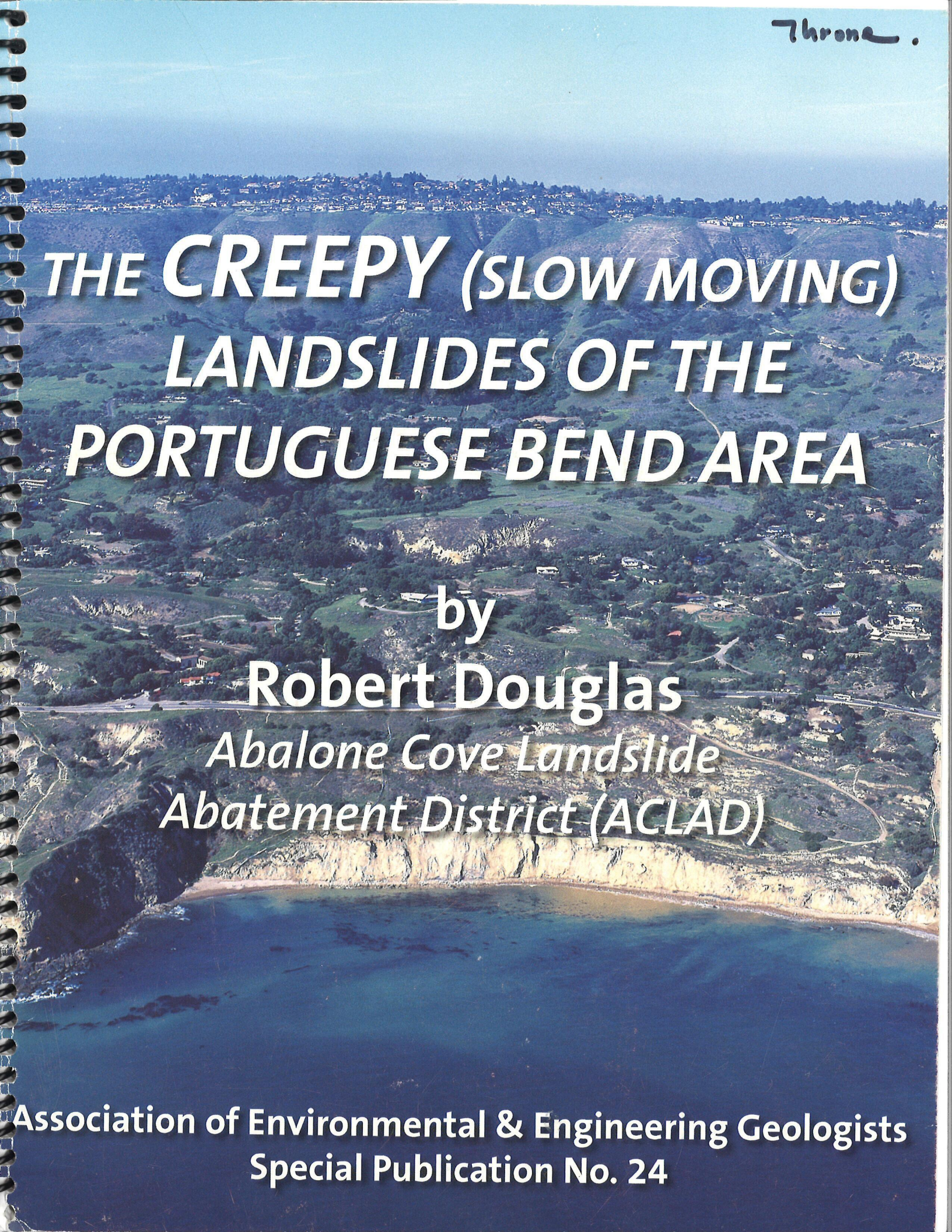
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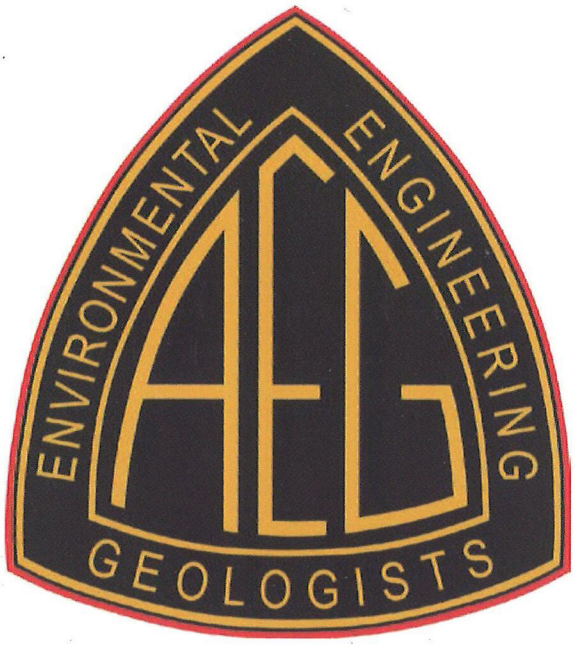
THE CREEPY (SLOW MOVING) LANDSLIDES OF THE PORTUGUESE BEND AREA

by

Robert Douglas
Abalone Cove Landslide Abatement District (ACLAD)

Association of Environmental & Engineering Geologists
Special Publication No. 24

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Aerial view of the Portuguese Bend-Abalone Cove area, Los Angeles County, California.
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To: Michael Thorne
with best regards
Bob Douglas
Feb 2014

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Robert Douglas[1]

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Prologue

From time to time, the City of Rancho Palos Verdes has convened workshops on the landslides in the city. At these presentations, I found that many in the audience were genuinely interested in learning about the Portuguese Bend landslides but the only source of information available was what they read in the local newspapers. Unfortunately, newspapers accounts are brief, present little in the way of background information and sometimes mangled the technical facts. Many often knew something about the landslides but what they knew was incomplete and/or the facts often were not quite correct. I found this disquieting because the landslides are and will continue to be important in the lives of Peninsula residents. There is a volume of information about the landslides in Portuguese Bend area but most of it is contained in unpublished technical reports and published scientific articles written by geo-experts for other experts. In response to people asking me if there was an article or book that offered a generally non-technical but comprehensive discussion of the Portuguese Bend landslides, I had to tell them that there wasn't one. So, finally, I decided to write this account. It is intended to be something that can be understood by a non-expert but still useful to the expert. It is presented in a narrative style that uses minimal geological vocabulary and technical citations.

Chapter 1—Introduction

Landslides located in the greater Portuguese Bend area move slowly and continuously and have done so for long periods of time. I call them "creepy landslides" and while "The Creepy Landslides of Portuguese Bend" may sound like the title of a horror movie, it describes a real phenomenon that exists in nature and confronts people and institutions.

Slow-moving landslides (rates of movement measured in hundredths of a foot to several feet per year) are a widespread type of mass movement that can cause major damage to roads, houses and other infrastructure (e.g. pipelines). Under the right conditions, typically an increase in pore-water pressure at depth due to a build-up of ground water, slow-moving landslides can be transformed into fast-moving, dramatic, and dangerous slope failures.

The slow-moving landslides common to the southern flank of the Palos Verdes Peninsula include the Abalone Cove, Portuguese Bend, Flying Triangle, Klondike Canyon and most of the Ancient Altamira landslides. The term also can be applied to slope failures elsewhere on the Peninsula but none of them are as well known nor as well studied as the ones in the Portuguese Bend area. Understanding these slope failures, what causes them, predicting when and how much they will move and, most of all, trying to mitigate them has been a serious challenge for geoscientists and engineers. For the City of Rancho Palos Verdes in which the landslides are located, they are a geological nightmare inherited from the County of Los Angeles when the city was formed. The damage to public works, especially roads, caused by the landslides requires constant maintenance and is a major drain on city coffers. Damages caused by the landslides to houses and property, real and imagined, have spawned numerous lawsuits, the most recent of which threatened to bankrupt the city. And there will be more in the future.

Some years back (1997) when I became a director of the Abalone Cove Landslide Abatement District (ACLAD), I imagined the landslides in the Portuguese Bend area were all well understood. After all, they have been investigated for more than 70 years by numerous students, experts, companies and agencies, including the drilling of countless boreholes and trenches and issuing innumerable reports. Most of the reports focus on specific problems within the landslides and, not surprisingly, on efforts to mitigate the landslides. Generally the emphasis has been on how to stop the movement so that the land could be used for development. Fewer reports focus on understanding and evaluating the underlying causes (e.g. Vonder Linden, 1972; Proffer, 1992; Ehlig, 1982; 1992). Much of what we know about the landslides is from the many technical reports and published papers by Perry Ehlig (1980-1999), a respected geoscientist who devoted a professional lifetime to investigating the landslides and their remediation, especially the Portuguese Bend landslide. I'm always amazed at how much he knew about the landslides and the mechanics that drives them. Since the passing of Ehlig, research on the landslides has focused more on trying to understand the hydrogeology (DiFilippo, 2004; Hill, 2000; Hill, et al., 2007) since ground water is the activator of creepy landslides.

Chapter 2—Landslides of the Area

A portion of the landslide map prepared by the California Geological Survey (2007) is shown in Figure 1. I have slightly modified the map labels to coincide with the landslide terminology used in this paper. The creepy landslides are labeled as well as some of the numerous other smaller features. The South Shores landslide, like the Ancient Altamira landslide is another major landslide complex that involves slides and slumps that have developed over a long period of time. This map provides a reasonable inventory of the landslides on the south flank of the peninsula as of the early 2000s. Missing are a number of small cliff failures such as the ones west of the Abalone Cove landslide. The map indicates whether the landslide is active, inactive or "dormant". The latter category is for failures that were moving in the historic past but are not now moving. These classifications are from the California Geological Survey and in the context of creepy landslides; the distinction between inactive, active, and dormant is probably less than suggested by the labels.

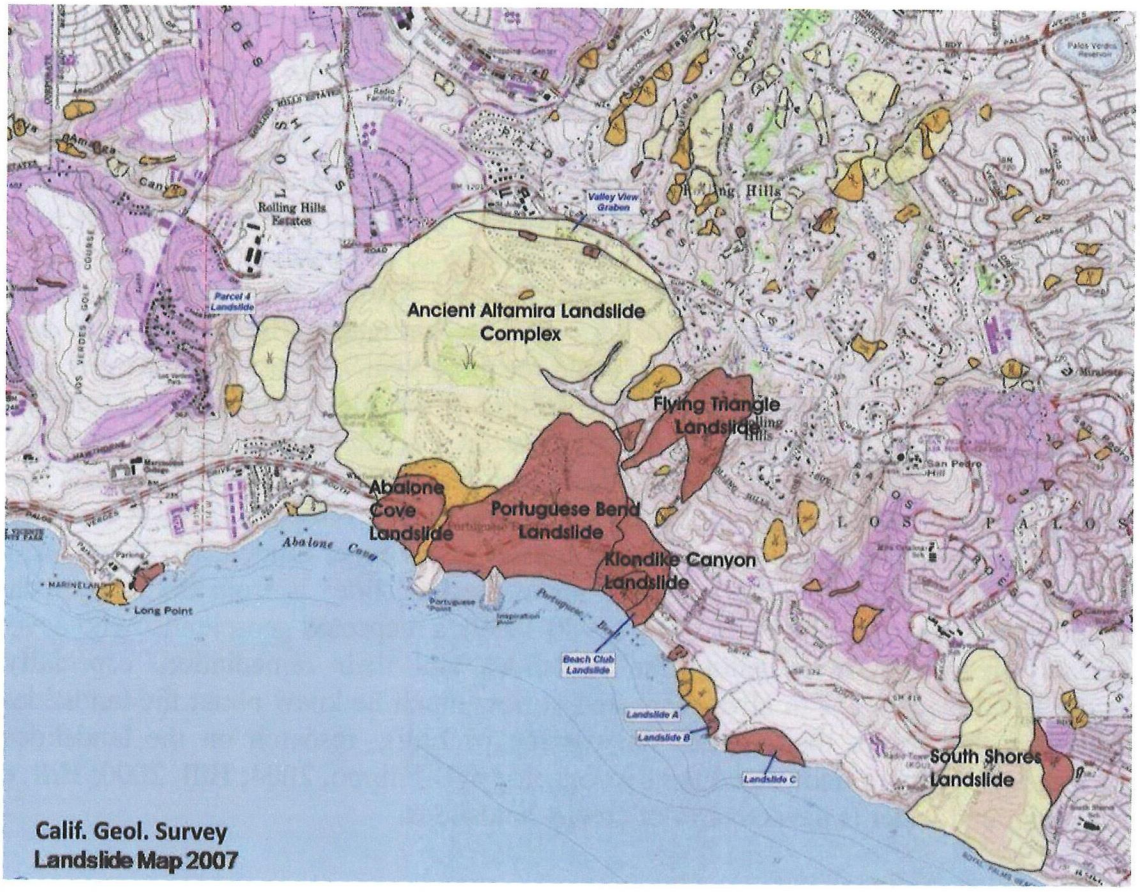


Figure 1. Landslide map of a portion of the south flank of the Palos Verdes Peninsula prepared by the California Geological Survey (2007). The major and some minor landslides are identified. Light yellow indicates that the landslide is inactive, red is active and orange is dormant.

For comparison examine Figure 2, a portion of the first geologic map of the area completed in the late 1920s and 1930s before development covered much of the area with houses, vegetation

and streets. Early geologists readily recognized that there were many landslides on the peninsula and that the large bowl-shaped area with the hummocky, rolling topography located above Abalone Cove and Portuguese Bend was an ancient landslide complex. They also identified a number of smaller failures, including what is now referred to as the Amphitheater landslide. Unfortunately, little attention was paid to their findings when housing development started in the Portuguese Bend area in the 1940s and 1950s. In their map, there is a large, unlabeled landslide that I call the Ancient Altamira landslide complex. This is to avoid confusion with the Portuguese Bend landslide, a reactivated portion of the ancient landslide. The name recognizes the fact that this ancient mass movement is centered on Altamira Canyon. The Portuguese Bend, Abalone Cove and Klondike landslides are not shown on Woodring's map because they did not exist as active features when the map was published in 1946. Reactivation of the coastal portions of the Ancient Altamira landslide occurred with development of the area and human activities played a significant role in the renewed movement.

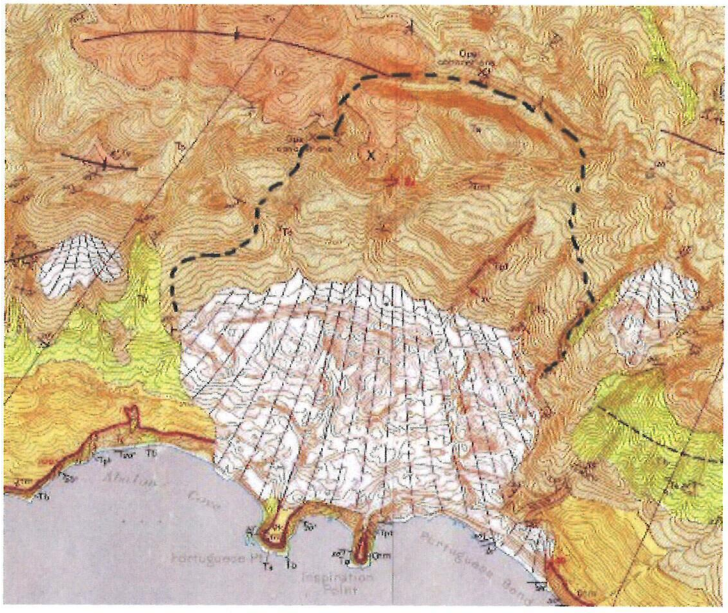


Figure 2. A portion of the geologic map from Woodring, et al., 1946, illustrating the Ancient Altamira landslide complex (uncolored area in the center) shown in Figure 1) before the reactivation of the Portuguese Bend, Abalone Cove and Klondike Canyon landslides. The smaller landslides are the predecessor of the Flying Triangle (right side) and the Amphitheater landslide (left side). The green areas are exposures of volcanic rocks. Today, the area covered by the Ancient Altamira landslide complex (dashed line) is recognized as much larger than that mapped by Woodring and colleagues.

Some geologic studies of the past 50 years have increased the size of the ancient landslide and, as shown in the 2007 map extend the northern edge to include the depression along Crest Road known as the Valley View Graben. This places the area around Del Cerro Park within the Ancient Altamira landslide. More about this is discussed in a later section.

Geologists describe the major landslides in the Portuguese Bend area as "translational rockslides", meaning that they originally were a block or slab of intact rock that moved down slope parallel to the dip of the beds. Over time, the blocks tend to break up. Another common feature of these landslides is that they are "slow, continuously-moving" landslides with typical rates of movement measured in hundredths of a foot (0.01 ft) up to a few tens of feet per year.

While the velocities vary with time, largely as a function of rainfall, they never seem to come to a complete halt. These landslides belong to a widespread type of active mass movement that can cause severe damage to houses and infrastructure and are precursors of sudden catastrophic slope failures. The pressure of the water trapped in the tiny openings in the rocks, called pore-water pressure, is commonly regarded as the most important factor among a number of factors which control slow-moving landslides. Thus, ground water is one of the major concerns when considering creepy landslides.

An often-asked question is, "Why are landslides so common on the south flank of the Palos Verdes Peninsula?" There are many factors which can cause or contribute to what geologists call slope failures (i.e., landslides) but in Palos Verdes there are four factors which are largely responsible for the landslides in the area. The first two factors have to do with the geology of the Altamira Shale: 1) the sedimentary beds in the Shale dip towards the ocean at an angle of 20° to 25° (Figure 3); and 2) the lower Altamira Shale contains numerous beds of volcanic ash and bentonitic clay which form impermeable layers or zones and are structurally weak (more details about the geology later). The third factor, 3) is the wave erosion of the sea cliff which removes lateral support to the dipping beds, and fourth, 4) is the ground water that controls the pore-water pressure in the subsurface. Of these factors, the first three are essentially constant; only the fourth, ground water, varies significantly in time, mostly as a function of annual rainfall patterns. These four factors can explain the majority of landslides on the Palos Verdes Peninsula.

Before getting to the discussion of the major landslides the reader needs to be acquainted with four topics: the geology of the south flank of the peninsula, including the nature of the rocks and their composition; a little about the geological structures beneath the surface; the origins and movement of ground water; and the features called "marine terraces".

Figure 4 is an illustration of a cross-section of a landslide to establish some terminology about landslides.



Figure 3. (left) Sedimentary beds of the Altamira Shale seen here on Portuguese Point. The beds dip towards the ocean at an angle of 20° to 25° and only the internal friction between beds keep them from sliding into the ocean. The beds are resting on a basalt sill which makes up the platform at the base of the sea cliff. (right) A typical sea cliff undergoing erosion along the Palos Verdes Peninsula; seen here is Sacred Cove.

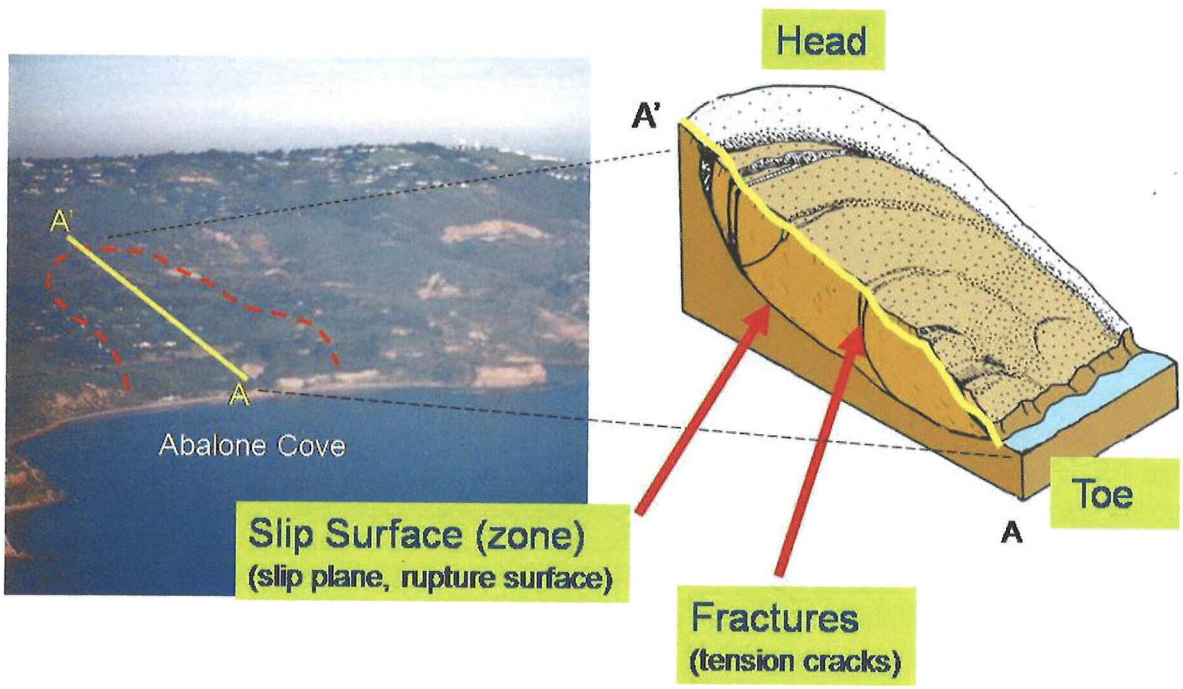


Figure 4. Illustration of a cross-section of the Abalone Cove landslide with the basic features of a landslide: Head, where movement begins; often marked by a small scarp (cliff), and Toe, which is at the terminus. All of the Portuguese Bend area landslides terminate at the shoreline, near mean low water. Important features within the landslides are the Fracture zones that often extend to the slip zone. The Slip zone is typically within or just above bentonitic clay layers.

Chapter 3—Geology

Sedimentary Rocks

The south flank of the Palos Verdes peninsula is underlain by south dipping, thinly bedded sedimentary rocks called the Altamira Shale and by intrusive volcanic rocks (basalt sills). In older reports these rocks are referred to as the Monterey Formation or the Altamira Member of that formation. The sedimentary rocks on the Peninsula were described in detail in U.S. Geological Survey Professional Paper 207 (Woodring, Bramlette and Kew, 1946), and this volume remains a basic source of information on the geology of the peninsula. Conrad and Ehlig (1983) updated the lithology studies with detail investigations of the exposures along the Crenshaw Extension and elsewhere and subdivided the rocks into three members (Figure 5): Malaga Mudstone, Valmonte Diatomite and the Altamira Shale. The two upper members are composed largely of biogenic materials (diatomites, diatom-rich shale, and phosphate-rich mudstones) mixed with clay and silt and have been removed by erosion from the southern flank of the peninsula. The Altamira Shale is further subdivided into three subunits: shale rich in phosphate nodules (Phosphatic Lithofacies), beds of porcelaneous shale and chert (Cherty Lithofacies) (Figure 6) and the beds rich in volcanic ash (Tuffaceous Lithofacies). In the Ancient Altamira landslide area, the exposed Altamira Shale (Tuffaceous Lithofacies) (Figure 7) is predominately siliceous and tuffaceous shale (meaning rich in volcanic debris) interbedded with thin beds of porcelaneous (siliceous) shale and chert, silty sandstone, and intrusive basalt sills.

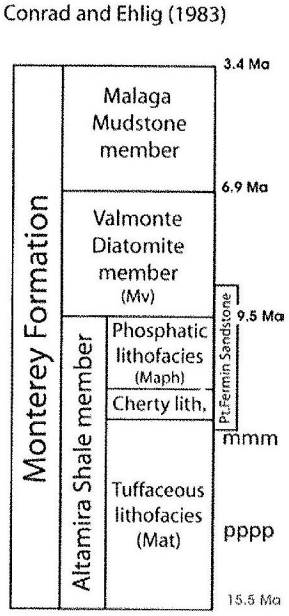


Figure 5. A schematic diagram of the sedimentary rocks that are found in the Portuguese Bend landslide area. There are two distinct units composed of tuff (volcanic ash) and bentonite present in the Altamira Shale; the upper is the Miraleste Tuff (mmm) and the lower the Portuguese Tuff (pppp). The rupture surface (slip zone) of the landslides is often within or above the upper surface of the Portuguese Tuff. The Malaga Mudstone and Valmonte Diatomite are not present in the Portuguese Bend-Abalone Cove area as they have been removed by erosion. (Modified from Conrad and Ehlig, 1983.)

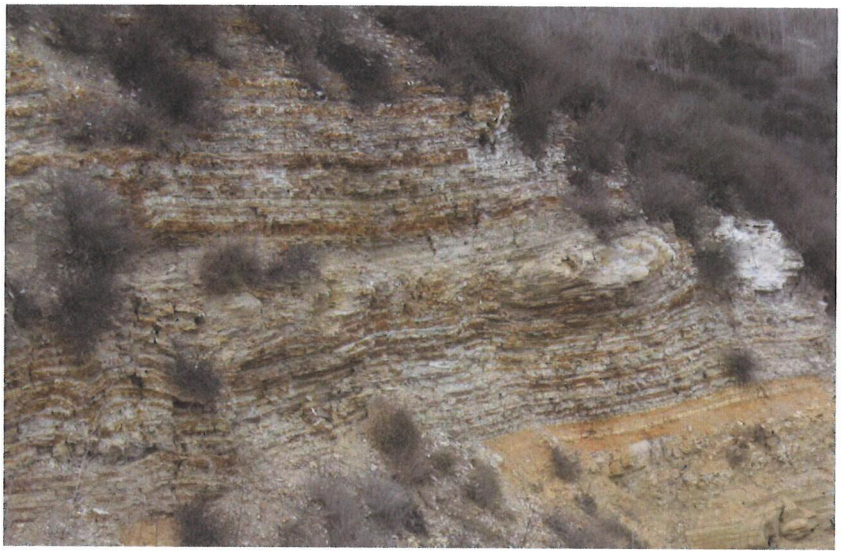


Figure 6. Cherty Lithofacies exposed along the Crenshaw Extension. The rocks are thinly-bedded (1-2 inches thick) chert and porcelaneous shale and often contain dolomite concretions (white boulders to right). The wavy bedding and reddish-brown stain is typical and makes the rocks easy to spot.



