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Large-scale Basement-involved Landslides, California Continental Borderland

M. R. LEGG[1] and M. J. KAMERLING[2]

Abstract— Large seafloor relief, shallow metamorphic basement, and seismic activity in the California Continental Borderland combine to produce major submarine slides capable of generating local tsunamis. The Catalina Schist basement complex of the Borderland contains melange units, faults between metamorphic facies, and foliation derived from a history of deep subduction underthrusting and subsequent tectonic exhumation along regional low-angle fault systems. Neogene volcanic and sedimentary rocks covered the exhumed metamorphic basement forming an interface with a strong contrast in material properties. Neogene transtensional block-faulting formed steep escarpments that cut through and elevated the low-angle detachment surface, providing slip surfaces with free faces susceptible to failure along the rheological boundary. Two basement-involved slope failure examples west of San Diego are described, including large block-glides and progressive rotational slumps along the steep northeast-facing Thirtymile Bank escarpment and along the southwest flank of Fortymile Bank.

Key words: Tsunami, submarine landslides, continental margin geology.

1. Introduction

The California Continental Borderland is a distinctive physiographic and structural province located offshore southern California, U.S.A., and northern Baja California, Mexico (SHEPARD and EMERY, 1941). The Borderland has numerous sets of parallel, generally northwest-trending ridges and islands separated by deep, elongate, fault-controlled basins (Fig. 1). This basin-and-ridge physiography presents high relief with numerous steep slopes that may be susceptible to failure. EMERY (1960) estimated that 63% of the Borderland is composed of slopes and deep irregular areas. Numerous submarine slope failures have been mapped on *sediment-covered* Borderland slopes (FIELD and EDWARDS, 1980, 1993; NARDIN *et al.*, 1979a,b; VEDDER *et al.*, 1986; CLARKE *et al.*, 1987). There are also many subaerial *basement-involved* landslides and landslide complexes 1–4 km across on Santa Catalina Island (BAILEY, 1941), and many large-scale, basement-involved, submarine landslides exist

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[1] Legg Geophysical, Huntington Beach, California, U.S.A.
[2] Institute for Crustal Studies, University of California, Santa Barbara, California, U.S.A.

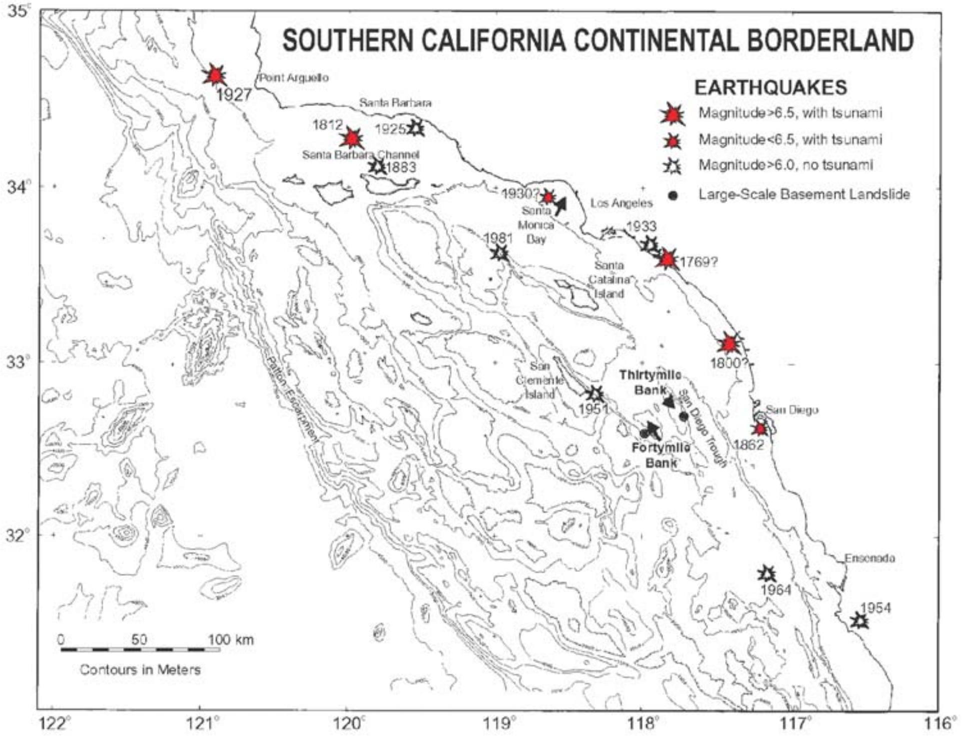
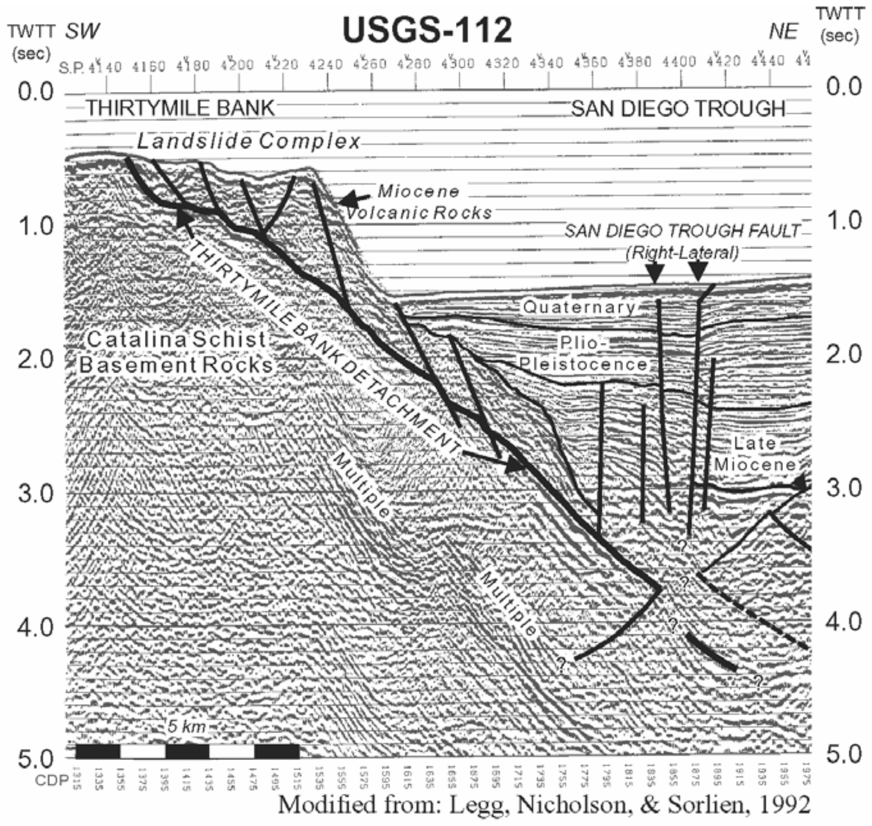


