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Structural and Geomorphic Characteristics of Landslides at Coyote Mountain, Anza-Borrego Desert State Park, California

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ABSTRACT

Coyote Mountain is an 8-mi-long (13 km) elongate fault block made up of granitic and metamorphic rocks in northeastern San Diego County, California. A series of landslides, most of which have distinct morphology and failure mechanisms, occurs in the tonalite and gneiss underlying the steep southwest slope of the mountain. The southernmost landslide area is the Peg Leg Smith landslide complex, which is composed of several translational slides and a unique remnant of a long-runout rock avalanche. In the central portion of the mountain, two distinct landslide types underlie the slopes near Coyote Peak. The first is represented by a pair of rock-block landslides, the Coyote Peak landslides, which failed along foliation planes in metamorphic rock. The second is the Coyote Ridge landslide, a 2-mi-wide (3.2 km) area of incipient landsliding in highly fractured tonalite. The Alcoholic Pass landslides, located at the northwestern end of the mountain block, are situated in tonalite. This complex consists of two juxtaposed landslides that failed at nearly right angles to each other. The base of the northernmost landslide is not exposed, and the failure mechanism is postulated to have been block sliding along a well-developed fracture system. The basal rupture zone of the southern landslide is composed of coarse, matrix-rich breccia. The southern flank of the slide grades into linear scarps which define the head of the Coyote Ridge landslide. The Alcoholic Pass landslides are concluded to be rare examples of fully developed translational failure resulting from formation of a through-going rupture surface created by incremental movement along interconnecting fractures.

INTRODUCTION

The purpose of this study is to: (1) identify the factors that lead to large-scale landsliding in granitic and metamorphic terranes, and (2) to describe how failure mechanisms are determined from landslide structural and geomorphic characteristics. Coyote Mountain is located in Anza-Borrego Desert State Park in the northeast corner of San Diego County, California (Figure 1). Coyote Mountain, an 8-mi-long (13 km), northwest-trending fault block that juts out abruptly into Borrego Valley from the north, is made up principally of Cretaceous granitic rocks, pre-batholithic metasediments, and gneiss. It is bounded on the west by the Coyote Creek fault and on the east by the Coyote Mountain fault, a northwest-trending splay of the San Jacinto fault (Figure 2). The western slope of the mountain is a steep fault scarp (Sharp, 1967) that rises from the surrounding valleys to an elevation of 3,192 ft (973 m).

The southwest-facing slope of the mountain extends from Alcoholic Pass on the north to the Peg Leg Smith monument at the south end of the mountain block, a distance of approximately 6 mi (10 km). This mountain front is occupied by a series of deep-seated landslides or landslide complexes, each of which has been assigned informal names for ease of discussion, beginning with the Peg Leg Smith landslide complex in the south and ending with the Alcoholic Pass landslides in the north (Figure 2). The landslide structure (basal rupture zones and rupture surfaces, internal slip surfaces, and stratification of landslide debris), as well as landslide morphology, suggests a variety of failure mechanisms, including slumping, rock-block failure, rock avalanche, and a newly proposed variety of incremental landsliding that is similar to sackung but results from seismic activity instead of gravitational stress. Identification of the landslides that make up the Peg Leg Smith landslide complex, as well as the Coyote Peak landslides in the central part of the range, was difficult because of erosional modification of headscarps and lack of quality field exposures.

GEOLOGIC SETTING

Coyote Mountain is situated in the eastern part of the Peninsular Ranges Geomorphic Province between the San Jacinto fault on the east and the Coyote

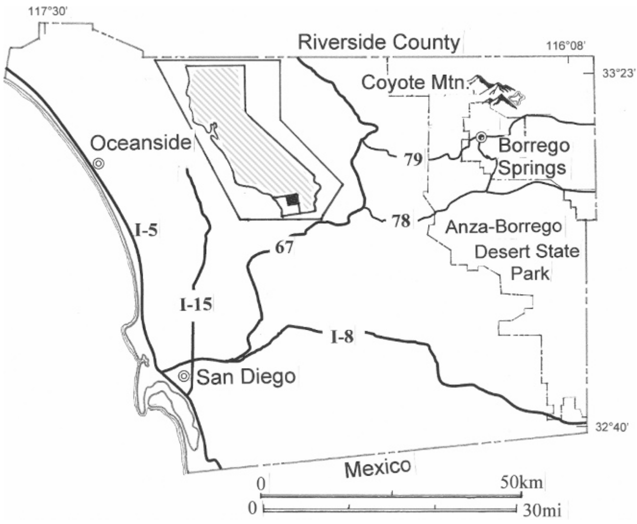

Figure 1. Location map.

Creek fault on the west. Coyote Mountain is a northwest-trending ridge dominated by 3,200-ft (973 m) high Coyote Peak after which the ridge is named. The bedrock that makes up the Coyote Mountain block has been divided by Theodore and Sharp (1975) into 15 mappable rock units, including two Quaternary sedimentary formations, several types of Cretaceous granitic rocks, and pre-batholithic metamorphic rocks consisting of gneiss, schist, and marble.

The southern part of Coyote Mountain, from Coyote Peak to the Peg Leg Smith historical marker at the southern end of the block, makes up the Coyote Mountain cataclastic zone (Sharp, 1967), in which both the plutonic and pre-batholithic rocks have been subjected to deep-seated plastic deformation that has created a generally east-dipping shear foliation. The northern half of the area is underlain by pervasively fractured and sheared hornblende-biotite tonalite.

The Pleistocene Ocotillo Conglomerate overlies the tonalite in the northern and central portions of the mountain block and occupies a prominent broad depression in the ridge north of Coyote Peak. At its southern limit, the Ocotillo Conglomerate lies in fault contact with tonalite and metamorphic bedrock. These deposits consist of poorly consolidated terrestrial sands and conglomerates that accumulated primarily under fluvial conditions in coalescing basins and fan environments (Sharp, 1967).

GEOLOGIC STRUCTURE

Outcrops of granitic rocks undisturbed by landsliding can be observed only in a few limited areas on the western slopes of Coyote Mountain, primarily in the central part just west of Coyote Peak. Here, the rocks exhibit intense fracturing and shearing resulting from gravitational stress, as well as tectonic stresses resulting from displacement along the nearby Coyote Creek and San Jacinto faults.

Sharp (1967) and Theodore and Sharp (1975) have indicated that motion on the Coyote Creek fault is primarily dip slip, based on the presence of the steep western slope of Coyote Mountain, which abruptly rises from the floor of Borrego Valley. It seems more probable, given the strike-slip tectonic environment in which the mountain block is situated, that the Coyote Creek fault also has a strong component of right slip and that this motion accounts for the fact that Coyote Mountain block is separated from the range front approximately 8 mi (13 km) to the north. The Alcoholic Pass landslides in the northern part of the mountain block have relatively young geomorphic features, such as well-defined headscarps and, in one location, a very young scarp in alluvium, while the landslides of the Peg Leg Smith landslide complex at the southern tip of Coyote Mountain have erosionally modified and much subdued scarps with basal rupture surfaces buried by alluvium of Coyote Creek. Based on the apparent age difference between the northern and southern landsides, described more fully later in this discussion, it is tempting to conclude that the mountain block has been separated from the ranges to the north primarily by right-lateral motion along the Coyote Creek fault, and, as a result, the older landslides occupy the southern parts of the block.

Low-angle shears with dips parallel to foliation of 10 to 25 degrees are accompanied by thick breccia zones and occur outside of areas underlain by landslides. One such area lies adjacent to the south flank of the Coyote Peak landslides. A prominent shear zone at this location was observed dipping into the mountain front at inclinations of 18 to 25 degrees. The complete lack of any geomorphic feature even remotely resembling a landslide upslope from the shear zone indicates that the shearing is tectonic in origin. Fractures, at least where they can be observed in the near surface in stream cuts, are primarily vertical and strike essentially parallel to slopes. In some areas, the fracturing is very intense, and there is a significant amount of silty matrix or breccia-like material separating the blocks.