Figure 7. Typical outcrop of weathered tuffaceous beds of the lower Altamira Shale. The thick, blocky beds at the notebook are thinly bedded porcelaneous and cherty shale.

Typically the tuffaceous shale contains thin interbeds of clay and bentonite that form impermeable horizons called aquitards or aquicludes that prevent the flow of ground water. Within these zones a build-up of pore-water pressure can occur. These rocks are not strong and create zones that rupture or fail under stress (shear zones). Both of these are important factors in the development of landslides.

Volcanic Rocks and Bentonite

The area contains rocks of volcanic origin that were both intruded into the sediments (intrusive) and extruded on to the seafloor (extrusive). Very hot (>800°C) fluid, basaltic lava intruded the sediments of the seafloor shortly after they were deposited or as they were being deposited, and formed sills (intrusions that parallel the bedding) that are found throughout the area. In many places, the hot hydrothermal fluids that accompanied the intrusions geochemically altered the sediments and basalt. In some cases the sediments were turned into light colored clays and in close proximity to the basalts, very fine grained, dark colored "cherts". At the base of the sills, where the hot lava came into contact with the existing sediments there is often a dark reddish brown "baked" zone. Thick intrusive basalt sills are exposed in Inspiration and Portuguese Points, around Point Vicente (for example, volcanic rocks are exposed along Palos Verdes Drive south and the intertidal area beneath the lighthouse) and in the former Livingston quarry. Several basalt sills are present in the subsurface and two major ones can be traced under most of the landslide area.

Generally basalts found at the surface have undergone some degree of weathering and range from very weathered olive-green colored basaltic soil to fresh dark colored (black) basalt. The basalts are usually fractured and where ground water penetrates the cracks, it turns a reddish-brown color from oxidization of the iron-rich minerals in the basalt (Figure 8).

Pillow basalt is the name given to basalts with a distinctive bulbous form that results when lava is extruded on or just under the sea floor. Pillow basalts are exposed in the 1956 landslide located just west of Paint Brush Canyon and north of the Crenshaw extension (Figure 9), and also in Portuguese Canyon, the old Livingston quarry and several other places. They indicate that extensive sea floor volcanism occurred in the area when these rocks were deposited and significantly influenced the composition and character of the Altamira Shale.

The lower Altamira shale contains from 5-10 percent volcanic ash (called tuff) ranging up to beds that are nearly pure ash. The ash material was derived from volcanic eruptions (roughly 9 to 15.5 million years ago) that occurred at the surface and underwater. The tuff (ash) beds include both very fine-grained pyroclastic (airborne) particles and lapilli (small shards of lava thrown through the air while still molten) and ash that was either generated by volcanic explosions on the seafloor or was transported in the ocean by bottom currents. The hot, molten basalt intrusions caused a hummocky seafloor with mounds and depressions. As the ash settled through the water to the seafloor, bottom currents tended to swept it in to the low areas and as a result the ash beds vary in thickness and continuity. The Portuguese Tuff, one of the two main volcanic-ash-rich/bentonite deposits in the Altamira Shale, typically varies from 20 to over 60 ft in thickness. However, a borehole located outside the Portuguese Bend landslide cored more than 80 ft of Portuguese tuff. The ash has a high silica content (some beds are nearly pure silica) and is unstable over geologic time, especially when it comes into contact with ground water and heat. As the ash breaks down it turns into a special type of montmorillonite clay called bentonite. When fresh, the bentonite clay is blue, blue-grey, blue-green, reddish-orange, white or yellow with a distinctive waxy texture (Figures 10, 11). Its distinct properties are a major reason for the landslides in the area.



Figure 8. Typical exposure of weathered basalt ranging from total breakdown (olive green, upper right), to fresh (dark material) with reddish-brown (iron oxides) partially decayed basalt along fractures.



Figure 9. Pillow basalts exposed in the small 1956 landslide located west of Paint Brush Canyon and north of the Crenshaw extension (see Figure 36). The distinctive "pillow" form indicates that the basalts were in placed at the surface or just beneath the seafloor.



Figure 10. Typical exposure of weathered volcanic tuff and bentonite which turns to a light grey color with yellow-brown streaks. This outcrop was exhumed by erosion at the end of the culvert leaving Portuguese Canyon.

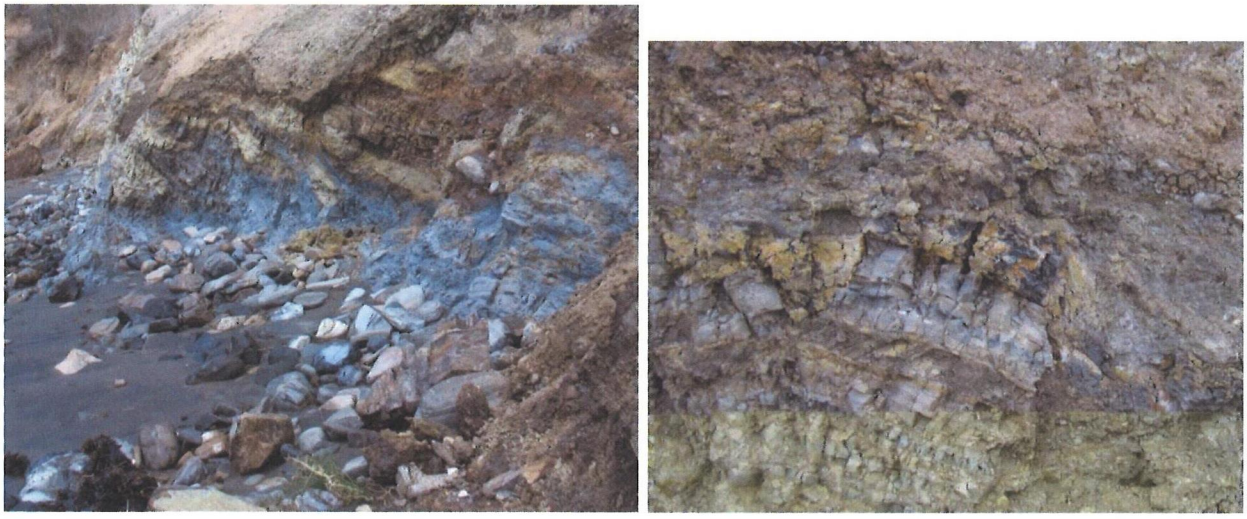


Figure 11. Outcrops of unweathered bentonite exposed in the sea cliff in Inspiration Cove at the toe of the Portuguese Bend landslide. Bentonite varies in color, depending upon its geochemistry from grey to green to blue-grey (most common), blue-green, white, orange, reddish brown and red.

Bentonite clay has a crystal structure in which the molecules are arranged in sheets held together by positively charged ions of sodium or calcium. The clay absorbs water molecules between the sheets, causing it to expand when moist and shrink when it loses water. This is the reason for the "expansive" (adobe) soils found in the area. Bentonite clay is weak, with little internal cohesion, and under pressure (stress) becomes plastic and flows. Experiments have shown that when bentonite is repeatedly stressed, it becomes even weaker and will undergo plastic flow on slopes of only a few degrees. When bentonite is exposed to ground water it swells and forms impermeable layers (called aquitards) that prevent or impede the upward or downward flow of ground water. As ground water builds up under bentonite layers, it increases the pressure of the water trapped in the pores and cracks in the rock and when the water is confined or trapped, the pore-water pressure can increase to the point where it approaches the weight (pressure) of the overburden. In such cases, the overlying rocks are actually being lifted, reducing the friction along the rupture (slip) surface. The result is slope failure and movement.

However, the numerous small cracks or fissures in the siliceous and tuffaceous shale allow some ground water flow, albeit slowly, and the failure condition tends to occur only when there is a marked increase in the water table. In the Portuguese Bend landslides, it appears that pore-water pressure is just enough to allow for plastic flow in the bentonites which results in a steady, slow movement (creep) of inches to feet per year (mm/d). In years of high rainfall, the additional infiltration of storm water to the ground water, largely through the bottom of the major canyons and surface fractures, causes pore-water pressure to increase and landslide movement to accelerate.

In many places throughout the area the landslide slip surface is contained in thin bentonite beds interbedded with tuffaceous shale located above the top of the Portuguese Tuff. But this is not the universal case. In other locations, e.g. near the shore line, the slip zone is at the base of the Portuguese Tuff. In the Abalone Cove landslide the slip zone is typically above the Portuguese Tuff but there is more than one slip zone.

Geological Faults and Folds

Several folds and faults occur in the landslide area but none are exposed at the surface. The largest are antiform (anticline) folds, meaning the layered rocks have been folded upward to form an arch. In nearly all cases they are asymmetrical, with one side steeper than the other. The folds are important because they have affected the direction of movement of the landslides.

Ignoring some small features, four or five folds are located on land (Figure 12) and at least two are located offshore (Figure 13) along with the only significant fault in the area). Little is known about this fault but it appears to be inactive. All of the folds are similar; they trend roughly E-W, have steeper dipping south limbs and plunge towards the west. These folds are fairly subtle, not visible at the surface and require good, closely spaced borehole data with information on the dip of the beds to delineate in the subsurface. All of these features are old and related to the geological events which uplifted and folded the entire peninsula rather than movement in the landslides.

The crest of the anticline located at the head of the Portuguese Bend landslide parallels the Crenshaw Extension and following heavy rains which erode the dirt road, beds which form the south limb are exposed in the road way (Figure 14). This anticline can be traced westward to Altamira Canyon and underlies the large hill called "Peacock Flats" in the subsurface. This anticline is an important feature that retards or blocks the seaward movement of the ancient landslide. A second, but more subtle anticline is located in the subsurface, north of the Abalone Cove landslide and extends westward beyond the Ancient Altamira landslide. In addition there are many small deformation features, folds and slumps that formed during deposition of the sediments but are older than the landslide movement. One of the more prominent is exposed in the large cliff located just west of Paint Brush Canyon (Figures 15, 16).

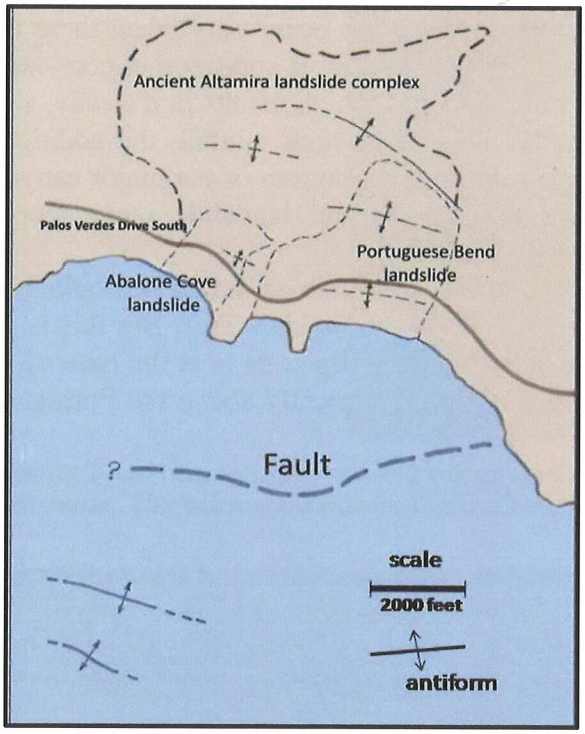


Figure 12. Portuguese Bend Area showing the location of an offshore fault and folds based on marine geophysical studies by Dill GeoMarine (1995) and important onshore folds (antiforms) and flexures found in the subsurface. The offshore folds are located at the edge of the continental shelf. The onshore folds are based on many sources, not all of whom agree on the exact location of the folds except for the anticline at the head of the Portuguese Bend landslide.

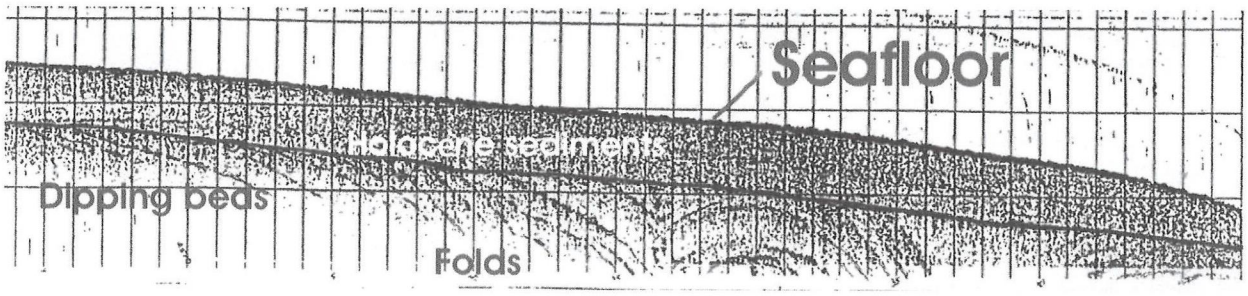


Figure 13. Structure of the continental shelf off Portuguese Point showing the seafloor, the layer of modern (Holocene) sediments deposited since the rise in sea level (ca. 14,000 years ago) that covers the eroded surface of the south dipping beds of the Altamira Shale. Towards the edge of the shelf are folds in the Altamira shale (shown in Figure 12), similar to the ones found in the landslide area. The folds are old and not related to the landslide movement No landslide-related features have been found on the shelf. (Figure based on a seismic study by Dill GeoMarine (1995).



Figure 14. Beds forming the south limb of the anticline exposed along the Crenshaw Extension after a major rain storm in 2005. Beds are dipping to the south. The light grey material (left) is volcanic tuff and bentonite; the brown beds are silty tuffaceous sandstone. It is the same lithology found beneath the slip zone in the Ancient Altamira landslide exposed in Altamira Canyon (see Figure 26).

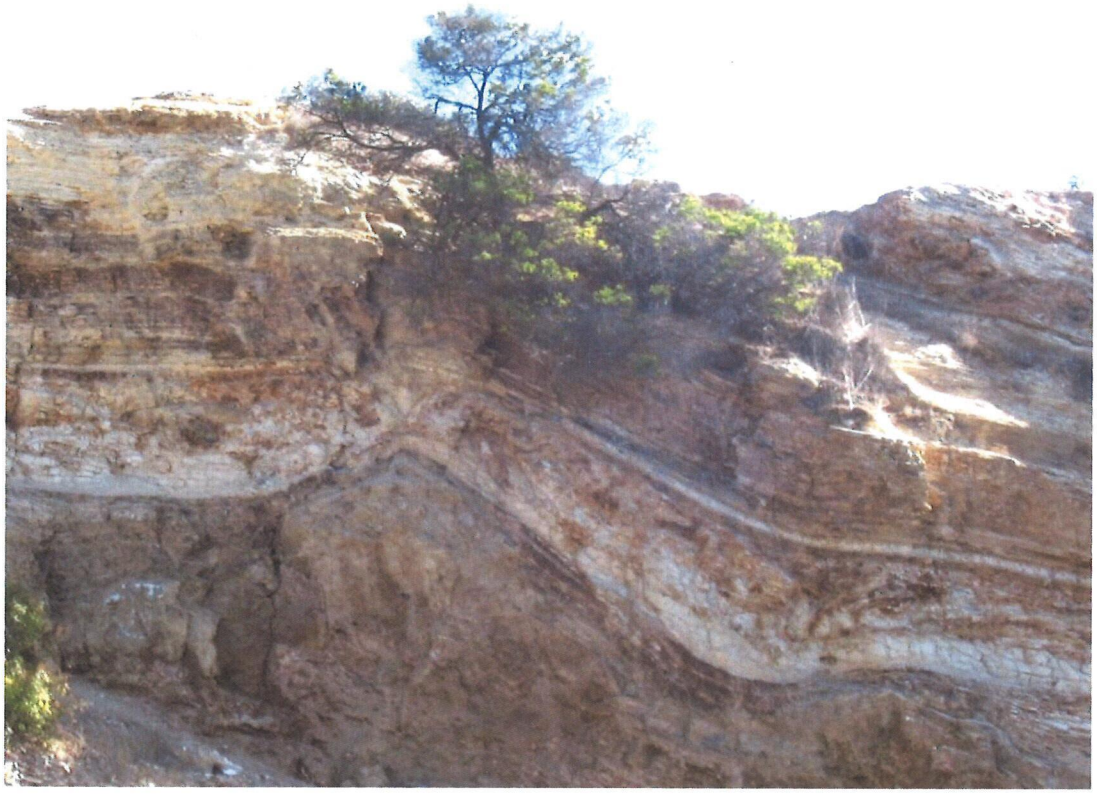


Figure 15. Slump fold in a thick bed (20-25 ft thick) of tuff (volcanic ash) (white bed in photo) and debris created by disruption of the seafloor by an intruding basalt sill (dark layer under the tuff). The hot intruding basalt created elevations (small hills) on the seafloor that disrupted the in place sediments and caused them to slide down slope. In the tuff can be seen basalt blocks and sediment debris that were displaced when the tuff bed slumped.



Figure 16. Detail of another tuff bed (approximately 20 ft thick) located just above the one in Figure 15, with large displaced blocks of Altamira bedrock, basalt and tuff. The reddish-brown material has been completely disrupted and mixed upwards into the sliding tuff.

Borehole data reveal two small flexures in the bedrock under the Portuguese Bend landslide that trend basically west to east. These flexures cause undulations in the surface of the slip zone (see Figure 40) and as the landslide moves over them, the movement (tension) creates large vertical fractures in the body of the landslide and impedes movement. The northern flexure is the boundary between the eastern and inland subslides.

While there are not many large geological structures (folds and faults) in the landslides, the ones in the upslope areas are important as they affected the direction and movement of the ancient Altamira landslide complex. In general, deformation in the landslides increases towards the beach and within the toe area most beds are highly fractured and contorted (Figure 17). The landslide masses probably begin as large, intact blocks of rock, with recognizable internal stratigraphy (layered rocks) but in the journey to the beach, they are reduced to a chaotic jumble of rocks and debris with little internal structure remaining. Because of the extensive deformation in the lower region of the Portuguese Bend landslide, it is probably better thought of as an earth flow rather than a landslide.



Figure 17. Highly folded, fractured and contorted beds of tuffaceous shale and dolostone (light colored) in the lower part of the Portuguese Bend landslide exposed in the sea cliff in Sacred Cove (2007). Such deformation is typical of the toe area of the landslides.

Chapter 4—Ground Water

When the Abalone Cove landslide began to move in 1978, geologists suspected that the cause was related to ground water and elevation of the water table following several years of exceptional rainfall. Boreholes drilled in the following months confirmed elevated ground water levels and shortly thereafter a program of pumping was begun to lower the water table. This was the first real confirmation of ground water as the causal factor in the slow-moving landslides of the Portuguese Bend area. Over the next several years, the water table was lowered by more than 25 ft and an organized program of dewatering the Abalone Cove landslide was established. Ultimately this program grew into the Abalone Cove Landslide Abatement District (1981). Similar dewatering wells were drilled in the Portuguese Bend landslide starting in the mid 1980s but most were destroyed by landslide movement before they could effectively dewater the landslide. In 2012 there were only six dewatering wells still operating in the Portuguese Bend landslide.

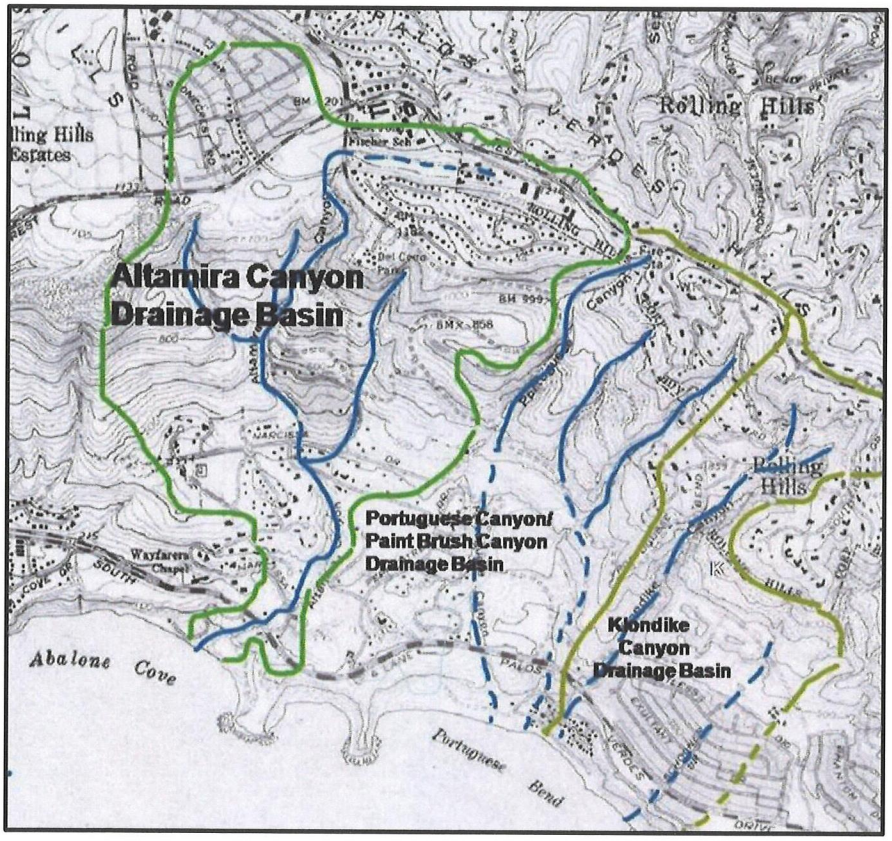


Figure 18. Drainage basins of the major landslides located in the Portuguese Bend area. Blue is storm-water pathway down the major canyons. Note that the lower reaches of Portuguese Canyon and Paint Brush Canyon have been destroyed by landslide movement and grading and both of these canyons now empty directly into the head of the Portuguese Bend landslide.

Most of the ground water in the area is rainwater which has passed through the soil and rock and accumulates at depth. There is a small contribution from domestic water (irrigation) from houses. When rain falls to the ground, some evaporates, some infiltrates and the rest runs off into

the gullies and canyons in the drainage basin. There are three drainage (containment) basins in the landslide area, the Altamira Canyon basin, the combined Portuguese Canyon and Paint Brush Canyon basin and the Klondike Canyon basin (Figure 18). Rain that falls within the watershed of these basins remains within the basins until it ultimately reaches the ocean.

How much of the rain that falls within the drainage basins actually becomes ground water? In Mediterranean climates like the Palos Verdes peninsula, only about 15-20 percent of the precipitation that falls over open ground makes it into the subsurface. The vast majority is lost through evapotranspiration (the combination of evaporation and transpiration from plants). When the soil horizon is dry, the loss is probably even greater. A saturated soil horizon allows more water to pass into the subsurface. The high ground at the top of the drainage basins receives on average about 40 percent more rain than lower elevations (Hill, 2000). Ironically, this higher rainfall occurs over the most urbanized area with extensive "hard-surfaces" (pavement, houses, roofs, sidewalks, etc.) that prevent infiltration into the ground and it generates higher storm run-off. In turn, this run-off is directed into the storm drain systems that feed directly into the canyons.

In Altamira Canyon, a significant percentage of the storm discharge water percolates through the bottom of the canyons and into the ground water. Hill estimated this amount was at least 13 percent of total annual rainfall. More recent data suggests that it is even higher. An important factor in the infiltration process is the occurrence of fractures and crevasses that cross the canyons. In Altamira canyon 60-70 percent of the discharge from individual storms can be lost down major fracture zones which act as direct conduits into the subsurface. Wells located close to fractures zones record an increase in production within days of major storm water discharge in the canyons.

Because of the large number of fractures (of all sizes) within the active landslides, it is impossible to prevent the infiltration of rainwater. Depending on the size and duration of the storm, only 1-18 percent of the storm water in Altamira Canyon actually reaches the ocean (Hill, 2000). In Portuguese and Paint Brush Canyons, the lower reaches of the canyons have been destroyed and 100 percent of the storm water from these canyon flows directly into the head of the Portuguese Bend landslide. The ideal approach to controlling the recharge of ground water is to prevent storm water discharge from ever reaching the canyons and landslides but for a number of political and engineering reasons, this is not possible.

Rain water percolates through the soil, filling the tiny openings between the grains and cracks in the rocks, dispelling the trapped air and eventually, comes to fill all of the openings in the subsurface materials. The zone between the surface and the level where all the air has been dispelled is called the unsaturated or vadose zone (openings filled with water and air), the level below where only water fills the openings is called the saturated or phreatic zone and the boundary between them defines the water table.

Because water is heavy, the pressure on the water in the tiny openings and cracks in the rocks increases with depth below the water table. Furthermore, the dipping strata of the Altamira Shale begin near the crest of the peninsula at an elevation of about 1,200 ft and extend to sea level so that there is a large potential hydraulic head which drives the ground water as it slowly moves through the subsurface. In order for the water to move through the rocks, there must not only be openings (porosity) but they must be connected (permeability) to facilitate movement. This is known as the hydraulic conductivity in rocks and in the Altamira Shale it is very low and nearly all of it is due to cracks in the rocks.

Estimates of the age of the ground water at various locations between the upper slopes and the beach provide a clue as to how fast ground water is moving through the rocks. Hill (2000) using geochemical methods and DiFilippo (2003) using a modeling approach obtained similar ages for ground water samples from the production wells (Figure 19). The ground water in the upper part of the Altamira drainage basin is typically 5 to 10 years old, around the middle of the basin (300 to 600 ft elevation) 10-30 years old and at the beach 20-40 year old. A surprising finding was that the water from Kelvin Canyon Spring ranges from under 10 years to over 40 years (Figure 19). It seems clear that there is more than one source of the water that flows out of the spring. Hill also found that the water seeping from the toe of the Portuguese Bend landslide was more than 40 years old. These estimates indicate that on average it takes decades for rain water that falls on the upper slopes to infiltrate into the deep ground water and finally make its way at depth to the beach.