Figure 1
Map showing bathymetry of the California Continental Borderland, location of large historic earthquakes, and possible large-scale basement-involved landslides.

in the area. If slide movement is sufficiently rapid, such events could generate destructive tsunamis to the adjacent coastal areas (Watts and Raichlen, 1994).

1.1 Tectonic Evolution of Borderland Slopes

Neogene oblique extension (Legg, 1991; Crouch and Suppe, 1993; Bohannon and Geist, 1998) unroofed the regional Catalina Schist basement (Kamerling and Luyendyk, 1985). The Catalina Schist is considered a metamorphic core complex similar to the higher grade Franciscan subduction complex exposed within the California Coast Ranges onshore to the north (Crouch and Suppe, 1993; ten Brink *et al.*, 2000). Widespread extension-related volcanism filled Borderland basins with volcanic and volcaniclastic rocks and covered the exhumed Catalina Schist at the prominent detachment fault interface. The contact between the Neogene volcanic/volcaniclastic rocks and underlying Catalina Schist basement may be structural, due to continued detachment faulting, or depositional atop the exhumed basement surface. In either case, a prominent rheological discontinuity exists today where these



Modified from: Legg, Nicholson, & Sorlien, 1992

Figure 2
Multichannel seismic reflection profile USGS-112 across Thirtymile Bank and west half of San Diego trough showing regional Thirtymile Bank detachment fault and large-scale landslide complex at crest of Thirtymile Bank (see Fig. 3 for location of profile). [Seismic processing by C. Sorlien].

contrasting lithologic units are juxtaposed, as is evident on Santa Catalina Island (CANN, 1985) and in regional seismic reflection profiles (Fig. 2; LEGG *et al.*, 1992; BOHANNON and GEIST, 1998).

Basin and ridge structure of the California Continental Borderland was established by Neogene block faulting and oblique extension (transtension). When the exhumed detachment fault systems, and subjacent ductile metamorphic basement rocks rose above the brittle-ductile transition level, moderate to high-angle normal faults broke through and dismembered the regional low-angle structure. Block faulting and tilting created the prominent Inner Borderland horst and graben structural style, uplifting ridges of both older basin fill and underlying basement rocks, and deepening new more localized sub-basins. In many areas the block faulting may have utilized pre-existing structures remnant from the ancient subduction structural fabric, including the Mesozoic to mid-Cenozoic subduction thrust system and overlying subduction complex fault structures (LEGG *et al.*, 1992). As a principal part of the new Pacific–North America dextral transform plate boundary, Borderland faulting likely involved oblique-slip on dipping structures or strain partitioning on subvertical strike-slip faults and moderate to low-angle normal faults. Continued growth of the San Andreas transform fault system and changing tectonic styles within the evolving plate boundary sustained the block fault physiography by Plio-Pleistocene shortening and strike-slip (transpression; WRIGHT, 1991). In many areas the high-angle and likely oblique faulting enhanced steep slopes and further elevated the Catalina Schist basement. The uplift exposed the low-angle detachment surface and overlying strata along steep slopes, creating gravitational instability and potential for slope failure.

2. Earthquake-induced Slope Failure Potential

Earthquakes may induce large-scale basement-involved landslides on oversteepened Borderland slopes. Topographic amplification of seismic shaking (GELI *et al.*, 1988) on submarine ridge tops may increase the potential for basement-involved slope failures. Large, fast moving, basement-involved slope failures may generate destructive local tsunamis.

2.1 Relative Seismic Slope Stability

To quantify the relative seismic slope stability of basement slopes in the Borderland, we use the method adapted from Newmark's dynamic slope stability analysis technique (NEWMARK, 1965) as applied by the U.S. Geological Survey (WILSON and KEEFER, 1983, 1985; LEGG and SLOSSON, 1984; WIECZOREK *et al.*, 1985; JIBSON, 1993). This two-dimensional model of a sliding inclined block is suitable for slumps and block slides which likely represent the initial movements of large-scale bedrock submarine slope failures. In equilibrium the block remains stationary, and the downslope forces are balanced by cohesion and basal friction. The downslope acceleration required to initiate block movement, called the critical acceleration, a_c is a measure of the seismic slope stability. Values of a_c are derived using the formula (modified from WILSON and KEEFER, 1985):

$$a_c/g = [\mathbf{C}'/(\gamma H)] + [(\rho - \rho_w)/\rho] \tan\phi' \cos\theta - \sin\theta \tag{1}$$

where g is the local gravitational acceleration, $\mathbf{C}$ is the cohesion of the materials, γ is the unit weight of the material, H is the thickness of the slide block, ϕ' is the effective angle of internal friction of the material, and θ is the slope angle. For submarine landslides, the additional effect of buoyancy forces must be included where ρ_w is the mass density of sea water, and ρ is the mass density of the slide material.

