Bedding-Parallel Shear Zones as Landslide Mechanisms in Horizontal Sedimentary Rocks

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ABSTRACT

The occurrence of large translational paleolandslides in horizontally bedded sediments can not be completely explained by the presence of "weak" clay rocks and oversteepened natural slopes. When the shear strength of a landslide's basal rupture surface is back-calculated, residual shear strengths are usually required for failure. This is because peak shear strengths are too high to allow failure, even assuming the most conservative estimate of ground-water levels. Data obtained during geologic mapping and downhole logging of large-diameter borings suggest that the principal factor leading to translational landsliding within horizontally bedded sediments is the presence of a pre-existing shear zone. A new term, bedding-parallel shear zone (BPS), is proposed for these features. When shearing parallel to bedding results from folding or thrust faulting, it is tectonic in origin. When similar shearing is found in horizontally bedded sediments that have not been tectonically deformed, it is often misinterpreted as conclusive evidence of landsliding. Mechanisms that produce BPS are:

1. **Elastic rebound.**
2. **Progressive failure of overconsolidated claystone.**
3. **Differential consolidation.**
4. **Gravitational creep.**

It is important for engineering geologists to recognize BPS and to have an understanding of the mechanisms responsible for their formation and relationship to translational landsliding. Knowledge of where and how BPS occur allows an understanding of why landslides have occurred in the past as well as allowing prediction of where large landslides are likely to occur in the future. Their misinterpretation as landslide slip surfaces has obvious effects on the accuracy of engineering geology studies and stability analyses. For example, a stability analysis for a typical landslide yielded a factor-of-safety of 1.2. An analysis of the same slope configuration representing a condition where a BPS is present, but not the entire landslide failure surface, yielded a factor-of-safety of 1.9.

INTRODUCTION

The reason landslides occur in a particular location on a slope, and not in another, is not always topmost in the minds of geologists, particularly when the landslide in question has created an emergency and lives or structures are in immediate peril. When more time is available to ponder this question, typically cited causes range from triggering events such as removal of earth from the toe or a rise in ground-water level, to preparatory factors such as the presence of weak clays and over-steepened slopes. The existence of large translational paleolandslides in areas of gently dipping to horizontally bedded sediments cannot be completely explained by any of these oft-cited landslide causes. For example, there seems to be no demonstrable relationship between the steepness of natural slopes and the occurrence of large translational bedrock landslides. On the contrary, such landslides commonly occur on relatively gentle slopes.

A common factor among all large translational landslides in sedimentary rocks is that basal slip surfaces coincide with shale or claystone beds. When the shear strength of the clay bed on which landsliding occurs is back-calculated, residual shear strength is required for failure. This is because peak shear strengths are too high to allow failure even assuming the most conservative estimate of ground-water levels. In order for landsliding to occur under the conditions described above, the strength at failure must be close to the residual strength value. Shear zones possessing residual strength have been found to be ubiquitous in horizontally bedded clay-rich rocks and are known by several essentially synonymous terms: bedding-parallel shears, bedding-plane shears, clay seams, and bedding-plane faults.

The purpose of this paper is to present evidence suggesting the principal preparatory factor leading to translational landsliding within horizontally bedded sediments is the presence of a pre-existing shear zone and to propose a new term, bedding-parallel shear zone (BPS) for these features. The term "bedding-plane shear" utilized by Fell and others (1988) and Davachi and others (1991) is abandoned because BPS often occur in massive, fissured clays with no discernible bedding. The literature in which the BPS phenomenon has been described is examined and various case histories from the literature and author's experience are presented. Several areas in southern California where BPS may be examined in outcrop are described (Figure 1). Finally, a summary of mechanisms proposed by various authors is presented and some new variations proposed. The conclusions of this discussion will deal with the significance and relationship of BPS to landslides and slope design.

DEFINITION: BEDDING-PARALLEL SHEAR ZONE

Bedding-parallel shear zones, as the name implies, occur parallel, or sub-parallel, to bedding in fine-grained, typically clay-rich, sediments. When shearing parallel to bedding results from folding or thrust faulting, it is tectonic in origin. When similar shearing is found in horizontally bedded sediments that have not been tectonically deformed, it is often misinterpreted as conclusive evidence of landsliding. A typical BPS is characterized by highly plastic, remolded clay that may vary from paper thin to three or four centimeters in thickness. This gouge zone is usually bound by striated, planar slip surfaces. Clay seams or thin clay beds that are not remolded (i.e., sheared, or possessing a shear fabric) cannot be called BPS.

Clays from several BPS in the Tertiary rocks of the San Diego area were analyzed and found to consist of volcanically derived smectite or "bentonite" (Berry, 1992, written communication). It has been found that clays associated with BPS often originate as ash-falls that alters

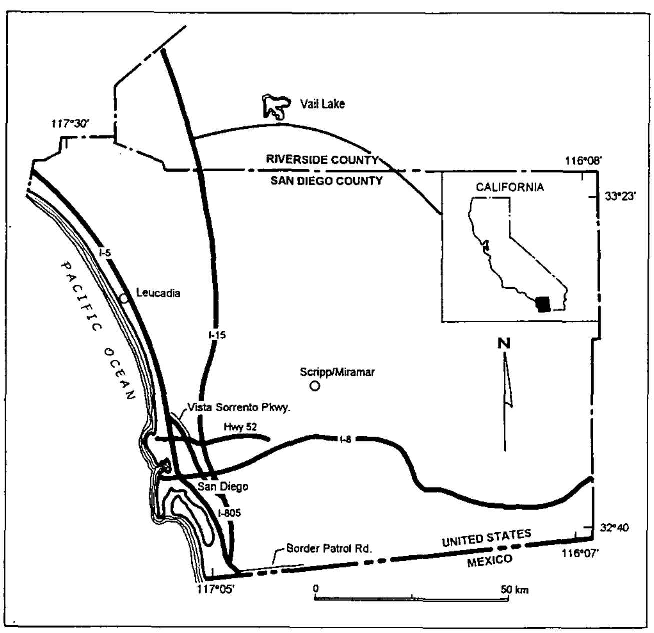

Figure 1. Map of San Diego County showing location of areas discussed in text.

to smectite on contact with seawater (Cleveland, 1960). BPS are commonly located at the top of highly fissured, waxy claystone beds. In other cases, such as the Highway 52 roadcut discussed later, the BPS occur within a thin clay bed overlain and underlain by massive sandstone and conglomerate. BPS may be very poorly developed and not traceable over distances of more than a few tens of meters or they may be very well developed and laterally continuous for hundreds of meters.

Observations of numerous exposures of BPS in outcrop and in large-diameter borings suggest the degree of development of these features may be related to the percentage of clay in the sediments, overburden thickness, degree of over-consolidation, the distance to the slope face, and the amount of total slip along the bed. At one locality in the San Diego area in the Mission Valley Formation, a Tertiary sequence of massive claystone and sandstone, approximately one meter of cumulative displacement along a BPS is suggested by horizontal offset of sand-filled paleodessication cracks in claystone (Figure 2). The thickness of the BPS at this locality varied from paper thin to several millimeters. While tempting to believe BPS thickness is always related to total slip, such may not be the case since the thickness often varies by several centimeters within horizontal distances of 5 to 10 m.

One of the most important characteristics of BPS is their very low shear strength. Skempton (1985) found, as a result of performing ring shear tests on clay samples, that displacements of 100 to 500 mm are necessary before residual shear strength values are attained. Skempton (1985) also found that even at 20 to 50 percent of the strain cited above, values of shear strength lie within one degree of the residual value. It is concluded from the results of Skempton's work and numerous observations of BPS in the field that BPS have resulted from differential horizontal movements of at least the amount necessary for creation of residual strength value reported by Skempton (1985).

PREVIOUS WORK

Numerous authors have described the phenomena of prefailure movements in slopes that result in either intense fissuring of overconsolidated clay sediments or the creation of a horizontal, or slope-parallel slip surface, accompanied by soft clay gouge. Skempton and Hutchinson (1969) describe limited movements that resulted in fissuring of overconsolidated claystones with randomly oriented and polished striated surfaces showing a preferred orientation sub-parallel to bedding. Skempton (1970) describes a mechanism whereby overconsolidated claystones develop lower than peak strengths in two stages that ultimately result in the development of shears of "appreciable" length—some of which eventually link

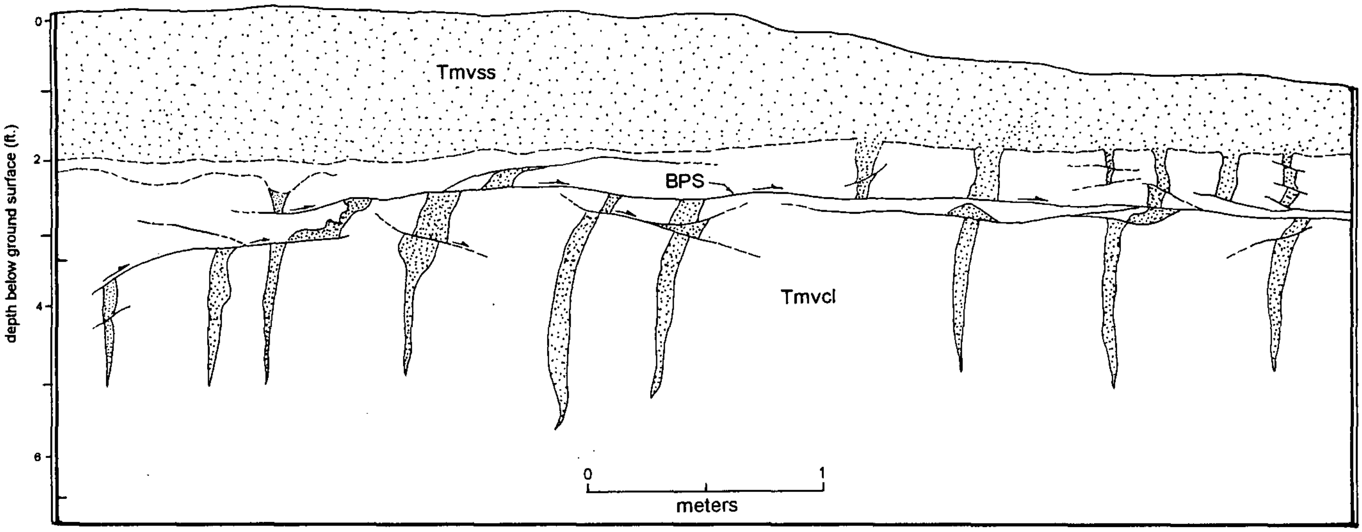

Figure 2. Horizontally offset sandstone-filled desiccation cracks in claystone of the Eocene Mission Valley Formation. Orientation of section is perpendicular to the natural slope. Arrows indicate apparent slip direction of filled desiccation cracks oriented at high angles to the plane of section. Tmvss = Mission Valley Formation, massive white sandstone; Tmvcl = fissured claystone; BPS = bedding parallel shear zone.