Rocks within the plastically deformed Coyote Mountain cataclastic zone exhibit a generally eastward-dipping shear foliation and a pronounced, roughly eastward-plunging lineation in the foliation due to streaked-out alternating concentrations of light and dark minerals Sharp (1967). The texture and coherence of the rocks within the cataclastic zone indicate deformation at considerable depth in the crust. In outcrop, the gneissic rocks are hard,

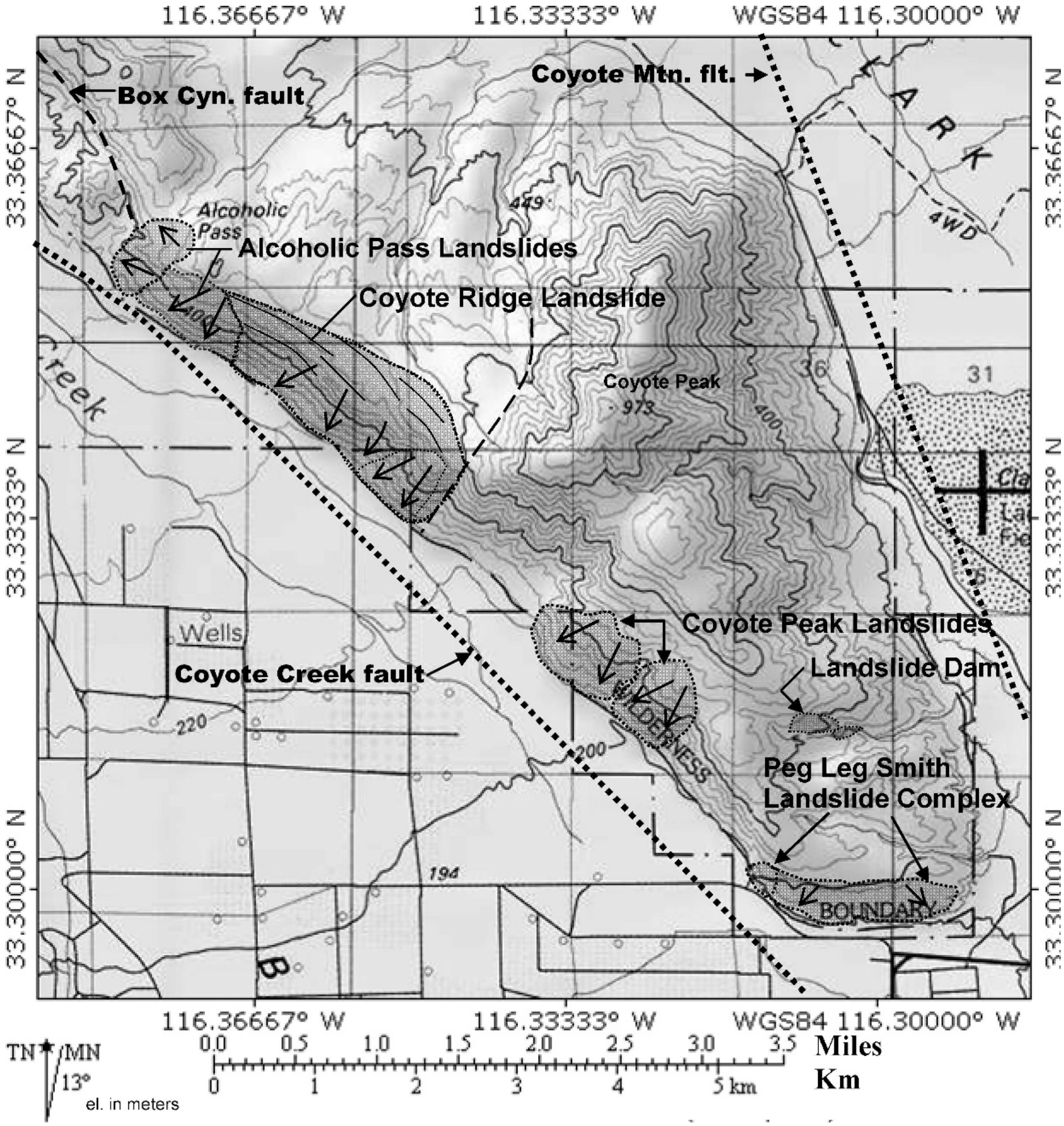

Figure 2. Topographic map of Coyote Mountain showing location of features discussed in text.

relatively fresh, and are poorly to thinly foliated with platy cleavage.

THE PEG LEG SMITH LANDSLIDE COMPLEX

The Peg Leg Smith landslide complex is named after a nearby monument honoring the mountain man, prospector, and teller of tall tales of the early 1800's who claimed to have found a rich gold strike in the Borrego area but unfortunately could not remember the location of the mine. Legends concerning its location abound and have enticed many unsuccessful amateur prospectors into the surrounding hills. The landslide complex consists of a 1.5-mi-long (2.4 km) series of coalescing and superposed landslides located at the southern terminus of the Coyote Mountain block (Figure 2).

Seven landslides occur within the Peg Leg Smith landslide complex, ranging in width from 600 ft (190 m) to over 3,200 ft (975 m). The westernmost of the landslides is a remnant of a possible rock avalanche, the more distal portions of which are buried by alluvium. The remaining six landslides and four landslides north of the complex on the east side of Coyote Mountain are large, essentially intact rock masses that failed along foliation planes. Accordingly,

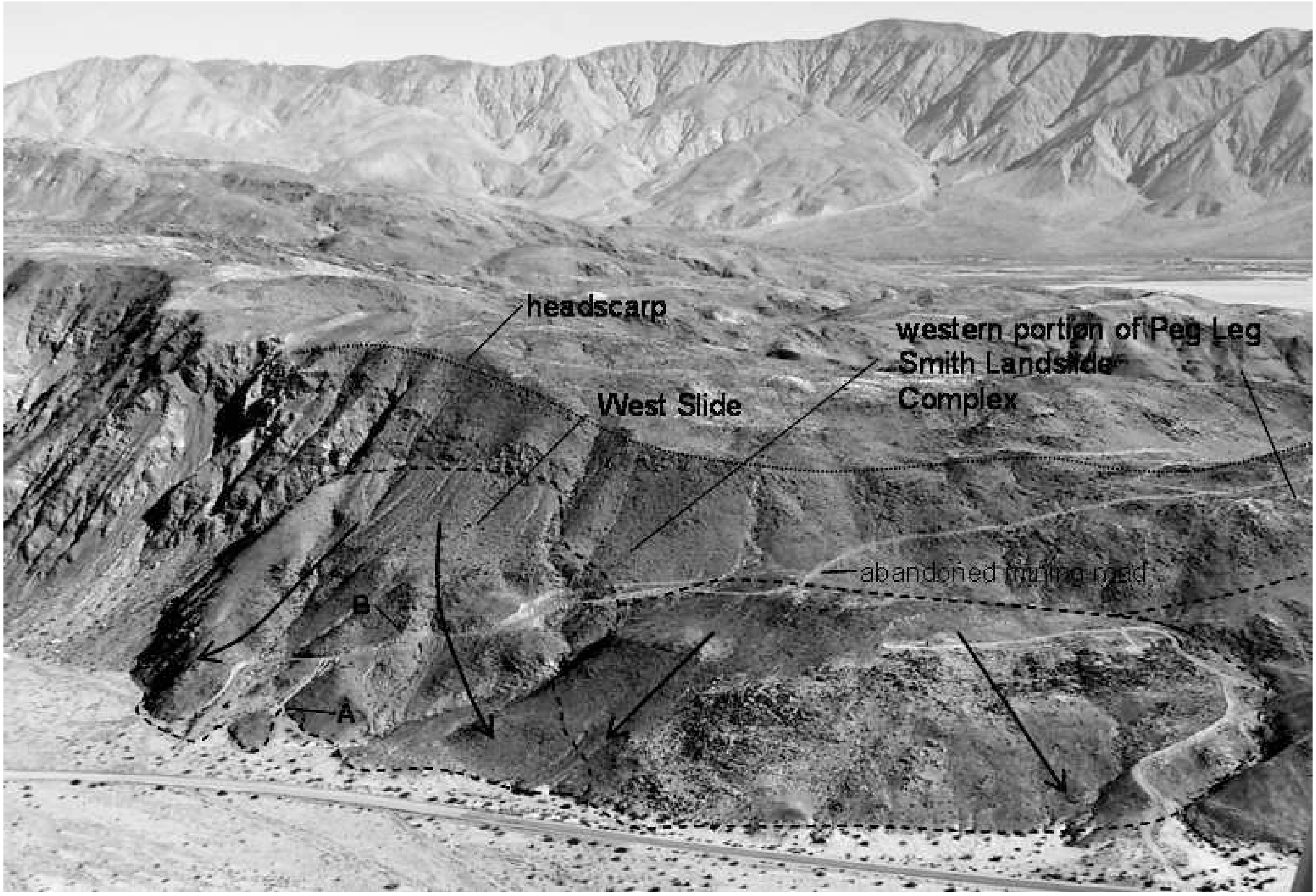

Figure 3. Southern terminus of Coyote Mountain showing the western end of the Peg Leg Smith landslide complex. View is toward the northeast. Santa Rosa Mountains are on horizon. Point A = location of Figure 4; B = location of Figure 5.

they are classified as rock-block slides after the classification of Varnes (1978). All the landslides occur within the Coyote Mountain cataclastic zone, which is made up predominantly of well-foliated gneiss and metasediments.