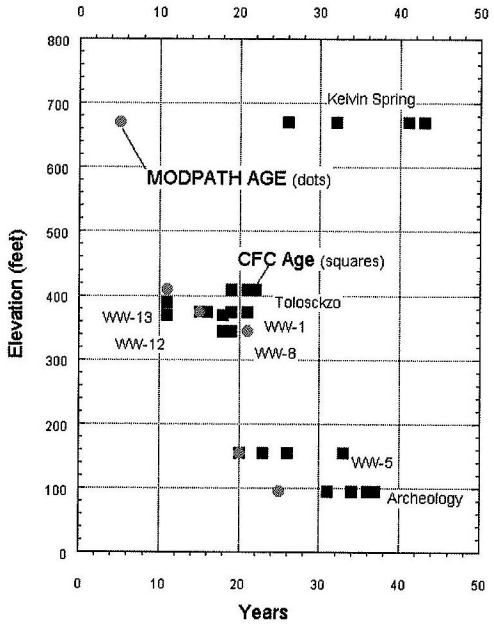


Figure 19. The age of the ground water in the Ancient Altamira and Abalone Cove landslides based on geochemical estimates using tritium and CFC gases from dewatering well water samples (black squares). Red dots are estimates derived from modeling ground water flow (data from Hill, 2000; DiFilippo, 2003).

However, we have a paradox. While the various estimates agree with the very low conductivity rate of the rocks and that it takes many years for the ground water to flow through the subsurface, Ehlig and others repeatedly found that in the Portuguese Bend landslide that landslide movement increased significantly within months of the winter rains. This suggested to him that the flow of ground water in the subsurface took months rather than years. Hill (2000) solved the paradox when she discovered that following the rains, as the water infiltrates into the subsurface it adds weight to the existing ground water and this weight generates a "pressure wave" that migrates through the system. It is the pressure wave that is controlling the increase rate of flow at the wells.

In 2009, ACLAD began installing Levelogger instruments in monitoring wells to automatically record the height of the water table. Previously this information was obtained manually by periodically lowering devices down the well that measured the depth to the water table. It is time-consuming and produces discontinuous records. Levelogger instruments operate on atomic

batteries and continuously record the pressure in the borehole which can be converted directly into water height. Typically the loggers are removed from the monitoring wells every three or four months and downloaded at the well head. The results of the Leveloggers have answered a number of questions about how rainwater infiltrates to become ground water and the variations that can exist in the water table.

The Levelogger records at two monitoring wells, LC4, located in the upper part of the drainage basin and NBW001, located at the southern edge of the basin are shown in Figure 20.

Each site recorded a rapid (within a few weeks) increase (nearly 4 ft) in the height of the water table following an exceptionally large rain storm in December 2010. Several months after the event, the water table slowly declined in LC4 while it continued to rise in the lower reaches of the basin at NBW001 indicating a slow flow of ground water at shallow depth down-slope towards the beach. As Hill discovered, because water is heavy (one gallon weighs more than eight pounds), this movement of water increases the pore-water pressure at depth within the landslide and ultimately it caused an increase in the rate of movement in the Abalone Cove landslide in 2011.

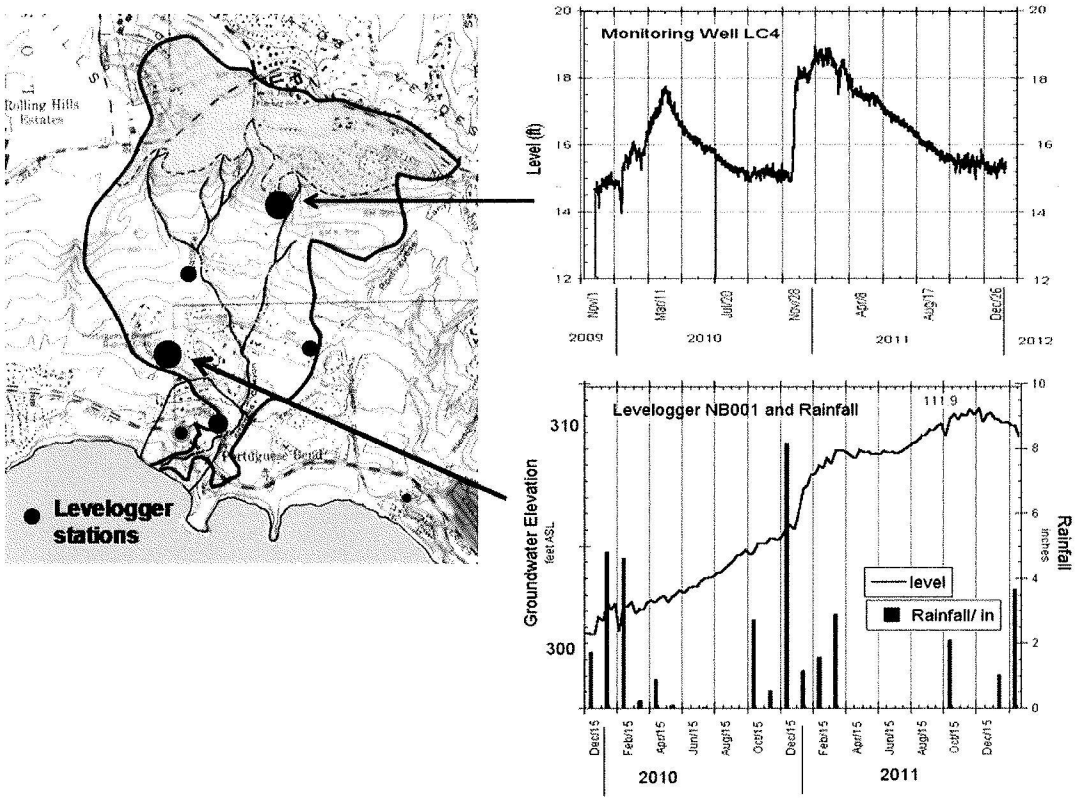


Figure 20. Two Levelogger records for late 2009 to early 2012 from monitoring wells LC4 (upper) and NBW001 (lower). Rainfall is shown as bars in the lower graph. The location of the instruments within the Altamira Drainage Basin is shown by large dots. Levelogger instruments automatically record the height of the water table and provide insights into the response of the ground-water aquifers to rainfall. Following the winter rains in 2010, the water table rose at both sites but began to decline during the summer months at LC4. Note that following the December 2010 storm which dropped 8 inches of rain the rapid increase in the water table at both sites. Over the next several weeks while water levels at LC4 slowly decreased, at NBW001, the ground water continued to increase through the next year.

We now realize that the height of the ground water table can change fairly rapidly (days, weeks) and that it varies considerably across the drainage basin. By carefully monitoring well production over the past decade, it has been possible to elucidate some of the complexities of the ground water system in the area. It is clear that there are two levels of flow in the ground water system. "Shallow" ground water typically flows above the bentonite layers (shear zones) that form the main slip zones and is fed largely by local fractures and the canyons. Wells pumping from this layer respond quickly (days to weeks) to major rain storms. A "deep" flow of ground water originates in the upper part of the drainage basin and is largely confined to below the rupture zones. It is the deeper flow that yields ages of many decades. Much of this flow is confined and ground water builds up over time. Older dewatering wells re-drilled to greater depth to intercept this water often encounter pressurized ground water zones below slip surfaces with an initial flow rate of greater than 100 gal/min.

Understanding as much as possible about the origins, movement and volumes of ground water in the area is a vital key in the strategy for remediating the landslide and the development of dewatering wells. Ultimately, controlling ground water is the best approach to controlling the stability of the landslides.

Chapter 5—Sea Level, Climate, and Landslides

Several of the geoscientists (e.g. Jahns, Vonder Linden, Ehlig) who investigated the Portuguese Bend landslides began to realize that the landslides are not random events in space and time but that there is a genetic connection between the landslides and climate, sea level, and uplift of the peninsula. The landslides develop when sea level comes to a still-stand and wave erosion develops a coastal platform and sea cliff which removes the lateral support of the south dipping beds on the flank of the peninsula. In turn, sea level over the past million years or so has been controlled by the waxing and waning of hemispheric ice sheets produced by the famous glacial-interglacial climatic cycles. And, finally, the geological evidence of these cycles, the marine terraces formed by the high-stand of sea level and which surround the peninsula and the landslides associated with them, would have been destroyed if it had not been for the continuous uplift of the peninsula caused by regional tectonic forces. These three factors, sea level, climate and tectonic uplift, provide the broad framework within which the landslides have developed and offer the basis for a model (hypothesis) to understand the history of the creepy landslides of Portuguese Bend. We began by briefly examining these factors before discussing the model.

Marine Terraces

Before the Palos Verdes Peninsula was extensively developed in the latter half of the 20th Century, the largely barren, open hills could be seen to form a series of stair-step like benches that wrapped around the peninsula as they rise from the ocean to the crest. They are like a series of "rings around the bathtub" on the western and southern flanks of the peninsula. Based on investigations in the 1930s (Woodring, et al., 1946) some 12 or 13 benches or terraces can be identified on the western and southern flanks of the Peninsula (Figures 21, 22).

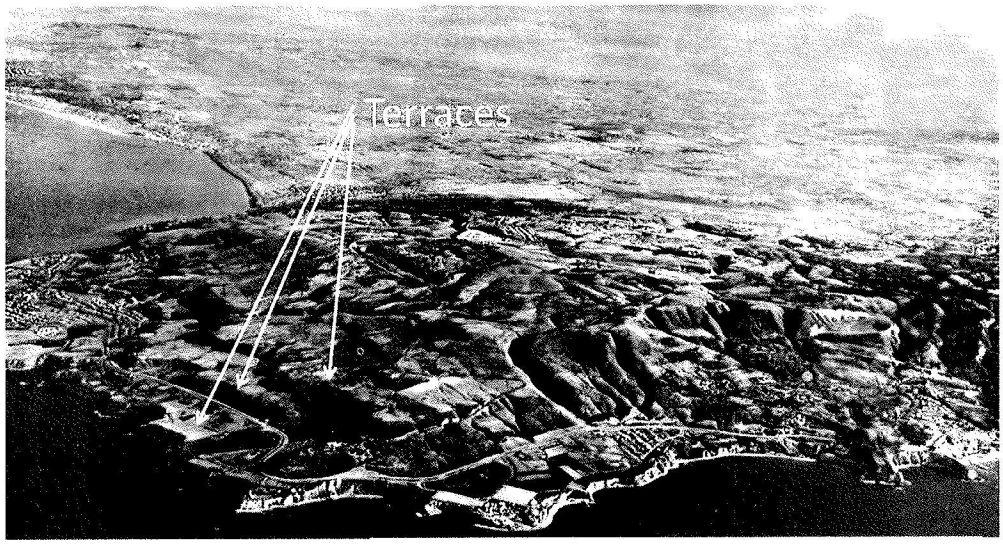


Figure 21. Marine terraces exposed on the Palos Verdes Peninsula. The oblique aerial photo was taken by John S. Skelton in 1958, before major development occurred.

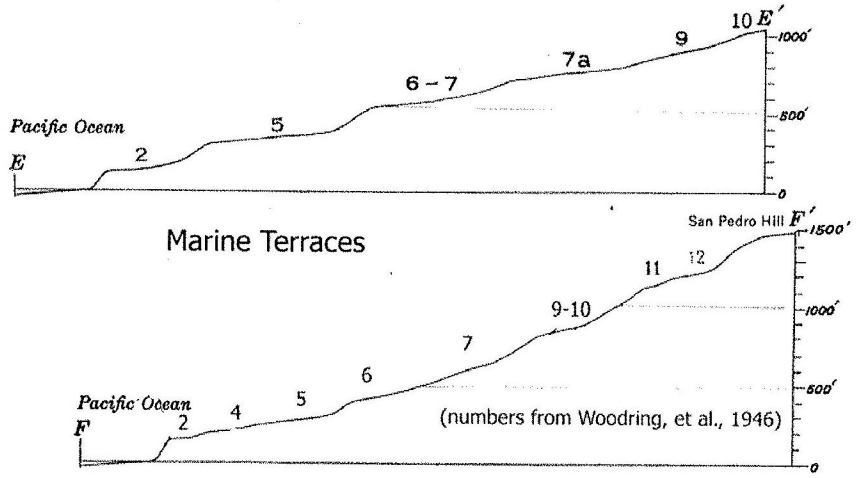


Figure 22. Profiles of the marine terraces from stable areas located to the west (Profile E) and the east (Profile F) of the Portuguese Bend landslide area. Profiles and terrace numbers from Woodring et al. (1946).

During the Ice Ages, sea level changed with the waxing and waning of the major glaciers that covered the northern hemisphere continents and Antarctica. In the last million years or so, there were at least 21 major glacial cycles. The ultimate source of the water for the glacial ice was the ocean and as the glaciers grew and expanded, sea level fell. Conversely, when the glaciers melted, water was returned to the ocean and sea level rose. During the last glacial maximum about 22,000 years ago, for example, sea level was about 120 m (360 ft) below modern sea level and all of the modern continental shelf was exposed. Following rapid melting of the glaciers 14,000 year ago, the melt water was conveyed back to the ocean by rivers and sea level rose to its present-day level by about 5,000 years ago. Sea level varied with each glacial cycle depending upon how much of the global ice volume melted. During the last interglacial before the modern one, 80,000 to 125,000 years ago, the glaciers on the continents, including most of the Greenland icecap, melted and sea level was 5 to 10 m (15 to 30 ft) higher than today. Generally the major glaciers formed slowly over several tens of thousands of years while typical interglacial phases were more abrupt and shorter, typically 10,000 years or less in duration; a typical complete glacial cycle lasted about 100,000 years. Also, during some interglacial's there was more than one high stand that reached within ± 10 m (30 ft) of modern sea level. At the end of each glaciation, sea level rose quickly as the ice melted and within a few thousand years, reached a maximum level.

The benches found on the flanks of the Peninsula were cut as sea level stabilized and remained at about the same height (still-stand) so that a wave-cut platform could be eroded at the base of the sea cliff (Figure 23). Each of the marine terraces on Palos Verdes represents the interglacial phase of a glacial cycle and by correlation with the well-known history of glacial cycles reconstructed from deep ocean sediments (e.g. Shackleton and Opdyke, 1973, 1976) (Figure 24) each terrace can be given an approximate age; all 13 terraces represent about the last 900 ka to one million years. When the peninsula actually rose above sea level is unclear as some tectonic interpretations yield ages of up to 2 million years (Shlemon, 2007; Olson, 1997; Francis and Legg, 2007). Nevertheless, evidence points to the peninsula being exposed as an island by about 1.4 million years ago and we will assume this is the correct age. Even after the peninsula became an island, uplift continued at rates of 0.2 to 0.4 mm/yr and preserved each interglacial terrace from erosion by the next cycle.



Figure 23. (left) Marine terrace 2, (ca. 125 ka), (layer of gravel and small cobbles at the white line in the middle of photograph) resting on nearly vertical beds of the Altamira Shale. The terrace has been buried beneath alluvium and soil (brown layer) eroded from uphill slopes. (right) Fossils of intertidal clams and gastropods occur in the gravels and holes in the surface of the Altamira Shale. Largest shell in the photo is approximately 1 inch across. Exposure is on the east side of Inspiration Point.

The graph in Figure 24 (left) is based on three sources of information: the elevation of the numbered terraces taken from Figure 19, the correlation of the terraces with the oceanic interglacial record (Marine Isotopic Stages (MIS)) and the age of the interglacial phases. This information allows us to relate the elevation of the terraces to the interglacial phase that created them and the approximate age. For example, Terrace 10, located at about 1,000 ft elevation is correlated with Marine Interglacial Stage (MIS) 19.1 and is approximately 780,000 years old; Terrace 7 correlates with either MIS 13.1 and/or 13.3 and is roughly 500,000 years old, and so on.

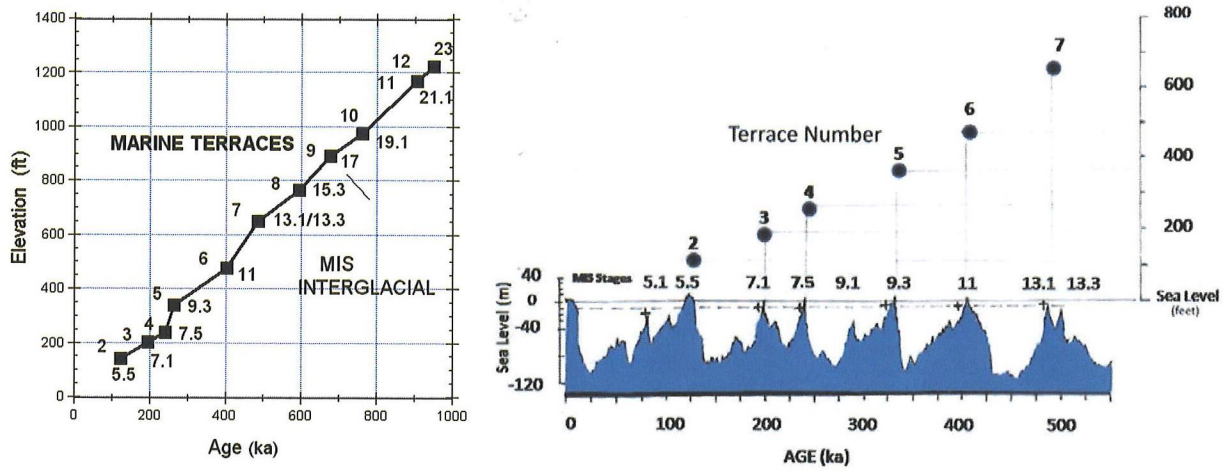


Figure 24. (left) Interpretation of the age (ka = thousand years), elevation and Marine Isotopic Stage (MIS) interglacial stage of the Palos Verdes marine terraces. Ages of the MIS interglacial stages that were within ± 10 m (30 ft) of present-day sea level is based on numerous sources (see references.). (right) Relative sea level curve derived from the oceanic sediment record for the past 500,000 years. By convention, the interglacial phases (sea level high stands) are given odd numbers (glacial periods are even numbered) and the multiple high stands numbered sequentially, e.g., 9.1 and 9.3. The terraces corresponding to the particular high stands are shown.

Model of Landslide Development and Movement

The model (hypothesis) proposed here (Figure 25) is that the landslides on the south flank of the Palos Verdes Peninsula developed during the sea level high stand that developed in the interglacial phase of each glacial cycle. As sea level approached its peak height and stabilized, wave erosion cut a platform and sea cliff that undercut the seaward dipping beds of the Altamira shale. This resulted in sea cliff failure, much like what is occurring along the modern coastline. Aiding this process was ground water build-up in the bedrock which led to an increase in pore-water pressure. The increased pore-water pressure within the layers sandwiched between the impermeable clay and bentonite beds of the Altamira Shale eventually exceeded the strength of the clays and the impermeable layers become shear zones and failed. The cliff failures propagated upslope (inland). Higher rainfall during the warmer interglacial climates accelerated this process and contributed to failure of the rocks. Once started, landslide failure continued whenever the pore-water pressure provided sufficient force to exceed the minimum strength within the bentonitic clay shear zones. Periods of high or prolonged rainfall significantly increased the slope failure and rates of movement; periods of low rainfall and drought eventually brought the movement to a near halt. During the glacial phase of the climatic cycle and low stand of sea level which exposed the continental shelf, landsliding on land was minimal and small scale as the process was shifted to the edge of the continental shelf. Evidence of major Ice Age slope failures are found at the edge of the modern continental shelf off Palos Verdes (Normark, et al., 2004; Bohannon and Gardner, 2004).

With this model in mind, we can now review the structure and history of the several landslides of the area.

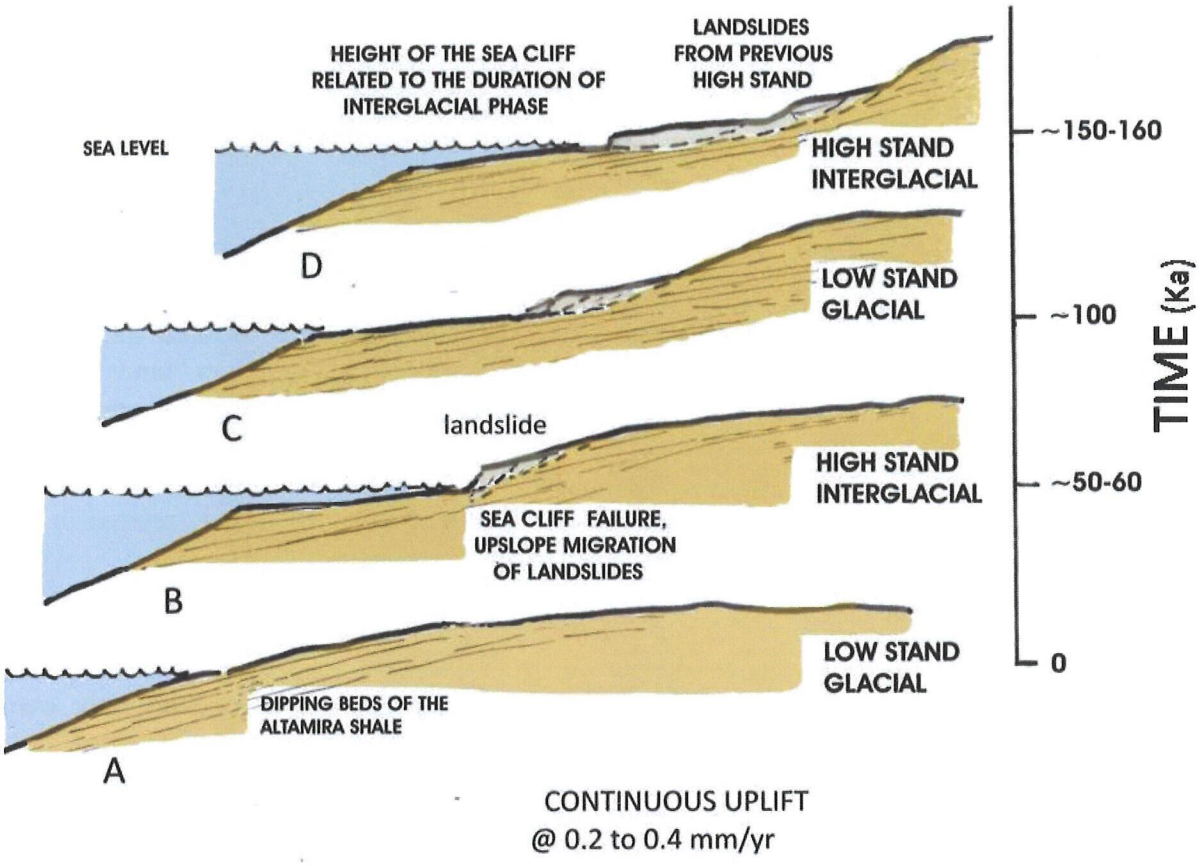


Figure 25. A conceptual model of landslide formation (see text). Key factors involve the dipping beds of the Altamira Shale, glacial/interglacial control of sea level, wave erosion of sea cliffs during sea level high stand and the continuous uplift of the Palos Verdes peninsula. Idealized stages: A-Low stand sea level during a glacial phase early in the Peninsula's history, B-High stand sea level during the next interglacial with the development of a wave cut platform and sea cliff; sea cliff failure follows., C- The following low stand; D-An Interglacial High stand and a repeat of the process at the sea cliff and migration of the landslide inland. Because of continuous uplift of the peninsula, the previous terraces and landslides are preserved.

Chapter 6—Ancient Altamira Landslide Complex

The two active landslides, Portuguese Bend and Abalone Cove, are reactivated parts of a much larger and older slide mass that covers over 2 square miles and extends from the crest of the peninsula, near Crest Road, to the shoreline (Figure 2). I call this ancient landslide mass the "Ancient Altamira landslide complex" to avoid confusion with and to distinguish it from the more recent slope failures in Portuguese Bend and Abalone Cove. The name is derived from Altamira Canyon which is located in about the center of the ancient landslide area and at several places the ancient landslide is exposed in the walls of the canyon. I use the term "landslide mass" to denote the fact that the ancient landslide is not a single unit or event but the composite of numerous slides including small slumps to large translational block slides that have occurred over much of the past 800,000 years (Pleistocene era). While the Flying Triangle and Klondike Canyon landslides are commonly considered separate failures, they are closely related in space and type and likely are also part of this ancient complex.

One would expect that such a large and prominent feature as the Ancient Altamira landslide complex would have been the focus of many geological studies. Indeed, there have been many investigations of portions of the landslide but not a single study of the entire landslide. The reason is that the studies were commissioned by individual land owners who only owned portions of the area covered by the landslide complex. Over the years, geoscientists employed by Crandall and Associates, Leighton and Associates and, recently, Ginter and Associates, are most responsible for what is known about the geology of the complex. The limited surface exposures found in the bottom of canyons and a few steep hillsides provide a limited basis for unraveling the internal structure and stratigraphy of the ancient slide complex (Figures 26, 27) and so reliance must be given to the numerous boreholes and trenches that have been dug over the years. The continuously cored boreholes with down-hole visual and geophysical logs provide the best source of information. They attest to the complexity of the ancient landslide in the subsurface and reveal that in places the landslide complex is over 200 ft thick. One of the problems in tracing the landslide from one location to another across the area is that there are very few distinctive beds that can be used to correlate from one borehole to another. The most distinctive units are the cherty shale (see Figures 5, 6) and the bentonite beds which compose the Portuguese Tuff (see Figures 5, 10, 11) but even here there are problems. The Portuguese tuff varies in thickness across the area, thickening and thinning and appears to be missing in the subsurface in some areas, such as north of the Abalone Cove landslide. Whether the Portuguese tuff was never deposited here or it has been removed by erosion as the overlying landslide mass moved across the area is unclear but an important question. Besides the Portuguese Tuff, there are many beds of bentonite and bentonitic clay in the Altamira Shale, some of which are several feet thick and can be mistaken for the Tuff.



