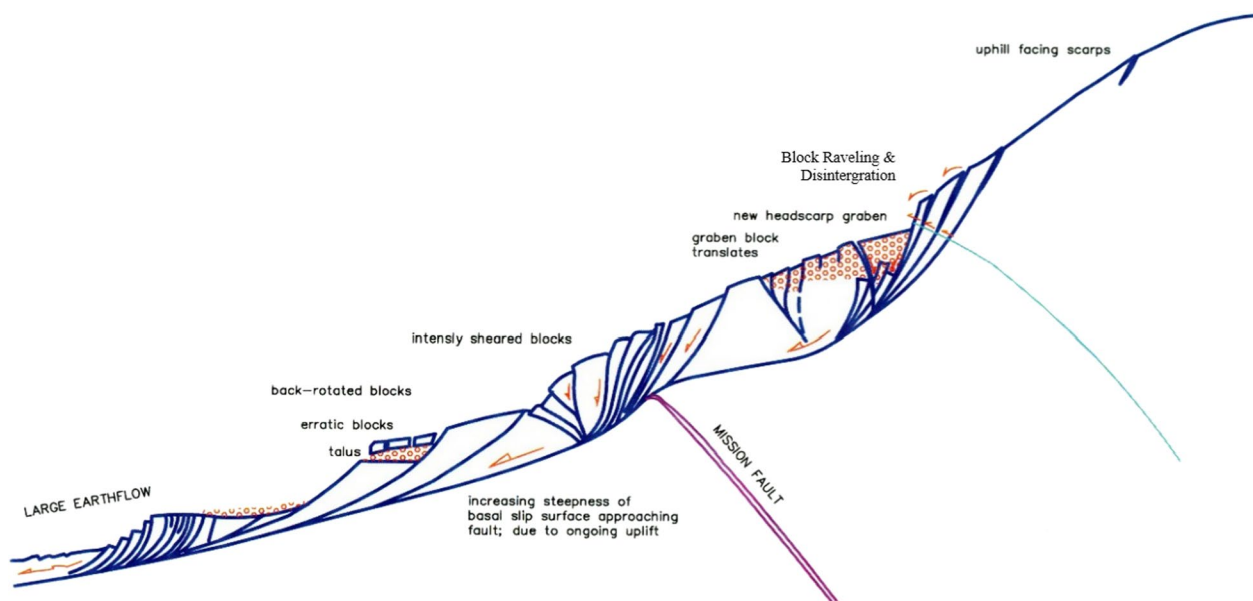
At first glance, it appears that this secondary ridge had simply pulled away from Mission Ridge, but close inspection revealed it to be composed of Orinda beds that were pervasively sheared and devoid of any recognizable structure. The resistant nature of the promontory was partly attributable to conglomerate lenses and overlying blocks of Briones Sandstone; however, some of the height appeared to result from tectonically induced, fault-related uplift along the Mission Fault.

Our evaluation of exposed outcrops at the base of Mission Ridge suggests that the Mission Fault does not lie at the base of the ridge, as proposed by Willis [37] in his “Fault Map of California”. The 1923 map also inferred the Mission Fault to be active because of its location at the base of an

upthrown ridge. Hall [2, 13] placed the fault at the abrupt change in slope, along the base of Mission Ridge. This sharp break in slope appeared to be stratigraphically controlled at the gradational contact between overturned sequences of the Orinda Formation and older Briones Sandstone, which was much more resistant. Graymer *et al.* suggested that the Mission Fault is located 152–183 m downslope of the formational contact [6], an interpretation that agreed with all of the observations made in 1998.

In order to evaluate the potential impact of uplift along the Mission Fault on the subject landslide complex, a series of 14 cross sections were drawn through the headscarp graben area to construct the cross section shown in Fig. 10. Small increments of downslope translation were modeled along with even smaller increments of vertical uplift along the Mission Fault, assuming its underlying position to be about 152 m downslope of Mission Ridge. One of the interesting aspects of this model was the compressional “flower structure” within the mantle of landslide debris along the fault outcrop.