The westernmost landslide is well-exposed along an old mining road that traverses the central portion of the slide mass and along two deeply incised gullies near its southern flank (Figure 3). The landslide extends from an elevation of approximately 1,000 ft (305 m) at the head to an elevation of 600 ft (183 m) along the valley floor, where the base of the slide is buried by alluvium and talus. The precise location of the southern flank of the landslide is not known because of insufficient outcrop. Although the base of the landslide is buried beneath alluvium and talus at its northern flank, the base of the landslide is well-exposed near its southern flank in the walls of a gulley just south of the mining road, approximately 30 ft (9 m) above the valley floor (Figure 4).

Several observations indicate that the landslide is an erosional remnant of what was a much larger landslide. First, the upper portion of the north flank of the slide mass lying above Coyote Creek has a slope that exceeds 45 degrees. The absence of talus at the base of slope at this location suggests that Coyote Creek is actively cutting into the slide mass and that much of the medial and distal portions of the landslide have been removed by stream erosion and buried by alluvium. Secondly, the crude stratification of the slide debris visible along the mining road is diagnostic of the proximal portion of rock avalanche deposits. Zones of pulverized slide debris and matrix-rich breccia observed in the road cut lie in near-horizontal contact with overlying fractured rock containing little or no matrix (Figure 5). Well-stratified slide debris with distinct vertical zones or facies, which vary from a slurry-like mixture of sand, silt, and clay at the base to a matrix-poor middle facies to an upper crackle breccia (megaclasts are parted along planes of weakness but show little or no displacement or rotation relative to one another), is characteristic of medial and distal portions of long-runout landslides. The more proximal portions of such landslides show little or no stratification (Yarnold and Lombard, 1989). While this evidence

Figure 4. Basal shear zone of the westernmost landslide, Peg Leg Smith complex. See Point A, Figure 3 for location of photograph.

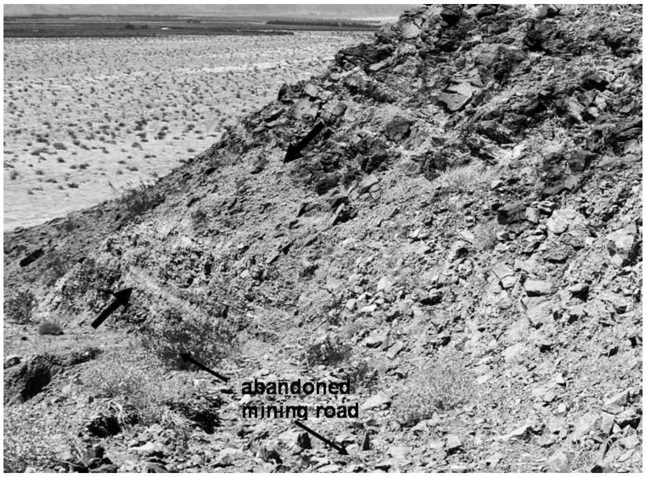

Figure 5. View to northwest along old mining road of crude stratigraphy in the western landslide, Peg Leg Smith landslide complex. Arrows delineate matrix-rich breccia and thin pulverized zone at base.

suggests that this landslide could be classified as a rock avalanche, the diagnostic medial and distal portions of the slide that would allow such a determination to be made with certainty are no longer present.

An exposure of the slide base occurs in a narrow gulley approximately 30 ft (9 m) in elevation above the valley floor (Figure 4). Here, the basal rupture zone consists of matrix-rich breccia that dips subhorizontally and parallel to the foliation in the underlying gneiss. A true slip surface typical of translational landslides is not present at this location, and the light brown, fine-grained material at the base of the slide mass has the consistency of fine silty sand with only slight plasticity. The elevated position of the basal shear above the valley floor indicates that the slide has a very irregular slip-surface geometry, since several hundred feet to the north, the basal shear zone lies much lower in elevation where it is buried by alluvium.

A group of six coalescing and superposed rock-block landslides, which occur over a distance of approximately 2 mi (3.3 km), makes up the remainder of the Peg Leg Smith landslide complex (Figures 6 and 7). Evidence of landsliding within this slide complex varies from very strong to weak and required consideration of a combination of structural and geomorphic evidence in order to have a high degree of confidence that landsliding was the responsible process. Geomorphic evidence of landsliding, such as the presence of scarps and ponded alluvium in side-hill benches, even in conjunction with what may be interpreted as structural evidence (chiefly shear zones and matrix-rich breccia), is strong but not necessarily conclusive proof of landsliding in an environment of active faulting. Some of the more important hypotheses to consider are: (1) the structure and landslide-like geomorphic features are a result of landsliding; (2) the features are the result of faulting; (3) the features are the result of faulting overprinted by later landsliding; or (4) the features are purely erosional in nature and are not related to any of the above.

The ability to positively identify landslides is directly related to the age of the slide and the quality of the exposures. A complication in landslide identification is the presence of landslide pseudomorphs, or landslide imposters, which are formed as products of differentially eroding rock types and preferential erosion along fractures and faults. In the case of the landslides in the Peg Leg Smith landslide complex, the availability and quality of structural and geomorphic evidence of sliding vary from slide to slide. When a single line of conclusive evidence was lacking, such as the presence of young diagnostic geomorphic features or a basal rupture surface, several lines of evidence tabulated next were utilized to obtain a high degree of confidence that the features in the Peg Leg Smith landslide complex were the result of massive landsliding.

Geomorphic Evidence

1. Rectilinear to somewhat sinuous scarps. The heads of the landslide “candidates” are delineated by eroded scarps, below which there occur topographic benches followed by valley-ward convex slopes. The fact that the scarps are discontinuous is further evidence that they were not caused by faulting.

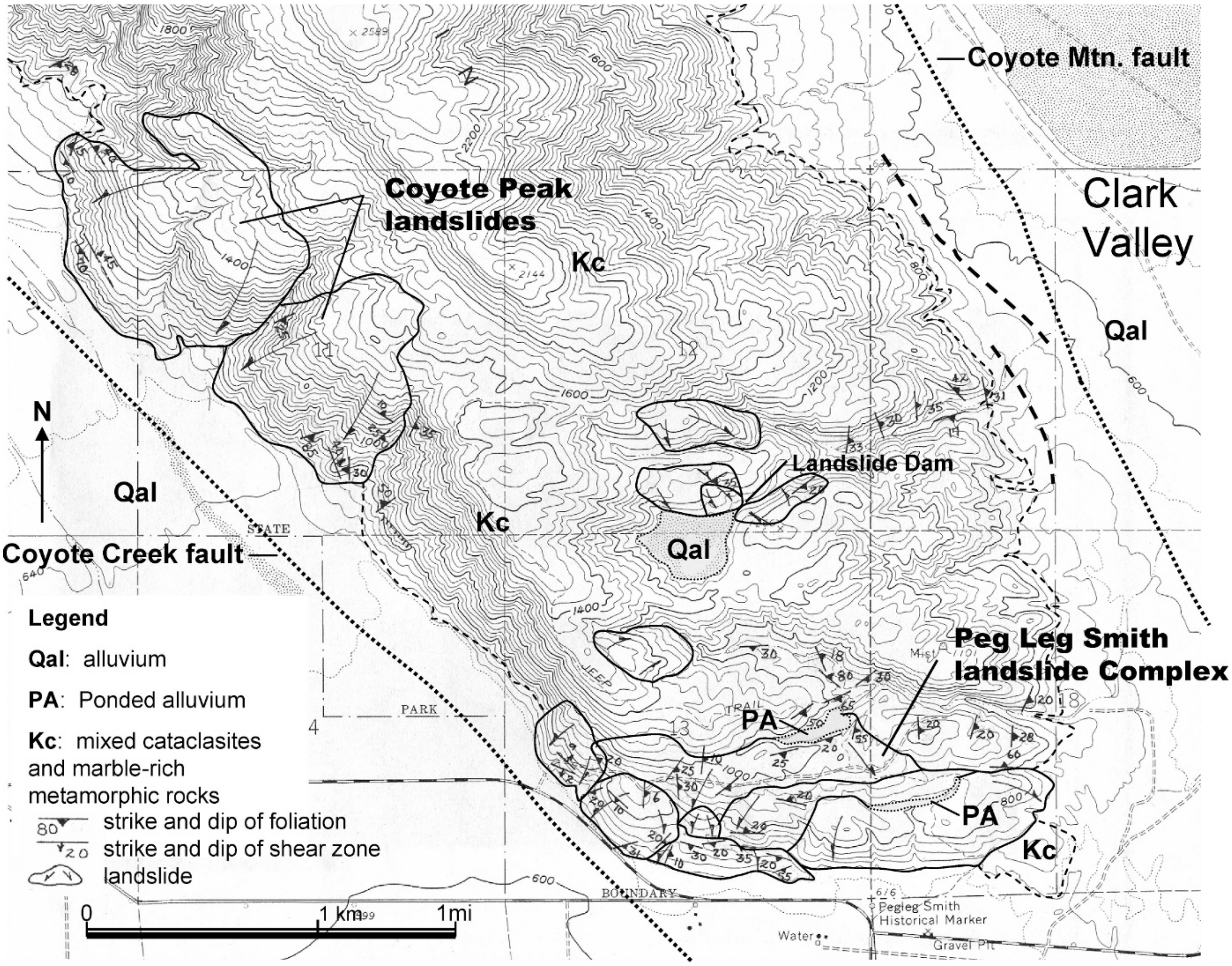

Figure 6. Map of Peg Leg Smith landslide complex and Coyote Peak landslides.