Figure 26. Bentonitic tuffs that form the base of the landslide slip zone of the Ancient Altamira landslide exposed in the bottom of Altamira Canyon. Following heavy rains in December 2010, stream erosion exposed the beds at and just below the slip zone. The basal beds of the overlying landslide debris are exposed in the eastern canyon wall. This exposure of the slip zone and base of the landslide was reported by Vonder Linden (1972) but slumping of the canyon wall had obscured it until stream erosion brought it to light. This location is a short distance north of the head of the Abalone Cove landslide.



Figure 27. Two views of the landslide slip zone (rupture surface) (dashed line) as exposed at the base of the Ancient Altamira landslide in Altamira Canyon. Here, cherty and tuffaceous shale overlay highly distorted and sheared brown tuffaceous silty sandstone. Bentonites of the Portuguese Tuff are exposed in the stream bed farther downstream. This slip zone can be traced into boreholes located approximately 150 to 200 ft to the west of the canyon. Photo to the right was taken in winter 2005, following heavy rains which eroded the canyon bottom and exposed the slip zone. The photo to the left was taken a year later and stream debris had begun to cover the slip zone; by 2011 debris and vegetation had covered the zone completely.

One of the most important geological relationships in the Ancient Altamira landslide is partially exposed at the inner edge of Portuguese Point (Figures 28, 29). Near where the arrow is located in Figure 28, the terrace is over-ridden by beds of the Ancient Altamira landside. This relationship is shown in the cross-section (Figure 28) where boreholes data provide additional information about the subsurface geology. Here the ancient landslide overrode marine terrace 2 that had been cut into the Altamira Shale and basalts during interglacial MIS 5.5, about 125,000 years ago. Intertidal fossils found in the terrace deposits recovered in boreholes drilled into Portuguese Point attest to its marine origin.. The hill at the inner edge (north) of the Point is the toe of the ancient landslide that cut through the basalt sill and marine terrace. To restore the marine terrace deposits to their original, nearly horizontal position, the block must be rotated clockwise nearly 50°. Exposed on the eastern side of the point are upturned beds of cherty shale and bentonite that were pushed into a nearly vertical position (Figure 28, insert). Similar displaced and upturned beds covered by terrace deposits are exposed on the eastern side of Inspiration Point. These two sites are all that remains of the toe of the Ancient Altamira landslide when it reached sea level sometime after 125 ka. This is the only definitely dated relationship in the Ancient Altamira landslide and provides a minimum age for when the mass movement was active.

When Vonder Linden (1972) conducted his field work in the 1960s, the outcrops along the Crenshaw extension road cut were still fresh as well as exposures of Portuguese Tuff in the walls of Portuguese Canyon, both of which are now blurred by time, weathering and vegetation. He described three large displaced blocks in the north and northeastern portion of the ancient landslide which he concluded were original sea cliff failures that started the landslide complex. The largest of these is the block called "Peacock Flats" that covers about 50 acres (Figure 30). Subsequent to Vonder Linden's work, numerous boreholes and trenches were dug in the flats when the area was being considered for development of a golf course and houses. These data provide details of the subsurface geology that were not available to Vonder Linden. The internal structure of the block reveals an asymmetrical anticline with a steeper south limb (Figure 31). The block, nearly 300 ft thick above the Portuguese Tuff, rests on the north limb which gently dips to the north. The block is cut by several shear zones located in beds composed of bentonitic clay and tuff that parallel the dip of the beds. In section B-B', multiple shear zones mark the location of a large slump that has displaced the distinctive chert and porcelanite shale that make up the crown of the block and cut down into the Portuguese Tuff, reducing it to about half its typical thickness. The cherty shale (chert, porcelanite) in the Del Cerro block is more than 250 ft above the Portuguese Tuff, but within the Peacock Flat block the cherty shale is only 100 to 200 ft above the Tuff. It suggests that at least 50 ft or more of section has been lost, probably by movement (erosion) in the shear zones. The antiquity of the block is suggested by the nearly 200-ft-thick layer of non-bedded and poorly consolidated landslide debris that mantles the slope to the south of the Flats. This debris is composed of tuffaceous shale, porcelanite and bentonite fragments eroded from the Peacock block over the past several hundred thousand years.

In contrast to Peacock Flats, the blocks on the western margin of the ancient landslide that are believed to be original sea cliff failures are less complicated geologically. Figure 32 is a simplified section through one of the several westernmost blocks that form a series of step-like features. As the blocks rotate away from the sea cliff, the space behind them becomes filled with debris off of the cliff (Figure 33). Boreholes indicate that the slip zone beneath these blocks is also bentonitic clay layers above the Portuguese Tuff. While the geomorphic evidence and

position at the top of the landslide suggest they are old, it is not clear exactly when these blocks failed or if they all failed at about the same time.



Figure 28. Panorama of Portuguese Point, looking west. The gently sloping surface of the point is marine terrace 2 (125,000 years old) covered by a thin layer of alluvial debris. At the inner edge of the terrace, about where the arrow is located, beds of the Ancient Altamira landslide override the terrace.

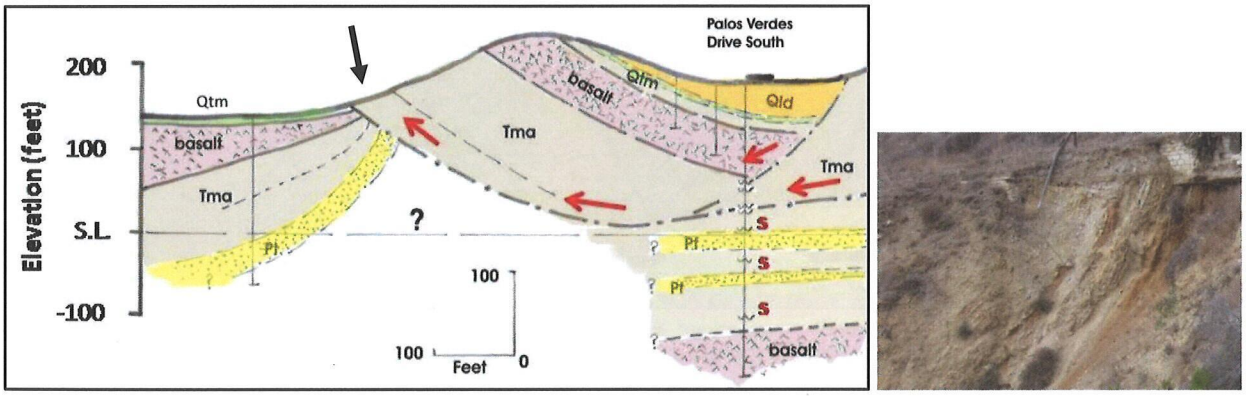


Figure 29. Cross-section of the inner edge of the marine terrace and adjacent areas. The basalt sill was broken by landslide movement and the detached piece makes up the hill to the north (right) in Figure 28. A remnant of the terrace deposit (Qtm) is exposed at the top of the hill. As the landslide over-rode the Altamira Shale, beds were upturned to a nearly vertical position (see inset). The slip zones are shown by red arrows; red S marks shear zones. A lack of boreholes makes unclear exactly how the geology on the right connects to the geology on the left (area shown by question mark (?).

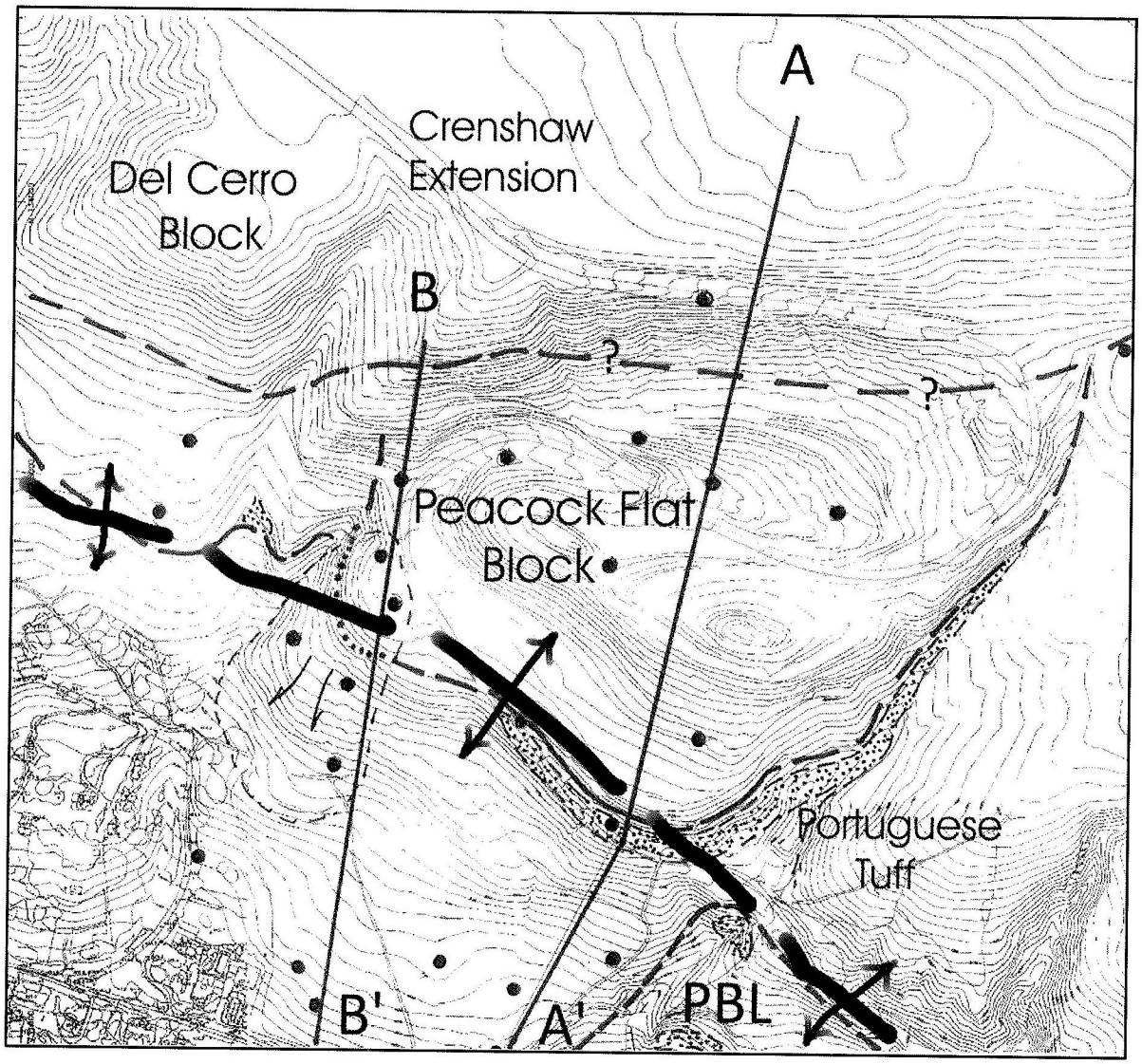


Figure 30. A map of the Peacock Flats area located in the northeast margin of the Ancient Altamira landslide. The NW corner of the Portuguese Bend landslide is shown. A west-east trending anticline crosses the area with the crest near the southern edge of the block. The Portuguese Tuff crops out in Portuguese Canyon and along the Crenshaw Extension where the base of the block is exposed. The boreholes that were used in constructing the cross-sections are shown.

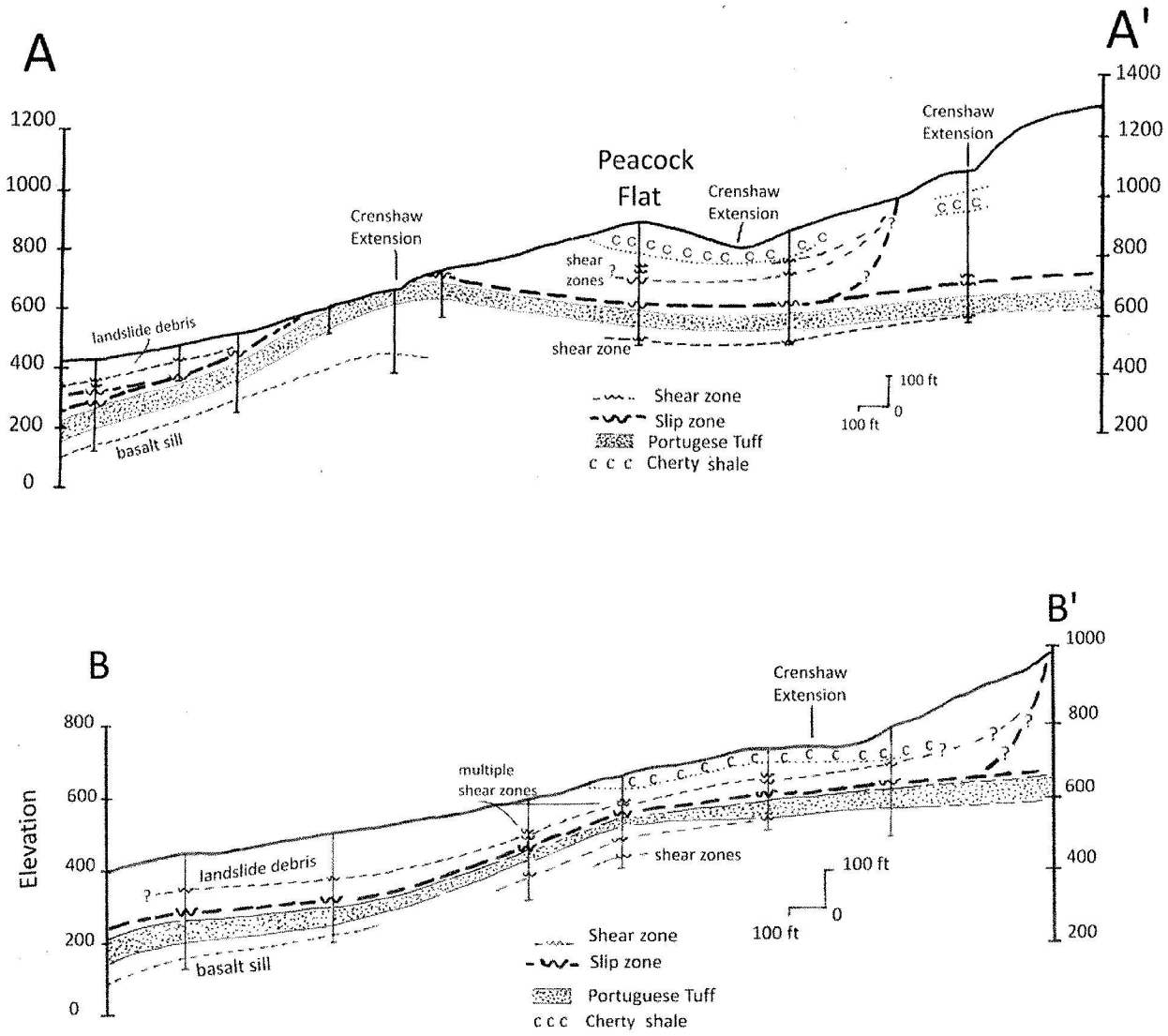


Figure 31. Cross-sections through Peacock Flats, one of several blocks in the northern part of the Ancient Altamira landslide that represent an early sea cliff failure. The block broke away from the then sea cliff (to the right) and moved over bentonitic clay layers located a few feet above the Portuguese Tuff. Southward progress of the block was retarded by the north dipping limb of a west to east trending anticline. There are several shear zones that may represent former slip planes. Section B-B′ to the west of the main block is cut by shear zones that are probably the westward continuations of those in section A-A′. A basalt sill occurs at depth beneath the south limb but was not cored under the block. Elevations are above sea level.

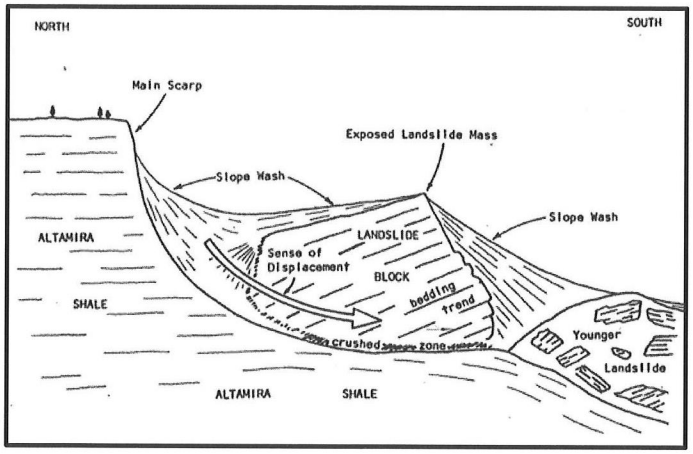


Figure 32. A generalized cross-section of one of the slump block/landsides on the western margin of the Ancient Altamira landslide as envisioned by Vonder Linden (1972). The rotated block is a sea cliff failure which slipped over layers of bentonitic clay, much like cliff failures today. With time the block separates from the sea cliff and is covered by slope debris.

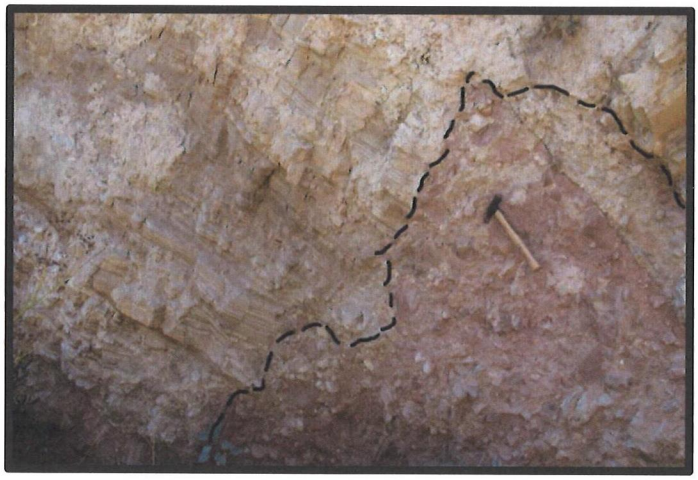


Figure 33. Debris back-filling the void created as a large block of chert and cherty shale pulled-away and rotated, similar to that shown in Vonder Linden's generalized section (Figure 32). The debris is a chaotic mixture of cherty shale fragments and small blocks in a matrix of tuffaceous material. The exposure is in Altamira Canyon near the basal slip zone shown in Figure 27; hammer is about 15 inches long.

The original geological map of the area indicated that the head of the Ancient Altamira complex was located along the steep hillside slopes about half way to the crest (Figures 1, 2). However, more recent studies have moved this boundary inland (northward) to include the depression known as the Valley View graben (Figure 2). This narrow depression (300-500 ft wide) parallels Crest Road and extends from approximately St. John Fisher Church eastward to Portuguese Canyon, a distance of about one mile. (Geologically, a graben is a narrow depression caused by downward movement along the faults on each side.) Two explanations have been offered for the origins of the graben: One is that the depression is a "tear" or crack located along the crest of the fold caused by tension (pull apart) when the sedimentary rocks of the peninsula

were folded into a large antiform. That is, the graben is the result of the tectonic forces and dates from when the peninsula was folded, a time well before the landslides. The other explanation is that the graben is the result of landslide movement in which the south flank caused the rocks to pull away from the stable rocks at the crest of the peninsula. If this is true, then the landslide slip zone should extend beneath the rocks south of the graben. The rocks at the crest are basically flat-lying or dipping slightly to the south-west. A number of boreholes were drilled in the area known as the Del Cerro block and Peacock flats block as well as within the graben to determine which theory was correct. As it commonly happens in science, the results are not as clear-cut as you might like. The boreholes established that there are shear zones but no clear slip zone in the bentonite-tuffs beneath the flat-lying rocks, implying but not proving that movement has occurred. The borings verified that the depression is a graben bounded on both sides by faults. The rocks in the center of the graben have been displaced downward about 100 ft as would be expected. Taken together, the evidence is strongest for a landslide origin and that the graben is the head-scarp of the ancient landslide.

The origin and geologic history of the Ancient Altamira landslide is another interesting question that is clouded with controversy. The outcrops on Portuguese Point (Figures 28, 29) provide a minimal date for the last movement of the landslide but its beginnings remain unclear. Two geologists from Stanford University, Richard Jahns and his student, Karl Vonder Linden (who investigated the Portuguese Bend landslide for his doctoral dissertation in the 1960s) wrote a paper in 1973 in which they suggested that the ancient landslide complex represented a series of semi-independent slides that formed in three separate time intervals during the late Pleistocene and Holocene (roughly the last million years). The up slope slides are the oldest and the slides next to the coast are the youngest. Portuguese Bend landslide was one of the youngest landslide masses. To date the landslides, correlation was made with the marine terraces described by Woodring, et al.. In this way, Jahns and Vonder Linden concluded the oldest landslides were above terrace 7 and older than 250,000 years. (terrace 7 is now correlated with Marine Isotope Stage 13 and dated at about 500,000 years old (see Figure 24.) They concluded that the youngest landslides were late Holocene (the time since the end of the Ice Ages, the last 10,000 years) based in part on a 4800 year old charcoal fragments found in pond deposits within the Portuguese Bend landslide. Thus, they saw the area as composed of a complex series of landslides that had developed separately over a long span of time (ca. 500,000 years) and are active right up to the present day.

After studying the landslide complex for many years, Ehlig came to a very different conclusion. He suggested that the whole complex is a megaslide that started moving as a unit but fragmented as movement progressed (Figure 34). He dated the original movement based on where the upturned edge of the old slide overrides the marine terrace deposits on Portuguese Point, about 125,000 years old (Figures 28, 29). Further, he could not document any of Woodring's, et al. terraces within the ancient landslide which supported his belief that the megaslide initially moved as a unit and destroyed any terraces which might have existed within it. Thus, he concluded that the megaslide could not be much older than the marine terrace deposits and at most no more than 200,000 years old.

An analysis of the terrace remnants within the landslide suggest landslide movement is older than 200 ka and the history of landsliding is closer to the model proposed by Jahns and Vonder Linden. The remnant of terrace 10, located at the site of the present-day California Water Service storage tank on the Crenshaw Extension (Woodring, et al., 1946) is the highest intact terrace within the landslide area and by inference, the steep slope behind it is the remains of an ancient

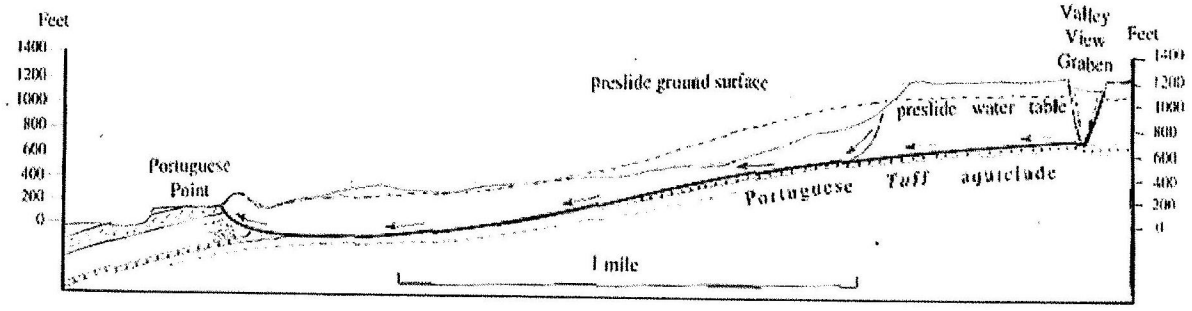


Figure 34. Megaslide envisioned by Perry Ehlig for the Ancient Altamira landslide. He believed that the slide broke up over time. Note that he placed the Valley View graben as the head of the landslide complex (from Ehlig and Bing Yen, 1997).

sea cliff from which the Peacock Flats block separated. This terrace correlates with MIS 19.1 and is dated at 780,000 years. This suggests that slope failure in the Ancient Altamira landslide complex began after this date. Intact lower terraces have not been identified in the landslide area except for terrace debris found in boreholes on the west side that by inference belong to terraces 5 and 6 and displaced sediments from terrace 4 including fossil beach deposits on Charlotte's Hill that overlooks Portuguese Point. By relating these terrace fragments within the landslide to the intact terraces outside the landslide and correlating them with the MIS interglacial ages, a simple though incomplete history of slide movement can be reconstructed. This history suggests that early landslides began with cliff failures (such as Peacock Flats, p. 30) in the upper part of the ancient landslide complex sometime after 780 ka and that mass movement occurred in episodes prompted by the development of a sea cliff during sea level high stands and the higher rainfall that occurred during interglacial periods. The slide complex is composed of several slides sequences, possibly as many as 6 that differ in age by thousands of years. (see model, Figure 25) These sequences correlate to the last 6 or 7 interglacial phases. During glacial phases with cooler and generally drier climates and lower stand of sea level, the landslide movement was probably limited. As would be expected, and noted by Jahns and Vonder Linden, the landslides in the upper and middle parts of the area are more deeply weathered and older than the ones by the coast.

Continuous tectonic uplift of the peninsula at 0.0116 to 0.0160 in./yr (0.29 to 0.40 mm/yr) (Bryant, 1982; McNeil, et al., 1995; Behl and Morita, 2007) was sufficient to preserve the terraces and landslides from subsequent marine erosion except for those terraces generated during interglacial phases that failed to come within 30 ft (10 m) of present-day sea level. For example, sea level during MIS 9.1 is estimated to have been more than 60 ft (20 m) below present-day level. Because the next event, 7.5, was a very high sea level stand 15 ft (5 m) above present-day and occurred only about 65,000 years later, uplift at roughly 1.14 ft/1000 yr (0.35 m/1000 yr) would not have been sufficient to position the 9.1 terrace high enough to avoid erosion by the next 7.5 interglacial cycle.