together to form a continuous shear. Palladino and Peck (1972) described numerous slope failures in overconsolidated clays in Seattle, Washington, for which they back-calculated strengths at failure. They concluded that the shear strengths at failure corresponded to residual rather than peak strengths and that the slides must have occurred primarily along pre-existing failure surfaces.

Davachi and others (1991) found shearing along bedding to be common in horizontally bedded Paleocene mudrocks during their study of the Oldman River dam foundation near Calgary, Canada. They provide a description of what they termed "bedding-plane shears" as follows:

1. They occur along contacts between strong and weak rocks parallel to bedding.
2. They occur as single shears, groups of closely spaced sub-parallel shears, or brecciated zones that may be up to 75 mm (3 in.) thick.
3. They are continuous for hundreds of meters and are most frequent within 10 to 15 m of the ground surface.

Fell and others (1988) also described similar "bedding-plane shears" in Permian coal deposits of south Australia where the rocks consist of interbedded sandstone, thin coal beds, tuff, claystone, and siltstone. They cited several case histories in which the bedding-plane shears occurred as thin bands in the coal and claystone. In another case, they described geotechnical studies that found bedding-plane shears in horizontally bedded strata over a 15 km square area of Tertiary clays and silts. They stated that a common feature of landslides in the Sydney Basin is the occurrence of a bedding-plane shear at the same stratigraphic level as the base of landsliding uphill from the landslide, and ascribed the cause of landsliding to the existence of these shear zones.

Barton and others (1983), in their study of slumps along the sea cliffs of Christchurch Bay in New Zealand, described what they termed "preferred bedding plane shear surfaces" along which landslides take place. They did not directly state the bedding planes were pre-sheared, but in a somewhat contradictory paragraph the landslide shear surfaces are described as being related to growth of a shear band made up of slip surfaces formed by shearing after peak strengths have been passed.

Thomson and Morgenstern (1979), in their study of landslides in argillaceous rocks of the Prairie Provinces of Canada, identified interbed slip as important to landslide studies. They presented a unique mechanism for such slip that is a special case of elastic rebound discussed later. (see Mechanisms of BPS).

Pinckney and others (1979) described the occurrence of BPS in Tertiary claystone of San Diego, California, and attributed the primary cause of landslides in the area investigated to be pre-existing slip surfaces they termed "bedding plane faults." Their paper was virtually ignored by the engineering geologic community probably because they attributed the formation of the BPS to an unlikely mechanism—flexural-slip resulting from gentle folding that produced dips of the same magnitude as the initial dip. In fact, many engineering geologists in the southern California area believed shearing parallel to bedding in essentially flat-lying rocks to be impossible.

TYPE LOCALITIES OF BPS IN THE GREATER SAN DIEGO AREA

The following discussion provides the reader with locations where BPS can be observed in the field. As might be imagined, BPS are not usually well exposed in natural outcrops because they are generally covered with landslide deposits or thick soils. Most descriptions of BPS are from direct observations in large-diameter borings made during geotechnical studies for hillside residential development or in cut slopes made during grading operations associated with those developments. However, several semi-permanent localities exist where BPS may be observed. The Highway 52 roadcut, Vail Lake, Vista Sorrento Parkway roadcut, and the Border Patrol roadcut are locations where, with some effort involving use of a rock pick or shovel, good examples of BPS may be observed. In addition, the Leucadia sea-cliff locality is accessible but is typically buried by beach sand except during the winter. These localities are described in detail below.

Highway 52 Roadcut

The Highway 52 roadcut is located at the south end of a narrow, irregularly shaped ridge on the north side of Highway 52 and 3.5 km east of Interstate 15 in San Diego, California (Figures 1 and 3). The ridge is underlain by the Mission Valley Formation and Pomerado Conglomerate; a sequence of massive to thinly bedded, Eocene sandstone, siltstone, claystone, and conglomerate (Kennedy, 1975). The BPS is located at an elevation of approximately 633 ft on the 45-m high cut slope shown on Figure 4. A small paleolandslide located 370 m northeast of the roadcut and at the same elevation as the BPS may have utilized the shear zone as a basal rupture surface (Figure 3).

This exposure is somewhat atypical in that the BPS occurs in a 2- to 3-cm thick, horizontal claystone bed within a thick sequence of sandstone and conglomerate. In most other localities in the greater San Diego area, BPS occur in exposures dominated by finer grained sediments such as siltstones and claystones. The BPS is characterized by two planar slip surfaces located at the top and bottom of the gouge zone. The gouge varies in thickness from paper thin to several inches (the full thickness of the clay bed). An analysis of the clay indicates it is 100 percent smectite, typical of other waxy bentonites of San Diego County. In a sieve analysis, 99 percent of the material passed the #200 sieve. Of the 1 percent

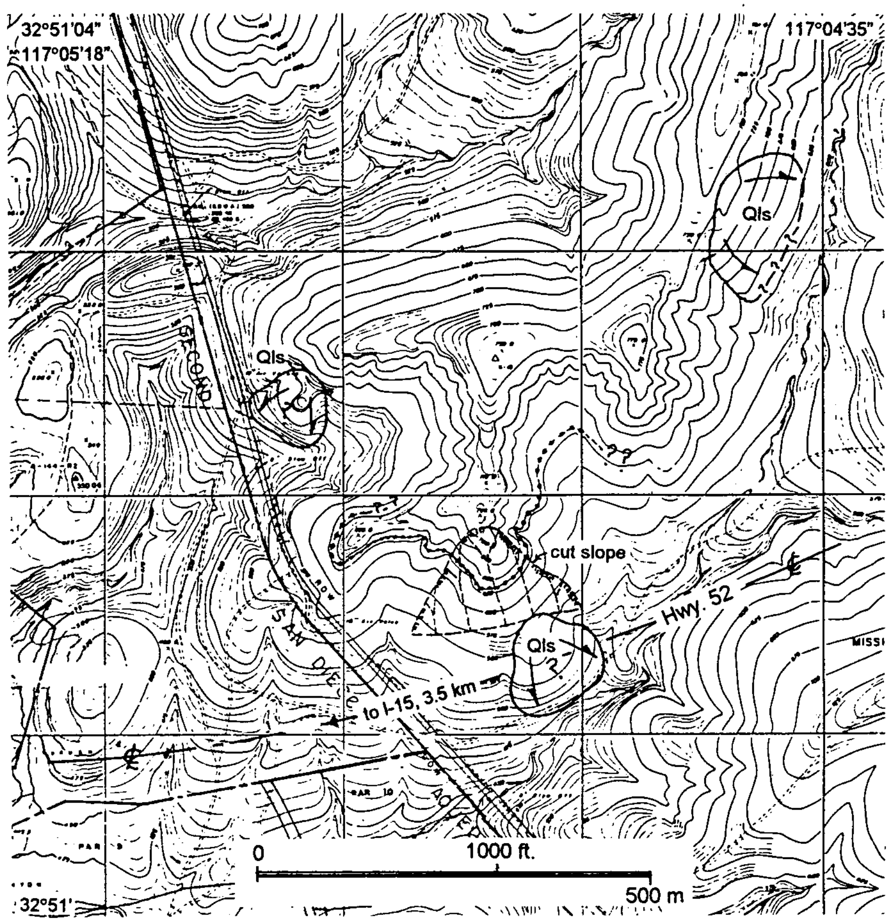

Figure 3. Topographic map of the area adjacent to the Highway 52 roadcut. The cut is approximately 130 ft high and exposes a BPS (dotted line) at an elevation of 633 ft.

Figure 4. View of Highway 52 cut slope looking north. BPS (arrows) occurs in a thin claystone bed within a sequence of Eocene sandstone and conglomerate.

retained, 33 percent consisted of volcanic glass shards that confirm an ash fall origin and classification as bentonite.

Vail Lake

The Vail Lake site is located near the east shore of Vail Lake approximately 2 km north of Highway 79 in southern Riverside County, California. The BPS is exposed in sub-horizontal sediments in a cut slope made for an unpaved truck trail. The cut is made in the Temecula Arkose (Kennedy, 1977) a Pliocene unit consisting of horizontal to gently dipping alternating lacustrine silts, marls, and beds of coarse arkose. The cut slope is approximately 110 m long, 3 to 5 m high, and located 15 to 20 m below the crest of a 55 m high ridge (Figure 5). The Temecula Arkose is cut by at least one minor steeply dipping fault near the BPS exposure. The closest major faults are the Lancaster and Agua Tibia faults, mapped approximately 1.6 km north and 3 km south of the exposure, respectively.