2. Ponded alluvium. Ponded alluvium, or anomalously large areas of alluvium with rock-floored outlets located in side-hill valleys below scarps, is a common characteristic of the Peg Leg Smith landslide complex (Figure 6). A short distance north of the complex (Figures 6, 7, and 8), there is a landslide dam that has ponded an estimated 150 ft (47 m) of alluvium. The ephemeral lake that once occupied the valley behind the dam is now completely filled with alluvium, and drainage now flows unimpeded toward the east into Clark Valley.

3. The head of the principal, or largest, of the landslide features is denoted by a long, essentially linear valley marked in some localities by ponded alluvium. The scarp is fully developed to where it intersects an opposite-facing descending slope at its upstream terminus. This type of abrupt termination is reminiscent of features created by stream piracy. In this case, it is evidence of a non-erosional origin of the canyon.

4. Arcuate drainage systems that in map view join to form the classic outline of the flanks and head of a landslide.

Structural Evidence

1. Near-horizontal shear surfaces overlain by pulverized rock debris or matrix-rich breccia.

2. Stream cuts located below possible headscarps that contain nearly continuous exposures of matrix-supported breccia consistent with the type of material expected to occur above a landslide's basal rupture surface.

3. Textures that are diagnostic of rock avalanche deposits, such as crackle breccia and matrix-supported breccia in several localities (Figure 9).

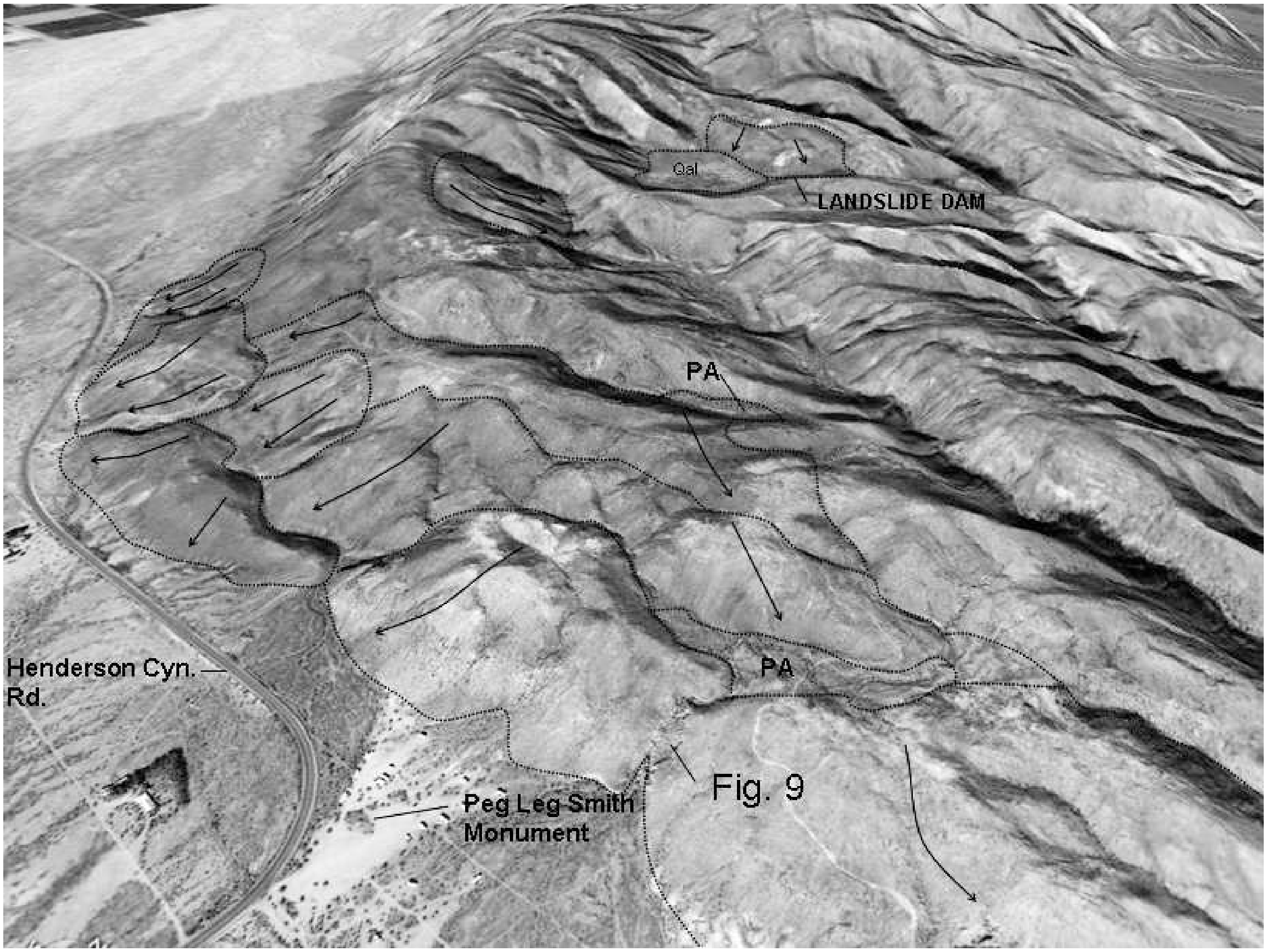

Figure 7. Annotated aerial view of Peg Leg Smith landslide complex showing areas of ponded alluvium and location of Figure 9.

4. Near-vertical "faults" exposed below and parallel to postulated headscarps. The occurrence of any one of these features is consistent with but not conclusive evidence of landsliding. When several lines of geomorphic and structural evidence are considered together, the evidence for landsliding is strong, even without exposure of the basal failure surface.

In the only location where a basal failure surface can be observed near the southern flank of the westernmost landslide, the material that makes up the shear zone is cemented with calcium carbonate and consists of what could be described, if it were wet, as a slurry composed of a mixture of rock fragments, sand, and silt with little clay. The appearance of the mud-like slurry observed near the base of several of the slides indicates that they likely occurred at a time when the slide mass was fully or nearly saturated. The lack of clay gouge along the rupture surfaces would seemingly require that failure occurred along foliation planes already weakened by tectonic slip, similar to flexural-slip faulting common in folded sedimentary rocks.

COYOTE PEAK LANDSLIDES

The Coyote Peak landslides are located on the west side of Coyote Mountain approximately 1 mi (1.6 km) north of the Peg Leg Smith landslide complex. Together, these landslides are 1.25 mi (2 km) wide and extend from the valley floor to an elevation of 1,640 ft (512 m) on the west side of Coyote Peak. The most striking geomorphic characteristic of the landslides is the drainage texture, which is dissimilar to that which occurs on the much steeper adjacent terrain. The landslide slopes are smoother and more rounded as a consequence of there being fewer and less-well-developed drainages within the slide mass. In addition, slopes in the medial and distal

Figure 8. Landslide dam north of the Peg Leg Smith landslide complex. See Figure 6 for location. Trapped alluvium in valley is estimated to be 150 ft (47 m) thick.