The values of cohesion, unit weight, and internal friction angle are related to site geology and water content or pore pressure. For submarine slides, the material is assumed to be saturated, and pore pressure may be assumed to be hydrostatic, including the overlying water column. Earthquake-induced pore pressure changes may be significant, but are ignored for simplicity in this analysis. Dynamic pore pressure effects would tend to reduce the critical acceleration values needed to initiate slope failure by weakening the slip surface. Reducing the effective angle of internal friction may account for this effect. Indeed, the natural slope angles may represent the real effective angle of internal friction.

Based upon subaerial landslide investigations, three general rock types, with associated shear strength parameters (Table 1) are used to determine the relative seismic slope stability values. Effective shear strength parameters are provided for saturated conditions as well as for slopes with bedding planes, joints, or other weak surfaces dipping parallel to or antiparallel to the downslope direction. For each rock type and slope gradient combination a range of critical acceleration, a_c, values is computed. These values are compared to the a_c limits for each relative seismic slope stability category and an appropriate stability level is assigned (Table 2).

For the large-scale submarine landslides considered in this study, the first term in equation (1) becomes insignificant as the block thickness increases to values in excess of 100 meters, and the cohesion term can be neglected. WIECZOREK *et al.* (1985) set the cohesion to zero for weakly cemented sandstones, shales and clays, which may be appropriate for the metamorphic basement (Catalina Schist) of the Inner Borderland. The relative seismic slope stability values shown in Table 2 are based upon the strength parameters shown below, which includes the small, but non-zero, cohesion factor. Therefore, the values used in this study are reasonable, and conservative. With regard to potential tsunami generation, large-scale and rapid slope movement is necessary and likely requires low to unstable values of relative seismic slope stability.

Table 1

Shear strength parameters for regional slope stability analysis (after LEGG and SLOSSON, 1984)*

Geologic Unit (Lithology)	Along Planes of Weakness**		Through Rock[1]	
	ϕ'	$C'/\gamma H$	ϕ'	$C'/\gamma H$
Serpentine – High talc content, usually sheared	7.5°	0.125	10°	0.5
Franciscan – Highly fractured, fault gouge and shattered rock	7.5°	0.25	15°	0.75
Franciscan – Relatively intact sandstone, graywacke, and well-consolidated shale, locally cemented	10°	0.5	20°	1.5

*Effective strength parameters, rock saturated but pore water pressure not considered in analysis (D. E. MORAN, pers. comm., 1981). Slide thickness, H, assumed to be 3 meters.

**Failure path along well-defined bedding planes, faults, or pre-existing slip surfaces.

[1] Failure path crossing bedding, through largely intact rock.

Table 2

Relative seismic slope stability (saturated, submarine case)

Slope		Lithology			
		Serpentine		Franciscan [Highly Fractured]	
Degrees	Percent	Dip	Anti-Dip	Dip	Anti-Dip
0–2.9	0–5	Moderate	Very stable	High	Very stable
2.9–8.5	5–15	Moderate	Stable	Moderate	Very stable
8.5–17	15–30	Low	High	Moderate	Very stable
17–27	30–50	Unstable	High	Low	Very stable
27–35	50–70	Unstable	Moderate	Unstable	Stable
>35	>70	Unstable	Moderate	Unstable	Stable-high

Very stable: Not likely to move under severe shaking, $a_c > 0.7\ g$.
Stable: May undergo slight movement under severe shaking, $0.5\ g \le a_c < 0.7\ g$.
High: May undergo moderate movement under severe shaking; Some slides related to steep slopes and adverse dips, $0.3\ g \le a_c < 0.5\ g$.
Moderate: May undergo major movement under severe shaking or moderate movement under moderate shaking; numerous slides, rock falls abundant, unconsolidated material undergoing deformation and failure, $0.1\ g \le a_c < 0.3\ g$.
Low: May undergo major movement under moderate shaking; abundant slides of all types, $0.01\ g \le a_c < 0.10\ g$.
Unstable: May undergo major movement under slight shaking; most of area and/or materials failing, e.g., oversteepened submarine canyon walls, $a_c < 0.01\ g$.
Adapted from LEGG and SLOSSON, 1984.

Earthquake-induced slope failure susceptibility can be derived using maps of bathymetry to measure slope gradient and seafloor geology to derive the relevant lithology group for each slope area. This technique has been used by the U.S. Geological Survey to predict subaerial seismic slope stability for microzonation studies (WIECZOREK *et al.*, 1981). Due to the limited scope of the present study, no regional mapping is attempted. Instead, a rough estimate of the relative slope stability for major Borderland escarpments is derived. The lithology group is estimated from seafloor geologic maps prepared by the U.S. Geological Survey (e.g., VEDDER *et al.*, 1974; CLARKE *et al.*, 1987). Seismic reflection profiles provide direct imaging of the suspected slide plane (detachment, Fig. 2), and the slope gradient of this surface is used to determine the relative seismic slope stability of the suspected slide block.

For regional slope stability analysis, most steep basement rock slopes of the Borderland have gradients within the 15–50 percent slope categories (middle rows in Table 2). For Borderland slope geometries where bedding or failure planes are inclined in the same direction as the submarine slope (Fig. 2; Table 2), the relative seismic slope stability is Moderate to Unstable. These low stability slopes may be prone to catastrophic failure and tsunami generation.