Unfortunately no terrace other than terrace 2 has been geochronologically dated and the ages suggested here are based on correlations that in some cases are speculative. Nevertheless, by relating terrace fragments found within the landslide to the intact terraces located outside the landslide and correlating those with the MIS interglacial ages, a rough history of movement can be reconstructed. It suggests that early landsliding began sometime after 780 ka and that movement has continued intermediately but continuously ever since. Geophysical data indicate that the peninsula was an exposed land surface by at least million years ago. The delay between uplift and exposure of the peninsula surface and the development of slope failures (780 ka) makes sense as the rocks of the upper part of the Altamira (Malaga Mudstone, Valmonte Diatomites, Phosphatic Lithofacies) (see Figure 4) that overlie the tuffaceous beds of the Altamira Shale are little prone to slope failure (landsliding). These rocks would have to be eroded away before the more landslide prone bentonitic clay and tuffaceous layers would be close enough to the surface to be subject to the effects of elevated ground water.

This scenario more closely agrees with the history of landsliding suggested by Jahns and Vonder Linden (1973) than the megaslide idea of Ehlig. The data, sparse as they are, point to the landslides as the result of the complex interplay between Ice Age ocean-climate cycles, sea level stand and regional tectonics. The ultimately test of these ideas and a more rigorous history must await obtaining reliable numeric dates on the older parts of the landslide and the discovery of remnants of more of the older terraces in the area.

Slope Stability Calculations in the Ancient Landslide Complex

Geotechnical experts try to assess slope stability, the extent that a slope is prone to move, using a method called the "factor of safety" (FOS). The factor of safety attempts to measure the forces (mostly gravity) that cause a hillside (slope) to fail compared to the forces (mostly the internal strength of the rocks) that hold the hillside in place. The results are expressed as a ratio; when the forces are exactly in balance the ratio is 1.0. Values less than 1.0 means the slope is unstable (forces causing it to fail are greater than the forces holding it in place) and prone to movement. FOS greater than 1.0 means the slope is stable. The higher the number, the greater the stability. For example, the factor of safety for the active Abalone Cove landslide calculated by Perry Ehlig and his students typically varied just below 1.0, meaning it is prone to move. Generally, the values calculated for the ancient landslide complex range widely, from about 1.1 to 1.7, suggesting that some parts are more stable than are others.

However, the "devil is in the details" because depending upon how the factor of safety is determined, the values can vary, sometimes significantly and different geoscientists can arrive at different factors of safety for the same area. Factors of safety for the ancient landslide complex vary considerably, depending upon how and where the measurements were made and by whom. That is what the judge in the Monks lawsuit found so frustrating. Cotton, Shires and Associates, when they reviewed the geology of "Zone 2", the already developed portion of the ancient landslide, concluded the factor of safety of the area is certainly above 1.0 and probably less than the industry standard of 1.5. In other words, stable but not by a lot.

Chapter 7—Portuguese Bend Landslide

The Portuguese Bend Landslide is one of the largest, continuously active landslides in the United States. It has achieved the level of a local "rock star", known to nearly everyone in the community and beyond, and the subject of numerous studies conducted by college students to professional geoengineering companies. One of its key characteristics is its slow, continuous rate of movement over time. Another is that the landslide rupture surface is typically in bentonite clay. While the south flank of the Palos Verdes Peninsula contains many active and inactive landslides, the Portuguese Bend landslide is the most conspicuous and well known (Figures 2, 36). It covers about 250 acres and has a maximum width of 3,600 ft and a maximum head-to-toe length of about 4,200 ft. The Portuguese Bend landslide, together with the Abalone Cove and Klondike Canyon landslides are reactivated parts of the large Ancient Altamira Landslide complex. Reactivation followed residential development in the area and human activities played an important role.

Since its reactivation in 1956, the Portuguese Bend landslide has moved in a slow, southward direction with the greatest movement (700-900 + ft) in the central-eastern portions and the beach area and the least in the west and inland areas (ca. 500 ft). In the past 55 years, the movement has sometimes slowed but the landslide has never stopped moving. Originally described by geologists as a "transrotational block-glide" type landslide in which a thick slab of strata fails and slides along a bedding plane, the continued movement and deformation within the mass over the past half century has reduced the central, eastern and seaward parts to a jumble of blocks and debris with little or no internal structural or stratigraphic continuity. Basically, it appears the landslide is moving by plastic flow on the bentonite beds at the slip/rupture surface. Secondary slumping in the head area indicates the landslide is slowly propagating upslope.

In the 1950s the Portuguese Bend was a popular suburban community with a spectacular view of the Pacific Ocean and Catalina Island. More than 150 homes covered the area, mostly built in the post-war boom of the late 1940s and early 1950s. On the beach was located the popular Portuguese Bend Beach Club and pier, a private recreational club (Figure 35). Ultimately, all of the homes adjacent to the beach (69), the Beach Club and the pier were so severely damaged they had to be razed (a few were moved). All of the inland houses sustained major damage and many were also razed; a few were repaired. Following the outcome of a lawsuit in 1961, Los Angeles County basically abandoned the area and allowed condemned houses to stand. Of the original homes, about 30 remain, including several that are not inhabited. The area has become well known for the novel engineering approaches used to stabilize and level houses in the moving landslide. One of the current methods is to use three steel cargo shipping containers arranged in a triangle as a foundation and to place the house on top of them. The containers are periodically re-leveled at the corners of the triangle. Living in a moving landslide is challenging as the residents will tell you. All services (water, gas) must be above ground and electric poles require re-alignment as the ground shifts. The area relies on septic tanks, most of which are old and in need of repair and the storm drains are in need of constant repair. The roads along with the topography have changed significantly over the years (compare Figure 36 to Figure 39) and locating some of the original addresses can be challenging.

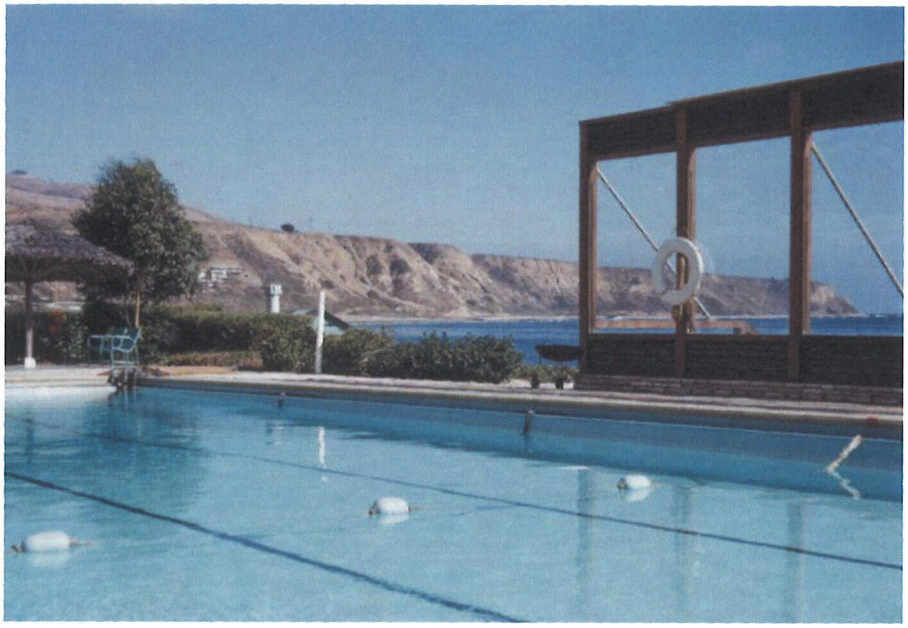


Figure 35. Pool at the Portuguese Bend Club, looking east towards the area now occupied by the Trump National Golf Course. Photo taken in the early 1950s, prior to the landslide and the destruction of the Club. (photo courtesy of Bernard Pipkin).

The landslide generated a major lawsuit between the County of Los Angeles and the property owners who lost homes. In 1961 the County of Los Angeles was held responsible for starting the landslide and the plaintiffs received a settlement of $9.5 million. The Court ruled that the County had failed to inform the property owners that the area was within a documented landslide (based on geological studies conducted in the 1920s and 30s). Construction of the Crenshaw extension caused the reactivation of the landslide by loading the head of the landslide. Largely ignored during the trial was the fact that the houses in the area were entirely on septic tank systems and without storm drains, both of which had significantly added to ground water build-up. Converse Consultants engineers hired by Los Angeles County correctly pointed out that by the time the landslide began, pore-water pressure caused by elevated ground-water levels was a more significant causal factor than the loading effect of 160,000 cubic yards of dirt.

The Portuguese Bend landslide lawsuit was a landmark case that led to the development of modern geoengineering practices and building codes that require geotechnical studies as part of the evaluation for a building permit.

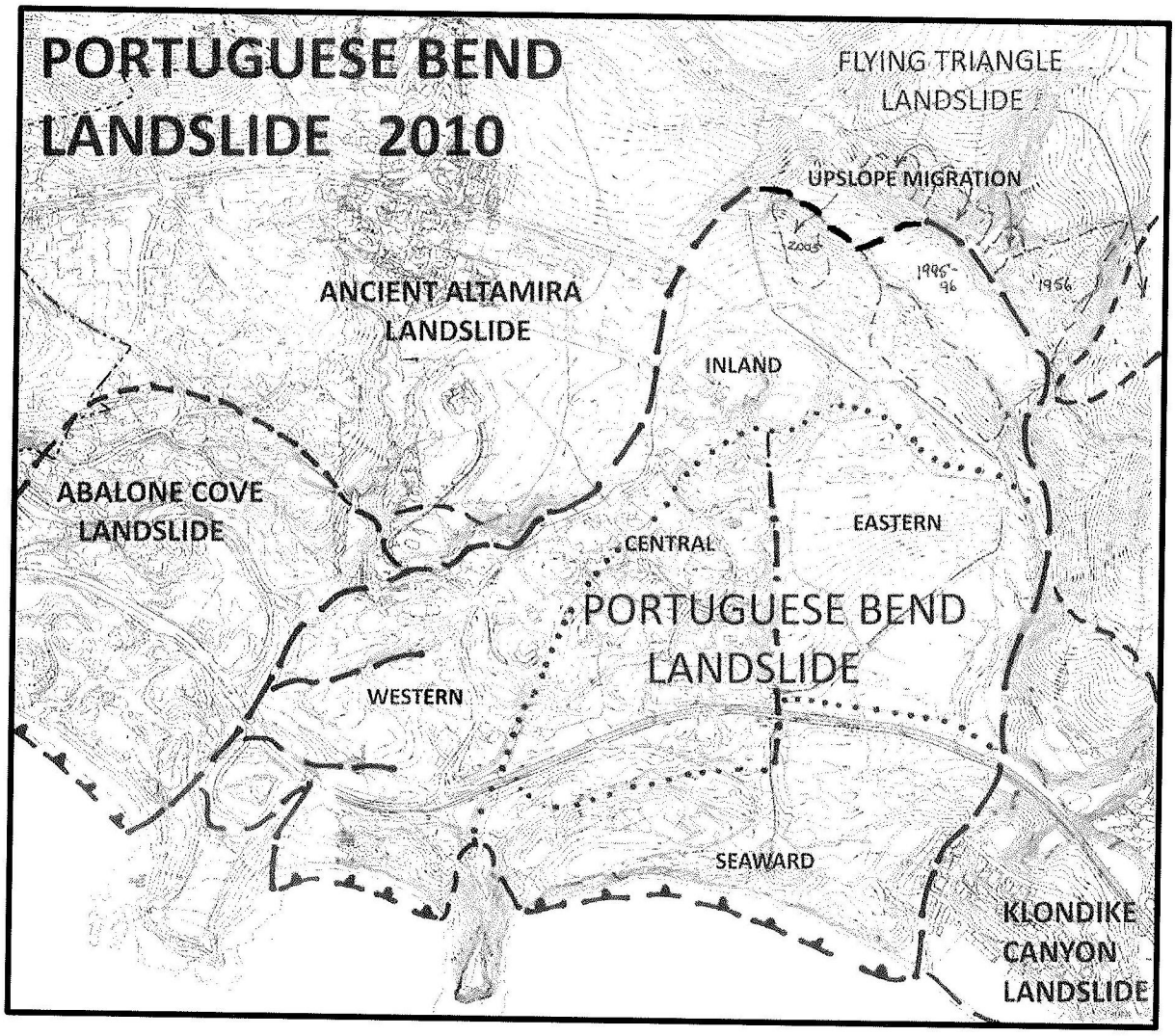


Figure 36. Map of the landslides in the Portuguese Bend area, including the Portuguese Bend, Abalone cove, Klondike Canyon, Flying Triangle and the Ancient Altamira landslides. The subslides of the Portuguese Bend landslide (seaward, eastern, central inland and western) are indicated. The small landslide labeled 1956 in the upper right is the first slope failure that was triggered by construction of the Crenshaw Extension (see Figure 36). About 160,000 cubic yards was removed from this slide and dumped on the head of the Portuguese Bend landslide, contributing to its reactivation. (Figure modified from Ehlig, 1997.)

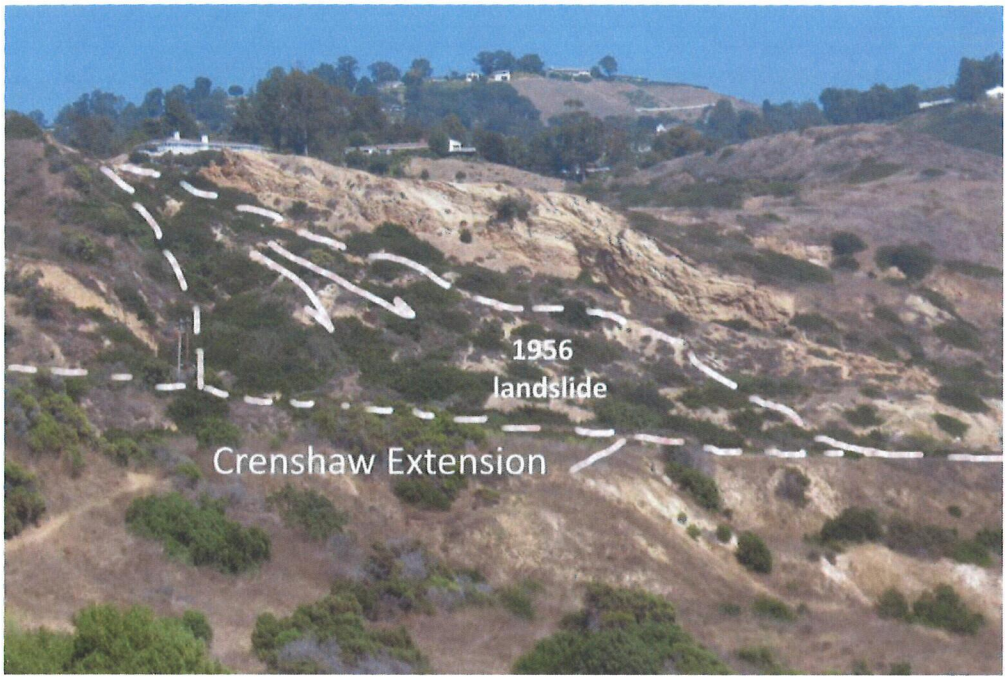


Figure 37. The small landslide that was triggered during road construction of the Crenshaw Extension in 1956. Approximately 160,000 cubic yards of material was removed from the landslide and dumped at the head of the Portuguese Bend landslide, contributing to its reactivation.



Figure 38. Upper surface of the small landslide in Figure 36 showing pillow basalts that have been altered by hydrothermal fluids, probably at the time of their emplacement.

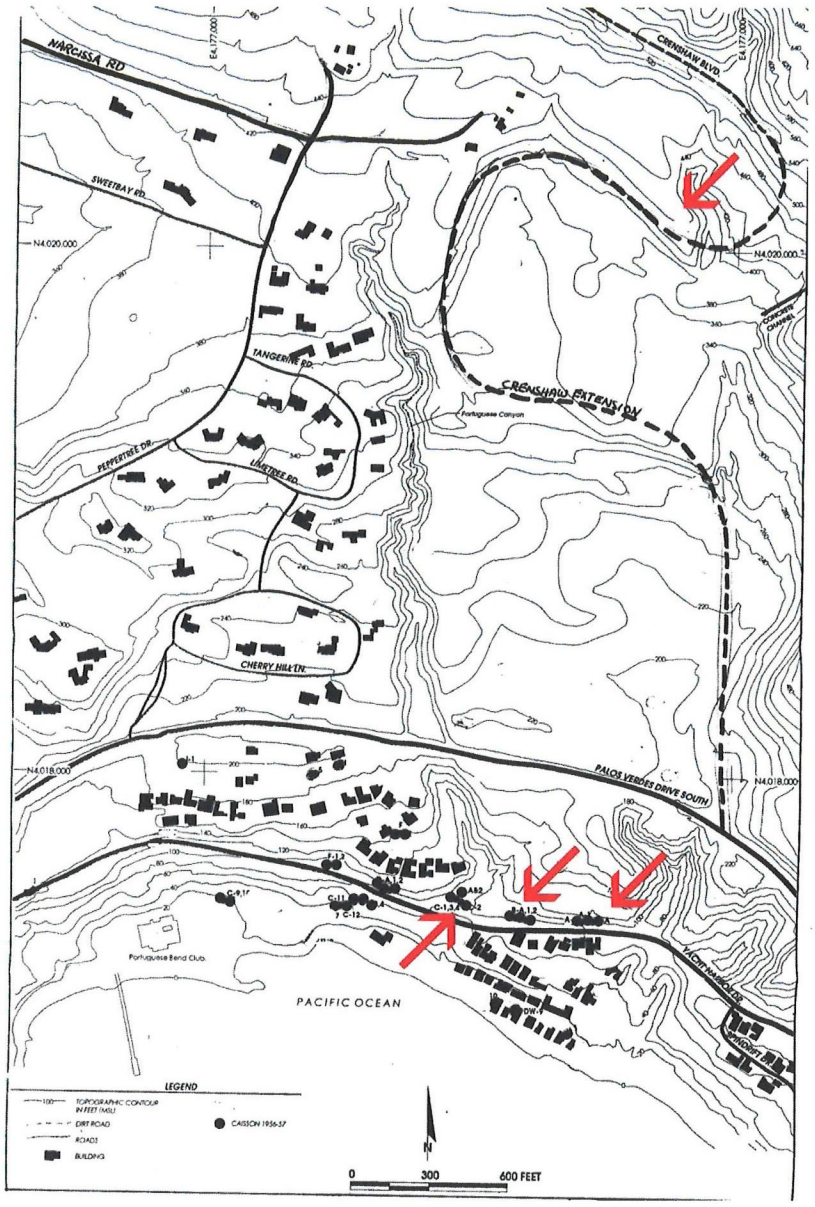


Figure 39. Map of the Portuguese Bend area in 1956-57 showing the then existing roads, houses, the Portuguese Bend Beach club and pier and proposed Crenshaw Extension. Also shown is the location of the caissons (•) (small red arrows) embedded just north of Yacht Harbor Road in 1956-57 by Los Angeles County and Palos Verdes Properties as the first attempt to halt the landslide. (modified after Ehlig and Bing Yen, 1997.) Upper red arrow is the approximate location of original failure.





Figure 40. (top) Aerial photo of the Portuguese Bend area in early 1956. Crenshaw extension is under construction but has not crossed Portuguese Canyon. The light spot below the switch-back in the center-right of the photo is the approximate location where the Portuguese Bend landslide movement began. (below) A view of the Portuguese Bend Beach Club and pier showing the scarp (curving white line) located behind the clubhouse in 1947.



Figure 41. Oblique aerial photograph of the Portuguese Bend area taken in the early 1960s after the Portuguese Bend Club and houses between Palos Verdes Drive South (road in the middle of the photo) and the beach had been removed. The Club's damaged and abandoned pier can be seen at the water's edge. Inland (upper right in photo) can be seen the fields that James Ishibachi was still farming. This area today is depressed below the road level as grading removed about 10 million cubic yards of material in an attempt to stabilize the landslide. (Photo courtesy of Bernard Pipkin.)

Subslides and Movement

The first indications of the slope failure that evolved into the Portuguese Bend landslide occurred in 1956. The County of Los Angeles was in the process of extending Crenshaw Blvd. to connect Crest Road with Palos Verdes Drive South and as the grading and canyon fill proceeded down the south flank into the Portuguese Bend area, a small landslide developed NE of the current landslide area (a small triangle-shaped landslide labeled 1956 in Figures 37, 38). Subsequently about 160,000 cubic yards of this slide material was used to establish a suitable grade into the Portuguese Bend area (Figures 39, 40, 41). On August 17, 1956, after placement of this fill, road engineers observed cracks in a recently completed road culvert and additional ground cracking quickly developed in the area and progressed southward. By September, a crack and four inch offset were observed in Palos Verdes Drive South along the eastern margin of the reactivating landslide and by October deformation was evident in the pier of the Portuguese Bend Club. The rapidity with which the landslide expanded strongly suggests that it was just barely stable at the time and the build-up of pore-water pressure following the heavy rains of the early 1950s and the domestic water from the newly constructed homes had brought it to a near-failure level. The sequence of development of the landslide is shown in Figure 42.

Based on variation in the rate of movement and amount of deformation, Perry Ehlig (then the City of Rancho Palos Verdes geologist) divided the landslide into several subslides, here simplified as the (1) eastern, (2) central, (3) seaward, and (4) western and inland subslides (Figure 40). From the beginning, the eastern, central and seaward portions of the landslide have been more active with higher rates of deformation than the inland and western portions and only

the small areas immediately inland from the two points, Portuguese Bend and Inspiration Points, have remained stable. This pattern has continued for the past 55 years.

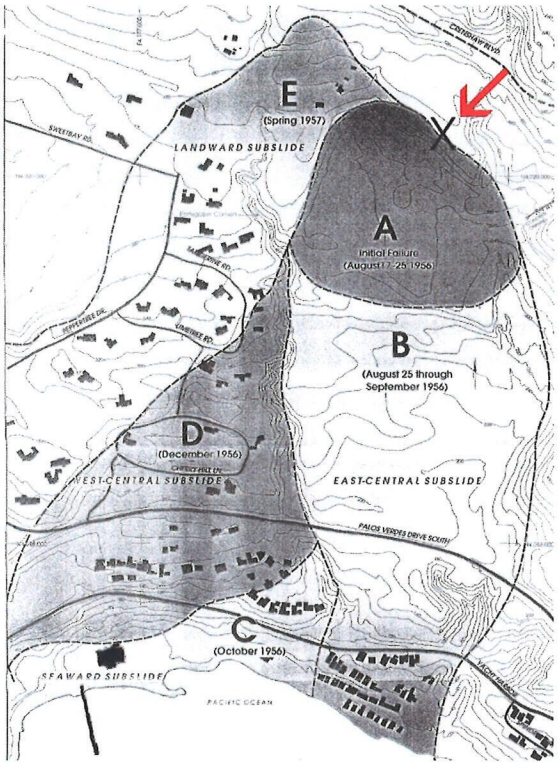


Figure 42. Approximate sequence in which the Portuguese Bend landslide developed following the initial movement (marked by the X located at the arrow). A-Aug 15 to 25, 1956; B-Aug. to Sept. 1956; C-Oct., 1956; D-Dec., 1956; E-Spring, 1957. (Modified after Ehlig and Bing Yen, 1997.)

Rates of movement over the years generally have ranged from less than 0.01 to several feet per year but in the beginning and during rainy years, movement has been more than an inch per day with the highest rates in the eastern and seaward subslides. Until recently rates in the western-inland subslide were less than 0.5 ft/yr. Generally the landslide accelerates during years of higher than normal rainfall and slows during droughts.

Although 1956 is usually given as the beginning (reactivation) of the Portuguese Bend landslide, Ehlig discovered evidence in early aerial photographs of movement prior to 1948 in the area directly behind the Portuguese Bend Club. Fresh scarps in this area are not seen in photos taken in the 1930s. Evidence was also found that the Portuguese Bend club pier experienced damage in 1946, in the same place that it failed in the 1956 landslide. It seems clear that movement began long prior to 1956 and the real question is how long has the area been unstable and prone to landslide movement? Judging from aerial photographs taken in the early

20th century, movement had been occurring for at least centuries. A more precise answer requires understanding the origins of the larger, ancient Altamira slide from which the Portuguese Bend landslide formed.

The rolling, hummocky topography of Portuguese Bend was recognized by Kew in 1926 as a landslide terrain. Woodring, Bramlette and Kew (1946) in their classic U. S. Geological Survey Professional Paper 207, based on geological mapping done in the 1920s and 30s, carefully documented the large, ancient Altamira landslide, reactivated portions of which now form the Portuguese Bend, Abalone Cove and Klondike Canyon landslides. They concluded that it was old, extending back into the Pleistocene (Ice Ages). Pond sediments exposed in a road cut along Palos Verdes Drive South (now destroyed by grading) contained fossil charcoal material that was radiocarbon dated by Emery (1967) as 4,800 ± 180 years old. The depression which held the pond, much like "Lake Ishibachi" which formed in the same area in later years, was created by landslide movement. The date provides evidence that movement in the Portuguese Bend landslide has been occurring for at least several millennia.

So, to answer the original question, the historic Portuguese Bend landslide reactivated in 1956 but the landslide is part of a much older feature, the ancient Altamira landslide that dates back at least 700,000 years. Based on the hummocky topography, the area was recognized as a landslide terrain in the 1920s and evidence suggests that movement has been occurring off and on for millennia and well before the residential development of the 1940s and 50s.