The BPS occurs at mid-height in the cut slope in a sequence of massively bedded to cross-bedded, medium- to coarse-grained sands and silty sands. The BPS dips 2 to 3 degrees to the west and makes up the entire thickness of the 5 to 10 cm thick claystone bed in which it occurs (Figure 6). Analysis of the clay (Berry, 1995) indicates it is primarily detrital in origin, but contains glass shards and smectite that is in places almost waxy in appearance suggesting the clays are in part bentonitic and have an ash-fall origin.

The BPS dies out to the east in a carbonate-rich zone as it approaches the ground surface. This apparent die out is likely a result of weathering and replacement of the clay which has essentially destroyed the shear fabric near the ground surface. The Vail Lake exposure is similar to the Highway 52 exposure discussed previously in that the BPS occurs in a relatively thick sequence of coarse-grained sediments. A landslide origin for the shear zone is ruled out by examination of the well-exposed geologic structure in the cut slopes, as well as a lack of recognizable landslide morphology on the adjacent natural slopes.

Vista Sorrento Parkway

This roadcut exposure is located between the elevations of 200 and 230 ft on the east side of Vista Sorrento Parkway, approximately 150 m north of its intersection with Mira Mesa Boulevard in San Diego, California (Figure 7). The approximately 20-m high cut slope is approximately 200 m in length and situated near the base of a gentle to moderate sloping hillside that extends to an elevation of 380 ft. The uniform natural slope gradient above the cut slope and unfaulted horizontally stratified

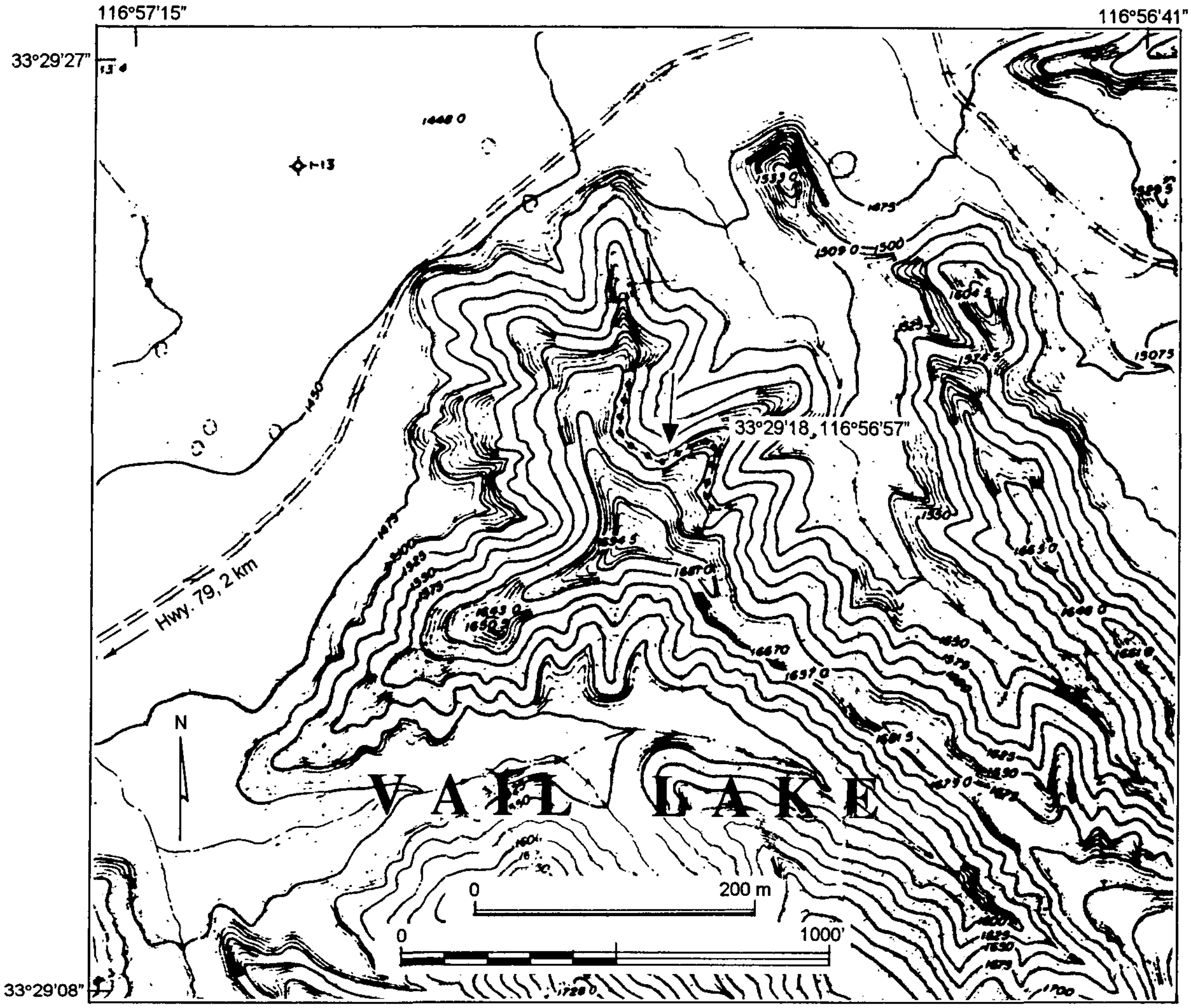

Figure 5. Topographic map of Vail Lake BPS locality (dotted line). Arrow points to roadcut (road not shown) and location of photograph (Figure 6). Note lack of geomorphic evidence of landsliding. Interval between bold contours is 25 ft.

siltstone and fine sandstone exposed in the cut slope provide good evidence that the BPS was not caused by landsliding (Figure 8).

The BPS occurs in the Eocene-age Scripps Formation (Kennedy, 1975) consisting of horizontally bedded, moderately well-cemented, fine-grained sandstone and siltstone. The BPS is located approximately 4 m below the top of the slope at a point 33 m south of its northern terminus. The shear zone is 2.5 to 6 cm thick and bound on the top and bottom by planar slip surfaces. The soft gouge located between the slip surfaces contains anastomosing internal shear surfaces and consists of remolded, slightly plastic clayey silt with numerous angular siltstone fragments varying in size up to 5 mm (Figure 9).

Grading of an industrial subdivision located east of the roadcut permitted an unusual opportunity to trace the BPS into the hillside. Mapping of the cut slopes within the subdivision confirmed the BPS remained parallel to bedding over a minimum horizontal distance of 250 m into the hillside and for a distance of approximately 500 m parallel to the slope (Figure 7). The grading also permitted a detailed examination of the rocks lying stratigraphically above the slip surface in cut slopes that varied from 10 to over 30 m in height. The sediments exposed in these slopes dipped to the west from 0 to 5 degrees and contained only a few tight fractures with no evidence of past landsliding. A geotechnical investigation for another industrial development 0.8 km north of the above-described project encountered a second stratigraphically lower BPS at an elevation of approximately 115 ft. Downhole logging of 0.75 m diameter boreholes indicated the BPS dips parallel to the bedding, approximately 5 degrees to the west, and extends into the slope a minimum distance of 250 m. Data obtained from the investigation of these two projects is significant in that it demonstrated:

1. The ability of BPS to be continuous over relatively long distances parallel to the valley walls.

Figure 6. BPS at the Vail Lake locality (dark zone behind coin with 2.5 cm diameter). Shear zone occurs in a 3- to 5-m high vertical road-cut within a sequence of sandstone and siltstone.

2. BPS have the capability of extending hundreds of feet into the hillside.
3. Landsliding was not the causative mechanism.

Border Patrol Road

The last description of a BPS outcrop is also located in the city of San Diego approximately 70 m north of the United States–Mexico border. The area in which the BPS is exposed lies within spectacular landslide terrain containing numerous large translational landslides all occurring within the nearly horizontally bedded Oligocene Otay Formation. The Otay Formation consists of three members (Walsh and Demere, 1991). The upper member, exposed throughout the border area, is composed of massive to thinly bedded tuffaceous sandstones with thin interbeds of bentonite (Cleveland, 1960). Overlying the Otay Formation is an early to middle Pleistocene marine terrace deposit, the Lindavista Formation, consisting of massively bedded red-brown sandstone and cobble to boulder conglomerate. The Lindavista Formation is approximately 10 m thick and forms the cap rock over an extensive series of mesas and intervening steep-walled canyons.

Grading for a new road for the U. S. Border Patrol, 70 m north of the international border, created a slope approximately 15 m high, trending perpendicular to the edge of the mesa. A horizontal bed of bentonite is exposed within massive sandstone of the Otay Formation at an elevation of 430 ft (Figure 10) on the cut slope. The thickness of the bentonite varies from a few centimeters to approximately 1 m. The bentonite is continuously exposed from the edge of the cut at its contact with the face of the natural canyon slope for a horizontal distance of approximately 150 m perpendicular to the canyon wall. This outcrop is similar to the Highway 52 exposure previously discussed, in that the BPS occurs in a solitary thin clay bed within a thick sequence of massive sandstone and conglomerate. Observations of the slip surface and gouge zone exposed in the cut slope were made at several locations to determine if the thickness and degree of development varied in relationship to the distance from the bluff face.

At a distance farthest from the bluff face the BPS occurs in an approximately 15-cm thick bentonite clay bed. The zone of shearing is characterized by two subparallel BPS separated by 8 cm of fractured, but not sheared, bentonitic dark brown claystone. The upper BPS is a poorly developed, subhorizontal gouge zone overlain by hard, clayey siltstone. The lower BPS is characterized by approximately 5 mm of soft, moist gouge and a well-developed planar slip surface underlain by hard, blocky, pink bentonite. Approximately 60 m west of the above locality in the approximate center of the cut, the remolded clay zones were slightly thicker and better developed (Figure 11).