2.2 Slope Failure Potential

The slope failure susceptibility is independent of the earthquake activity. When expected shaking levels are considered, slope failure potential can be estimated. Using dynamic slope stability analysis, curves of predicted slope displacement can be computed for particular earthquake time histories by integrating strong-motion accelerograms for various values of critical acceleration (WIECZOREK *et al.*, 1985; WILSON and KEEFER, 1985). Alternatively, the predicted displacements may be correlated with other shaking measures such as Modified Mercalli Intensity (LEGG and SLOSSON, 1984) or Arias Intensity (WILSON and KEEFER, 1985; JIBSON, 1993). For potential tsunami generation, the submarine landslide must move rapidly over a substantial distance, perhaps kilometers. Based upon the predicted displacement from the simple dynamic analysis, the study by LEGG and SLOSSON (1984) presented five levels of slope failure intensity (Table 3). For large displacements, the simple assumptions for the dynamic analysis are invalid, and the predicted displacement may be underestimated. Nevertheless, the slope failure intensity levels are believed to provide useful indices of the relative slope failure severity expected in real earthquakes. It is suggested herein that only catastrophic slope failure would generate tsunamis, and a predicted slope movement in excess of about five meters is used as the threshold for catastrophic failure. More quantitative study of the dynamics of submarine slope movement is necessary to substantiate this assertion or derive better methods to estimate catastrophic failure potential (e.g., SYVITSKI and HUTTON, 2003; LOCAT *et al.*, 2003; MARTEL, 2003).

Table 3

Slope failure intensity matrix (probability of damage state in percent)

Slope Stability:Unstable: $a_c \leq 0.01\ g$

Damage State	Modified Mercalli Intensity				
	VI	VII	VIII	IX	X
Light Disp < 0.5 cm	0	0	0	0	0
Moderate 0.5 cm < Disp < 5.0 cm	0	0	0	0	0
Heavy 5.0 cm < Disp < 50 cm	60	50	40	30	20
Severe 50 cm < Disp < 500 cm	30	40	45	50	55
Catastrophic 500 cm < Disp	10	10	15	20	25
$\sum$ Probabilities	100	100	100	100	100

Disp = Predicted slide displacement.
Adapted from LEGG and SLOSSON, 1984.

Numerous active faults within the Inner Borderland may produce strong earthquakes and shaking levels that exceed local critical accelerations and trigger slope movement. Most of the larger steep slopes in basement rocks are fault related, and consequently, adjacent to the strong earthquake source regions. Indeed, observations from submersible show that vertical and overhanging slopes are present along active Borderland faults (J. WARME, pers. comm., 1985; C. GOLDFINGER, pers. comm., 2000). Furthermore, the complex patterns of tectonic faulting break up the basement rock providing additional failure surfaces that tend to control the location and size of individual slope failures. Because major active faults lie subparallel to and along the large escarpments, the potential for large-scale, basement-involved, submarine landslides exists.

3. Examples of Large-scale Basement-involved Landslides

Two specific features are described herein that may represent large-scale, basement-involved, slope failures. Examples are based on detailed bathymetry from dense hydrographic soundings, multibeam swath bathymetry, and side-scan sonar systems that allow recognition of slide morphology. Both high-resolution, single-channel, and moderate resolution, multichannel, seismic reflection profiles help to define the internal structure and identify possible basal shear surfaces.

3.1 Thirtymile Bank

Thirtymile Bank is a northwest trending ridge of Catalina Schist mantled with Miocene volcanic and sedimentary rock. Seafloor samples from dredges and dart cores by the U.S. Geological Survey during the 1970s (Fig. 3; VEDDER, 1990; VEDDER *et al.*, 1974, 1976) consist of middle Miocene volcanic, volcaniclastic and sedimentary rocks in the area of the postulated submarine landslide complex. A sample from the crest of the triangular block was described as hornblende-hypersthene andesite with an altered glassy ground mass (VEDDER *et al.*, 1976); many of the samples in the landslide area include a tuffaceous matrix, altered, fractured and deformed. From a few kilometers northwest of the inferred slide complex to the northwest end of Thirtymile Bank, dredge and dart cores from the steep escarpment and crest of Thirtymile Bank recovered Catalina Schist basement rocks that included glaucophane schist and riebeckite schist (VEDDER *et al.*, 1974). The Thirtymile Bank detachment fault is exposed at the seafloor where these rocks were recovered, and correlates with the strong reflector imaged on USGS-112 (Fig. 2). The Catalina Schist and volcanic rocks, especially where ash is altered to bentonite or serpentine is present, provide well-defined slip surfaces for large-scale submarine landslides along the steep Thirtymile Bank escarpment.

