SPECIAL REPORT 184

# LANDSLIDES IN THE HIGHWAY 101 CORRIDOR BETWEEN WILSON CREEK AND CRESCENT CITY, DEL NORTE COUNTY, CALIFORNIA

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# INTRODUCTION

Highway 101 is the major North-South highway in coastal California. North of Eureka, the highway follows the coast through rugged, mountainous terrain. The segment of the highway between Wilson Creek and Crescent City crosses terrain that is particularly rugged and landslide prone, especially the 2 ½ miles north of Wilson Creek known as "Last Chance Grade." The Last Chance Grade area includes several distinct types of landslides, all of which have been active historically and have disrupted the highway. Movement of several deep bedrock slides in the late 1980's and early 1990's led Caltrans to investigate landslide repair options.

To place the landslides at Last Chance Grade in regional perspective and provide background data for proposed projects, the California Department of Transportation, Office of Infrastructure Research contracted with the California Department of Conservation's California Geological Survey (DMG) to prepare maps of the Highway 101 corridor between Wilson Creek and Crescent City. These maps include a geologic map, a map of landslides in the highway corridor, and maps of those landslides most likely to affect the highway. The mapping area includes the highway alignment and the surrounding area up to 1½ miles to the east and west. The maps do not indicate the probability of movement of any individual landslide or the stability of areas outside of mapped landslides. However, the characteristics of each mapped landslide and physical properties of the geologic units can be used by engineers and geologists at Caltrans in planning of more detailed evaluations for roadway improvement projects. These maps will allow Caltrans to compare the scale and activity of landsliding at Last Chance Grade with the landsliding found in the surrounding region, plan for mitigation of landslides and evaluate possible bypass routes that have been proposed to avoid the landslides at Last Chance Grade.

The maps presented here were prepared at a scale of 1:12,000 (1 inch = 1000 feet) by compilation of previous mapping, interpretation of aerial photographs and original field mapping. These maps were prepared using a computer geographic information system (GIS) on scanned images of USGS 7.5-minute topographic quadrangles. Portions of the Sister Rocks, Childs Hill and Requa quadrangles form the base map of Plates 1 and 2. The geologic and landslide maps were drawn in the computer GIS, which includes database tables describing each feature mapped.

# REGIONAL OVERVIEW

The Coast Ranges geologic province extends for about seven hundred miles within California from Santa Barbara County to the Oregon border, and then continues through Oregon and Washington. South of Cape Mendocino, the province is characterized by northwest-trending mountain ranges and valleys bounded by right lateral strike slip faults. North of Cape Mendocino, the oceanic plate beneath the sea floor, the Juan De Fuca plate, is being subducted beneath the North American continental plate. The active subduction in this area leads to active compressional tectonics and uplift.

Partly because of this change in tectonics, the northern coast ranges do not have the broad northwest-trending valleys that make natural transportation corridors in the southern Coast Ranges. Highway 101 north of Eureka follows the coast and the valleys of several minor streams but is forced to climb or traverse numerous steep slopes. All of these slopes are more or less prone to landslides so maintaining this part of the roadway is a continuing challenge.

Rocks of the northern Coast Ranges are typically sedimentary rocks of Cretaceous through Tertiary ages. The most widespread unit is the Franciscan Complex, composed of fine to medium grained graywacke sandstone, highly sheared shale and several other rock types including serpentine, greenstone and chert. There are also areas of younger Tertiary sedimentary rocks overlying the Franciscan south of the study area and patches of marine terrace deposits on erosional surfaces cut into the bedrock. All of the rock types tend to be weak, sheared sedimentary rocks or overlying unconsolidated deposits. The compressional tectonics of the area, driven by the subduction of the oceanic plate beneath the North American Plate, has lead to uplift of these young sedimentary rocks in recent geologic time. Rapid uplift of such weak rocks leads to high rates of erosion and to abundant landslides.