Approximately 6 m from the face of the bluff, the gouge zones and slip surfaces are the most highly developed. At this location, an approximately 5-cm thick intensely sheared remolded zone is present, bounded by

Figure 7. Vista Sorrento Parkway BPS locality. Two BPS (dotted lines) are present in this location within the Eocene Scripps Formation and Ardath Shale. Note relatively uniform slope contours and lack of distinctive landslide morphology. Interval between bold contours is 25 ft.

upper and lower parallel slip surfaces. The shear zone overlies 5 to 7 cm of hard, fractured, waxy bentonite. The variations in thickness and degree of development of the BPS observable at this locality suggest the development of the BPS decreases as distance from the slope face increases. The thickness and lateral continuity of highly plastic claystones, and in particular, bentonitic clays are highly variable in most outcrops within the Otay Formation. Where the bentonite beds gradually thin or where they become contaminated by terrestrial coarse-grained sediments, the BPS also tend to die out.

RELATIONSHIP OF BPS TO LANDSLIDES

In the following case studies, a correlation is made between BPS and basal rupture surfaces of translational landslides. The Leucadia sea-cliff locality was studied for the purpose of preparing a report on the rate of sea-cliff recession for a homeowner. The Scripps/Miramar site was investigated during a geotechnical study for a hillside development.

Leucadia Sea-Cliff

Leucadia is a small beach community within the City of Encinitas in northern San Diego County, California. The coastline is characterized by 15- to 30-m high sea-cliffs. Typically, the lower approximately 1/3 of the cliff is near-vertical and underlain by flat-lying Eocene bedrock consisting of clayey sandstone, siltstone, and thin claystone. The upper portion of the cliff varies in steepness from 30 to 50 degrees with localized near-vertical sections and is composed of massive, coarse-grained marine terrace deposits.

Two large prehistoric bedrock landslides occur on the sea-cliff directly below and to the south of an area known

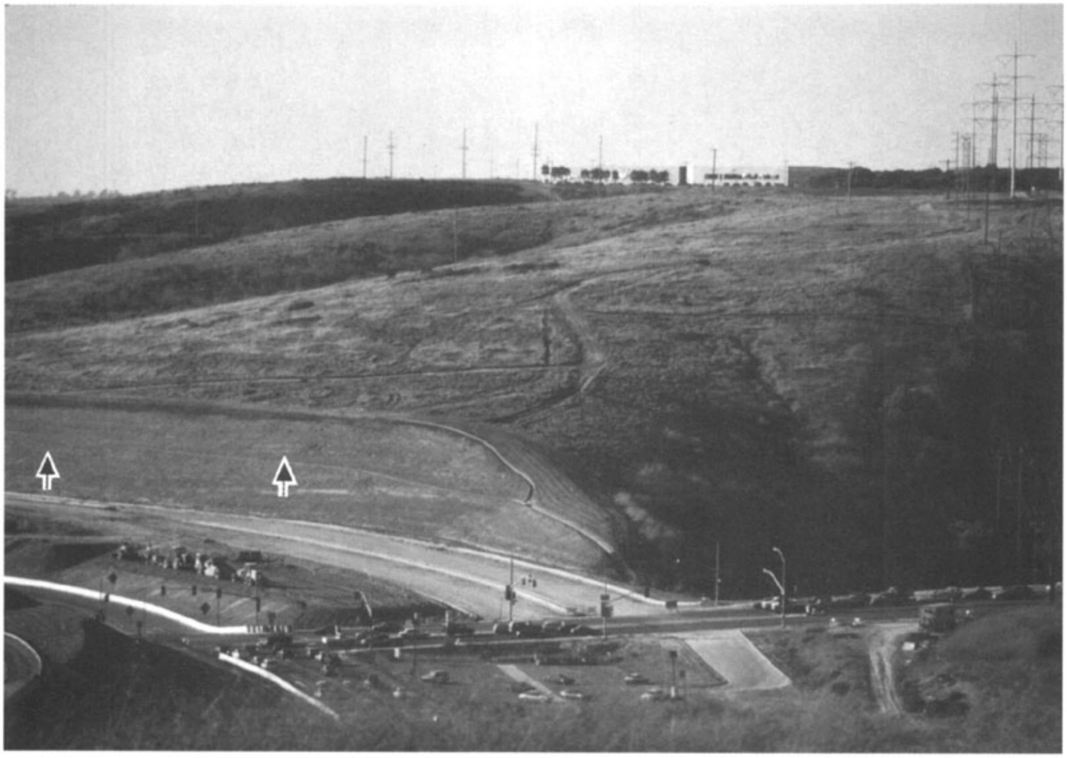

Figure 8. Vista Sorrento Parkway cut slope excavated into uniform natural slope lacking landslide morphology. The BPS (arrows) occurs just below the drainage bench at mid-height of the slope. Location of cut slope is depicted in lower right corner of Figure 7.

as Beacons Beach. In the summer of 1996, a large bedrock landslide occurred between the two prehistoric slides (Figure 12). This landslide was approximately 80 m wide and extended 5 to 7 m landward of the cliff edge. The slide translated over 50 feet seaward on a BPS located at the base of the cliff that at the time of sliding was buried by less than 1 m of beach sand.

Geologic mapping of the sea-cliff immediately after the 1996 landslide revealed that this landslide, as well as the two older landslides, failed on the lowest of two BPS exposed in the cliff (Figure 13). The lower BPS is exposed continuously at the base of the sea-cliff (except where buried by the 1996 landslide) from the southern edge of the Beacons Beach landslide to the southernmost prehistoric landslide, a distance of approximately 310 m where it is terminated by a fault.

An interesting additional consequence of the presence of the BPS is the large blockfalls and topples, whose frequency of occurrence has accelerated since the 1996 landslide. Periodic visits to the site since the landslide occurred indicate large blocks of the Eocene rocks making up the lower vertical portion of the bluff are failing by translational creep on the BPS. Some of the largest blocks have rotated out at the base, and the tops of the failed blocks have collapsed inward toward the bluff (Figure 14). One possible explanation for the abrupt increase in the frequency of blockfalls is that the adjacent landsliding has resulted in widening of bluff-parallel fractures already present in the adjacent rocks. Ground water flowing along the contact between the terrace deposits and the Eocene rocks is then able to flow into the fractures and the resulting hydrostatic pressure forces the blocks outward at the base where pressure is the highest.

Radbruch-Hall (1978) describes a similar process northeast of the town of Green Bay, Wisconsin, where massive, light gray Silurian dolomite, underlain by Ordovician shale, forms 6- to 9-m high cliffs on the southeast shore of Green Bay. Wide, cliff-parallel fissures are abundant, and where the blocks of the dolomite have moved outward, some of the blocks have broken, rotated, and fallen to form a jumbled mass at the base of the escarpment. Radbruch-Hall attributes the movement of the blocks to squeezing of the shale underlying the more resistant rocks. As a result, the overlying dolomite fractured along joints and moved out, gradually widening the fissures, until equilibrium had been reached. The occurrence of blockfalls described by Radbruch-Hall differs in one important way from the Leucadia site; the movement of the blocks at Green Bay is described as taking place concurrently with the "squeezing out of the shale underlying the more resistant rocks." The shear zone at Leucadia was present prior to the most recent blockfall events, as evidenced by exposures of BPS at the cliff base where no recent blockfalls have occurred. The mechanism for

Figure 9. Approximately 2.5 cm thick gouge zone of Vista Sorrento Parkway BPS. Note the angular clast of siltstone at tip of pencil.