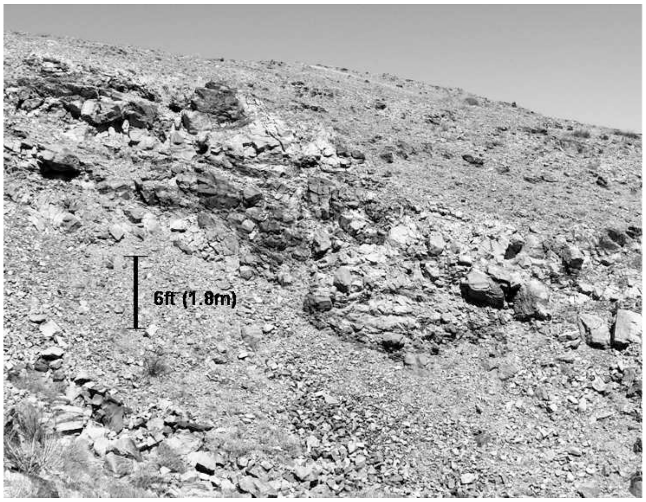

Figure 9. View to east of brecciated landslide debris in Peg Leg Smith landslide complex. See Figure 7 for location.

portions of the landslides are much gentler than slopes that make up the west side of the mountain front to the north and south.

The relatively subtle headscarps of the Coyote Peak landslides occur to the west of a more obvious, longer, and much higher scarp (Figure 10), which at first glance appears to be a headscarp of a larger landslide. A closer evaluation, however, reveals that the scarp continues further south than the landslide terrain and eventually terminates in an area removed from any evidence of landsliding. Although it is tempting to attribute the origin of the scarp to landsliding, outcrops of in-place metamorphic rocks in the deep canyon at the northern terminus indicate an erosional or perhaps fault origin. Shallow rockfall debris estimated to be approximately 20 to 30 ft (6 to 9 m) thick occurs on the bench below the scarp. Evidence for landsliding consists of the subtle head-

Figure 10. Heavily eroded north slide and portion of south slide, Coyote Peak landslides, showing location of Figures 12, 13, and 14. Short arrows point to top of headscarps. View is to east from Borrego Valley.

scarps (Figures 10 and 11), the presence of matrix-rich landslide debris, and low- to high-angle shear zones exposed in several deeply incised canyons.

The northernmost of the two landslides has an approximately 200-ft-high (60 m) headscarp partly separated from the body of the slide by a deep, northwesterly draining canyon. Erosion has removed most of the landslide debris from the head of the slide and has exposed the underlying gneissic bedrock. Remnants of landslide debris below the steep headscarp can be seen from the canyon bottom, where the basal shear zone truncates a steeply dipping mafic dike within well-foliated migmatite country rock approximately 200 ft (60 m) above the canyon floor. The base of the slide can also be observed high on the canyon wall just west of the headscarp, and it is manifested by a zone of shearing and a disaggregated sub-horizontal dike. The metamorphic bedrock at this location is highly shattered and contains numerous high- to low-angle shear zones that parallel the foliation, making precise determination of the limits of landsliding difficult.

An approximately 300-ft-long (90 m) and up to 15-ft-high (4.5 m) exposure in a stream cut at the northern edge of the landslide reveals classic landslide debris. At this location, highly fractured, sheared, and, most significantly, contorted metamorphic and gneissic rocks are terminated by a low-angle shear zone composed of several feet of pulverized metasediments. The contact between the thoroughly pulverized materials in the shear zone and the overlying brecciated rocks is formed by ¼-inch-thick (5 mm) clayey gouge that dips 20 degrees to the northeast. Further to the west, along the fringe of the alluvial fan, erosion has exposed matrix-rich breccia that consists of a mixture of angular gneissic and metasedimentary clasts with a distinctly chaotic structure typical of material expected near the toe of a landslide (Figure 12). To the east of this exposure, there are outcrops of undisturbed, lightly fractured

Figure 11. Coyote Peak landslides. View is to east of the south slide.

metamorphic rocks with foliation dipping gently to the southwest. The eastern limit of the landslide cannot be directly observed at this locality but is inferred between the well-exposed slide debris in the stream cut and the in-place migmatite observed in the steep walls of the adjacent canyon. Minor drainages along the toe of the slide include numerous outcrops of moderately dipping shear zones and matrix-rich breccias. The reentrant southerly draining canyon, the mouth of which is located along the south flank of the slide, exhibits good exposures of thin, white dikes that are so thoroughly sheared that they are now best described as white breccia zones consisting of clasts rotated along the planes of the dikes during shearing and translation (Figures 13 and 14).

The southernmost of the two landslides has a highly eroded arcuate headscarp that varies from 80 to 160 ft (24 to 50 m) high (Figure 11). Smaller, secondary scarps are located at the head of the slide, and there is a low uphill-facing scarp near the toe. Structural evidence of landsliding is present in several small canyons along the toe of the slide, where thin zones of shearing and breccia can be observed. The basal shear zone of this slide is buried beneath the

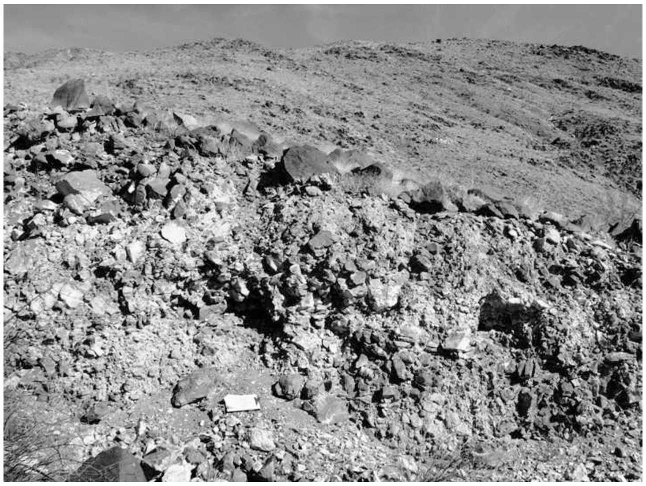

Figure 12. Coyote Peak landslides. Landslide debris can be seen at the toe of the north slide. Clipboard at base of stream cut is shown for scale.

alluvium of Coyote Creek. The north wall of the canyon located along the southern flank of the slide exhibits good evidence of landsliding, such as steeply dipping shear zones, as well as matrix- and clast-supported breccia. As previously discussed in the section on the Peg Leg Smith landslide complex, the presence of shear zones and breccia is not conclusive evidence of landsliding; however, the combination of this structural evidence with geomorphic evidence (the presence of a well-defined headscarp) allows a high degree of confidence in a landslide interpretation.

The steep, highly dissected slopes directly south of the Coyote Peak landslides also exhibit thick zones of brecciated rock and shear zones dipping up to 20

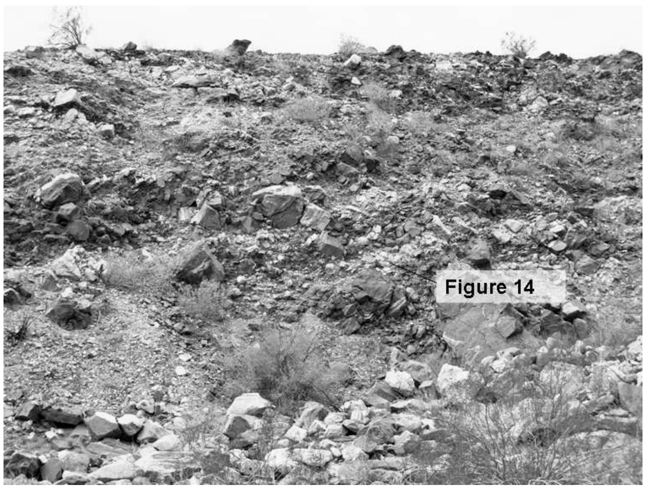

Figure 13. Coyote Peak landslides. Landslide breccia on west side of the canyon near the toe of the north slide shows location of rotated clasts comprising disrupted low-angle dike in Figure 14.

Figure 14. Rotated clasts of white dike material near toe of north slide. Largest clasts have maximum dimension of approximately 1 ft (0.3 m).

degrees into the mountain front. Low scarps estimated to be 20 ft (6 m) in height occur at the crest of the west-facing slopes south of the landslide complex. There is also a 15-ft-high (4.5 m) uphill-facing scarp near the foot of the slope. A shallow stream cut across the northern terminus of the scarp exposes a steeply east-dipping shear zone which trends parallel to the slope and is manifested by brecciated and sheared metamorphic rocks. The discontinuous nature of the scarp, which extends only a few hundred feet, suggests that it is not the result of faulting. Foliation planes measured in the canyon along the southern flank of the slide area have a strong out-of-slope dip component that varies between 25 and 45 degrees to the southwest. Because this portion of the slope exhibits no geomorphic evidence of large-scale landsliding, these features are most likely the result of small incremental movements triggered by local earthquakes, the same mechanism ascribed to the Coyote Ridge landslide described next.