Role of the Bentonites

In the area of the Portuguese Bend landslide, only beds of the lower Altamira shale are present, all of the younger members of the formation have been removed by erosion in the geologic past. As mentioned earlier, this portion of the Altamira Shale contains varying amounts of volcanic ash (called tuff), including beds that are nearly pure ash. Of critical note is the presence of interbedded sequences of thin ash-rich shale, clays and bentonitic clay. These sequences form impermeable zones that become the shear zones which fail and create slip surfaces or zones.

Bentonite clay is weak, with little internal cohesion, and under pressure (stress) becomes plastic and flows. Experiments have shown that when bentonite is repeatedly stressed, it becomes even weaker and will undergo plastic flow on slopes of only a few degrees. When bentonite is exposed to ground water it swells and forms impermeable layers (called aquicludes) that prevent or impede the upward or downward flow of water. As ground water builds up under bentonite layers, it increases the pore-water pressure and when the water is confined or trapped, the pore-water pressure can increase to the point where it equals the weight (pressure) of the overburden. In such cases, the overlying rocks are actually being lifted, reducing the friction along the rupture surface. The result is slope failure and movement. However, the numerous small cracks or fissures in the siliceous and tuffaceous shale allow some ground-water flow, albeit slowly, and the failure condition tends to occur only when there is an increase in the water table. In the case of the Portuguese Bend landslide (and the other landslides in the area resting on tuff and bentonite), it appears that pore-water pressure is just enough to allow for plastic flow in the bentonites and steady, slow movement (creep) of tenths of an inch per year (mm/d). In years of high rainfall, the additional infiltration of storm water to the ground water, largely through the bottom of the major canyons and surface fractures, causes pore-water pressure to increase and landslide movement to accelerate.

Subsurface Structures

Boreholes drilled through the Portuguese Bend landslide have helped to reveal several small geological structures in the bedrock which play a significant role in the landslide's movement. These structures confine the landslide to a shallow depression that prevents its lateral expansion. On the eastern margin there are very steep, westward dipping shale beds (a monocline) that forms an eastern barrier (Figure 43); to the north is a small E-W trending anticline with steeply dipping beds in the southern limb that forms a northern barrier and in the subsurface, located approximately underneath Portuguese Canyon in the middle of the landslide is a small north-south trending fault that offsets the bedrock and basal beds of the landslide (Figure 36). The fault forms the boundary between the central and western subslides and tends to confine higher rates of movement to the east. Collectively these structures form a shallow trough or depression along which the landslide is moving. What may also be important in the western area of the landslide is the distribution of the major basalt sills in the subsurface. Also in the subsurface are two small flexures (Figure 44) that, like the anticline in the north, trend basically west to east. As the landslide moves over these flexures they cause vertical fractures in the landslide and impede movement. The northern flexure creates the boundary between the eastern and inland subslides. According to Ehlig, the landslide rupture surface (slide plane) in the north is contained in a thin bentonite bed interbedded with volcanic ash located near the top of the Portuguese Tuff whereas near the shoreline it is at the base of the Tuff. Elsewhere, the basal rupture can occur in a variety of lithologies, generally above the Portuguese Tuff.

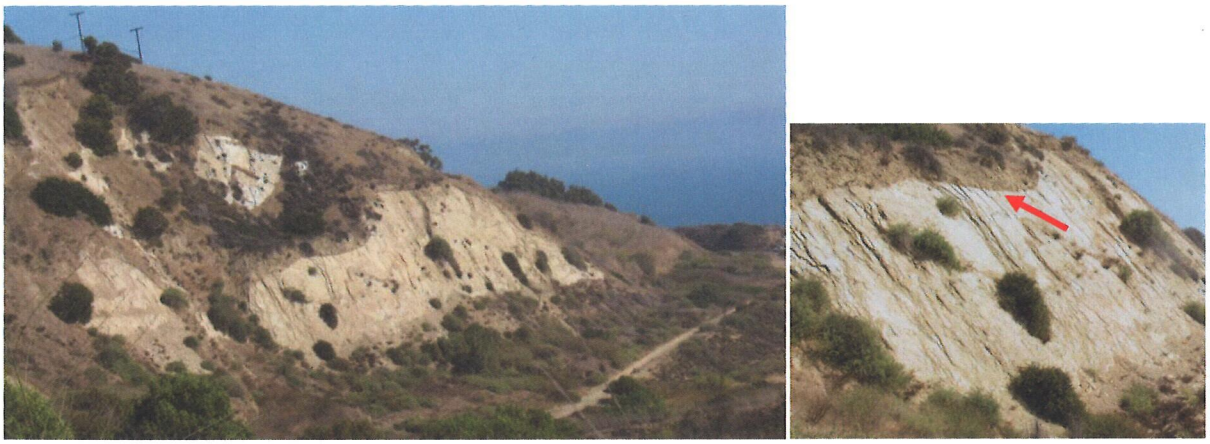


Figure 43. An exposure of the steeply dipping beds of Altamira Shale that form the eastern margin of the Portuguese Bend landslide. The view is south. (right) Close up of the outcrops showing the thinly bedded shale. The contact at the top of exposure (arrow) is the trace of the old road that crossed the area in the 1930s.

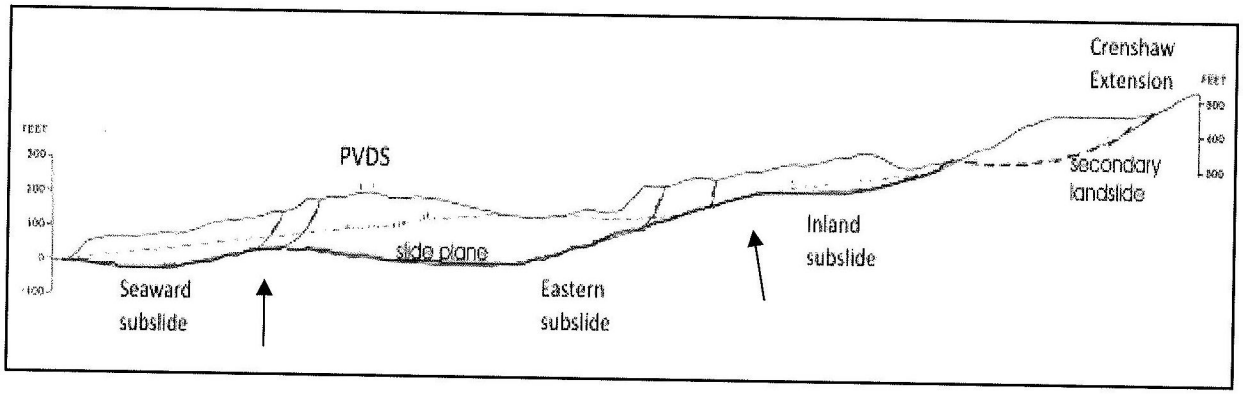


Figure 44. A cross-section of the Portuguese Bend landslide through the eastern margin of the landslide. Note the two small flexures (arrows) in the bedrock below the slide surface over which the landslide must move. These flexures tend to divide the landslide into the subslides. (Modified from Ehlig, 1986; 1992.)

Remediation Efforts

Numerous efforts have been made over the years to halt the land movement in the Portuguese Bend landslide, including regrading and shifting landslide materials, gabions and caissons, installation of culvert drains, dewatering wells, and altering the geochemistry of the bentonites. Initially, the Los Angeles County road engineers believed the landslide would be short-lived and stop by itself.

When it became clear that movement was continuing, the County of Los Angeles and Palos Verdes Properties (the major landowner at the time) attempted to "pin" the landslide by insertion of shear pins; 4 ft- diameter, 20 ft-long, steel-reinforced caissons that were embedded 10 ft into the bedrock below the failure surface (rupture plane). Twenty-three pins were emplaced, mostly located south of Palos Verdes Drive South in the seaward subslide (see Figure 38). The landslide slowed from 0.8 to 0.25 in./d for about five months but in early 1958 abruptly returned to its earlier rate of movement. The shear pins had failed and several intact caissons ultimately were displaced to the shoreline by landslide movement. In 1993 a caisson appeared on the eastern edge of the landslide that had traveled more than 700 ft from the point where it was installed in 1956. Pieces of the caissons can still be found on the beach at the toe of the landslide.

Following a series of rainy years in the late 1970s and early 80s which increased movement, the City of Rancho Palos Verdes in 1984 initiated the first of a series of steps to halt the landslide. Funded by a $2 million grant from the City's Redevelopment Agency (RDA), these efforts were directed by Perry Ehlig and continued for the next fifteen years (until his unexpected death in 1999). They involved several projects: (1) Extensive grading and shifting of landslide materials from the interior of the eastern and central subslides to the toe, (2) installation of dewatering wells, (3) installation of gabions along the beach to reduce wave erosion, (4) building a culvert system to convey storm water from Portuguese Canyon across the landslide to the ocean, and (5) initiating an experiment of injecting fluids to facilitate a sodium to calcium cation exchange in the bentonite clay to increase its strength.

During the three phases of regrading to shift weight from the middle of the landslide to the shoreline (thereby increasing the friction at the toe) more than 10 million cubic yards of material were moved. In the mid 1990s, the mound of soil and debris created a 30-80 foot high sea cliff at

the shoreline (Figure 45). Ultimately wave erosion over the next 15 years removed nearly all of this material. Today, there is little evidence of the mound that once existed at the toe.

Based on the success of dewatering wells in lowering the ground-water table in the Abalone Cove landslide, about twenty five dewatering wells were drilled, located mostly across the upper and western part of the landslide. The wells extracted ground water at rates of up to 20,000 gal/d from within and below the landslide in an effort to reduce pore-water pressure and increase stability. Unfortunately, the wells were drilled in the mid-1980s following the years of high rainfall and when landslide movement was high. Well pipes were deformed and ultimately sheared in many of these wells, typically within a matter of a few years after their installation; others were shut down due to low production. Today, only six wells located in the northeast corner of the inland subslide remain operational.

Following intense wave erosion of the landslide toe by El Niño-generated storms in the 1980s, gabions, steel-mesh, rock-filled baskets, were placed at the base of the sea cliff in an attempt to reduce cliff erosion and protect the materials which had been shifted to the toe. The gabions had limited success and eventually were destroyed by wave action. Pieces of them can be found at the shoreline.



Figure 45. View looking north from Inspiration Point at the sea cliff at the toe of the Portuguese Bend landslide in 2006. The cliff was 30-80 ft above the beach as material graded from the central and eastern subslide was placed on the toe to increase its weight and friction. As can be seen in the photo, the material was being rapidly eroded by wave erosion.

One of the most controversial remediation measures is the 24-inch-diameter steel culvert storm drain that crosses the landslide. The culvert originally linked the storm outlet in Portuguese Canyon, where the Crenshaw extension crosses the canyon, to the ocean. Much of the steel culvert is a half-round to allow easy access for debris removal (Figure 46). The culvert crosses the lower part of the eastern and central subslides and as movement has occurred, it has changed the grade, disrupting flow in the pipe and separated the pipe segments. It was expensive to install and had a very limited life and was in disrepair nearly from the beginning. Also, by 2004, the culvert had separated at the junction with the outflow from Portuguese Canyon and storm water from the canyon now flows directly into the head scarp of Portuguese Bend landslide.



Figure 46. A view of the steel culvert ("half round") which was designed to convey storm water from Portuguese Canyon, across the landslide to the ocean. Due to landslide movement the pipe separated and was ineffective. The culvert is now separated from the outlet at Portuguese Canyon which allows storm water from the canyon to flow directly into the head scarp of Portuguese Bend landslide.

Low shear strength is the major reason why bentonite or bentonitic clays are typically the materials which fail and form the basal rupture surface in the Portuguese Bend landslide. Thus, Ehlig reasoned that if it were possible to increase the strength of the bentonite clay then it would be possible to prevent the bentonites from failing or at least to increase the friction at the slide plane and reduce the rate of movement. Bentonite is a type of montmorillonite clay which can be sodium or calcium rich, the sodium rich variety being the most common in the area and also much weaker than the calcium variety. Engineers have long known that it is possible to increase the shear strength of clay by the addition of lime (calcium ion). In theory, exchanging calcium for sodium within the bentonite has the potential for increasing the shear strength and improving the stability of the landslide. Laboratory tests showed that the addition of $CaCl_2$ to bentonite from the area could increase its strength by 70 percent so Ehlig proposed a field experiment in which calcium-rich fluids were injected at the rupture surface in order to facilitate a cation exchange (Ca^{++} for Na^{++}). The experiment was conducted at the margin of the eastern subslide where the slide surface is a 3-inch-thick bentonite bed at shallow depth. A series of 6-inch-diameter PVC pipes were inserted through the landslide, down to the rupture surface and calcium chloride solution injected. The experiment was conducted for about a year and discontinued shortly after Ehlig's death in 1999. While the cation exchange to strengthen the bentonite was a clever idea, the results from the short experiment were inconclusive. However, there are good reasons to doubt that the method would have worked, primarily because 1) the impermeable nature of the bentonite that prevents fluid flow within the clay, and 2) whether enough bentonite could have been strengthened to really improve the stability of the landslide.

In sum, while some of the remediation efforts caused temporary reductions in the rate of movement, by 2005 the landslide movement had returned to pre-1984 rates and it is safe to say that none of the remediation efforts have had a long-term effect of halting movement of the landslide. The City of Rancho Palos Verdes' Redevelopment Agency eventually invested more than $3 million in the attempts to halt and stabilize the Portuguese Bend landslide. Despite the setbacks, Ehlig remained confident that the landslide could be halted. It is interesting to speculate what might have occurred if Perry Ehlig had lived and been able to continue the remediation efforts. The outcome might have been quite different.

The Landslide 50 Plus Years Later

In the years since the Portuguese Bend landslide reactivated there have been many changes, some resulting from the continuous deformation and movement and some from the efforts to stabilize and halt the land movement. When the landslide began, two roads crossed the area, one near the beach that provided access to the beach homes and the Beach Club and Palos Verdes Drive South, and several small residential lanes. Only Palos Verdes Drive South remains, after having been relocated twice to accommodate the constant shifting and it remains in need of constant repair. The seaward road (Yacht Harbor Drive) is long gone and many of the small lanes have had to be rerouted. In the 1950s, Palos Verdes Drive South was bordered by a road-cut 20 ft higher than the road on the inland (north) side of the road (see back page photo). This area is now a depression ("the sand box") that floods during major rain storms. The material was removed as part of the remediation effort and relocated to the toe of the slide. Over the past 20 years the mound at the sea cliff has been eroded away by wave action and the seaward subslide now tilts seaward, further jeopardizing Palos Verdes Drive South.

In 1956 two canyons cut across the area. Portuguese Canyon (see Figures 18, 39; back page photo) was a deep ravine that bisected the area and conveyed rain water to the ocean. The ravine is now abandoned, cut-off from its head-waters by the growing depression (graben) at the head of the landslide. Storm water from the upper canyon now flows directly into the head of the landslide. Paint Brush Canyon was located along the eastern margin of the landslide. Grading destroyed the canyon and storm water from upper Paint Brush Canyon now dumps into the head scarp. The rate of movement in 2010 remains unchanged (hundredths to tenths of an inch per day) from historic averages; in that year the central and eastern subslides moved over 2 ft while the seaward subslide moved more than 5 ft. Of the many remediation projects completed in the 1980s and 1990s, only six dewatering wells, located in the northwest corner, close to Peppertree Lane, are still operational. All the others have failed or are no longer operational. And the landslide keeps moving.

Chapter 8—Abalone Cove Landslide

Following years of heavy rainfall in the mid 1970s, ground water built up in the Abalone Cove area and caused another part of the ancient Altamira landslide complex to move, the Abalone Cove Landslide (Figure 47). The first signs that the landslide had reactivated was observed in a small road to the beach. Cracks in the road and indications of movement were noticed by engineers for the County of Los Angeles at the beach in 1974, they continued to spread inland and by 1976 extended north of Palos Verdes Drive South. By 1978 fractures were detected in lower Narcissa Drive and residents reported significant cracks, buckling, and other signs of distress caused by landslide movement. It was clear that the hillside and the houses it contained were moving. Ultimately 80 acres would become involved in the landslide.

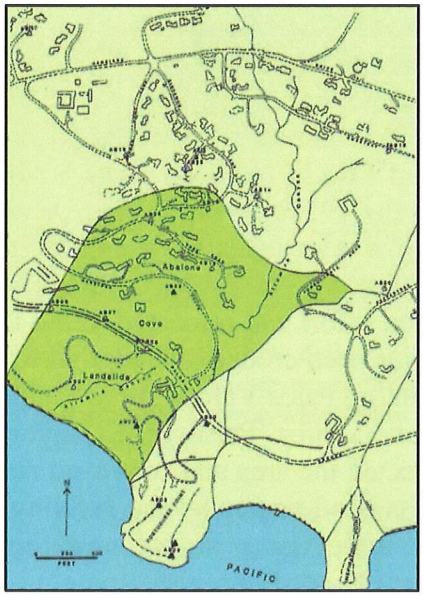


Figure 47. Abalone Cove landslide (dark green) and the community that surrounds it. The slope failure covers about 80 acres and was reactivated in 1978.

Residents of the area joined together and retained geologists and engineers to evaluate the slide and suggest solutions. Robert Stone and Associates recommended seven dewatering wells be drilled to remove water and lower the ground-water level. This was done and by 1981 ground-water levels in the landslide had been lowered 15 to 25 ft and movement significantly decreased.

Following the experience of the Portuguese Bend landslide, the Abalone Cove movement was recognized as a major geological hazard. Perry Ehlig (then City Geologist), Rancho Palos Verdes city officials, and state representatives introduced a bill in the state Legislature that created geological hazard abatement districts in which communities can help themselves by assessing the residents to pay for mitigation efforts. The Abalone Cove Landslide Abatement District (ACLAD), established by a vote of the residents in 1981, was the first geohazard district created under the new state law. ACLAD is a joint creation of the residents, the city and the state and is a political subdivision of the State of California. It remains the only geo-hazard abatement district managed by local residents/property owners.

In 1982 a number of property owners filed suit in Superior Court against the City of Rancho Palos Verdes and County of Los Angeles contending the landslide was due to failure to control

rainwater runoff in the area. As part of the plan to effect a settlement, a panel of geological and engineering experts (Perry Ehlig, David Cummings, Rickard Krankian, Richard Meehan, John Mann and James Slosson) was jointly appointed by the City and residents. The panel initiated a series of field investigations and analyses, including drilling six new boreholes (ACL 1-6), several with piezometers (to measure water pressure) and slope indicators and a model analysis of slope stability to calculate the factor of safety. They also recommended several remediation measures, including 1) installation of a domestic sewer system, 2) drainage improvements in Altamira Canyon and along streets and improved lots, and 3) construction of a toe berm and shoreline protection to reduce wave erosion. Installation of the sewers finally occurred in 2000 and significantly reduced the infiltration of domestic water into the ground water. For a variety of political and financial reasons, the shoreline and Altamira Canyon protections were never pursued.

The north to south cross-sections of the Abalone Cove landslide (Figures 48, 49) illustrate the evolution in the understanding of the landslide. In the beginning, borehole information derived from studies of the area in the 1960s suggested that the landslide was a singe layer of rock and debris 100-110 ft thick moving towards the beach over beds of bentonite in the Portuguese Tuff. Similar to the Portuguese Bend and Klondike landslides, the slide zone extends to below sea level before abruptly ramping up and terminating at the shoreline, approximately at mean low water. Near the beach, the landslide is about 170 ft thick and extends nearly 100 ft below sea level.

As additional boreholes were drilled and instrumented with devices to measure ground-water pressure and landslide movement at different depths, our concept of the Abalone Cove landslide began to change. Data from the boreholes revealed that there is more than a single slip zone, that the landslide mass is thicker than originally understood and that movement is occurring at several depths, including a deep rupture zone. Another discovery was that the several slide (slip) zones are not always associated with the Portuguese Tuff but with thin beds of bentonite and clay that occur both above and below the slip zones. Basically the landslide is composed of three layers superimposed on top of one another with slip zones separating them (Figure 47). The landslide is a complex, compound landslide. The upper layer is the oldest and dates to an earlier phase in the landslide's history. The deepest layer is the youngest and most active with the rate of motion in the middle of the landslide being 0.3-0.5 in./yr. At the beach the rate is higher and in rainy years can approach 0.8 in./yr. GPS measurements over the past 17 years have verified these rates.

The model of landslide development discussed earlier (see p. 24-25) relates the slope failures to the interaction between the continuous tectonic uplift of the peninsula and the stand of sea level controlled by glacial/interglacial climate cycles. Activation of the landslides occurs when sea level still-stand allows wave erosion to cut a platform and sea cliffs like today. Based on this model, the upper landslide layer is older and dates to the previous interglacial period and high stand of sea level at 125 ka. This is the level of Terrace 2 that is found on the top of Portuguese and Inspiration Points and around much of the peninsula. The deepest landslide layer is the youngest and was activated when sea level reached its present-day level, about 5-6 thousand years ago.

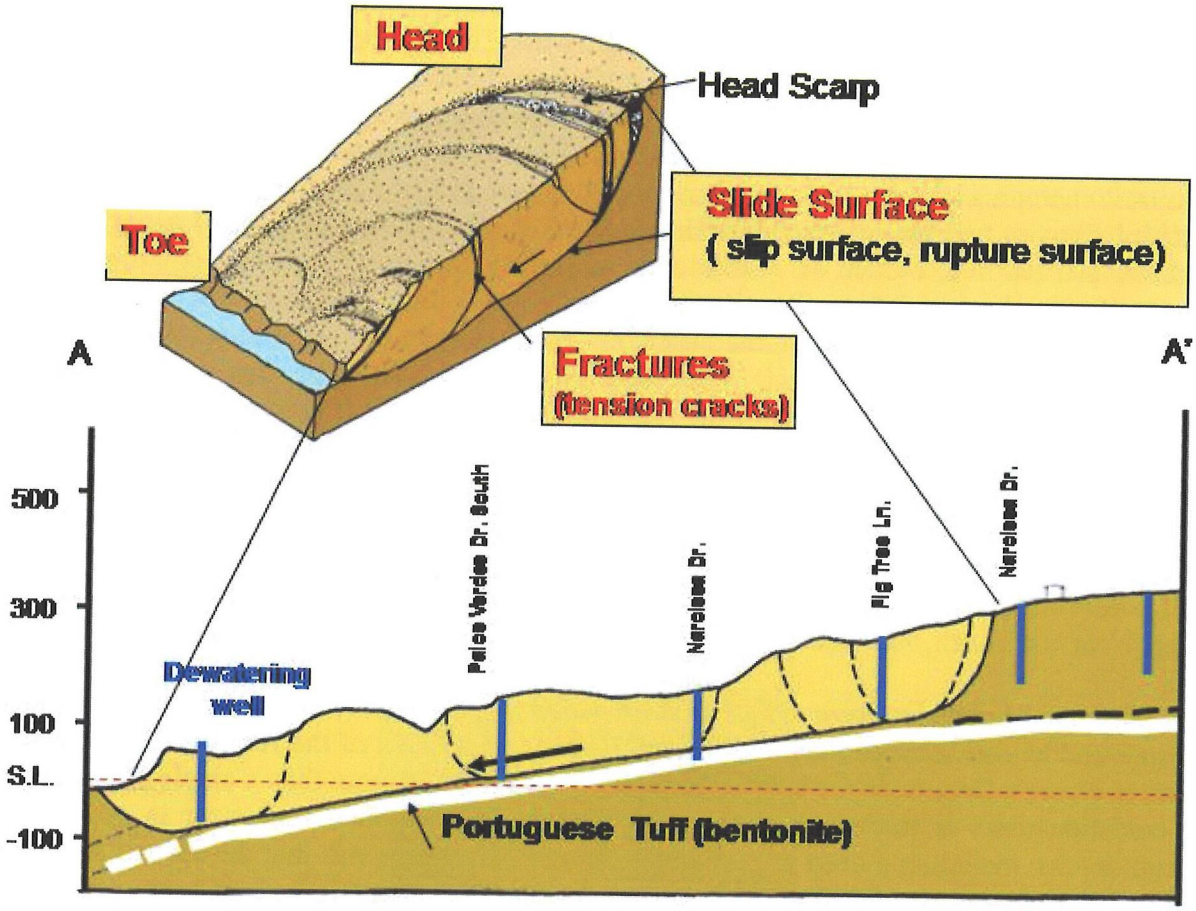


Figure 48. The Abalone Cove landslide as understood about 1979 (shortly after movement began) was a single mass of material about 110 ft thick riding on the bentonites of the Portuguese Tuff. Vertical lines indicate the location of early dewatering wells. (Based on Stone and Associates, 1979.)

The several slip zones, active and inactive, act as impermeable layers to ground-water movement and divide the landslide vertically into separate compartments that trap water (confined aquifers). Ground-water pumping indicates that the upper part of the slide mass responds to shallow ground-water movement and the deeper zones to deep ground water. Because the landslide extends below sea level at the toe, the rocks are water saturated and pore-water pressure is higher than in the middle or head of the landslide. This helps to explain why the area of the toe moves faster than the rest of the landslide.