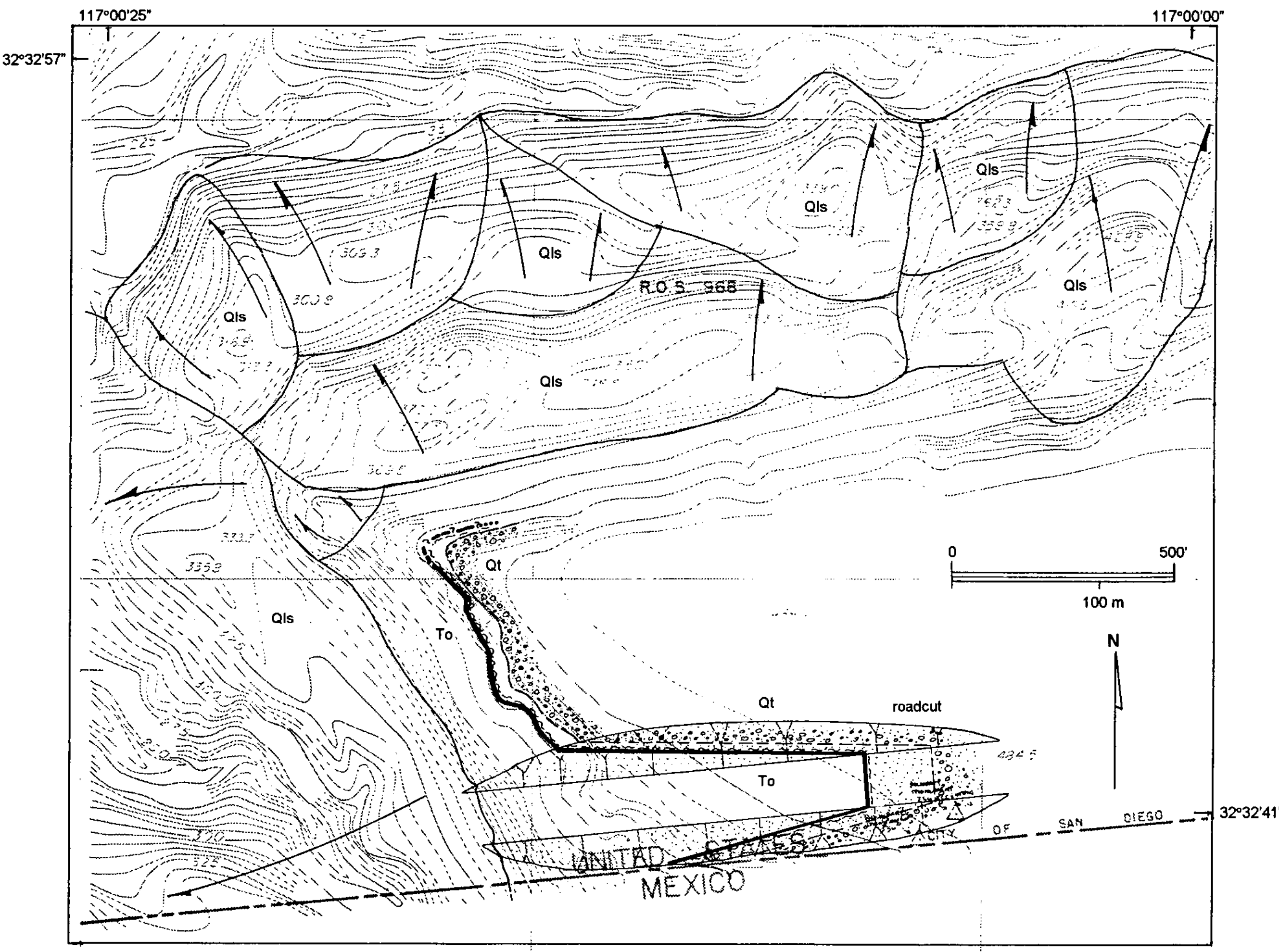

Figure 10. Border Patrol roadcut and geologic map. Roadcut occurs on west-facing slope of a mesa rimmed with translational landslides. BPS (heavy solid line) occurs in a horizontal bentonite bed. Qls = translational landslide; Qt = Lindavista Formation (marine terrace deposits); To = Otay Formation. Contour interval is 5 ft.

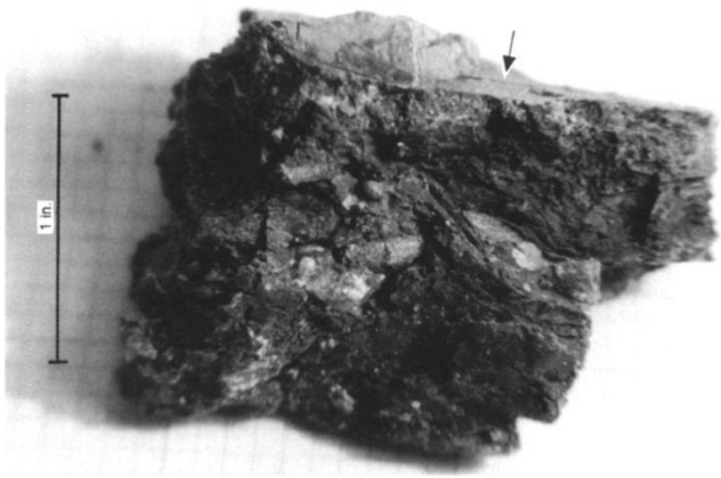

Figure 11. Gouge zone showing anastomosing shears and upper slip surface (arrow) of BPS in Border Patrol roadcut.

the formation of the BPS at this locality, however, could be widespread creep that has occurred over the last few hundred or thousands of years as described later.

Scripps/Miramar Subdivision

A cut slope made during grading for a residential subdivision in the northern part of the city of San Diego provided an excellent example of the relationship between BPS and landsliding. The project was developed in the Mission Valley Formation, the same unit in which the Highway 52 roadcut was made. The Mission Valley Formation in the Scripps/Miramar area is also horizontally bedded and composed of alternating beds of claystone, siltstone, and sandstone. No faults of significance are known to occur within several miles of the project.

The BPS occurs approximately 1.5 m above the base of a cut slope oriented perpendicular to the trend of a

Figure 12. Recent blockfalls and translational landslide in sea-cliff, Leucadia, California. Blockfalls and landslide (arrow) utilized BPS at base of cliff as basal failure surface.

Figure 13. BPS (arrow) near base of sea-cliff, Leucadia, California. Note pinch-and-swell nature of gouge zone suggesting squeezing of clay bed and plastic flow.

Figure 14. Unique mode of block failure, Leucadia, California. Block in center of photo failed by translating seaward on BPS at base of slope resulting in backward rotation of block.

narrow ridge (Figure 15). The shear zone occurs at the top of a 1-m thick claystone bed and could be traced continuously for nearly 60 m across the face of the cut to where it merged with the basal rupture surface of a small landslide. The BPS became less well developed in a westerly direction and died out gradually as the clay-rich sediments graded into fine-grained sandstone. This exposure was significant for several reasons; first, it showed the discontinuous nature of BPS and that they may die out laterally in coarse-grained sediments; second, the exposure demonstrated how landslides utilize BPS as their basal rupture surface. Lastly, the exposure's unique physical location, extending through the center of a ridge and the fact that it was observed to die out gradually in a sandstone, is convincing evidence that BPS are not merely misidentified landslide slip surfaces are but distinct features caused by a totally different mechanism.

MECHANISMS OF BPS

From the foregoing case studies and references relating to the occurrence of BPS, large translational landslides, at least in horizontally and near-horizontally bedded sediments, are clearly preceded by the development of a continuous sliding surface. Mechanisms that can produce slip along bedding surfaces (BPS) are well-documented.

Pinckney and others (1979) recognized the relationship between what they termed bedding-plane faults and the occurrence of large translational landslides. Based on limited exposures that were available in the 1970s, Pinckney and his co-workers observed that the shear zones were similar to flexural-slip or bedding-plane faults that occur as a result of tectonic deformation or folding. Such interbed slip occurs in a manner analogous to inter-sheet slippage that can be observed when bending a deck of cards or a thick package of paper (Billings, 1960). They theorized that "bedding-plane faults" occurring in the nearly flat-lying sediments of San Diego were a result of very broad warping of the sediments into folds with amplitudes measured in terms of a few meters over a distance of 2 or 3 km. While flexural-slip faulting is a well-known phenomenon in moderately to tightly folded sediments, the mechanism is here dismissed as a potential cause of BPS in horizontal and sub-horizontal sediments for several reasons: first, broad warping of sediments is

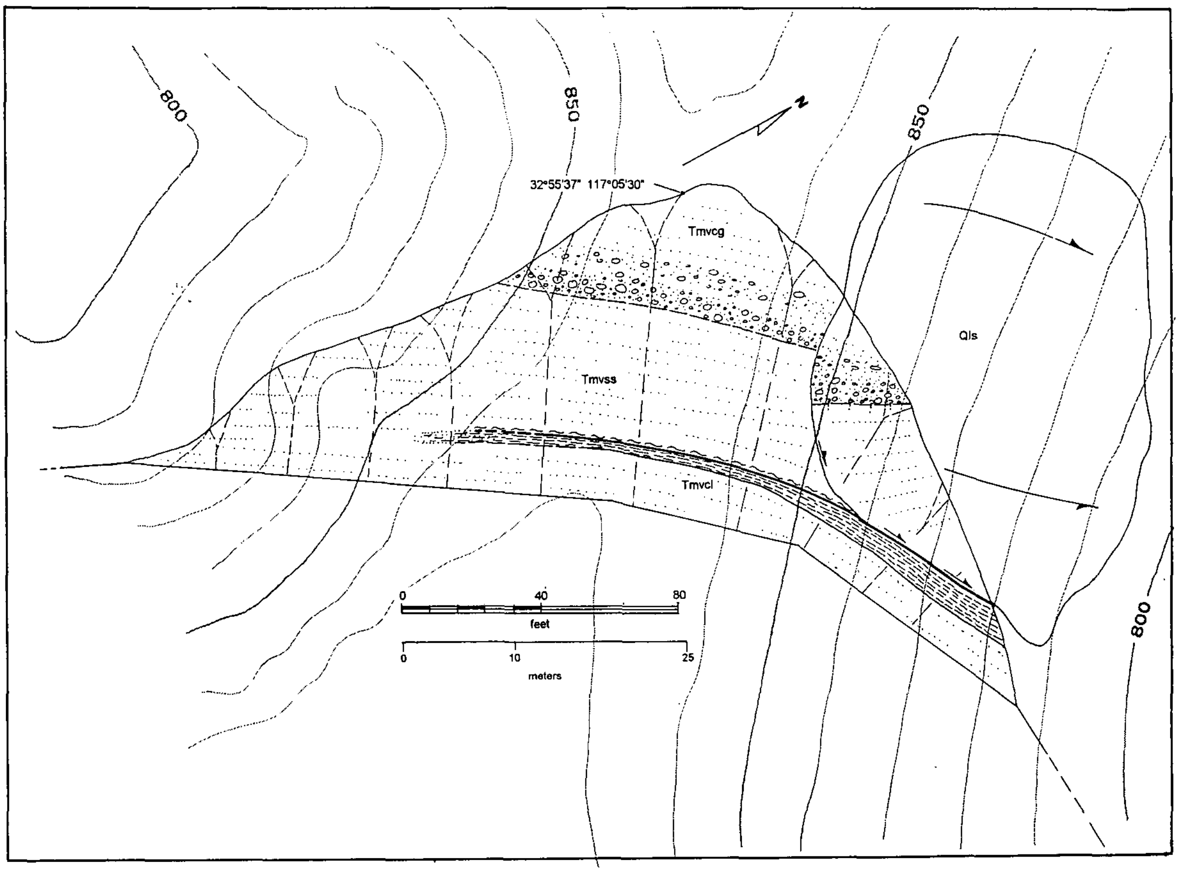

Figure 15. Sketch of cut slope in Scripps/Miramar subdivision, San Diego, California. BPS is heavy solid line near base of slope on top of clay bed. Note that BPS dies out as clay bed grades into sandstone near west end of cut slope. Landslide has utilized BPS as basal rupture surface. Qls = Landslide; Tmvcg = Mission Valley Formation, conglomerate; Tmvss = sandstone; Tmvcl = claystone.

unlikely to result in flexural-slip, because the small amount of strain that occurs in such broad folds is more likely to be absorbed internally by plastic deformation. Second, and more importantly, there are other much more plausible mechanisms.