## STUDY AREA

The Highway 101 corridor described here extends from the highway bridge over Wilson Creek on the south to Crescent City on the north. It includes steep sea cliffs that extend up to an elevation of 1200 feet, broad ridges, and the canyons of Wilson Creek and the West Branch of Mill Creek. The coastal areas, including the ridgetop that the highway follows, are within Del Norte Coast Redwoods State Park and Redwood National Park. Much of the Mill Creek watershed is owned by Stimson Lumber Company. Most of the Wilson Creek watershed is owned by the Simpson Timber Company.

The route now followed by Highway 101 between Wilson Creek and Crescent City was established as a county wagon road in the 1890's (Smith, 1978). That route was designated a state highway in 1909. The state highway department relocated the highway between 1919 and 1923 to a new alignment along the current Enderts Beach Road, then across the cliffs south of Enderts Beach and around the headwaters of Damnation Creek, intersecting the old wagon road just north of Last Chance Grade. By 1930, landslides on the cliffs south of Enderts Beach forced the highway department to abandon that alignment and establish the current route, roughly along the original wagon road. Much of the 1920's roadway remains as trails within the State and National Parks, but the portions on the sea cliffs have been completely obliterated by landslides.

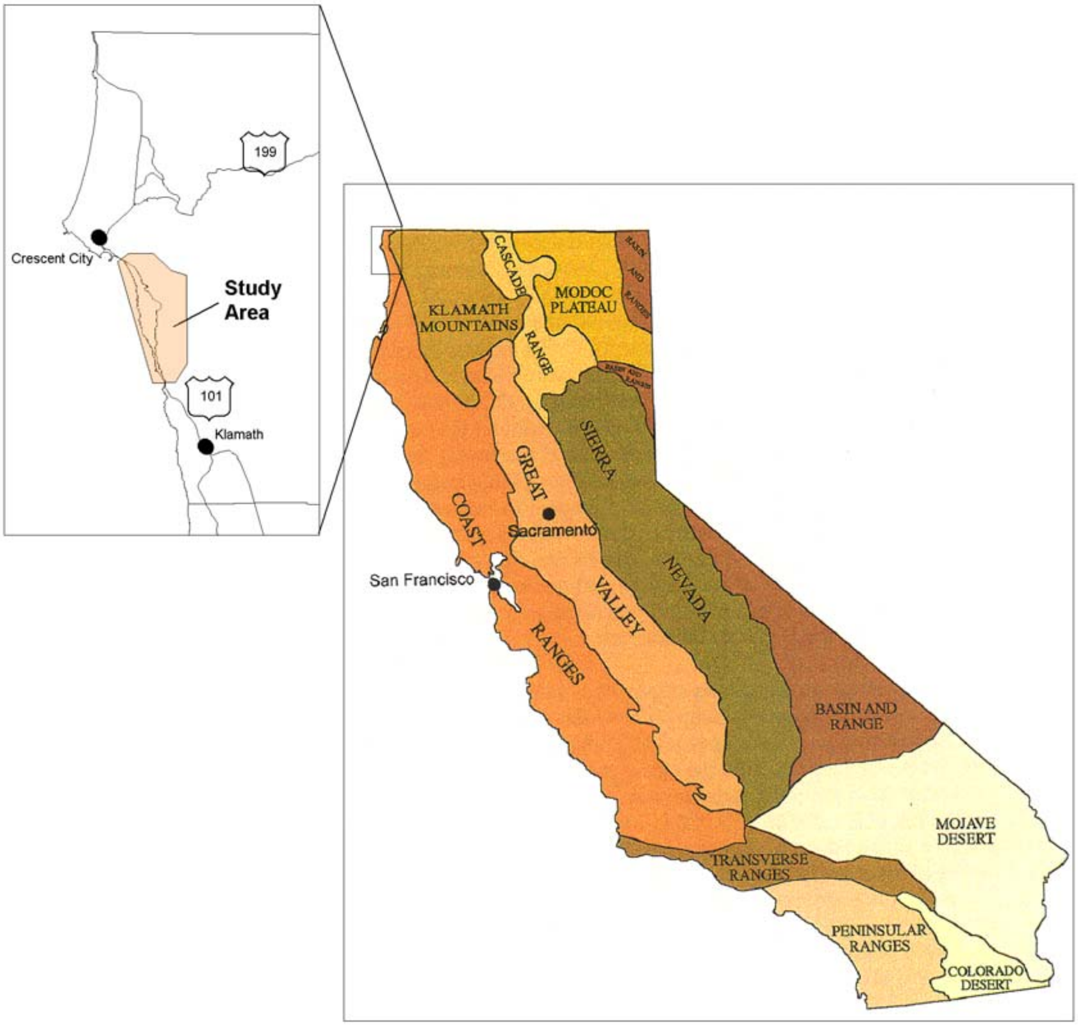


Figure 1. Location map showing the study area.

## Geologic Mapping

The geology within this highway corridor is typical of the northern Coast Ranges of California. The main bedrock unit within the region, and the corridor, is referred to as the Franciscan Complex. The Franciscan is an extensive sequence of rocks, most of which began as sedimentary deposits in a deep ocean environment. These rocks were intensively sheared and fractured as the oceanic crust they were deposited on was subducted beneath the North American continental plate. The deformed sedimentary rocks, along with fragments of volcanic and metamorphic rocks from the crust and mantle of the oceanic plate, were attached to the North American Plate along a series of faults.