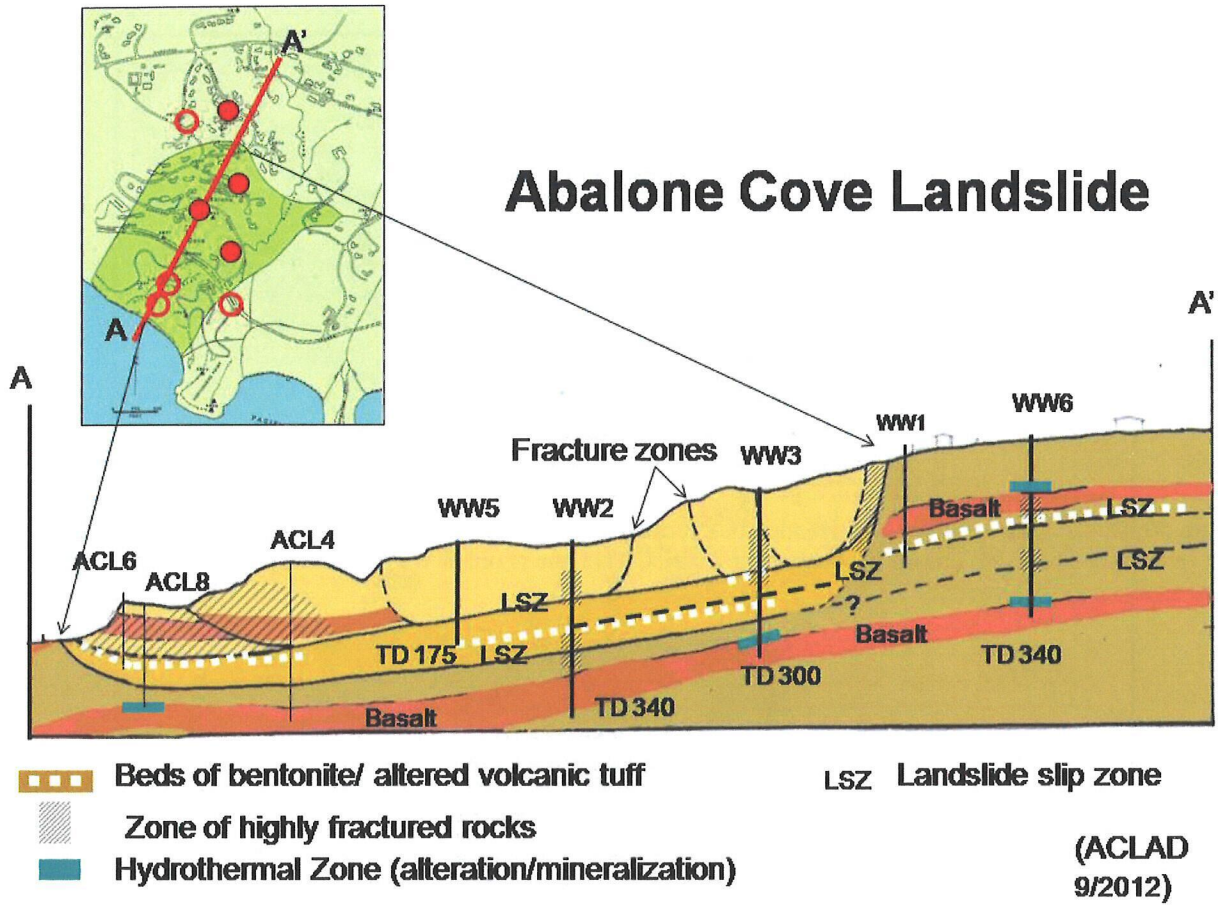


Figure 49. North-South cross section of the Abalone Cove landslide, approximately down the middle of the slide. Additional boreholes and down-hole instruments installed between 1984 and 1995 revealed a much more complex landslide of multi-slip/shear zones and a thickness of over 260 ft. A large basalt sill underlies the landslide at depth. Location of the boreholes and dewatering wells used for control are indicated by vertical lines (e.g. WW2; ACL6).

Dewatering Wells and Production

Following the seven original wells installed in 1979-80, additional wells have been drilled within and upslope from the Abalone Cove landslide (Figures 50, 52). In the past decade, many of the older wells have been re-drilled to 300-350 ft to intercept deeper ground water (Figure 53). Sixteen or seventeen wells are typically in production at any time and pump between 130,000 to 180,000 gallons per day (gal/d), depending upon the season and rainfall patterns. During the exceptionally rainy years in the 1990s production exceeded 300,000 gal/d. In the very dry years of the 2000s, typical production has been around 150,000 gal/d. Four of the original wells located in the Abalone Cove landslide no longer produce because of clogging from iron oxide (limonite) in the ground water (Figure 51), a common problem throughout the area. The source of the contaminant is the tiny pyrite crystals (composed of iron sulfide) in the basalt which break down when exposed to ground water. The iron oxidizes and mixes with water and clay to form a thick, yellow-brown sludge.



Figure 50. Dewatering well. A small wooden box located close to a power pole is the visible part of a dewatering well in the Abalone Cove Landslide Abatement District. This one is old WW2, located along Narcissa Drive, close to the entrance to the community.



Figure 51. Pump clogged with limonite (iron oxide and clay) mud extracted from the ground water during pumping. This is a major problem in the Abalone Cove landslide area. (Photo courtesy of Daphne Clark.)

Not all wells are equal producers, and generally the upslope wells pump significantly more water than the wells located within the landslide (Figure 52). About 90 percent of the water recovered comes from the area above the landslide (see graph in Figure 52). This is by design, so that the ground water is intercepted before it can enter the landslide. Ground water within the landslide is difficult to remove because of lower permeability, the iron oxide problem and slow, continuous movement at the slip zones eventually shear the well pipe where it pierces the zone. For this reason, WW2 has had to be re-drilled four times in the past 35 years.

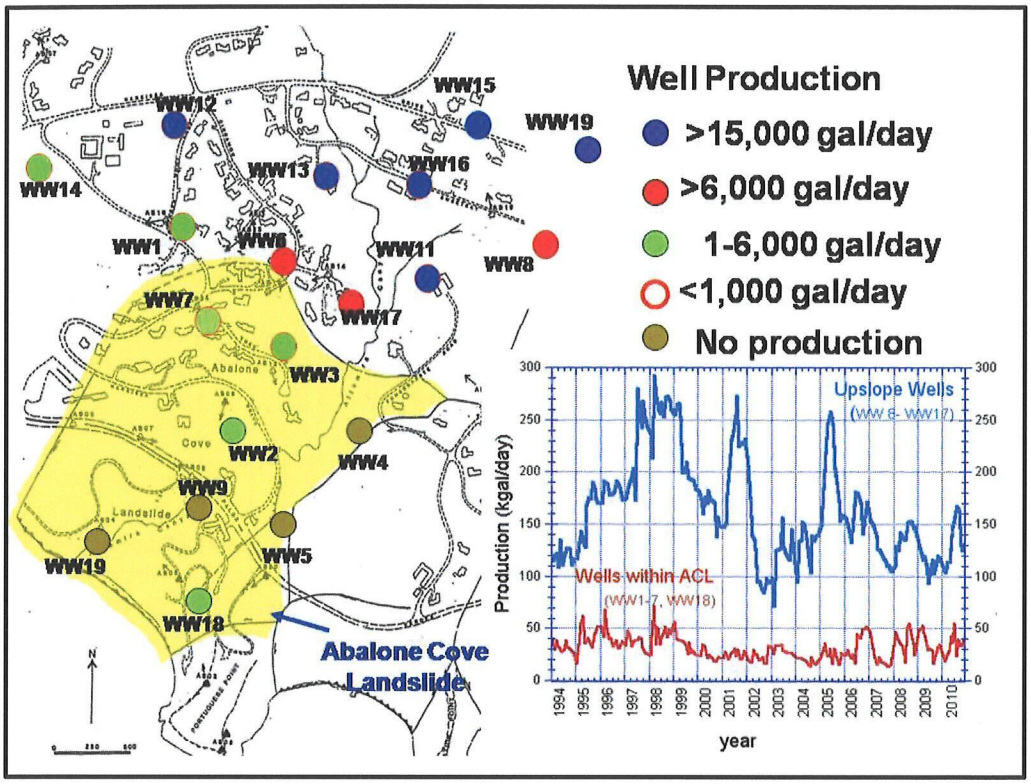


Figure 52. Location of the dewatering wells within ACLAD. Inset graph indicates the total production from within the landslide (red) and from wells upslope of the landslide (blue).



Figure 53. Re-drilling dewatering well WW6, located in a vacant lot between several houses. In such close quarters finding room to set up and operate drilling equipment is a challenge that requires the cooperation and support of residents, drilling companies and ACLAD.

Comparing the variation in well production offers useful insights into the flow of ground water in the area. There are three basic patterns: wells that pump from "shallow" ground water and whose production varies with annual rainfall patterns; wells that pump from deeper ground water

and whose production only varies with long-term climatic patterns; and wells located close to major fractures or Altamira Canyon with erratic production patterns.

Well WW13 illustrates production from shallow ground water recharged by Altamira Canyon and which fluctuates in close agreement with annual rainfall patterns. In contrast, well WW 15, draws from deeper ground water and varies little except for long-term rainfall patterns (Figure 54). Well production within the landslide varies considerably due to a number of problems: movement along the slip zone, occurrence of iron oxide sludge in the ground water, location close to fracture zones, etc. It is necessary to re-drill these wells about every 20-25 years in order to maintain a reasonable production.

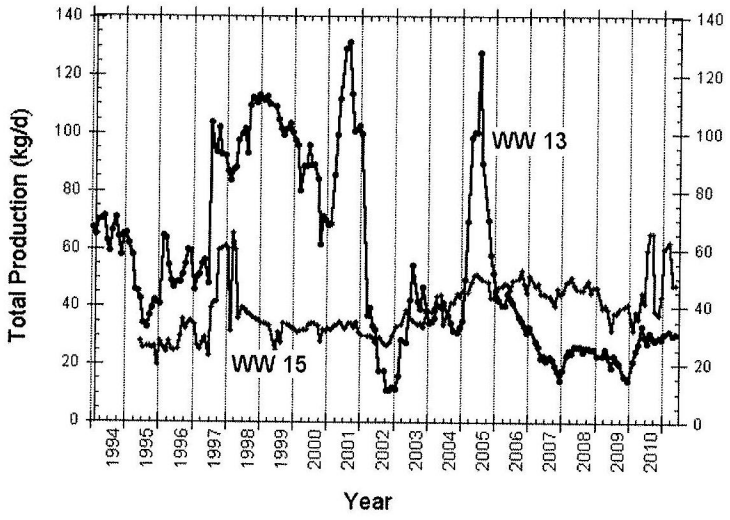


Figure 54. WW 13 is located near Altamira Canyon and drains old stream deposits at depths of 40- 120 ft. It is fed by storm water discharge from the canyon. Note the wide fluctuation in production that follows the long-term rain cycle; very wet in the 1990s, dry through most of the 2000s, except for 2005. In contrast, WW 15, located on Narcissa, east of Altamira Canyon, and directly downslope from the Kelvin Canyon spring, pumps at a relatively constant rate and varies little with time. It is pumping from deep ground water at 190 ft, fed in part by the spring that accounts for most of the year to year variations.

Dewatering well WW18 is located in the landslide toe area, close to the beach and just east of the outlet of Altamira Canyon. Its annual production varies considerably (Figure 55) and its monthly production can swing from very low, a few thousand gallons per day, to high, tens of thousands of gallons per day depending upon the storm discharge in Altamira Canyon. Clearly the well is being fed by water which infiltrates in the bottom of the canyon and through the numerous fractures which are located in the toe.

Well production can signal longer-term changes in the ground water (Figure 56). An example is on the western side of the drainage basin at wells WW14 and WW12. When WW14 was drilled in 1994, the two wells had about the same level of production, but over time, while the level has dropped at both wells, it has dropped much more at WW14, especially after about 2000. This decline agrees with data on the elevation of the water table that also has declined in the past decade. It appears that dewatering is slowly drying up the ground water on the western edge of the landslide.

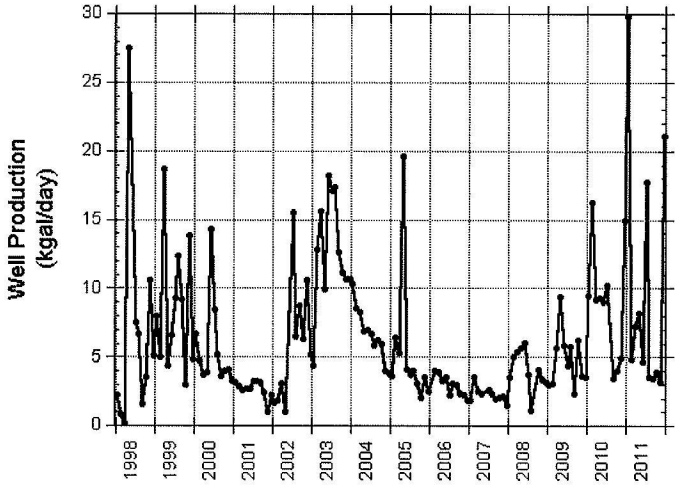


Figure 55. WW18 is located near the beach at the toe of the landslide. Its pump is located at 35 ft below sea level, any deeper and the well would pump seawater. It is also close to the course of Altamira Canyon, near its terminus. Production is irregular and can swing from a few thousand gal/d to over 20,000 gal/d when rainwater discharge from major storms flows out of the canyon.

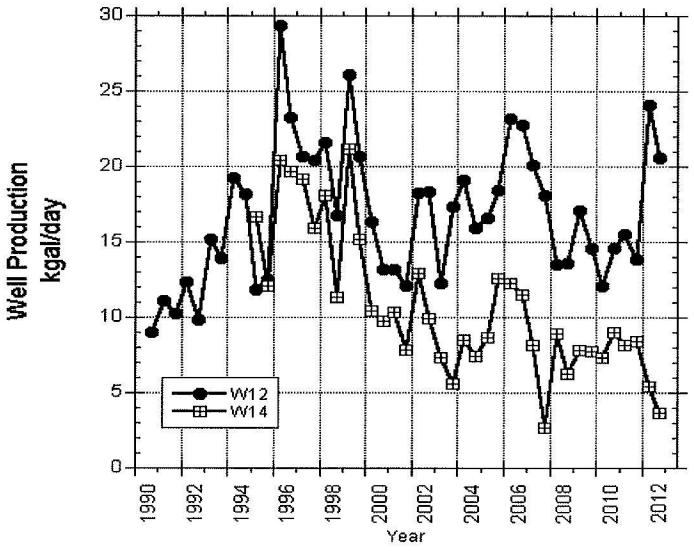


Figure 56. Two wells on the western edge of the Altamira drainage basin signal a slow, but long-term decline in the ground water, with the most dramatic change occurring at the western-most edge, WW 14.

ACLAD is often asked about using the well water rather than conveying it through a pipeline to the ocean. In the past 20 years, there have been four independent studies of the well water to access its potential use. The geochemical analyses of the well water conducted by the several agencies and by ACLAD are all in close agreement.. The well water has a high sulfur, iron, and dissolved solids content and doesn't meet State of California standards for human consumption and the high content of dissolved solids greatly reduces its usefulness for agricultural purposes (Table 1). The most recent study by the Water Replenishment Board of Southern California (2010) concluded that the capital cost of treating, blending, and pumping the water to potential

users is nearly $12 million and the resultant cost per acre-foot of water exceeds that of water available through the California Water Service.

As a result of the dewatering wells, ground-water levels within the Abalone Cove landslide as well as in the upslope area have been lowered significantly. The removal of ground water has been a critical factor in stabilizing the Abalone Cove landslide and the surrounding area, including portions of the ancient landslide complex. In the future, additional dewatering wells need to be drilled in the upslope area to intercept as much ground water, especially deep ground water, as possible.

Table 1. Abalone Cove nuisance ground-water quality (from Palos Verdes Groundwater Beneficial Reuse Study [2009]).

Parameter	Units	Typical Observed Range[1]	Average[1]	Drinking Water Limits[2]	Potable Water Quality (Avg.)[3]
Total Dissolved Solids (TDS)	mg/L	2,700 to 3,300	3,045	1,000 SMCL	436
Sulfate	mg/L	1,700 to 2,300	2,040	500 SMCL	134
Nitrate (as Nitrogen)	mg/L	5 to 28	17	10 MCL	0.6
Calcium	mg/L	411 to 561	464	None	44
Sodium	mg/L	258 to 463	351	None	78
Magnesium	mg/L	248 to 323	276	None	19
Potassium	mg/L	16 to 22	19	None	Not reported
Chloride	mg/L	389 to 563	450	500 SMCL	86
Bicarbonate	mg/L	410 to 517	462	None	Not Reported
Silicon Dioxide	mg/L	29 to 36	32	None	Not Reported
Conductivity	µS/cm	3,900 to 4,800	4,298	None	747

Footnotes:

1. Data provided by ACLAD, 1997-1998.
2. MCL = Maximum Contaminant Level
   SMCL = Secondary Maximum Contaminant Level.
3. Data provided by Cal Water per 2008 Water Quality Report.

Chapter 9—Slide movement

Types of Movement

Two frequently asked questions are, "Is the area outside the active landslides likely to move?" and, "Is the area stable?" Simple questions with complicated and somewhat controversial answers.

Recently the courts attempted to answer the questions in a lawsuit (Monks v. City of Rancho Palos Verdes, 2009) brought by several property owners of vacant lots. After reviewing many geotechnical reports the trial judge ruled that due to the differing and sometimes conflicting opinions that he could only conclude the area's stability was 'uncertain'. However, judges are not geoscientists and despite the frustrating differences, there is reasonable agreement among geo-experts who have spent many years investigating the area. Before getting to that, it is useful to review a bit about the kinds of "movements" that occur in the active landslides as well as in the ancient landslide complex.

It may be a surprise to learn that the entire peninsula, like nearly all of southern California, is dynamic and moving. The Palos Verdes Peninsula, for example, is a block of the earth's crust that is slowly drifting northwest at rates of 3-4 mm/yr relative to the Los Angeles Basin. The movement is taking place along the Palos Verdes Fault that forms the northern margin of the peninsula and separates it from the flatlands of Redondo Beach, Torrance, and Wilmington. The peninsula is also being uplifted about 0.3-0.4 mm/yr. Neither of these rates sound like much but when they are multiplied by thousands of years, it adds up. About a million years ago the peninsula was a shallow, offshore bank covered by seawater. It has been uplifted more than 1400 ft above present sea level (ignoring the elevation that has been lost due to erosion along the crest). This horizontal and vertical movement takes place so gradually that no one notices it. It is only with sophisticated satellite surveys that the motion can be detected and measured.

Another type of movement common in the peninsula results from something called "expansive soils." Weathering and erosion of the Altamira bedrock has produced a soil that is rich in clay minerals which have distinctive properties. These clays have the ability to absorb and expel water so that they can swell (expand) or shrink (contract), typical of what experts call adobe soils. When it rains, the clays in the soil absorb water, expand and become sticky. In the summer, they dry out, lose water and contract. In the dry months the soils in the area develop cracks, sometimes more than an inch across and up to a foot deep. In the rainy months, the cracks disappear as the clays absorb water. In the process of wet-dry, expansion-contraction, the soil on the hillside slopes responds to gravity and slowly migrates downslope. This is called soil creep and is the reason that tree trunks on hillside slopes are often curved. Expansive soils are also a problem for slabs or foundations or anything that is placed in or on the ground without proper footing. Expansive soil movement is related to rainfall patterns and can amount to tenths of an inch to inches per year (mm to cm/yr). Whether or not they realize it, most everyone on the Palos Verdes Peninsula knows about this expansive soil movement because it causes small cracks in walls, foundations and concrete slabs. In older houses with inadequate footings, it can cause significant damage over time. It often occurs in conjunction with compaction of the soils used in creating the material beneath building sites. Expansive soils and compaction together are responsible for much of the cosmetic damage seen in homes in the Abalone Cove area. The good news is that the effects of expansive soils can be controlled with adequate foundations and

simple good home maintenance habits like roof gutters and extended down spouts that empty onto the roads (the roads are the storm drain system in the area).

The GPS System

Finally, there is the movement due to mass movement. In active landslides the movement must be accurately measured and rates calculated in order to understand the mechanics of motion as well as to evaluate the effectiveness of any remediation efforts.. In the early days of the Portuguese Bend and Abalone Cove landslides, land surveys were made to measure the movement. However, land surveys are time consuming, difficult in rough terrain and the precision is too low for measuring very slow-moving landslides. When the satellite-based Global Positioning System (GPS) became available to the public in 1994, the City of Rancho Palos Verdes established a GPS-based surveying network to replace the land surveys. About 190 stations distributed over the greater Portuguese Bend-Abalone Cove-Klondike Canyon area have been installed over the past 18 years to monitor the annual movement in both the active landslides and the ancient landslide complex. Approximately 68 of these stations are currently in use (Figure 57) as many stations have been destroyed over the years due to movement in the active landslides as well as by human activities (e.g. trenching and road work). Since 2007 the system has been maintained and surveyed by McGee Surveying Consulting of Santa Barbara under contract to the City of Rancho Palos Verdes.

Based on the GPS measurements, the landslides are moving at rates that range from a barely detectable "extremely slow" (hundredths of a foot per year) to "slow" (tens of feet per year). The two active landslides are moving at very different rates although they were more comparable in the early stages of the reactivation of the Abalone Cove landslide.

Today, movement of the Abalone Cove landslide ranges from 0.01 ft/yr to 0.1 ft/yr, with the toe area moving the fastest. Since its reactivation in the past 35 years areas along the beach, at the toe of the landslide, have been displaced about 35 ft with most of this movement occurring in the years prior to 1985. Since the GPS network was established in 1994, the total displacement has been about 2.5 ft (Figures 58, 59). While the GPS network permits a reasonable assessment of movement within the active landslides, the precision of the method is at its limit and barely adequate to detect very small changes that might be occurring within the ancient landslide complex. Measurements collected over the past 15 years suggest a small (tenths of an inch scale) southward shift in some of the stations upslope of the active landslides, data that support the idea that the ancient Altamira landslide is a very slow-moving failure.

When the Abalone Cove landslide reactivated in the late 1970s, it was moving several inches per day but as the dewatering wells were installed, the movement came to an apparent halt. Generally, today, movement is mostly limited to periods of high rainfall, usually when the annual rainfall exceeds about 20 inches (Figure 60) and occurs largely in the toe region of the landslide, near the beach and along the fracture zones that cross the landslide. Following the heavy winter rains of 2004-05, "accelerated" movement that lasted a few months caused cracking in a few houses within the landslide. GPS measurements indicate that the toe of the landslide, where ocean waves erode it, undergoes slow creep even in dry years. Despite the dewatering wells, the large number of fractures in the landslide permit rainwater to infiltrate directly into the ground water, so that the pattern of small movement during wet years and slow creep during exceptionally dry years will continue into the future.

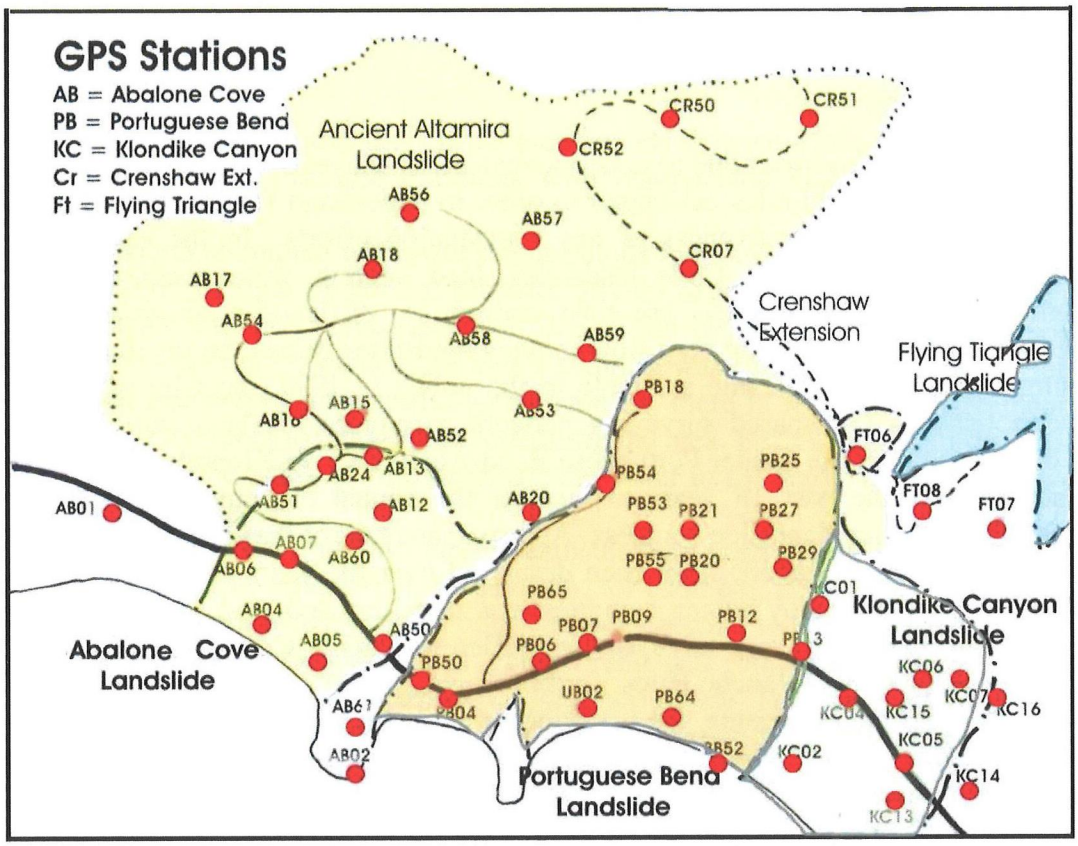


Figure 57. Map of the Global Positioning System (GPS) stations in the area. Currently about 70 stations are measured each year and provide the basis for calculating the amount and rates of motion occurring in the area. Stations within the active landslides, especially the Portuguese Bend landslide, must be replaced every few years due to displacement and vandalism.