A similar “step” in the basal slip surface of the 1998 landslide appeared to exist, evidenced by the backward rotation of the headscarp. This backward rotation was observed by the diminished slope of the talus fan just below the apex of the headscarp, as shown in Fig. 11. This upper block not only back-rotated but also underwent 6–12 m of simple downslope translation. In this zone, the slip surface(s) steepened markedly, downslope of the prominent “secondary ridge”, which formed the downslope side of the headscarp graben. Recent uplift



**Fig. 10** A series of 14 cross sections are cut through the headscarp graben area to construct this section, which shows the unusual step of the basal rupture surface because of tectonic offset along the active Mission Fault. Note the multiplicity of retrogressive tensile scarps between slide blocks.

along the Mission Fault likely formed the prominent “secondary ridge” along the strike of the Mission Fault. Ongoing movement and uplift along the Mission Fault might be one of the primary mechanisms reactivating the landslide during the Holocene.

### 3.6 Block kinematics of observed failure sequence

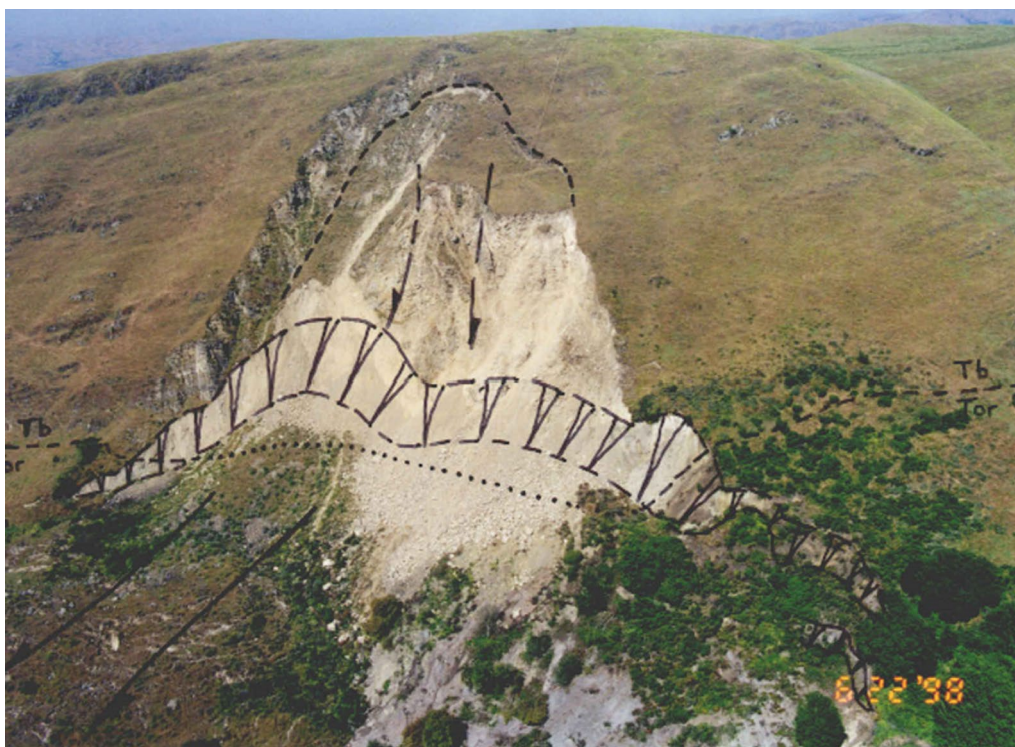
Based on pre-existing topography, analysis of aerial photo stereopairs, and site investigations conducted in 1998–2000 [22], the 1998 landslide sequence likely initiated on the slope between elevations 1,275 ft and 950 ft, where three earthflow slides had previously been triggered in early 1983, following 3 years of above-normal precipitation.