Figure 2. View north over Last Chance Grade area. From the Wilson Creek Bridge at lower right, Highway 101 crosses an earthflow complex above Footsteps Rock (left center), then crosses into much more resistant bedrock characterized by deep-seated rock slides and surficial debris slides.

The geologic map (Plate 1) was prepared by compiling previously published geologic maps (Davenport 1984a, 1984b; Ristau, 1979) and performing additional interpretation of aerial photographs and field mapping. The previously published geologic maps had major differences in the identification and location of geologic units. Field mapping was necessary to resolve the differences between the sources of mapping, improve the accuracy of locations of contacts between rock units and add detail to the map.

## Geologic units

The two units of the Franciscan Complex in the study area are referred to as "broken formation" and "melange." Both are composed of intensely sheared and fractured sandstone, siltstone and shale.

"Broken formation" is composed mainly of gray, thickly bedded sandstone with siltstone and shale interbeds. Although the sedimentary bedding is prominent in outcrops, it is not possible to trace individual beds for great distances. The outcrops commonly represent relatively intact blocks of rock bounded by shear zones. The massive, hard sandstone blocks, bounded by weak, sheared zones leads to steep slopes and slides of large intact blocks of rock.

"Melange" is composed of dark gray, highly sheared siltstone and shale. Outcrops commonly show highly contorted bedding or rock so sheared that bedding cannot be traced across the outcrop. If "broken formation" is considered a mass of hard sandstone blocks separated by shear zones, "melange" can be considered essentially a large shear zone containing relatively few intact blocks.

Within the melange unit, some blocks of different kinds of rocks are large enough to be mapped separately. These blocks may be graywacke, greenstone, chert or serpentinite. The blocks in the melange unit near the mouth of Wilson Creek are shown as undifferentiated by Davenport (1984a).