Each of these mechanisms is discussed below beginning with Skempton's (1964) classic paper on the long-term stability of clay slopes and ending with a publication by Davachi and others (1991) on the shear strength of foundation rocks for the Oldman River Dam south of Calgary, Canada. Most of the theories relate to a specific type of rebound mechanism. For example, Peterson (1958) describes two phases of rebound in the Bearpaw Shale of western Canada: elastic rebound that occurs immediately after unloading, and time rebound that takes place over thousands of years and involves an increase in moisture content. Peterson (1958) cites an interesting and significant case in which a shale bed moved laterally 0.5 m after excavation of a 2-m wide, 100-m long test drift for a dam investigation. Tests indicated lateral pressures in the shale were 150 percent of vertical pressures at a depth of 65 ft. Duncan and Dunlop (1969) came to a similar conclusion and found that horizontal stresses in slopes may exceed overburden pressure by 50 percent or more, with one instance where lateral pressures were calculated as three times the overburden pressures. The question of how lateral pressures form and the ultimate long-term effects such pressures have on overconsolidated claystones are answered by Skempton (1964) and Bjerrum (1967).

Progressive Failure

Skempton, in his classic 1964 paper "Long-Term Stability of Clay Slopes," provided several case studies in which he showed that the factors-of-safety for landslides calculated with peak shear strengths were up to three times the value that resulted from using residual strengths, and concluded that shear stresses at failure of the landslide were nearly equal to the residual shear strength. From this he concluded that slides in overconsolidated clays were preceded by development of a continuous sliding surface resulting from progressive failure. Skempton (1970) indicated post-peak changes in the strength of overconsolidated clay-stone may be considered to be composed of two successive stages:

1. Dilatency and opening of fissures leading to an increase in water content and culminating in a drop in strength to a fully softened value with a softened shear zone containing numerous discontinuous shears.
2. Development of principal shears of appreciable length, some of which eventually link together to form a continuous shear.

Bjerrum (1967), in an attempt to answer the question of when should engineers expect progressive failure to occur, provided a succinct explanation of the progressive failure mechanism. Briefly, the mechanism occurs in overconsolidated claystones that possess what Bjerrum refers to as "recoverable strain energy," resulting from elastic deformation of flexible flake-shaped particles of clay as they are consolidated. When load is removed, the particles tend to regain their original shape. The amount of recoverable strain energy depends on the consolidation pressure and the properties of the clay. As the clay is unloaded, such as by erosion, the clay has a tendency to expand and increase its water content. Differential stresses occur as a result of expansion of the clay body towards the area of least resistance such as a canyon slope. This produces a redistribution of internal stresses. If the stresses exceed the peak strength of the clay, a local shear failure producing a slip surface will occur and will proceed as far as the shear stresses exceed the strength of the clay. Bjerrum states that in some instances the slip surface can advance parallel to the slope but he also cites numerous cases where the failure surface has developed in a horizontal or nearly horizontal direction following the direction of the bedding planes.

The slip surface lengthens as each succeeding theoretical block moves laterally and transfers stresses to the adjacent block (Figure 16). Progressive failure halts at a distance where lateral pressure exerted by the downhill block has become so large that shear stress at the end of the failure surface is just equal to the peak shear strength of the clay. At the completion of this sequence, true landsliding has not yet occurred but there exists a slip surface that formed to accommodate an increase in volume of the overlying claystone.

Elastic Rebound of Valley Rims

Matheson and Thomson (1973) describe a unique mechanism for the formation of bedding-parallel gouge, or zones of mylonite, resulting from elastic rebound of valley rims in Canada. Their study was performed in heavily overconsolidated flat-lying sediments consisting of Upper Cretaceous shales containing bentonite beds. The area of study was in a 1.5- to 3-km wide valley, 60 to 125 m in depth. The sediments had an anticlinal flexure in the valley bottom of 4 m over a distance of 150 m. This flexure, or arching, beneath the valley resulted in raising the valley rims accompanied by bedding-plane slip and gouge zones. The gouge zones are described as "near-horizontal soft layers about 0.25 to 0.5 in. (0.6 to 1.3 cm) thick," and composed of remolded material along the contact between strata of different lithology or at intervals of 2 to 4 ft (0.7 to 1.2 m) along bedding planes. Typical rebound values ranged between 3 to 10 percent of the valley depth.

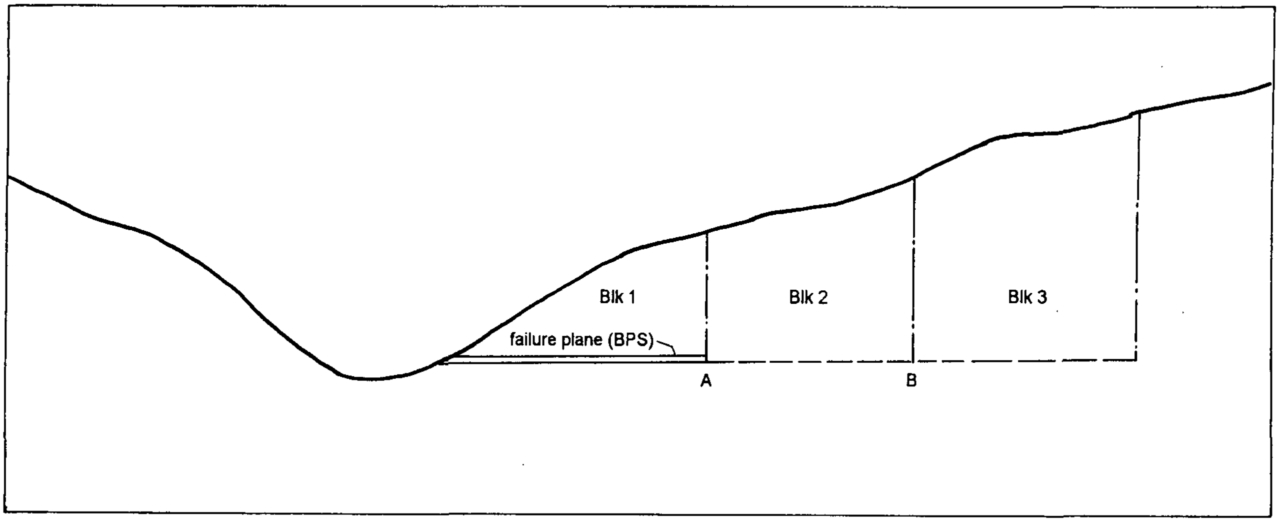

Figure 16. Progressive slope failure in overconsolidated clay (after Bjerrum, 1967). 1) Removal of lateral support causes unequal distribution of internal lateral stresses, clay expands towards valley. 2) Shear develops at base of Block 1 along bedding plane if lateral stress exceeds peak shear strength. Failure proceeds to Point A. 3) Reduction of shear stresses at base of Block 1 throws additional stress on clay in Block 2. 4) Failure then proceeds to Point B. Progressive failure halts when shear stress at end of failure surface just equals peak strength of clay.

Differential Consolidation

Fell and others (1988) attribute the cause of well-documented BPS in horizontal strata in south Australia to differential consolidation of beds with the shearing due to the concentration of stress at unit boundaries during the consolidation process. The details of this hypothesis are not included in their discussion. Differential compaction, however, is believed to be the mechanism responsible for shear zones observed at the contact between sediments and basement rocks at several localities in the San Diego area. Landslides are common along such contacts and the existence of a preexisting shear surface, coupled with a steeply sloping unconformity, can be major factors in landsliding.

Gravitational Creep

There are some occurrences of BPS that seem to be inexplicable by any of the above failure mechanisms, such as the Highway 52 and Border Patrol roadcuts, and to some degree the Leucadia exposure. None of the BPS exposed at these localities occurs in a thick claystone sequence, nor have they been affected by tectonic activity or valley rebound. The sediments at the Highway 52 and Border Patrol sites, with the exception of the thin clay bed in which the BPS occurs, are classified as medium- to fine-grained sandstone. The sediments exposed at the Leucadia site with the same exception are classified as clayey sandstone and siltstone with low plasticity.

One possible mechanism that could explain such occurrences is gravitational creep (Radbruch-Hall, 1978; Pasuto and Soldati, 1996). Radbruch-Hall (1978) describes a process of deep rock creep (as opposed to shallow creep of surficial materials), whereby valleyward squeezing of weak ductile rocks overlain by or interbedded with more rigid rocks occurs. This causes tensional fracturing and outward movements of the more rigid overlying rocks. The outward movements of the upper rigid blocks are reported to often result in the formation of wide fractures and subtle graben-like depressions termed surface depression synclines (Pasuto and Soldati, 1996). A study of topographic maps and aerial photographs of areas where BPS are known to occur in San Diego has failed to reveal the formation of surface depressions or wide fractures. However, open fractures, a few millimeters to approximately one centimeter in width, that strike parallel to valley walls are commonly observed in the more rigid rocks above BPS. These fractures are minor compared to the large-scale fracturing described by Radbruch-Hall (1978) and they can be observed only in deep excavations.