A detailed spatial analysis of the 1998 slide suggests that the massive headscarp graben back-rotated as it dropped, translating southwestward on a slight incline (Step 1 in Fig. 12). This initial movement occurred along a prominent “secondary ridge” that existed 183–305 m southwest of the crest of Mission Ridge. At first glance, this escarpment appeared to be massive blocks of Briones Sandstone, as shown schematically in the lower half of Fig. 3. The topography of this lower ridge/bench may also be ascribable to associated uplift along the Mission Fault (Fig. 10). The lower ridge formed an over-steepened slope. The initial series of slump-earthflows

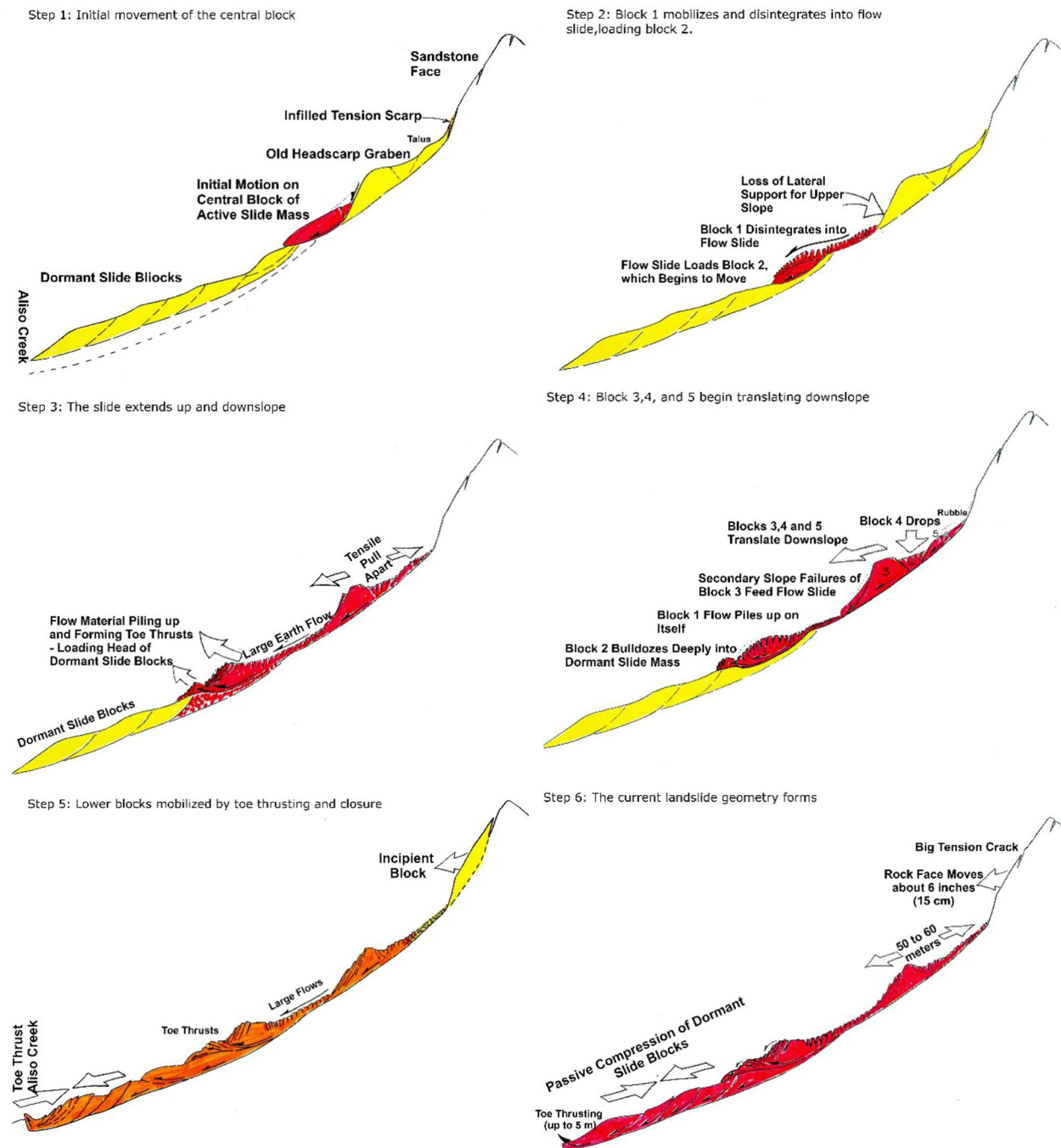
occurred on the southwest-facing slope of this secondary ridge between elevations 1,050 ft and 1,350 ft (Step 2 of Fig. 12). This initial series of earthflows appeared to have extended between elevations 1,275 ft and 700 ft and were up to 36.6 m deep (see isopleths of basal rupture surface as red contours in Fig. 5). The parent material was older slide debris derived mainly from the Orinda Formation. These materials exhibited a mottled series of gray, red, and olive-colored sediments.