There are several different criteria that can be used to distinguish areas of broken formation and melange in an area of sparse outcrops. Melange is thought to represent zones of shearing related to subduction, commonly including blocks of "exotic" rocks from the oceanic crust or mantle within the matrix of sheared shale. Therefore, areas with exotic blocks can be mapped as melange. “Exotic” blocks near the mouth of Wilson Creek suggest this area is melange. Melange is also commonly recognized because it forms distinctive terrain: the material is so weak and prone to landslides that areas of pervasive earthflow-type landslides are commonly mapped as melange. The mapping of Aalto and others (1981) and Davenport (1984a,1984b) apparently used these criteria to show the area north of the mouth of Wilson Creek as melange. Additionally, areas with outcrops that are largely sheared siltstone and shale and areas of "soft" topography (gentle slopes, broad flat-topped ridges) can be considered melange. The mapping of Ristau (1979), compiled from Wagner (1973), depicts melange as covering more extensive areas, probably based on these additional criteria. Field mapping for this project verified that outcrops within the area mapped as melange by Ristau (1979) are composed of sheared shale and siltstone, and are found on relatively gentle slopes. Because these areas have similar lithology and engineering properties as melange, the boundaries mapped by Ristau (1979) were digitized for our map and the areas of melange extended based on similar rock types and topography.

In addition to the Franciscan complex bedrock, there are several surficial geologic units in the study area.

Quaternary older alluvium: Much of the upland area east of the study area has broad flat-topped ridges, some with remnants of alluvial deposits on them. These deposits were described by Davenport (1984b) as composed of sand and gravel. One area mapped as this unit is shown in the study area east of Wilson Creek. Because this deposit is outside any anticipated roadway route and not associated with any known landslides, it was not examined in the field.

Quaternary marine terrace deposits: Sand and some gravel deposited in a beach and shallow offshore environment is now exposed in two small areas at the mouths of Nickel Creek and Damnation Creek.

Beach deposits: The plain that Crescent City is built on is an erosional surface, planed off by wave erosion then uplifted. It is covered with a thin veneer of beach deposits, composed predominantly of sand.

Alluvium: Stream deposits are found in the floodplains of Wilson Creek, the West Branch of Mill Creek and several smaller creeks. These deposits are unconsolidated sand and sandy gravel with some layers of finer grained materials.

Landslide deposits: Landslide deposits on the geologic map are the larger and deeper slides from the landslide map. Smaller slides are not shown on the geologic map for clarity and because small, shallow landslide scars can have the best outcrops of fresh, intact rock in places where the landslide has removed the soil and weathered rock. The materials in the landslide deposit are highly variable, depending on the source material and range from nearly intact sandstone to completely disrupted clay soils.

## LANDSLIDES

More than 200 landslides were mapped in the Highway 101 corridor area between Wilson Creek and Crescent City (Plate 2). These landslides tend to be the larger, deep seated slides that affect large areas. Although we have attempted to show all landslides, there may be many small shallow slides that are obscured by thick forest cover and could not be seen.

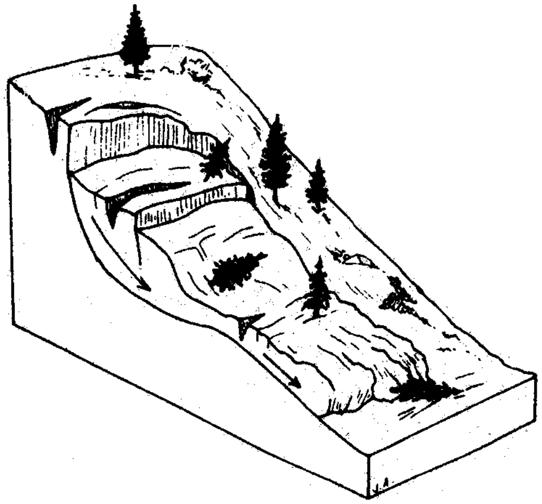
The landslide map (Plate 2) was prepared primarily by interpretation of aerial photographs, with review of previous reports and field checking. Landslides shown on previous maps (Davenport, 1984a, 1984b; Ristau, 1979) and in reports prepared for Caltrans, the California Department of Parks and Recreation, and timber companies, were checked on aerial photos and in the field, if possible. The boundaries of landslides from previous work were revised and additional landslides were added based on geomorphic interpretation for this investigation.