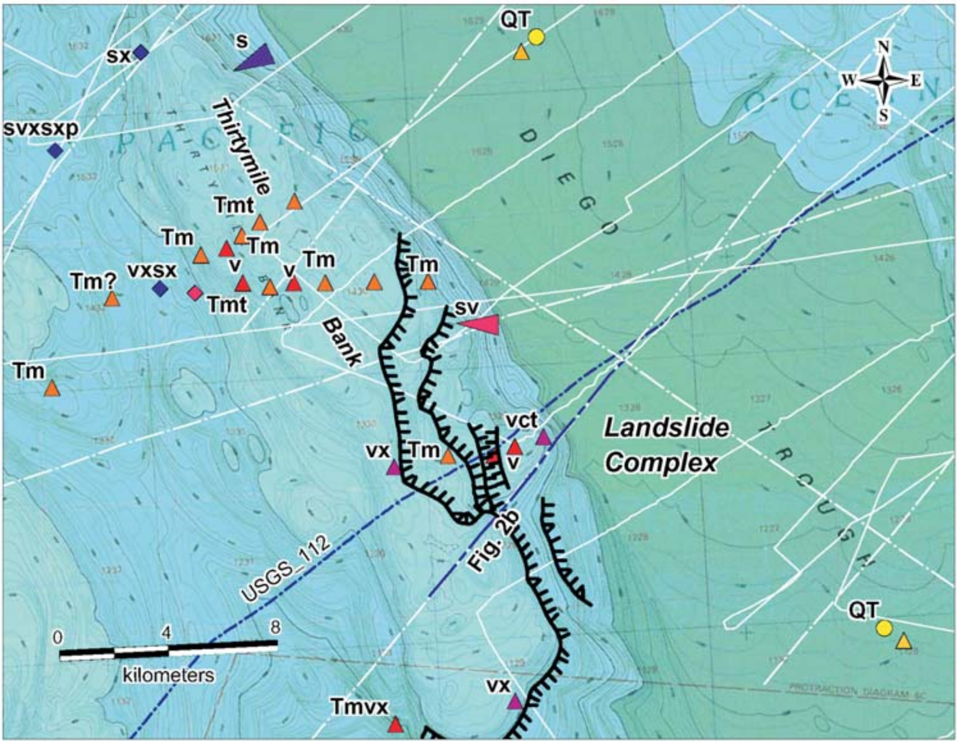


Figure 3
Bathymetric map showing the morphology of the Thirtymile Bank landslide complex, locations of tracklines for seismic profiles, and USGS bottom samples (Vedder, 1990; Vedder *et al.*, 1976). White lines are high-resolution, single-channel tracklines; dash-dot line is multichannel seismic trackline. Small symbols represent dart cores, large triangles are dredges. Triangles represent Tertiary (T), mostly middle Miocene, sample locations; diamonds represent Mesozoic(?) Catalina Schist basement rock samples; circles represent Plio-Pleistocene and younger (QT) sedimentary samples. Labels are: m = marine sedimentary, v = volcanic; vc = volcaniclastic; t = vitric tuff or bentonite; s = schistose rocks; x = detritus; p = phosphorite.

Comparison of the rocks and structure of Thirtymile Bank and Santa Catalina Island shows strong similarities. The island is composed of blueschist, greenschist, amphibolite, and sausserite gabbro intruded by Miocene igneous rocks (Bailey, 1941; Platt, 1975; Sorensen *et al.*, 1991). Miocene sedimentary and volcanic rocks overlie the basement rocks. San Onofre Breccia occurs directly on the basement and above Miocene volcanic rocks. The San Onofre Breccia exposed on the mainland coast is composed of large blocks and debris from the Catalina Schist basement and represents talus or mass wasting debris off steep scarps. Modern large-scale submarine breccia deposition could generate local tsunamis. The rocks of the Catalina Schist basement complex are very weak and prone to failure as evidenced by the numerous subaerial landslides mapped on Santa Catalina Island in the Catalina

Schist (BAILEY, 1941; ROWLAND, 1984; CANN, 1985; FRANCIS *et al.*, 1998). The southwest margin of the island is primarily a large slide and slump complex in the blueschist facies Catalina Schist (BAILEY, 1941). The Fisherman Cove slide on Santa Catalina Island resulted from strong volcanic rocks resting on sheared and fractured glaucophane-talc schist at the head of the slide area (CANN, 1985). The Fisherman Cove slide is 1.7-km long, 0.65-km wide, with a maximum thickness of 60 m. The angle of the slope is 11 degrees (CANN, 1985). The similarities in rock types, stratigraphy, and structure, between Thirtymile Bank and Santa Catalina Island and known slope failures on the Island suggest that Thirtymile Bank and other Borderland slope areas of Catalina Schist will also be prone to failure.

Along the generally straight, northwest-trending, Thirtymile Bank escarpment is an irregular area about six kilometers long and three kilometers wide just north of the U.S.–Mexico border (Figs. 2–3; USGS-112). This area is inferred to be a large submarine basement landslide complex. The largest block in this complex has a roughly triangular shape in map view with apex directed downslope to the northeast and base parallel to the main escarpment. This block is roughly equilateral with sides about 3.5 kilometers and covers an area of about 3 km^2. The block thickness varies from about 350 meters near its head to over 600 meters at its thickest where there is a local seafloor peak at the crest of the steep Thirtymile Bank escarpment (Fig. 2, SP-4140 to 4280). In cross section, there appears to be three to five individual back-tilted blocks separated by normal faults, in domino or bookshelf fashion, with the largest block representing a small horst that forms the local bathymetric peak. Farther east, within the subhorizontal sedimentary fill of the San Diego trough, there appears to be a large displaced block. This may be an older slide block, or alternatively, a remnant hanging wall block from the Neogene transtensional episode. An exploration industry seismic profile in this area shows possible sliding of the steep slope material out and over the flat-lying turbidites of the La Jolla submarine fan within the San Diego trough. The base of the tilted and displaced blocks is a strong reflector interpreted as the Thirtymile Bank detachment fault (LEGG *et al.*, 1992; BOHANNON and GEIST, 1998). To the northwest of the triangular block along the escarpment, several smaller irregular-shaped blocks are apparent in the bathymetry, whereas a large rectangular block about three kilometers long, forms a bench along the steep escarpment to the southeast. The overall morphology of this area is similar to that of large subaerial basement landslide complexes mapped in the Peninsular Ranges of southern California (e.g., Tin Can Flat, Vallecito and Oak Mountain landslide complexes, HART, 1991).