When these large earthflows began moving downslope, they removed lateral restraint from the adjacent upslope blocks, forming a temporary minor scarp approximately 40 m high, as sketched in Step 2 of Fig. 12. On the following day, the upslope masses began to reactivate as a tensile pull-apart structure (Step 3 in Fig. 12). On the downslope side, the large earthflows extended to depths of as much as 55 m below the slide’s surface (Supplementary Figs. S1–S3).

The sudden evacuation of so much material reduced lateral restraint at the base of Mission Ridge, which began crumbling and collapsing into the headscarp on March 22, 1998 (Step 4 in Fig. 12). The movement of the upper block appeared to have involved the zone between surface elevations 1,275 ft and 1,425 ft. The headscarp evacuation scar, initially exposed in late March 1998



**Fig. 11** Aerial oblique view of landslide headscarp, showing the initial headscarp separation across the talus cone, with conspicuous raveling. The approximate limits of upper rock wedges and the contact between Orinda Formation (Tor) and Briones Sandstone (Tb) are shown as the dashed (where observed in outcrop) and dotted lines (where hidden) in the image.



**Fig. 12** Schematic representations of the 1998 Mission Peak Landslide, which evolved over a period of 6 days. Note how the initial movements occurred just downslope of the old headscarp graben (Step 1), which was filled with gravel and boulder detritus to depths of over 30 m. During the first few days, no one expected the slide to reactivate the older “dormant slide blocks” shown in yellow in Steps 1-2-3-4.

(Fig. 11), was apparently filled with Briones Sandstone breccia and detritus, which obscured the underlying structure. Between Days 4 and 5, the lower slide blocks 1 and 2 slammed onto the dormant slide complex (with a surface gradient of about 10°) mantling the lower slope.

During the night, the dormant lower slide complex was surcharged by as much as 20–30 m of slide debris characterized by enormous toe thrusts (Step 5 of Fig. 12).

On the fifth day, all of the previously dormant lower slide complex was subjected to passive loading that

caused the entire mass to progressively rupture, proceeding downslope to Aliso Creek (Step 5 of Fig. 12). The right bank of Aliso Creek was enveloped in retrogressive back thrusting, with uphill-facing scarps. Beyond this, reverse and thrust faulting was noted, allowing large blocks to thrust westward, parallel to the creek channel. The incised bank of Aliso Creek (approximately 7.6 m high) physically obstructed and absorbed much of the toe thrusting on that day.

On the sixth day, the lowermost blocks, between elevations 700 ft and 520 ft, were surcharged by as much as 30 m ft of slide debris (Step 6 in Fig. 12). The lower blocks were forced into “passive reaction,” triggering mobilization of passive soil pressures within this ground mass along intersecting log-spiral-shaped shear surfaces oriented at  $45^\circ - \phi/2$  to the applied thrust (where  $\phi$  is the angle of internal friction). These lower blocks were pushed approximately 5 m beneath Aliso Creek, extending adjacent to the residence at 2978 Grapevine Terrace and the channel of Aliso Creek, from elevations 550 ft down to 520 ft.