In this study we have recognized, classified and mapped landslides based on their geomorphology. Landslides displace parts of the earth's surface in distinctive ways, and the resulting landforms can show the extent and characteristics of the landslide. Recognition of these landforms (scarps, troughs, benches and other subtle topographic features) allows the geologist to recognize, map and classify most landslides. For this study, landslides were recognized by their topographic expression, as interpreted from topographic maps and aerial photographs, and seen in the field. For each landslide we have attempted to record the characteristics of the slide, generally following the recommendations of Wieczorek (1984). Portrayal of landslides on the map includes a symbol, which designates the type of slide (materials and type of movement). The color of the slide area signifies its level of activity, and the thickness of the outline signifies the confidence of our interpretation as described below.

### Types of landslides

Each landslide is classified according to the materials involved and the movement type, as deduced from the associated landforms. A two-part designation is given to each slide, based on the system of Cruden and Varnes, (1996). Materials are called either rock or soil, and soil is subdivided into fine-grained (earth) and coarse-grained (debris). This system was designed to allow a series of names that completely describes the materials and processes involved in a landslide. We have simplified the system slightly to use it in preparing an inventory map of an area. We use the terms and definitions of Cruden and Varnes, but have attempted to simplify the designations by listing only the primary classification of a given landslide. For example, our example diagram of a rock slide, (see below), is a rotational rock slide- flow in which the upper part of the slide has moved by sliding, but the lower part has disaggregated and is flowing. On this map this type of slide is shown simply as a rock slide. Using the Cruden and Varnes system to classify rock versus soil is also complicated by the various vague and overlapping meanings of those terms in common usage. In California, many geologic formations are not hard or indurated rock and it is possible to find all gradations between weak, soil-like, and hard rocks. Our general system is to call material “rock” if it has a geologic formation name and the original geologic structure can be discerned. By these criteria, numerous weak, poorly consolidated formations are “rock”. Franciscan melange commonly is “earth” because its original tectonic fabric in many places has been destroyed by pervasive landsliding.

Applying the system of Cruden and Varnes, with the criteria described above, there are four predominant types of landslides in this area.

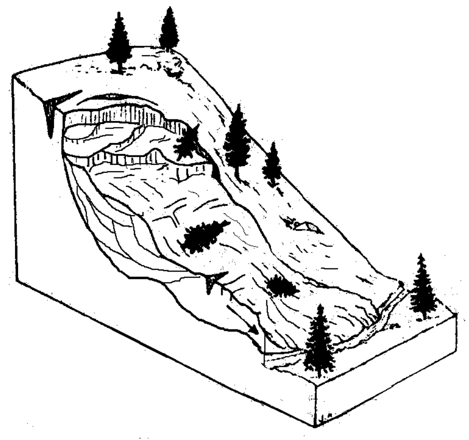


ROCK SLIDE: A slide involving bedrock in which much of the original structure is preserved. Strength of the rock is usually controlled by zones of weakness such as bedding planes or joints. Movement occurs primarily by sliding on a narrow zone of weakness as an intact block. Typically these landslides move downslope on one or several shear surfaces, called slide planes. The failure surface(s) may be curved or planar. In some older classification systems, slides with curved failure surfaces are commonly referred to as slumps, while those with planar failure surfaces are called block glides.

Rock slides commonly occur on relatively steep slopes in competent rocks. Slopes are commonly from 35% to as steep as 70%. Movement of an intact rock mass along a curved slide plane leads to a steep headscarp at the upper boundary of the slide. Immediately below the headscarp is a block that is commonly rotated so that it is less steep than the surrounding hillslopes. Below the bench, the slide mass may be intact and similar gradient to the surrounding slopes or may have additional scarps and benches. The lower parts of the slopes may bulge outward and be steeper that the surrounding slopes.

The rotation of the block that typically occurs in the upper part of a “slump” rock slide leads to a less steep area or in some cases a closed depression. These areas may accumulate and hold water more than the surrounding slopes. Recognition of landslides is aided if the accumulated water leads to significantly different vegetation, especially phreatophytic (water loving) vegetation in such areas. The improved water holding capacity of these areas also decreases the overall stability of the slide mass by allowing water more time to infiltrate the slide.