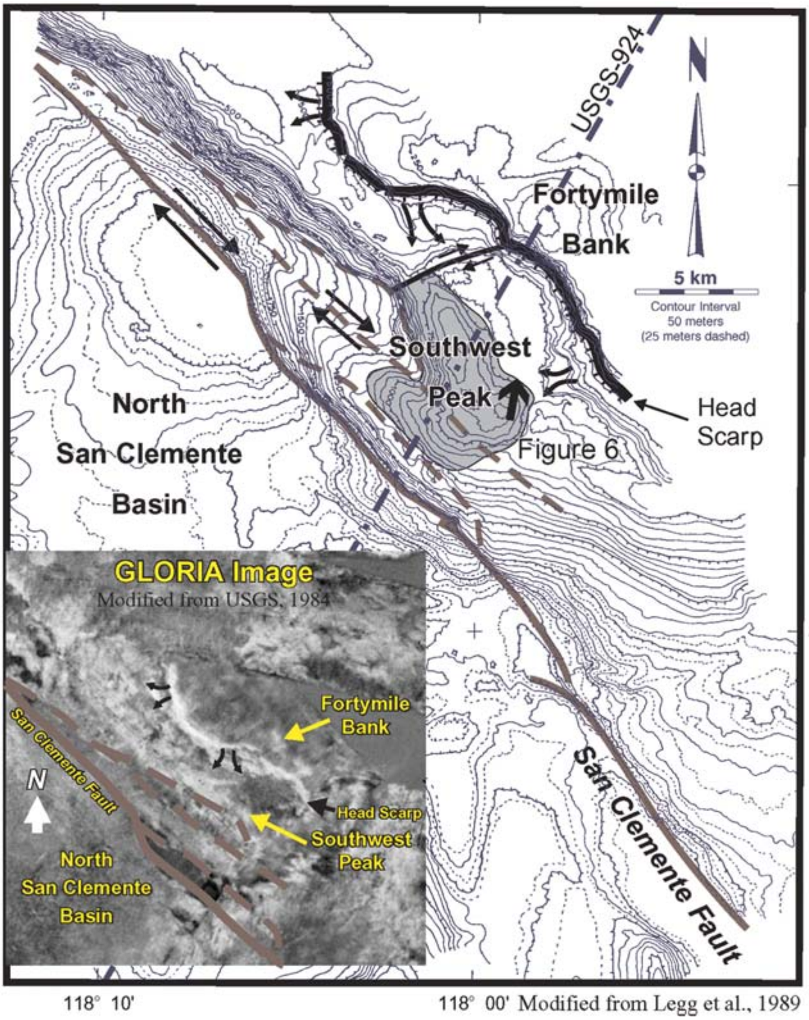
Like large-scale basement-involved subaerial landslides (SHREVE, 1968; HART, 1991), the failure mechanism of the Thirtymile Bank complex appears to be composite with slumping, as shown by the back-tilted block character, and block sliding. The buried rock mass in the San Diego trough appears to be displaced about two kilometers laterally and 800 meters vertically to the northeast of the crest of the escarpment where the horst block now lies. Such a transport distance, if by a slide mechanism, is similar to that of long run-out landslides, with a H/L ratio less than 0.5 (MELOSH, 1987). Long runout landslides typically occur rapidly, and therefore, if submarine, present potential sources for local tsunamis (see also VON HUENE *et al.*, 2003). The internal character of this block is difficult to determine, although there appears to be some irregular layering present in the seismic images (Fig. 2). We cannot say whether this is bedding with the available data, however, long runout landslides often preserve the relative stratification of the displaced rock mass (CAMPBELL *et al.*, 1995).

Burial of this block by La Jolla fan turbidites suggest that the feature is old. Seismic stratigraphic correlations and crude estimates of sedimentation rate in the San Diego trough (EMERY, 1960; LEGG, 1985; TENG, 1985) imply an age of late Miocene to Pliocene (>2 Million years ago). Other slide blocks still on the escarpment or overlying turbidites of the La Jolla fan may be Quaternary in age, perhaps within the past 100,000 years.

Individual slide blocks within the complex are located at all levels of the escarpment, from near the crest to the base. DENSMORE and HOVIUS (2000) suggest that earthquake triggered bedrock landslides tend to be more evenly distributed across the steep slopes; coseismic shaking induces slope movement at all slope levels, although some topographic amplification near the crest is possible. The nearby active San Diego trough fault zone may provide the necessary earthquake source region (Fig. 2). The remaining steep slope along the Thirtymile Bank escarpment and blocks of Cenozoic volcanic rocks atop the detachment surface suggests that future slope failures may occur due to this unstable configuration. Rapid movement of large submarine landslides toward San Diego, resulting from earthquake triggering or other instability, could generate a destructive tsunami along the adjacent mainland coast.

3.2 Fortymile Bank at North San Clemente Basin

Along the steep, southwest-facing escarpment that separates Fortymile Bank and North San Clemente Basin (relief exceeding 2000 meters), another large potential submarine landslide is identified. SeaBeam bathymetry (LEGG *et al.*, 1989) shows an irregular, north–northwest trending block about 7–8 km long by 4–5 km wide (Southwest Peak, Fig. 4) that appears displaced laterally about 5 km from the steep arcuate-shaped escarpment near the crest of Fortymile Bank. A high-resolution seismic profile that crosses this feature shows northeast-tilted reflectors within the offset block compared to subhorizontal reflectors within the main Fortymile Bank block (Fig. 5). Limited subbottom penetration and possible side-swipe artifacts preclude accurate delineation of the basal surface of the postulated slide block, although this surface may be exposed within the steep scarp along the active San Clemente fault. Earthquake-triggered slumping is considered the likely source of the 1998 Papua New Guinea tsunami (TAPPIN *et al.*, 2003), and the Fortymile Bank slide block is of similar scale (about 5–10 km^3).