Much of the strain was accommodated by 5 m of translation along an unnamed minor fault parallel to the creek, while a lesser amount of strain was distributed over a zone about 76 m wide beyond the left bank of the Aliso Creek. Beyond this reaction zone, there were no physical manifestations of earth movement. The slide mass came within 5 m of the highest residence in the developed area (2978 Grapevine Terrace), but did not cause any physical damage to preexisting structures, only diminishing the flow capacity of Aliso Creek. The movement sequence described above was observed between March 21st and 27th, 1998.

### Frequency of landslippage

Ample geomorphic evidence suggests that similar movements have occurred in recent geologic past, impacting the thalweg profile of Aliso Creek (Fig. 8), which was choked with debris. A sobering aspect of the 1998 slide was movement noted between Aliso Creek and elevation 700 ft, within a zone of ancient landslide blocks that appeared quite dormant. Nilsen correctly mapped the slide up to the bank of Aliso Creek [3] (Fig. 1), exactly where the 1998 slide stopped. Various geotechnical consultants had suggested “no-build” or “buffer zones” between the Holocene-age slides and developable areas, usually within 61 m of the more active slide complexes. The 1998 landslide sequence suggests that structural setbacks might be extended, as a function of the scale of the hazard being avoided. In this case, the landslides mapped by Nilsen were shown to be between 915 m and 1,375 m long [3]. Instead of providing a structural setback of 30

or 60 m, in this case, a setback of 500 m might have been more appropriate.

## 4 Conclusions

The 1998 Mission Peak landslide was approximately 1.66 km long, 244–427 m wide, with an elevation differential of just over 400 m between crest and base. It was the largest landslide to impact the developed slopes of the San Francisco Bay Delta Region, which had been initially settled in 1797. The reasons for reactivation of the 1998 Mission Peak landslide are listed below, in descending order of importance. One should realize that the *prima facie* reasons for reactivation of ancient landslides lie in their pre-existing failure surfaces. Underlying geologic conditions control where slides occur, while transient hydrologic conditions tend to control when they occur. Accordingly, the reasons outlined below are split into two categories: (1) geologic conditions; and (2) hydrologic conditions.

### Geologic conditions promoting failure

1. The 1998 landslide occurred within a pre-existing deep-seated slide complex that obscured the underlying geology of the hillocks below Mission Ridge, between Agua Caliente and Ohlone Community College in the Mission San Jose area of Fremont, California, USA. The area between Aliso Creek and Ohlone College was mapped as a landslide by every geologist who studied the area between 1956 and 1994.
2. Considerable evidence suggests that Holocene-age movement has occurred within the Mission Ridge landslide complex over the past several hundred years. The most recent movements likely occurred within the past 200–500 years, based on the geomorphology of the landslide toe area along Aliso Creek. In addition, back-facing tensile scarps in the Briones Sandstone outcrops testify to geologically recent incipient block movements. These features are similar to the separations observed after the 1998 slide, which were monitored for 10 years.
3. The site is tectonically active, with an apparent high rate of uplift. This serves to lift Briones Sandstone along the west Mission Fault, like an inclined “loading ramp”. This mechanism provides an abundant supply of sandstone blocks that are subsequently entrained in the coalescing earthflows mantling the lower flanks of Mission Ridge. Crustal compression between the Hayward and Calaveras Faults has caused extreme folding and faulting of the intervening block of land.
4. This is an area of high seismicity. Historic seismicity along this zone has been monitored since 1969, and

has been found to be one of the most seismically active belts in the San Francisco Bay Region. To date, earthquake epicenters along the Mission Fault have only been recorded, and focal mechanisms confirmed, at depths greater than 3 km, where the fault plane is essentially vertical and exhibits right-lateral slip.

### Hydrologic conditions promoting failure

5. The principal reason for the 1998 reactivation appears to have been the unprecedented levels of moisture recorded in the area between January 1993 and March 1998 (113 cumulative inches recorded along lower Agua Caliente), 2-, 3-, 4-, 5-, and 6-year running sums of cumulative precipitation recorded at the nearby Niles station (ACWD Gage 50) suggest all-time highs in cumulative rainfall during that period, following a 6-year period of record-low cumulative precipitation between 1986 and 1992.