The larger and deeper rock slides are sensitive to conditions that affect the entire slope. A rise in the water table that may occur in high rainfall years may decrease the overall stability. Undercutting of the base of slope or addition of fill to the upper slope also tends to destabilize an existing slide. Movement is usually slow, on the order of millimeters per year, and incremental, sometimes only occurring in years of higher than normal rainfall. Movement can, however, accelerate in some cases to the point that the mass fails more rapidly, moving several meters in the course of a few days, or by breaking up into smaller rock falls and debris slides which can move several meters in a few minutes.

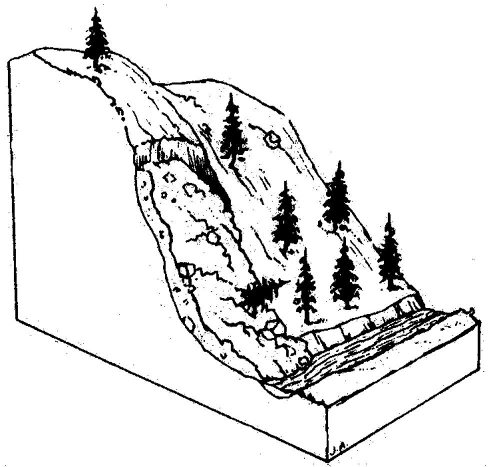


EARTH FLOW: A landslide composed of mixture of fine grained soil, consisting of surficial deposits and deeply weathered, disrupted bedrock. The material strength is low through much of the slide mass, and movement occurs on many discontinuous shear surfaces throughout the landslide mass. Although the landslide may have a main slide plane at the base, many internal slide planes disrupt the landslide mass leading to movement that resembles the flow of a viscous liquid.

Earth flows commonly occur on less steep slopes than rock slides, in weak, clay-rich soils or disrupted rock units. Slopes are commonly from 10% to as steep as 30%, although steeper slopes may be found in headscarp areas and where landslide toes are being eroded. Movement of a slide mass along numerous curved failure surfaces leads to an irregular steep headscarp at the upper boundary of the slide. Immediately below the headscarp is a series of blocks that are commonly rotated so they are less steep than the surrounding hillslopes. Below the bench, the slide mass is made up of many smaller masses which may move as intact masses for a time then break up into smaller masses and flow on a multitude of failure surfaces. The flowage of weak material with blocks of relatively intact material leads to a lumpy “hummocky” slope that is typical of large earth flow areas. The lower parts of the slopes usually bulge outward and are steeper than the surrounding slopes.

The rotation of the blocks that typically occurs in the upper part of an earthflow leads to a less steep slope which sometimes holds closed depressions. These areas may accumulate and hold water more than the surrounding slopes. Recognition of landslides is aided if the accumulated water leads to significantly different vegetation, especially phreatophytic (water loving) vegetation in such areas. The improved water holding capacity of these areas also decreases the overall stability of the slide mass by allowing water more time to infiltrate the slide.

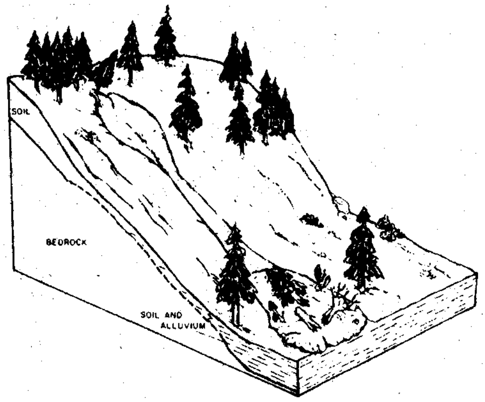
Earthflows are sensitive to conditions that affect the entire slope and to disturbances to any part of the slope. A rise in the water table that may occur in high rainfall years may decrease the overall stability. High water pore pressures, typically following a sustained period of heavy rains, may trigger earth flows, which then may continue to move for a period of days to weeks. Undercutting of the base of slope or addition of fill to the upper slope also tends to destabilize an existing slide. Because the slide mass is weak and contains slide planes throughout, cuts or fills on the slide mass may destabilize a part of the slide. Movement may occur for years as creep of the surficial soil as it shrinks in dry seasons and swells in wet seasons. Movement of the entire mass is more common in years of higher than normal rainfall. Movement is generally slow, in the millimeters or centimeters per day range, but can accelerate to as fast as meters per day in exceptional circumstances.