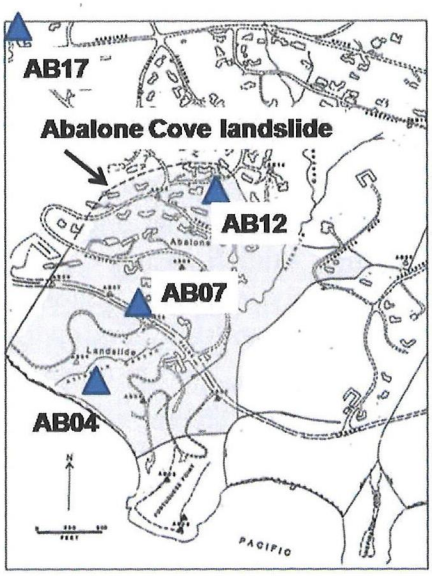


Figure 58. GPS measurements of landslide displacement in the Abalone Cove landslide. Location of selected GPS stations, three of which (AB04,07 and 12) are within the active landslide; AB17is in the "stable" area (Ancient Altamira landslide) upslope of the landslide.

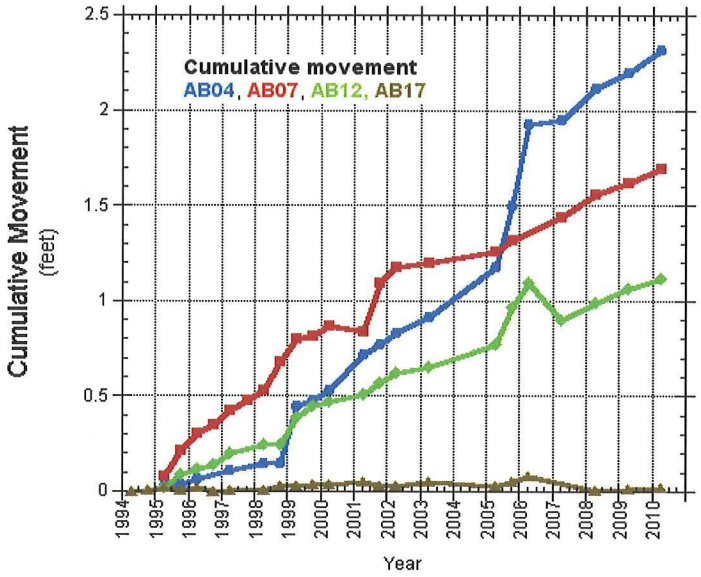


Figure 59. Cumulative displacement of the stations in Figure 56 since 1994 when the GPS network was established. AB04, near the toe, has moved about 2.5 ft while AB12, at the head, has moved about a foot. AB17 appears to have moved little.

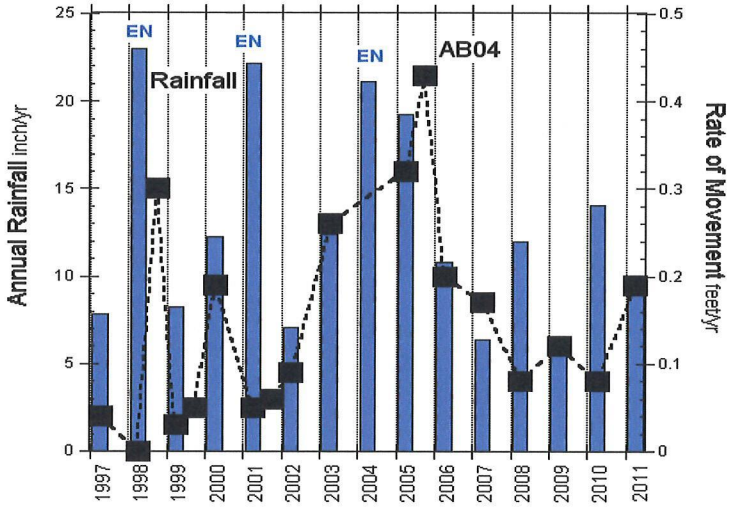


Figure 60. Comparison of the rate of movement at AB04 (square dots) and annual rainfall (bars). Note the significant increase in the velocity at AB04 following the major storms of 2004-05 and 2005-06. Under low rainfall of the past several years, the velocity has decreased.

In the Portuguese Bend landslide, movement began dramatically with the 1956 reactivation and the landslide has never stopped moving since. The rate of movement varies considerably within and across the landslide, with the highest velocities occurring in the eastern and seaward subslides (see discussion under Portuguese Bend landslide). It is difficult to determine the total horizontal displacement today because so much of the original beach area has been destroyed. Based on old survey records and a comparison of 1950s topographic landmarks to the present-day, the total displacement of the landslide is at least 800 to 900 ft in the seaward subslide. At the head of the landslide, a house which was originally at the end of Narcissa Drive is today

located near the end of Peppertree Lane, an offset of about 540 ft. In the western subslide, movement was very slow for many years and only in the past 20 years have rates exceeded about 0.01 ft/yr. Currently the face of the sea cliff in Sacred Cove is eroding rapidly, at several inches to a foot per year and the rapid movement is jeopardizing Palos Verdes Drive South by removing lateral support to the road.

Using the GPS measurements, a long-term pattern of differential movement can be seen in the Portuguese Bend landslide (Figure 59, upper right). Stations at the toe (near the beach) and in the center of the landslide are moving faster than stations located at the road or at the head. The east-central stations, including PB 20, 25, 27 and 29, are currently moving at 2-3 ft/yr, relatively slow, compared to years when the rainfall exceeds 20 inches (Figure 61). Stations near the beach are moving at rates of many feet per year. During the El Niño rains of 1997-98 and 2005, rates exceeded 8-10 ft/yr (Figure 62).

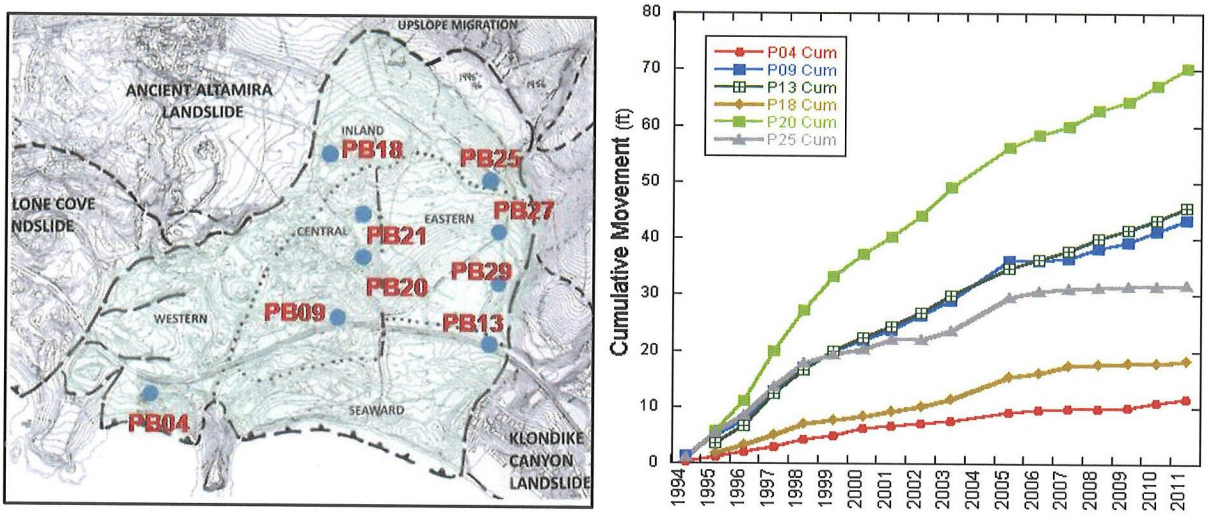


Figure 61. GPS based measurements of movement in the Portuguese Bend landslide. (left) Location of the select GPS stations shown in the graph of cumulative movement (right). Note that while the highest rate of movement appears to be the center of the landslide, it is actually at the toe, near the beach. However, none of the stations located in the toe (see Figure 53) survive for more than a few years and cannot provide a long-term view of displacement.

The total horizontal displacement of the landslide area since 1994 is shown in Figure 63. Interestingly, the one-foot contour very closely matches the outline of the two active landslides and the 0.05 foot (15 mm) contour defines the size of the area that is in slow-motion. Note that there is no zero contour; it is simply that the measurements reach the limits of the precision of the GPS method. To accurately assess the limits of the area of extremely slow movement will require a much longer term study than currently available. The distribution of GPS stations covers a significant portion of the Ancient Altamira landslide that is immediately adjacent to the reactivated landslides. While I have labeled this area as "stable" on the map, it is undergoing very slow continuous movement and hints that the stability of the ancient landslide may be less than that determined by more conventional geotechnical methods (see discussion, p. 33). To confirm this will require the installation of inclinometers and other instruments in boreholes across the area.

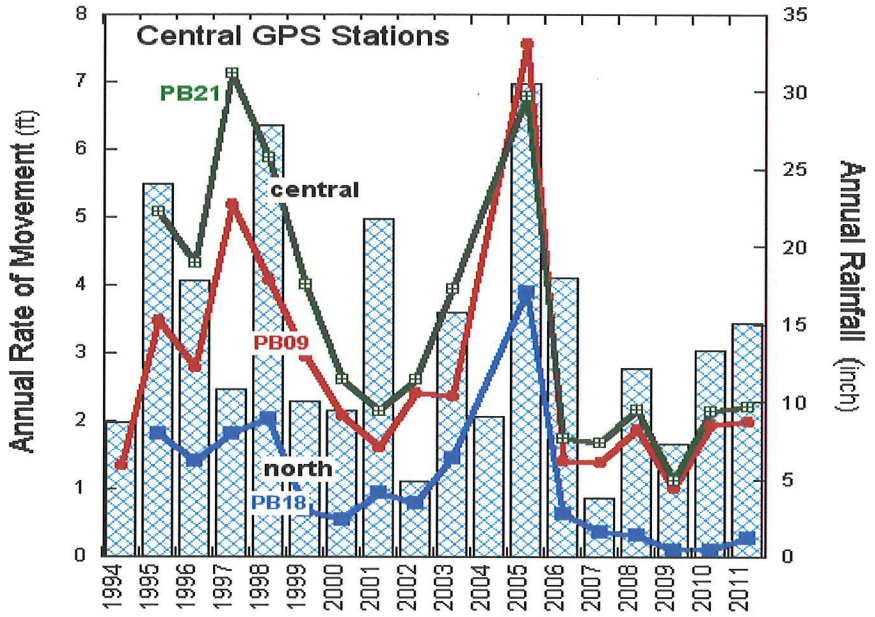


Figure 62. GPS stations located in the middle of the landslide (PB 18, 21, 09) compared to annual rainfall. Note that the landslide velocity generally increases during high rainfall and decreases during low rainfall although the correlation is not perfect. When rainfall exceeds about 20 in./yr, movement increases dramatically.

Note that the area of "fast velocity" in the Portuguese Bend landslide defines a long, relatively narrow band that is coincident with a trough-like depression in the subsurface beneath the landslide. It seems like the landslide mass is sliding down a chute into the ocean and pulling the surrounding area along with the it.

In the discussion about the stability of the Ancient Altamira landslide (see p. 35), one of the important questions was whether the landslide mass was active. GPS technology offers a means by which we can determine if it is moving. When the local GPS network in the landslide area was established in 1994, the relative accuracy of the method used to assess the Portuguese Bend stations was too low to provide reliable results to document very slow movement. In 2007 the system was modernized and upgraded to achieve a relative accuracy of horizontal movement of 0.022 ft at a 95 percent level of statistical confidence. Since then considerable attention has been given to eight stations located outside of the active landslides, especially stations located in the northern part of the ancient landslide. The cumulative movement measured at these stations since 2007 is shown in Figures 64 and 65.

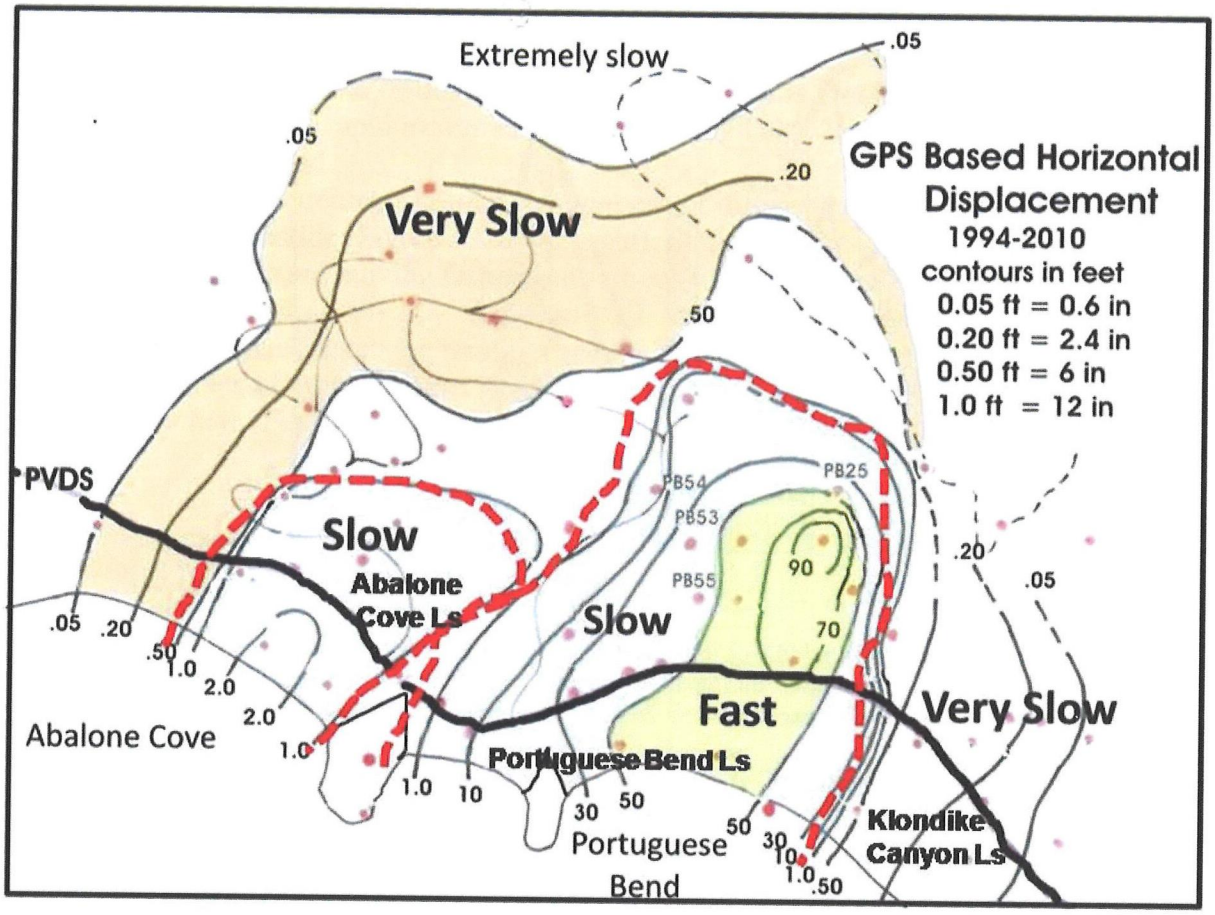


Figure 63. Map of the total horizontal displacement that has occurred in the area since installation of the GPS network in 1994. The data are contoured in feet. The "fast" area in the central-eastern portion of the PBL is a minimum measurement because most of the stations between Palos Verdes Drive South and the beach only last a few years until they are lost due to landslide movement.

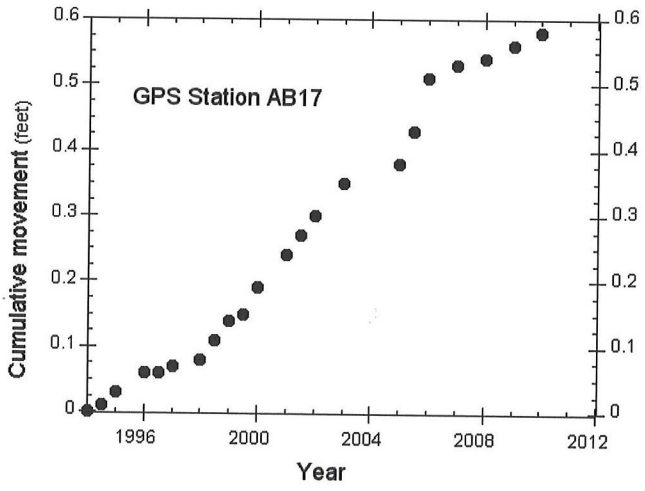


Figure 64. Cumulative movement of GPS station AB17 since its installation in 1994 (see Figure 57 for location). Note that the monument was replaced in 2006, hence the apparent shift. This station is located above the Abalone Cove landslide and considered to be in the "stable" area of the Ancient Altamira landslide although the GPS measurements indicate about 7 in. (18 cm) of movement in the past 17 years.

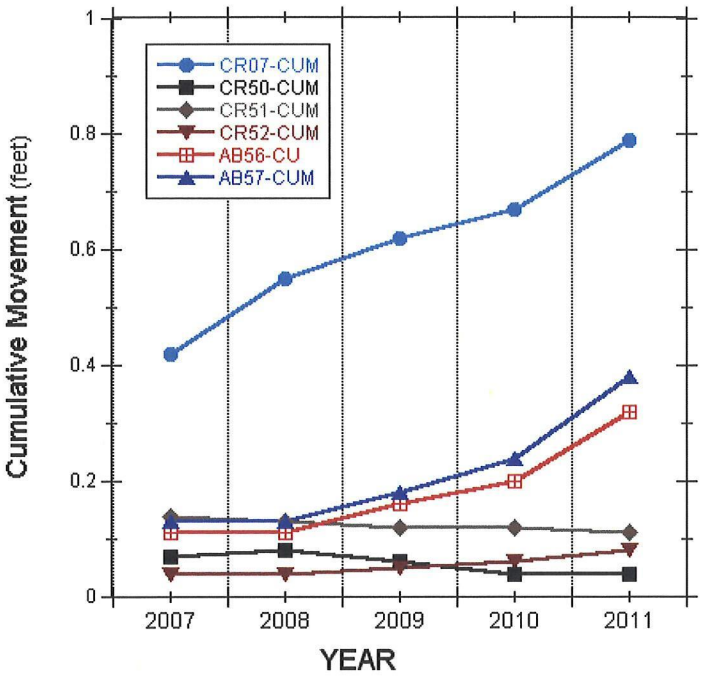


Figure 65. Cumulative movement of stations located within the Ancient Altamira landslide (see Figure 57 for the locations). There are two patterns: Stations CR07 and AB56 and 57 record slow, continuous creep to the south whereas stations CR 50, 51 and 52 are stable showing little or no movement. The accuracy of the GPS method is 0.02 ft at the 95 percent level of confidence (data collected by McGee Surveying, 2012) so these data are at the accuracy threshold but the consistency of the trends over time suggests they are real.

AB17 is located at the end of Fruit Tree Road and has long been considered as "stable". Based on the total set of measurements since 1994, the station has moved about 6 inches. The other stations provides a mixed pattern. Three of the stations (CR07, AB56 and 57) record a steady southward drift of 0.01 to 0.04 ft/yr with the great displacement occurring at CR07, located on the Crenshaw Extension close to where it crosses the Portuguese Canyon. The other stations (CR50,51 and 52) are located north of Peacock Flats and appear to be stable. Based on these data, it appears that the area just north of the Abalone Cove landslide may be very slowly drifting southward while the area to the north of the Crenshaw Extension is not moving. It should be pointed out that the stations that appear to be slowly moving are located on slopes and there is the possibility that the GPS measurements are due to slope creep from expansive soils. Only long term measurements over decades will provide the basis for separating the effects of soil creep from real mass movement.

So the answer to the question, "Is the Ancient Altamira landslide moving?" is, "Possibly, but if it is, it is certainly very slow."

Chapter 10—The Future

Another commonly asked question is what will happen to the landslides in the future? Will they still be moving? What might be expected to happen to the area?

The locals suggest, only partly in jest, that the best course of action for the Portuguese Bend landslide is to do nothing and turn the bay that will eventually develop into a marina. Notwithstanding the value of water-front property, this is probably not going to happen. A hind-cast of the Portuguese Bend landslide over the past 60 years probably offers a more reliable picture of what to expect in the future. Unless the landslide can be effectively dewatered, that is the ground water levels significantly lowered, there is little indication that the movement will slow much, let alone come to a halt. In the next half century it will move another 900+ ft and significantly thin the thickness of the slide at the toe. As this occurs, it will increase the stress on the upper part of the landslide and the western and inland subslides will fail at faster rates. Preventing the discharge of rainwater from the upper reaches of Portuguese and Paint Brush canyons from flowing directly into the head of the landslide would make a significant difference in the outcome. Unless this happens, however, there is little chance of significantly slowing or halting the landslide.

The dewatering wells have had a significant effect in slowing the Abalone Cove landslide but it continues to move, especially in very wet years when rainfall at Crest Road exceeds about 20 inches. More dewatering wells strategically located in the Ancient Altamira landslide complex, especially upslope of current dewatering wells is a very good idea. This is particularly the case with the possibility of future development in the area. Also to more effectively dewater the landslide, a solution must be found to the problem of the iron oxide sludge clogging the pumps. Currently wells in the lower part of the landslide require high maintenance and frequent replacement of the pumps. In some cases, the limonite sludge reduces the permeability around the wells to the point that the well is no longer usable.

Of greater concern is the apparent creep in the Ancient Altamira landslide that is recorded at some though not all of the GPS stations. The movement is very small and although the fact that it is continuous and in the same direction lends it credibility, time is needed to see if the trends continue and if it indicates movement at depth or hillside soil creep. Several boreholes instrumented with modern inclinometers would help distinguish the difference.

And finally, a point that some city administrators and many residents of the area have a hard time appreciating is that the landslides are forever. These features have existed for thousands of years and will be with us well into the distant future. They will require funding, human attention and the application of the best geotechnical methods to remediate them and keep them from turning into catastrophic failures. Landslides inevitably cause problems for human infrastructure and ignoring them is the biggest risk of all.

Acknowledgements

In the past 70 years, a small army of engineers and geologists, from students to professionals, have studied, probed and analyzed the active and inactive landslides of the Portuguese Bend landslide complex. They produced hundreds of reports, from dissertations to company files that describe their results. While a few of them are published in the scientific literature, the vast majority are internal company reports and files, including the logs of literally hundreds of boreholes, auger holes and trenches prepared by geoscientists for the City of Rancho Palos Verdes or consulting companies hired to investigate some aspect of the landslides. Regrettably, many of these reports, like the scientists who prepared them, are now gone and a treasure load of information has been lost with them.

For this book I have particularly relied upon the reports by: Karl Vonder Linden, whose Stanford University doctoral dissertation (1972) was the first comprehensive investigation of the Portuguese Bend landslide; Richard Merriam (1960) and William Easton (1973), whose early ideas shaped many of those that followed; Richard Jahns and Karl Vonder Linden (1973); Perry Ehlig (1984, 1986, 1992, 1997, 1999), who spent a professional lifetime investigating the Abalone Cove, Klondike Canyon and Portuguese Bend landslides, often with his students, and directed most of the efforts to remediate them; the many unpublished company reports and files of Leighton and Associates, Robert Stone and Associates, Moore and Taber, Law Crandall and Associates, and Ginter and Associates; and upon the research I conducted, often with my students, for the Abalone Cove Landslide Abatement District. To all of them my thanks and appreciation; however, any errors in reporting or interpreting the results described herein are mine alone.

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Appendix A

Table 1. General Features of the major landslides on the Palos Verdes Peninsula.[1]

Landslide	Age (yr)	Thickness (ft)	Area (acres)	Displacement (ft)	Type	Status
Ancient Altamira Complex	>200,000 possibly 800,000	50 to >150	>1300	Unknown	Slow moving	Inactive
Portuguese Bend	1956[2]	80-250	260	~900 ft since 1956	Slow Moving	Active
Abalone Cove	1978[2]	70-200	80	~35 ft since 1956	Slow Moving	Active
Flying Triangle	1978[2]	150-200	90	>30	Slow Moving	Active
Klondike Canyon	1979[2]	150-200	50	~1 to 2 ft since 1956	Very slow moving	Active
Beach Club	Several 1,000 (?)	20-50	~20	Unknown		Inactive
South Shores	>16,200	>50	>150	Unknown		Inactive

Table derived from many sources, including Haydon (2007), Ehlig (1986, 1992), Kerwin (1982), Slosson et al. (1987), Leighton et al. (1989).

[1] Table prepared for the City of Rancho Palos Verdes Landslide Workshop, July 30, 2012.

[2]These landslides are reactivated parts of the Ancient Altamira Landslide Complex. Age is the date of renewed movement.

About the author

Robert Douglas spent much of his childhood growing up on the Palos Verdes Peninsula where he developed a love for rocks and fossils before deciding to become a geologist. He received his training at the University of California, Santa Barbara (BA degree, 1959) and the University of California, Los Angeles (Ph.D. degree, 1966) and served on the faculties of the University of California, Davis and Case Western University (Cleveland, Ohio), before moving to the Department of Earth Sciences at the University of Southern California in 1974. There he served on the faculty before becoming the Dean of Natural Sciences and Mathematics from 1987 to 1995 and retiring in 2009 as Professor Emeritus. Since moving to the Portuguese Bend area in 1996, he has been a member of the Board of Directors, Abalone Cove Landslide Abatement District and its chairman since 1997. He is a Science Advisor to the Palos Verdes Peninsula Land Conservancy.



View of the Portuguese Bend area in 1931, looking northwest across the Ancient Altamira landslide, towards the crest of the peninsula at the top of the picture. The photo was taken prior to the activation of the Portuguese Bend and Abalone Cove landslides but the rolling topography with weathered fractures is indicative of movement in the past. The road in the lower foreground is Palos Verdes Drive South. The point to the left is Inspiration Point and Portuguese Canyon is the deep incision in the middle of the picture, much of which was destroyed during landslide remediation efforts in the 1990s. (Photograph by Spencer Air Services, 1931, used by courtesy of Don Christy.)

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