COYOTE RIDGE LANDSLIDE

For the purposes of this discussion, Coyote Ridge is that low-lying area located about midway between Coyote Peak on the south and Alcoholic Pass on the north (Figure 2). Coyote Ridge, as a consequence of uplift along the Coyote Canyon fault, has an asymmetrical profile, and the western side is very steep and difficult to climb because of its steep inclination and the presence of loose bouldery slope debris. The eastern slope is a gentle, deeply dissected dip-slope that has an average gradient of 6 degrees toward Clark Valley on the east side of Coyote Mountain.

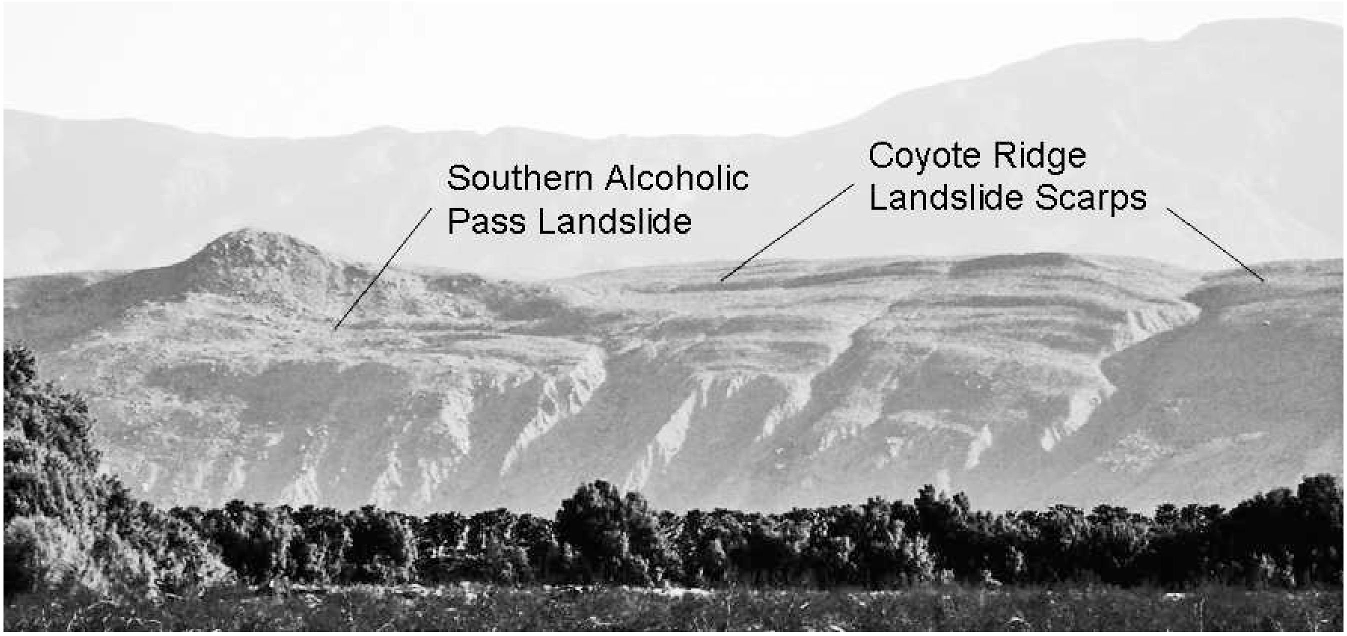

Figure 15. View to northeast of Coyote Ridge landslide scarps. Santa Rosa Mountains are on horizon.

The ridge is capped by a variable thickness of Pleistocene gravels correlated with the Pleistocene Ocotillo Conglomerate. Just south of the Alcoholic Pass landslides, the conglomerate attains an estimated thickness of 100 ft (30 m), while at the northern foot of Coyote Peak, this unit is over 800 ft (245 m) thick where it has been down-faulted against granitic and metamorphic bedrock. Underlying the relatively thin cap of Ocotillo Conglomerate, there are pre-batholithic metamorphic rocks and tonalite that make up the bulk of the landslide mass. Nearly the entire face of the steep western slope is veneered with talus resulting from numerous rockfalls and small slumps composed of granitic and conglomeratic debris. Since loose debris derived from the Ocotillo Conglomerate covers much of the lower portions of the slope, nearly the entire face of the ridge was previously mapped by Sharp (1967) and Theodore and Sharp (1975) as Ocotillo Conglomerate.

The Coyote Ridge landslide is manifested by a 1.75-mi-long (2.8 km) zone of scarps, some of which are 30 ft (9 m) in height, and intervening grabens filled with alluvium. The scarps occur in a 2,000-ft-wide (610 m) zone and descend as a group of en-echelon and sub-parallel features (Figure 15) from the high point of the ridge to the sharp break in slope at the face of the mountain front. Evidence of any bulging that might have been present near the base of the slope is not present because of erosion by Coyote Creek and the masking effect of smaller landslides, rockfalls, and talus. These surficial features also obscure any basal rupture surface that might be present near the base of the slope.

The tonalite underlying Coyote Ridge is homogeneous, and although low-angle detachment faults have been utilized as basal rupture surfaces of very large landslides in other areas of the Imperial Valley and Anza-Borrego State Park (Baldwin, 1986; Hart, 1991), there is no indication that such features are present on Coyote Mountain. Since the shear strength of the unfractured rock is very high, it is suggested that movement occurs along interconnecting fracture systems in step-like fashion as a result of high transient shear stresses produced during earthquakes along the nearby Coyote Creek and San Jacinto faults.

The San Jacinto fault, located only 3 mi (4.8 km) to the east, is one of the most active faults in California. This fault is capable of producing earthquakes of M 6.8 and peak ground accelerations (neglecting possible topographic amplification) at Coyote Mountain of approximately 0.6 *g*. The Coyote Creek fault that lies buried beneath alluvium at the western foot of Coyote Mountain has similar seismic potential. Shakal and others (1994) showed that unusually high accelerations are possible near the crest of hills near the seismic source. During the Northridge, California, earthquake of 1994, for example, amplification values of horizontal accelerations were measured on a hilltop that were twice those observed at other sites with similar epicentral distances.

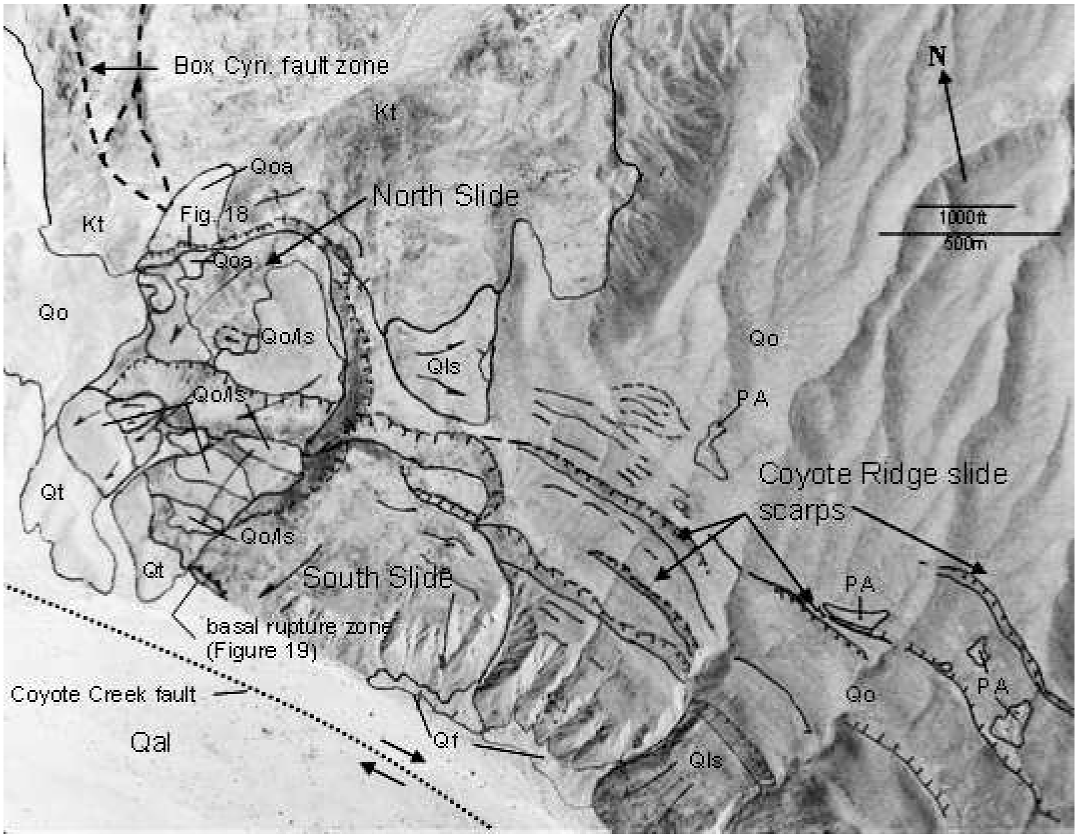

Figure 16. Annotated vertical aerial photograph of Alcoholic Pass landslides and adjacent Coyote Ridge landslide scarps. Qoa = older alluvium; Qal = alluvium; Qt = stream-terrace deposits; Qls = landslide; Qo = Ocotillo Conglomerate; Qo/ls = Ocotillo Conglomerate displaced by landsliding; Kt = tonalite; PA = ponded alluvium.