DEBRIS SLIDE: A slide of coarse grained soil, commonly consisting of a loose combination of surficial deposits, rock fragments, and vegetation. Strength of the material is low, but there may be a very low strength zone at the base of the soil or within the weathered bedrock. Debris slides typically move initially as shallow intact slabs of soil and vegetation, but break up after a short distance into rock and soil falls and flows.

Debris slides commonly occur on very steep slopes, commonly as steep as 60% to 70%, usually in an area where the base of a slope is undercut by erosion. They are most common in unconsolidated sandy or gravelly units, but also are common in residual soils that form from the in-place weathering of relatively hard rock. Movement of the slide mass as a shallow slab leads to a smooth steep, commonly curved scar. The debris is deposited at the base, commonly as a loose hummocky mass, although the deposit may be rapidly removed by erosion. Debris slides form steep, unvegetated scars. Debris slide scars are likely to remain unvegetated for years. Revegetated scars can be recognized by the even steep slopes, and the shallow amphitheater shape of many scars.

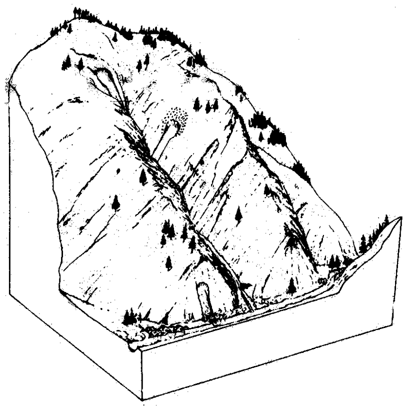
Because debris slides are relatively shallow they are sensitive to changes that are smaller and may occur over shorter times than those that affect deeper slides. A single heavy rainstorm or series of storms may deliver enough rain to trigger debris slides. Individual debris slides may move at rates ranging from meters per day to meters per minute. Debris slide scars are extremely steep and therefore are very sensitive to renewed disturbance. Natural erosion at the base of debris slide scars may trigger additional slides. Cutting into the base of a debris slide scar by man may also trigger renewed slides. Even without additional disturbance, debris slide scars tend to ravel and erode, leading to small rock falls and debris slides from the same slope.



DEBRIS FLOW: A landslide in which a mass of coarse-grained soil flows downslope as a slurry. Material involved is commonly a loose combination of surficial deposits, rock fragments, and vegetation. High pore water pressures, typically following intense rain, cause the soil and weathered rock to rapidly lose strength and flow downslope.

Debris flows commonly begin as a slide of a shallow mass of soil and weathered rock. Their most distinctive landform is the scar left by the original shallow slide. The path of the debris flow may be marked by a small drainage that has been stripped of vegetation. The debris flow may not leave any deposit if it flows directly into a larger creek and is immediately eroded away. Many debris flow deposits are ephemeral, but in some cases successive debris flows may deposit material in the same area leading to a debris fan, which resembles a small, steep alluvial fan.

Because debris flows are relatively shallow they are sensitive to changes that are smaller and may occur over shorter times than those that affect deeper slides. Debris flows are especially sensitive to changes in water conditions in slopes. They are triggered in natural conditions by factors that increase the pore pressures in the shallow subsurface, commonly at the base of the soil. A single heavy rainstorm or series of storms may deliver enough rain to trigger debris flows. Individual debris flows may move at rates ranging from meters per hour to meters per second. Works of man that tend to concentrate water on steep slopes have to be carefully designed to avoid increasing the potential for debris flows.