*Memorial note* In Honor of Dr. J. David Rogers (1954–2025)

The publication of this study on the Mission Peak Landslide carries profound significance, as it represents the final major research contribution of Dr. J. David Rogers, who passed away on August 23, 2025, in Rolla, Missouri, USA. Completed in collaboration with his final postdoctoral fellow, Dr. Dan Wang, this work fulfills Dr. Rogers' long-standing wish to document one of the most complex landslide investigations of his career for the benefit of the global engineering community.

Dr. Rogers was a towering figure in the field of engineering geology and forensic geotechnical engineering. He held the Karl F. Hasselmann Chair in Geological Engineering at the Missouri University of Science and Technology (Missouri S&T) from 2001 until his retirement. A graduate of the University of California, Berkeley (Ph.D., 1982), he began his career as a consultant in the San Francisco Bay Area, where he led investigations on some of the most challenging geohazards of the late 20th century. His expertise was not limited to academia; he was a sought-after voice in analyzing disasters ranging from the St. Francis Dam failure to the New Orleans levees.

The Mission Peak Landslide, detailed in this manuscript, epitomizes Dr. Rogers' holistic approach to geohazards. He viewed this massive 1998 slope failure not

merely as a stability problem, but as a complex interplay of tectonic structure, stratigraphy, and hydrogeology. In his final years, despite battling health challenges, Dr. Rogers remained dedicated to synthesizing decades of data from this site. He envisioned this paper not as a personal achievement, but as an open resource to help future engineers recognize the nuances of large-scale block kinematics.

Dr. Rogers' impact extended far beyond technical papers. He was a consummate educator and a compassionate mentor who viewed his students as family. This spirit of generosity is best exemplified by his relationship with the corresponding author, Dr. Wang. Their collaboration began in 2017, when Dr. Rogers, recognizing a promising student working odd jobs to support his studies, intervened to fund Dr. Wang's education. This act of kindness launched a mentorship that spanned nearly a decade. Even as the COVID-19 pandemic forced a shift to remote teaching, and later as Dr. Rogers faced the progressive difficulties of a terminal illness, he continued to work alongside Dr. Wang—often for hours daily—to ensure his knowledge was passed on.

His contributions were recognized at the highest levels. In September 2025, shortly after his passing, the Association of Environmental & Engineering Geologists (AEG) honored him posthumously as an Honorary Member at their Annual Meeting in Chicago, a testament to his lifelong service to the profession.

Dr. Rogers often said that his goal was to "help others see the world more clearly through geology". Through his lectures (which have garnered hundreds of thousands of views online), his mentorship of countless students, and works like this final paper, he achieved that goal.

As Dr. Wang reflected upon his mentor's passing: "Death is not the end; being forgotten is. As long as we remember his teachings and his kindness, Dr. Rogers remains with us."

### J. David Rogers Scholarship Fund

In honor of Dr. Rogers' outstanding contributions to Missouri S&T and to the thousands of students who both enjoyed and benefited from his mentorship, the J. David Rogers Scholarship has been established to support students in Geological Engineering who embody his spirit of curiosity, engagement, and generosity. The scholarship will recognize not only academic achievement but also

active involvement in fieldwork, professional growth, and the life of the program.

To donate to this scholarship, please visit the website of [J. David Rogers Scholarship Fund](#).

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s44517-026-00002-0>.

Supplementary material 1.

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## Author contributions

Both authors contributed to the study conception and design. Material preparation, data collection, and data analysis were performed by J. David Rogers and Dan Wang. The first draft of the manuscript was written by J. David Rogers, and updated and finalized by Dan Wang. Both authors commented on previous versions of the manuscript. Both authors read and approved the final manuscript.

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## Data availability

No datasets were generated or analyzed during the current study.

## Code availability

Not applicable.

## Declarations

## Competing interests

The authors declare no competing interests.

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