Many examples of large-scale gravitational creep cited by Radbruch-Hall (1978) involved entire mountain sides. Also included, however, are examples of creep in flat-lying interbedded hard and soft rocks on slopes less than one hundred meters in height. The mechanism is described as a very slow downward and outward movement of earth mass with the possible formation of discontinuous rupture surfaces. The squeezing of soft clay from between more rigid materials would be analogous to jelly squeezing out the sides of a sandwich after applying a heavy normal load. Radbruch-Hall (1978) concludes the squeezing results from plastic deformation of the rock rather than movement along discrete rupture surfaces. It seems likely, however, that such movement and squeezing would result in formation of a shear fabric in the plastic clay characterized by a number of anastomosing shear planes. An exposure of severely deformed bentonite located above a BPS in San Diego (Figure 17) and the pinch and swell structure of the BPS at Leucadia (Figure 13) supports the theory that, at least in some localities, the gravitational creep mechanism may be operative.

Chemical Weathering

Valleyward creep of relatively rigid sandstones over thin clay beds, as a result of deep chemical weathering and alteration of feldspar sand grains to clays, is another possible mechanism. As a result of observing numerous BPS in sediments that were otherwise relatively coarse-grained, it was hypothesized that an increase in rock volume might occur that would be proportional to the degree of alteration. To examine this possibility, thin sections of clayey sandstones (containing 20 percent clay or less) overlying well-developed BPS from four separate localities in the San Diego area were made. In general, the findings indicated the feldspar sand grains were not significantly altered and for the most part were clear and unfractured. One possible explanation for the presence of BPS in these types of sediments is that the progressive failure mechanism can also be operative in materials with relatively low clay contents. This has yet to be demonstrated and could be the subject of additional research.

DIFFERENTIATING BETWEEN LANDSLIDE SLIP SURFACES AND BPS

Pinckney and others (1979) attempted to provide criteria by which BPS and landslide slip surfaces could be differentiated. They concluded physical properties of remolded clay along BPS and landslide slip surfaces are similar and therefore, laboratory-measured physical properties do not make it possible to distinguish the two. Comparisons of properties of landslide shear zones and BPS made from numerous borings and cut slope exposures also indicate no reliable visual criteria exist by which the shear zones may be differentiated. The surest way to properly interpret the shear zone is to have an outcrop of sufficient size to determine if diagnostic structural landslide features are present, such as high-angle secondary shears, rotated or offset bedding, or pull-apart (graben) zones.

One method of distinguishing a slide surface from a BPS is illustrated by a case history involving a residential subdivision in the San Diego area. The subdivision is underlain by horizontally bedded Tertiary sandstones, siltstone, and claystone. The claystones are at least moderately overconsolidated, as they at one time were buried by several hundred feet of sediments that have been gradually removed by erosion. Elevations on the property vary from approximately 390 ft along the northern property line to approximately 500 ft at the southern site boundary. Evidence obtained from shallow exploratory test pits excavated with a backhoe during the preliminary

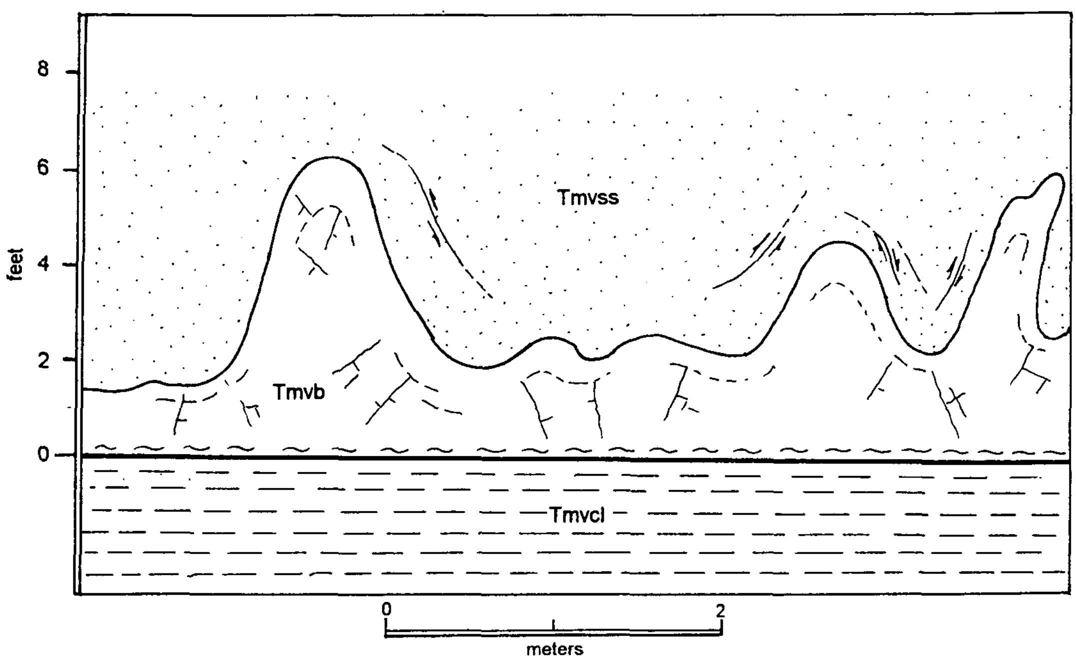

Figure 17. BPS (heavy black line) developed at base of plastically deformed bentonite bed (Tmvb) in Mission Valley Formation, San Diego, California. Tmvcl = Mission Valley Formation claystone; Tmvss = sandstone.

geotechnical investigation concluded the property did not exhibit evidence of paleolandsliding and was suitable for development.

The property was then developed by shallow cut and fill grading operations following the recommendations of the geotechnical report. Sometime in the late 1980s many of the residents began to experience minor distress to foundations, interior walls and floors, and exterior concrete flatwork. The homeowner association retained a geotechnical firm to investigate the cause of distress. The investigating firm reviewed stereographic pairs of aerial photographs and found subtle geomorphic evidence to suggest the presence of a large paleolandslide that, if present, would underlie the entire property and extend off-site to the east and west of the property. Numerous 30-in. (0.75-m) diameter borings were then excavated to confirm the aerial photo interpretation. Nearly all borings encountered multiple near-horizontal slip surfaces throughout the property at various depths. The deepest shear zone was interpreted as a basal landslide slip surface that at its distal end intercepted the ground surface near the north property line. The head of the "landslide" was estimated to lie off-site approximately 10 m beyond the south property line. None of the borings located in that area, however, encountered a steeply dipping slip surface or graben-zone that could be interpreted as representing the southern terminus of landsliding.

Both the plaintiff's and defendant's geotechnical experts confirmed that a well-developed near-horizontal shear zone existed beneath the property. The problem was that each side had a different interpretation as to the significance of the shear zone. The plaintiff's expert admitted that the distress to the residences was caused by a combination of fill settlement and highly expansive surficial soils, but insisted that the slip surface represented a basal rupture surface of a large paleolandslide that, if present, would cause diminution of property values by representing a risk of future reactivation. The defense argued that since no other structural evidence of landsliding was observed in the borings, such as secondary high-angle shears, breccia deposits, graben-zone materials, or rotated bedding, the shear was more likely a BPS with a much lower risk of future failure. The plaintiff's expert could not even agree that a BPS was a reasonable hypothesis. It was decided that the only way to positively determine if a landslide was present was to search for a diagnostic pull-apart zone or "graben" that should be present at the head of a landslide, or lacking such a feature, to search for the steeply dipping upper terminus of the slip surface.

An approximately 70-m long exploratory trench was excavated from a point beyond the southern limits of possible landsliding, as determined from aerial photographic interpretation, to a point well past the midpoint of what was interpreted as the possible landslide. The results of the trenching revealed that bedding continued unbroken across the feature interpreted as the head of the landslide. On the basis of this evidence, it was concluded the slip surfaces were BPS and there was, therefore, no evidence of paleolandsliding at the site.

This example illustrates why BPS may be easily misidentified as landslide slip surfaces, particularly if subtle geomorphic evidence of landsliding is present, and that extensive investigative techniques are necessary to differentiate between the two. Making a correct interpretation as to whether a slip surface represents a basal rupture surface of a landslide, or a BPS, is significant because even though the shear strength along both types of shear surfaces have been shown by testing to be similar, the results of stability analyses for landslides and natural slopes underlain by BPS are significantly different.

SIGNIFICANCE OF BPS

BPS are important to engineering geologists and geotechnical engineers for several reasons. First, knowledge of where and how BPS occur allows an understanding of why landslides have occurred in the past, as well as allowing prediction of where large landslides are likely to occur in the future. Secondly, their misinterpretation as landslide slip surfaces has obvious effects on the accuracy of engineering geologic and geotechnical investigations. For example, the results of a stability analysis for two interpretations of geologic conditions are compared on Figure 18. Case 1 assumes that a translational landslide is present in gently dipping sediments with a slip surface extending along line ABC. Case 2 represents a gently dipping BPS at an elevation of approximately 25 ft (Line ABD). (Note that a complete analysis of the slope would also include a search for additional critical slip surfaces to the left of Point C). A stability analysis for Case 1 utilizing Spencer's method and SLOPE/W (Ver. 3) results in a factor-of-safety of 1.24 for the landslide condition. Case 2, representing a condition where the BPS is present (line ABD), but not the slide surface between points B and C, yields a factor-of-safety of 1.87 for the same surficial slope geometry. The significant structural difference between Cases 1 and 2 is the presence of the high-angle landslide slip surface present between Points B and C in Case 1.