Modified from Legg et al., 1989

Figure 4
Map showing SeaBeam bathymetry (Legg *et al.*, 1989) of the southwest flank of Fortymile Bank and GLORIA side-scan image (USGS, 1986) of proposed large-scale landslide blocks. Heavy line with ticks shows the major head scarp for the large-scale slope failure. Dashed lines are branch and secondary faults, and double arrows show postulated smaller landslide features. The principal displacement zone of the active San Clemente fault is shown by the solid line with arrows for sense-of-slip. Arrow labeled Figure 6 shows approximate 3-D view shown in subsequent figure.

Seafloor samples in the Fortymile Bank area are similar to those of Thirtymile Bank, with volcanic, volcaniclastic and sedimentary rocks of generally middle Miocene age reported (Vedder *et al.*, 1974, 1976). Catalina Schist basement rock types are also reported from inferred outcrops on the steep, 1100-meter high escarpment to the northwest of Southwest Peak. Samples retrieved by submersible

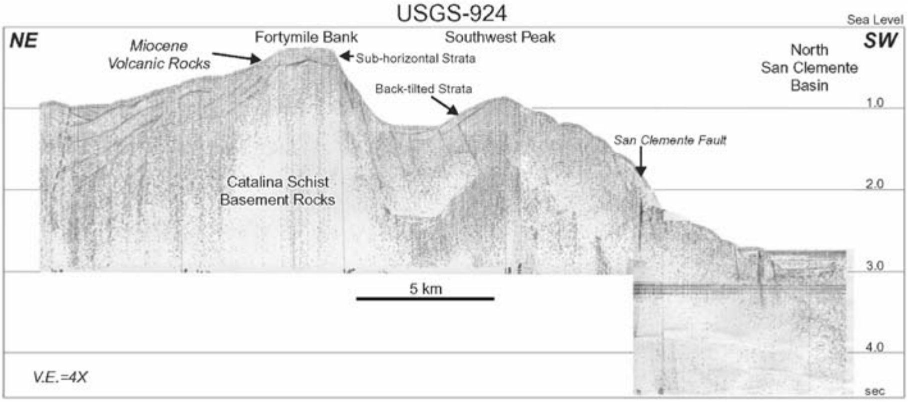
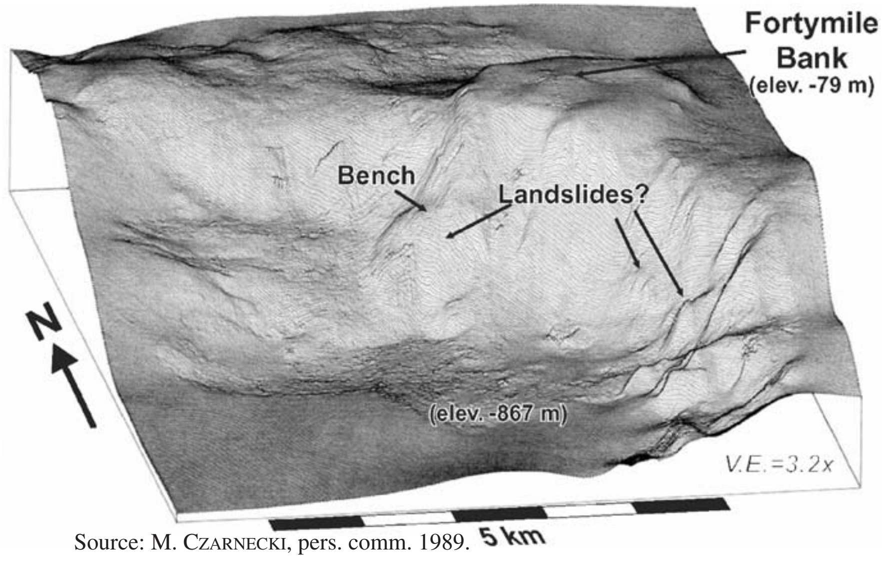


Figure 5
Sparker seismic reflection profile USGS-924 (VEDDER, 1975) across Fortymile Bank and San Clemente Basin showing back-tilted bedding in the inferred slide block.

from the upper Fortymile Bank escarpment, directly to the west and below the crest of Fortymile Bank, included tuffaceous and silty sandstones, as well as a one-half meter diameter "tectonic" rock covered with slickensides (M. LEGG, unpubl.). The cataclastic rock was retrieved from a small (100-m wide) mud-covered bench, located



Source: M. CZARNECKI, pers. comm. 1989.

Figure 6
Three-dimensional perspective view from the south showing steep escarpment and possible landslide features near crest of Fortymile Bank.

midway up the steep escarpment (Fig. 6); the bench may be the top of another slide feature. About 1 km west of the bench, where the more gentle west-trending slope gradient increases to 30–40 degrees, the seafloor is covered by boulders (10s to 100s of centimeters in diameter) suggesting submarine mass transport.

The Fortymile Bank escarpment is related to active right-slip on the San Clemente fault zone (SHEPARD and EMERY, 1941; LEGG *et al.*, 1989). The principal displacement zone is located along the steep, 500-meter high escarpment located a few kilometers southwest of Southwest Peak, although subparallel branch and secondary fault zones lie along a hillside bench immediately below the postulated slide block. Other fault traces appear to disrupt and possibly offset the southwest corner of the slide block (Southwest Peak) to the northwest. The north trend of the elongate slide block, about twenty-five degrees clockwise from the San Clemente fault trend, may result from vertical axis rotation of an originally northwest-trending, fault-parallel, detached horst block in a zone of right-lateral shear.