This type of failure mechanism is similar in some respects to rock creep as described by Bisci and others (1996). The driving mechanism for rock creep, however, is gravity working on extremely high and steep mountain fronts (Radbruch-Hall, 1978; Dramis and Sorriso-Valvo, 1994). The difference in elevation between the valley floor at the base of Coyote Ridge and the ridge crest is approximately 1,000 ft (312 m); this height is not likely to result in the type of rock creep or sackung phenomena described by Bisci and others (1996).

ALCOHOLIC PASS LANDSLIDES

The two Alcoholic Pass landslides are located near the northern terminus of the Coyote Mountain block and are contiguous with northern flank of the Coyote Ridge landslide (Figures 2 and 16). These moderately sized landslides, the headscarps of which intersect at approximately 90 degrees, occurred in massive, hornblende biotite tonalite overlain by the Ocotillo Conglomerate. The south slide (Figures 16 and 17) is approximately 3,700 ft (1130 m) wide and extends from an elevation of 800 ft (244 m) near Coyote Creek to an elevation of 1,980 ft (604 m) at the top of the headscarp. There are several smaller and younger landslides superposed on the landslide manifested by a series of westward-descending topographic benches capped by Ocotillo Conglomerate. Movement of the much smaller secondary slides occurred after primary failure of both landslides and buried stream terrace deposits on the east side of Coyote Creek.

The approximately 100-ft-high (30 m) headscarp of the north slide has offset Ocotillo Conglomerate beds as well as younger alluvial deposits at the top of Alcoholic Pass, producing a prominent 20-ft-high (6 m) scarp in alluvium (Figure 18). The arcuate headscarp suggests that the landslide is a complex slide characterized by rotational movement at the head combined with primarily translational movement along fracture surfaces in the medial and distal portions of the landslide. The south landslide has a more linear headscarp and becomes slightly more arcuate near the southern flank. The linearity of the scarp suggests primarily translational movement with little or no rotation at the head. The Alcoholic Pass landslides appear from their geomorphic expression (well-defined geomorphic features and headscarp in

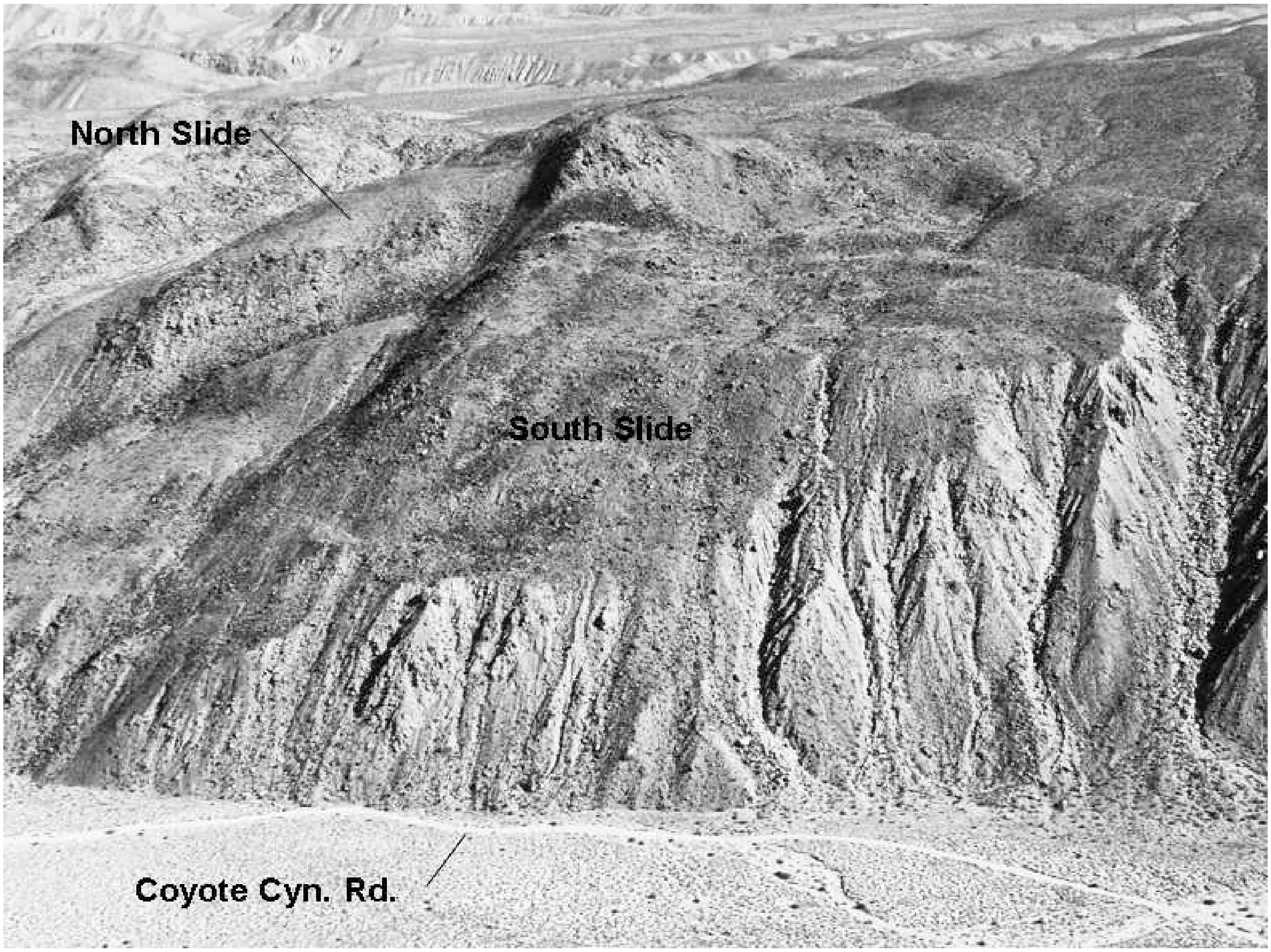

Figure 17. Alcoholic Pass landslides. View is to northeast from over Borrego Valley.

alluvium) to be the youngest of the larger landslides that have occurred on the western slopes of Coyote Mountain.

The most interesting aspect of these landslides is their failure mechanism. As is often the case, the basal rupture surface is not well exposed, and failure mechanisms must be inferred from the geologic and geomorphic characteristics of the slide. The failure surface of the north slide is not exposed, and there is only one poor exposure of the base of the south slide near Coyote Creek. At this location, approximately 30 ft (9 m) above the valley floor (Figures 16 and 19), the fractured rock that makes up the landslide debris overlies a sedimentary breccia that contains highly angular, cobble-sized, metamorphic and granitic clasts grading downward over a vertical distance of approximately 25 ft (7.6 m) to sandy, well-rounded cobble conglomerate resembling adjacent stream-terrace deposits. The outcrop does not expose that portion of the failure surface developed on bedrock.

Because of the high strength of homogeneous granitic rocks, large translational landslides often utilize existing low-strength planes of weakness in the rock, such as low-angle detachment faults, as basal rupture surfaces. This is not the case at Coyote Mountain, since the Coyote Creek and the Box Canyon faults either lie outside the zone of landsliding or have been demonstrated to dip nearly vertically in the vicinity of the landslides (Theodore and Sharp, 1975). Therefore, another mechanism must be responsible for the formation of the basal rupture surface. Several prominent scarps formed during incremental movement of the Coyote Ridge landslide are coincident with the headscarp and a prominent secondary scarp of the southern Alcoholic Pass landslide. This suggests that the landslides are related and have similar failure mechanisms.

It is here proposed that the Alcoholic Pass landslides are examples of translational landslides that developed from seismically induced incremental movement in highly fractured, massive granitic rocks.