CONCLUSIONS

The occurrence of BPS is ubiquitous in sequences of horizontally bedded claystones and clay-rich shales throughout the world. Formation of BPS is one of the principal preparatory mechanisms required for the occurrence of large translational landslides that would otherwise be precluded by high peak shear strengths of soils making up the slide mass. The main mechanisms of BPS formation are progressive failure of overconsolidated

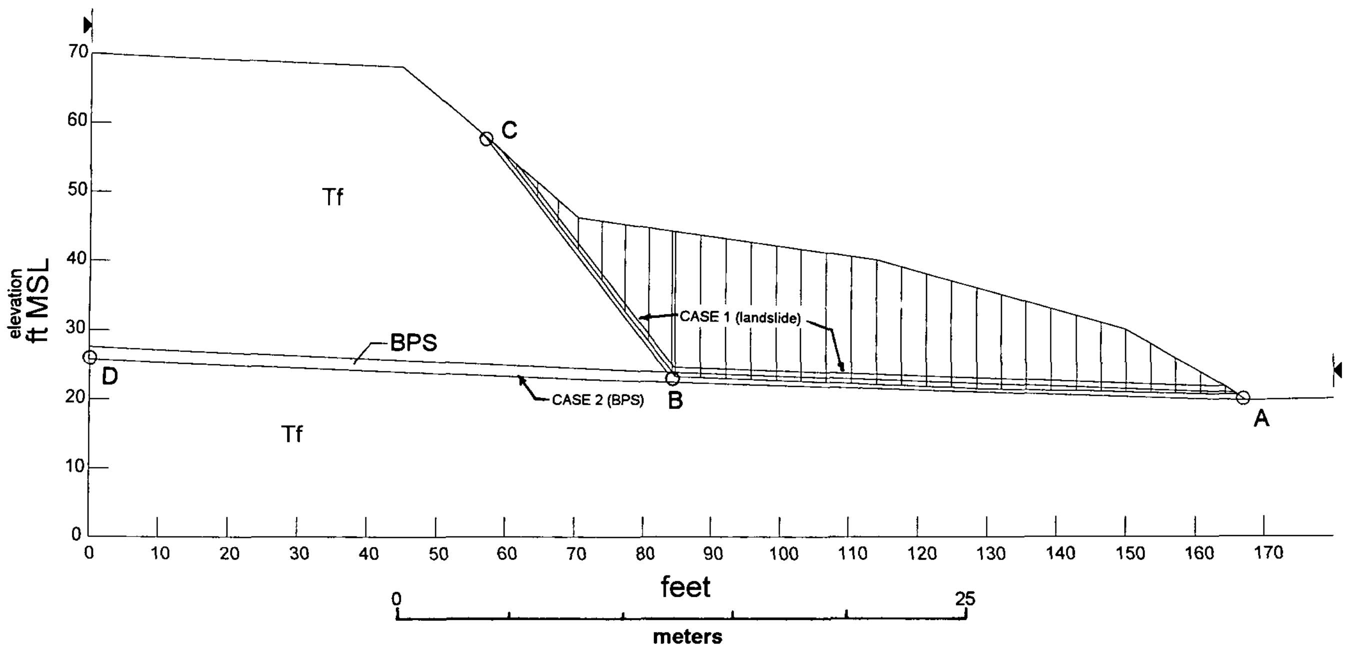

Figure 18. Analysis of factor-of-safety for typical translational landslide (Case 1) and BPS (Case 2) on natural slope. Slope has topographic bench at elevation 50 ft similar to a bench that might result from translational landsliding. Factor-of-safety = 1.24 for Case 1 and assumes an existing paleolandslide and residual shear strength along line ABC. Case 2 assumes a BPS is present with no paleolandslide: F.S. = 1.87; residual shear strength utilized along line ABD, peak shear strength along line BC.

claystone, elastic rebound of valley rims, differential consolidation, and gravitational creep.

Two primary mechanisms are probably responsible for most BPS observed in the Tertiary sediments of San Diego County. The first is progressive failure of overconsolidated claystone as described by Skempton (1970) and Bjerrum (1967). This process is dominant in thick sequences of fissured claystones. The second mechanism is valleyward squeezing of weak ductile rocks overlain by, or interbedded with, more rigid rocks (gravitational creep). This process is dominant where thin claystone beds, such as bentonite, occur in otherwise homogenous sandstone sequences. Both processes result in tensional fracturing and valleyward movements of the more rigid overlying rocks. Movement associated with gravitational creep in the San Diego area has not been of sufficient magnitude to result in surface fracturing or the formation of surface depressions.

It is important for engineering geologists to be able to recognize BPS in excavations and to have an understanding of the various mechanisms responsible for their formation and relationship to translational landsliding. Knowledge of where and how BPS occur allows an understanding of why landslides have occurred in the past, as well as allowing prediction of where large landslides are likely to occur in the future. BPS also represent zones of weakness along which cut and fill slope failures may occur. Incorrect identification of a BPS as a landslide slip surface is a significant error in geologic interpretation that may result in overly conservative project design.

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REFERENCES

Barton, M. E.; Coles, B. J.; and Tiller, G. R., 1983, A statistical study of the cliff top slumps in part of the Christchurch Bay coastal cliffs: *Earth Surface Processes and Landforms*, Vol. 8, pp. 409–422.

BERRY, R., 1995, *Unpublished X-ray Analysis of Four Clay Samples:* San Diego State University, San Diego, CA.

BERRY, R., 1992, written communication, Department of Geological Sciences, San Diego State University, San Diego, CA 92182.

BILLINGS, M. P., 1960, *Structural Geology,* 2nd Edition: Prentice-Hall, NJ, 514 p.

BJERRUM, L., 1967, Progressive failure in slopes in over-consolidated plastic clay and clay shales: *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers,* Vol. 93, No. SM5, pp. 3–49.

CLEVELAND, G. B., 1960, *Geology of the Otay Bentonite Deposit, San Diego County, California,* Special Report 64: California Division of Mines and Geology, San Francisco, CA, 16 p.

DAVACHI, M. M.; SINCLAIR, B. J.; HARTMAIER, H. H.; BAGGOTT, B. L.; AND PETERS, J. E., 1991, Determination of the Oldman River dam foundation shear strength: *Canadian Geotechnical Journal,* Vol. 28, pp. 698–707.

DUNCAN, JAMES M. AND DUNLOP, PETER, 1969, Slopes in stiff-fissured clays and shales: *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers,* Vol. 95, No. SM2.

FELL, R.; SULLIVAN, T. D.; AND MACGREGOR, J. P., 1988, The influence of bedding plane shears on slope instability in sedimentary rocks, in *Proceedings of the 5th International Symposium on Landslides,* Lausanne, Switzerland, pp. 129–134.

KENNEDY, M. P, 1975, *Geology of the San Diego Metropolitan Area, California,* Bulletin 200: California Division of Mines and Geology, Sacramento, CA, 56 p.

KENNEDY, M. P, 1977, *Recency and Character of Faulting Along the Elsinore Fault Zone in Southern Riverside County, California,* Special Report 131: California Division of Mines and Geology, Sacramento, CA, 12 p.

MATHESON, D. S. AND THOMSON, S., 1973, Geologic implications of valley rebound: *Canadian Journal of Earth Sciences,* Vol. 10, No. 5, pp. 961–978.

PALLADINO, D. J. AND PECK, R. B., 1972, Slope failures in an overconsolidated clay, Seattle, Washington: *Geotechnique,* Vol. 22, No. 4, pp. 563–595.

PASUTO, A. AND SOLDATI M., 1996, Lateral spreading. In Dikau R.; Brunsden, D.; Schrott, L.; and Ibsen, M-L. (Editors), *Landslide Recognition: Identification, Movement and Causes:* John Wiley & Sons Ltd., Chichester, England, pp. 122–148.

PETERSON, R., 1958, Rebound in the Bearpaw Shale, western Canada: *Bulletin of the Geological Society of America,* Vol. 69, pp. 1113–1124.

PINCKNEY, C. J.; STREIFF, D.; AND ARTIM, E. R., 1979, The influence of bedding-plane faults in sedimentary formations on landslide occurrence, western San Diego County, California: *Bulletin of the Association of Engineering Geologists,* Vol.VXI, No. 2, pp. 289–300.

RADBRUCH-HALL, D. H., 1978, Gravitational creep of rock masses on slopes. In Voight, Barry (Editor), *Rockslides and Avalanches,* 1: Elsevier Scientific, Amsterdam, pp. 607–657.

SKEMPTON, A. W., 1964, Long-term stability of clay slopes: *Geotechnique,* Vol. XIV, No. 2, pp. 77–101.

SKEMPTON, A. W., 1970, First time slides in over-consolidated clays: *Geotechnique,* Vol. XX, No. 3, pp. 320–324.

SKEMPTON, A. W., 1985, Residual strength of clays in landslides, folded strata and the laboratory: *Geotechnique,* Vol. XXXV, No. 1, pp. 3–18.

SKEMPTON, A. W. and Hutchinson, J. N., 1969, Stability of natural slopes, in *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering,* Mexico, pp. 291–340.

THOMSON, S. AND MORGENSTERN, N. R., 1979, Landslides in argillaceous rock, prairie provinces, Canada. In Voight, Barry (Editor), *Rockslides and Avalanches,* 2: Elsevier Scientific, Amsterdam, pp. 515–540.

WALSH, S. L. AND DEMERE, T. A., 1991, Age and stratigraphy of the Sweetwater and Otay Formations, San Diego County, California. In Abbott, P. and May, J. (Editors), *Eocene Geologic History, San Diego Region:* Pacific Section of the Society of Economic Paleontologists and Mineralogists, Los Angeles, CA, pp. 131–148.