Based on the tilted strata within the slide block, and the inferred displacement of about 5 kilometers, both slumping and block sliding may have occurred here. The basal surface may be the detachment fault that separates Cenozoic volcanic and sedimentary rocks from Catalina Schist basement rocks, as observed at Thirtymile Bank, but data are insufficient at this time to confirm this assertion. The estimated vertical drop of about 500–600 meters, compared to the lateral offset again is consistent with a long runout slide mechanism, but it is also possible that the feature is an older tectonic fault block remnant from the Neogene transtensional episode. A thin layer of sediment (<100 m) ponded in the small basin between the slide block and steep upper Fortymile Bank escarpment suggests a more youthful landslide age – less than 1 Million years using the late Quaternary hemipelagic sedimentation rate for this area (LEGG, 1985). The steep escarpments and the strong lithologic/rheologic contrast, between Cenozoic rocks and schist basement, imply that large-scale slope failure is feasible for this unstable configuration. Indeed, numerous small slope failures were mapped on the steep escarpments based upon the seafloor morphology imaged by SeaBeam (LEGG *et al.*, 1989). It is possible that large-scale basement-involved slide blocks have overrun the active trace of the San Clemente fault, displacing the surface trace westward into the deep basin. Similar morphology occurs along the Elsinore fault where it marks the steep escarpment on the southwest flank of the Salton trough near the U.S.–Mexico border (PINAULT, 1984; LAMAR and ROCKWELL, 1986).

4. Tsunami Potential

All large earthquakes (Magnitude >6.5) historically recorded in the southern California offshore region have generated local tsunamis (Fig. 1; December 21, 1812; November 4, 1927; MCCULLOCH, 1985). Two other large events (July 28, 1769 and

November 22, 1800) may have occurred in the coastal or offshore area based upon sparse intensity observations, but evidence of local tsunamis for these events is speculative at present (LEGG *et al.*, 1994; LISA GRANT, pers. comm., 2000). Some moderate offshore earthquakes (Magnitude = 5.5–6.5) apparently generated small local tsunamis (May 27, 1862; August 30, 1930, uncertain tsunami; March 10, 1933; LANDER *et al.*, 1993). To date, no local southern California tsunamis have been destructive. Repetition of tsunamis similar to earlier historical events may be damaging to the modern heavily developed coastal areas. Whether generated by tectonic displacements or submarine slope failure, the source mechanisms of historical Borderland tsunamis are unknown.

Using the equations demonstrated by VON HUENE *et al.* (2003) estimates of the maximum tsunami wave height generated by Borderland submarine landslides may be derived. The Fortymile Bank submarine landslide is best defined by the available data, and it is modeled in two ways: 1) as a rotational slump; and 2) as a translational slide. The slide dimensions were given above (7-km wide by 5-km initial length, and 650 meters mean water depth), and an initial failure thickness of 200 meters is assumed. For the rotational slump model, an angular displacement measured from the backtilted sediments is 0.1375 radians (about 7.9 degrees). For a mean slope of the failure scar of about 25 degrees, measured from the bathymetry, and an assumed radius of curvature of about 15 km, a maximum tsunami wave height of 7–9 meters is computed. For the translational slide model, the maximum tsunami wave height is predicted to be about 50 meters, similar to wave heights estimated for tsunami generation by the large Palos Verdes debris avalanche off Los Angeles (BOHANNON and GARDNER, 2003; LOCAT *et al.*, 2003). With nearly an order-of-magnitude variation in predicted wave heights from two different models, it is clear that the dimensions and mechanism of the submarine landslide be carefully determined before an accurate prediction of tsunami character can be made. Nevertheless, both models predict a wave height in the 10-meter range, which could be destructive to adjacent coastal populations.

5. Summary and Conclusions

Two large-scale basement-involved submarine landslide features have been described within the California Continental Borderland. Both appear to be multi-kilometer scale slide complexes with several individual blocks. The blocks are suggested to slide along well-defined shear surfaces, likely influenced by the Catalina Schist basement structure and lithology, and also appear to be back-rotated in seismic reflection profiles. The well-defined slide plane and rotation are characteristic of slumping, although some block sliding is also likely. Accumulations of incoherent reflection sequences, with hummocky surfaces, may represent break-up of the slide blocks into more plastic or fluidal slope failures on the steep (25 degrees) escarpments (e.g., NARDIN *et al.*, 1979b). Thus, the failures may initiate as slumps or slides, but evolve into plastic debris flows or possibly turbidity currents as movement progresses.

For regional prediction of potential slope failures, and slide-generated tsunami, simple estimates of seismic slope stability using the Newmark dynamic analysis technique may be appropriate offshore southern California. Application of this method to the Borderland suggests that earthquake triggering of mass movements on the unstable Catalina Schist basement slopes is feasible. Areas where pre-existing fractures and other weaknesses dip in the same direction as the steep slopes have the greatest displacement potential.

Timing or frequency of occurrence for large-scale basement-involved submarine landslides in the Borderland is presently unknown. The age of last movement for the two large features is undetermined at this time, although ponded sediments in the graben between the head scarp and large slide block at Fortymile Bank suggest a late Pleistocene age, within the past Million years. Stratigraphy from seismic profiles, and sedimentation rates inferred from bottom samples, may provide reasonable estimates of the age of some large Borderland submarine landslides, but such work remains to be completed. Combining slip rate data on offshore faults and historic seismicity may allow probabilitistic hazard assessments of the slope failure and tsunami potential.

The present study only begins to investigate the potential for large-scale basement-involved submarine landslides on the steep Borderland slopes. At present, only crude determinations of slide displacement, during single events or multiple, possibly progressive, failures has been made. This study predicts substantial initial tsunami wave heights, from 7–50 meters depending upon the slide model. High-resolution seismic profiling combined with high-resolution swath bathymetry are needed to more accurately describe existing submarine landslides. Theoretical studies on submarine landslide mechanics, analog modeling, and numerical simulations of the slope failure dynamics are needed to infer failure mechanisms and rates. These parameters can then be used to simulate observed failures and examine potential tsunami generation and risk to coastal populations.

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