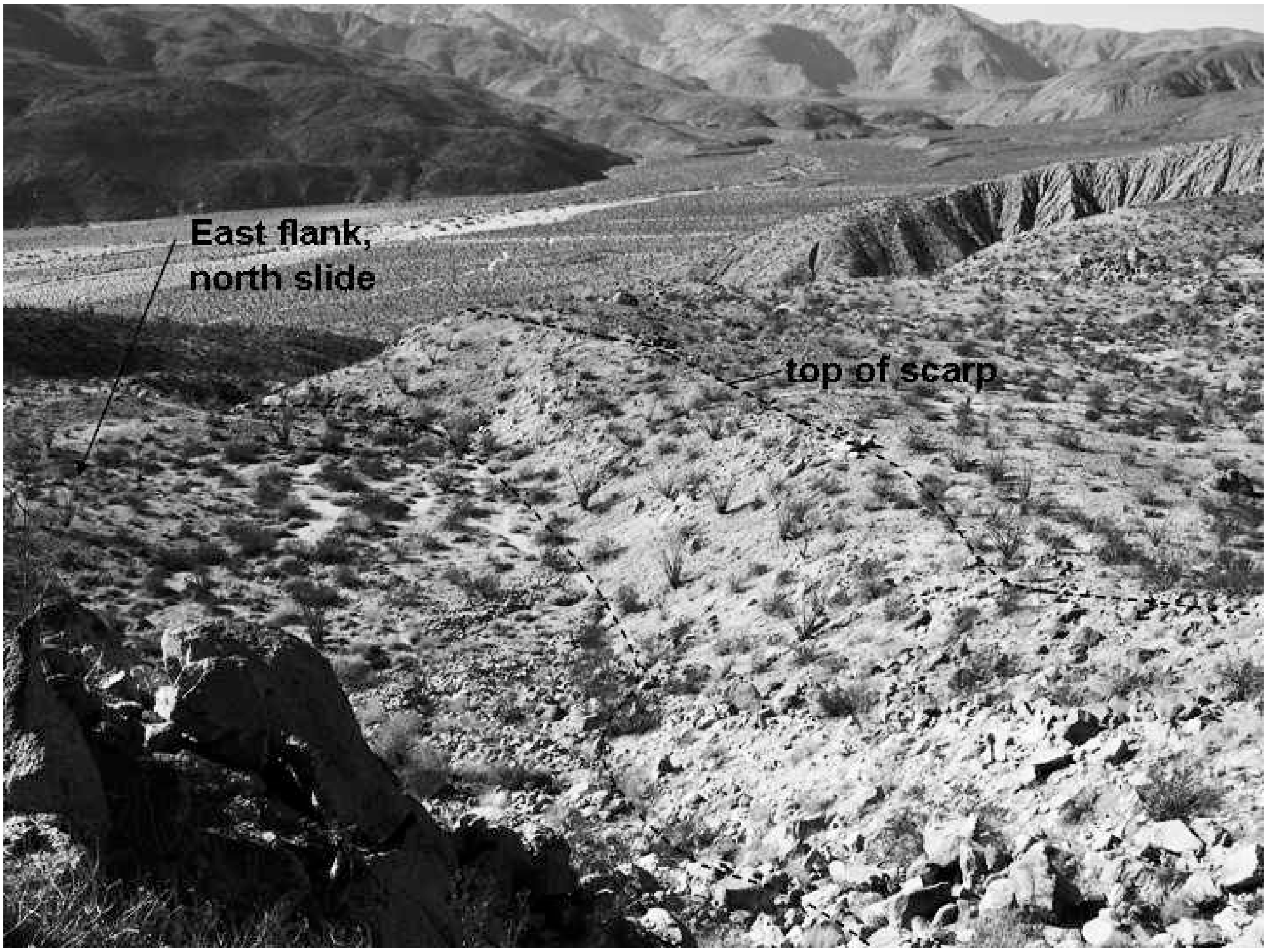

Figure 18. Northern Alcoholic Pass landslide and scarp in older alluvium on the eastern flank. Mouth of Coyote Canyon can be seen in the distance.

Since significant translational movement is necessary to produce the observed scarp heights and runout indicated by the exposure of the landslide debris overlying the alluvium shown in Figure 19, the landslides must have a continuous basal rupture surface. The most likely mechanism for the formation of such a surface is the joining of randomly oriented fracture surfaces through relatively small incremental movements. After sufficient movement has occurred, there would be high potential for a continuous slip surface to form. Once a slip surface has formed, the overall shear strength and resistance to fully developed translational movement would be greatly reduced.

CONCLUSIONS

Positive identification of very old and erosionally subdued landslides in granitic and metamorphic terrain in mountainous areas can be made by careful observation of stream cuts and other exposures. Certainty of identification depends on several factors, the most important of which are the age of last significant movement, the tectonic history of the host rock, and the quality of the outcrops. For relatively young landslides, identification can be made with certainty on the basis of classic landslide morphology alone. As the landforms become more subdued by erosion, differentiation of fracturing and shearing caused by active faulting and rock creep from that resulting from landsliding becomes increasingly more difficult and important. In the Peg Leg Smith landslide complex, evidence such as ponded alluvium in drainages located at head of the landslides and discontinuous arcuate and linear headscarps in combination with extensive zones of brecciation and sub-horizontal shearing combines to allow a high degree of certainty that landsliding is the responsible process. Because landslide-like geomorphic features are common in granitic and metamorphic rocks, there

Figure 19. Basal rupture zone exposed at the toe of the southern Alcoholic Pass landslide. Note how matrix-supported angular breccia clasts grade upward to clast-supported breccia.

should be a combination of structural and geomorphic evidence in order to have a high degree of certainty of landslide identification.

The south flank of the fully developed southern Alcoholic Pass landslide grades into a zone of incipient landsliding in massive tonalite. For this reason, it is postulated that the southern Alcoholic Pass landslide is an example of a fully developed translational landslide that developed from incremental movement in highly fractured, massive granitic rocks.

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REFERENCES

Baldwin, J., 1986, Martinez Mountain rock avalanche. In Guptill, P. D.; Ruff, R. W.; and Gath, E. M. (Editors), *Geology of the Imperial Valley, California*: Guidebook of the South Coast Geological Society, Santa Ana, California, pp. 37–48.

Bisci, C.; Dramis, F.; and Sorriso-Valvo, M., 1996, Rock flow (sackung). In Dikau, R.; Brunsden, D.; Schrott, L.; and Ibsen, M. (Editors), *Landslide Recognition*: Report 1 of the European Commission Environment Programme, Contract No. EV5V-CT94-0454, John Wiley & Sons Ltd., Chichester, UK, pp. 150–160.

Dramis, F. and Sorriso-Valvo, M., 1994, Deep-seated gravitational slope deformation, related landslides, and tectonics: *Engineering Geology*, Vol. 38, pp. 231–243.

Hart, M. W., 1991, Landslides in the Peninsular Ranges, southern California. In Walawender, M. J. and Hanan, B. B. (Editors), *Geological Excursions in Southern California and Mexico*: Geologic Society of America Guidebook for the 1991 Annual Meeting, Geological Society of America, Boulder, CO, pp. 349–365.

Radbruch-Hall, D., 1978, Gravitational creep of rock masses on slopes. In Voigt, B. (Editor), *Rockslides and Avalanches*, Vol. I: Elsevier Scientific, Amsterdam, pp. 607–657.

Shakal, A. F.; Huang, M. J.; and Darragh, R. B., 1994, Some implications of strong-motion records from the 1994 Northridge earthquake. In SMIP94: Proceedings of the Seminar on Seismological and Engineering Implications of Recorded Strong Motion Data, California Div. Mines & Geology.

Sharp, R. V., 1967, San Jacinto fault zone in the Peninsular Ranges of Southern California: *Bulletin Geological Society America*, Vol. 78, No. 6, pp. 705–730.

Theodore, T. G. and Sharp, R. V., 1975, *Geologic Map of the Clark Lake Quadrangle, San Diego County, California*: U.S. Geological Survey Map MF 644. Scale 1:24,000.

Varnes, D. J., 1978, Slope movement types and processes. In Schuster, R. L. and Krizek, R. J. (Editors), *Landslides Analysis and Control*: Special Report 176, Transportation Research Board Commission on Sociotechnical Systems, National Research Council, Washington, D.C., pp. 11–33.

Yarnold, J. C. and Lombard, J. P., 1989, A facies model for large rock-avalanche deposits found in dry climates. In Colburn, I. P.; Abbott, P.; and Minch, J. (Editors), *Conglomerates in Basin Analysis: A Symposium Dedicated to A. O. Woodward*, Vol. 62: Pacific Section, Society of Economic Paleontologists and Mineralogists, Book 62, pp. 9–32.