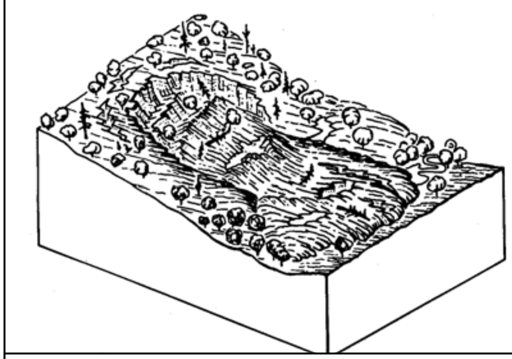


DEBRIS SLIDES and DEBRIS FLOWS are commonly found on a landform called a DEBRIS SLIDE SLOPE, which represents the coalesced scars of numerous landslides that are too small to depict on a map of this scale. These landforms are generally very steep, and have developed in areas of weak bedrock mantled with loose, thin soils and covered with sparse vegetation.

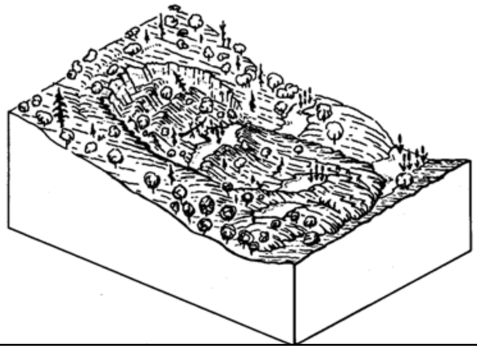
Debris slide slopes are typically very steep, 60% and steeper is common. Areas in which the dominant form of erosion is by debris slides and debris flows are characterized by uniform very steep slopes, commonly with each small canyon having rounded amphitheater-shaped heads.

**Activity of landslides**

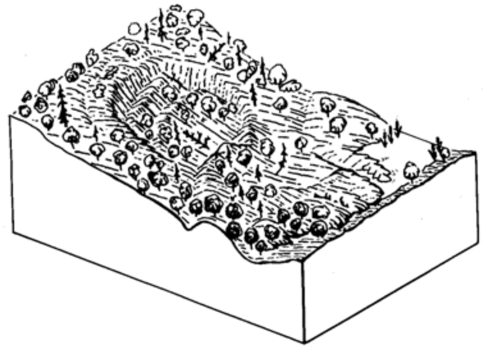
Each landslide is classified based on the recency of activity into one of four categories based on the system of Keaton and DeGraff, (1996). The diagrams below illustrate levels of activity (diagrams from Wieczorek, 1984).



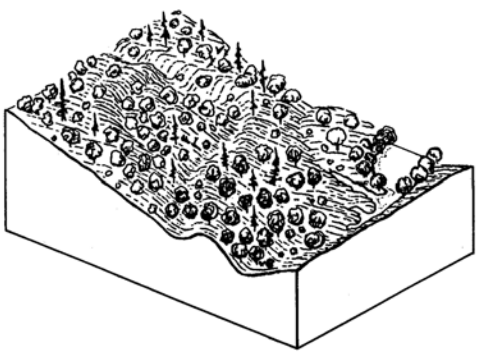
active or historic: The landslide appears to be currently moving or movements have been recorded in the past. Fresh cracks, disrupted vegetation or displaced or damaged man-made features indicate recent activity. Water may be ponded in depressions created by rotation of the slide mass or blockage of stream drainage.



dormant-young: The landforms related to the landslide are relatively fresh, but there is no record of historic movement. Cracks in the slide mass are generally absent or greatly eroded; scarps may be prominent but are slightly rounded. Depressions or ponds may be partly filled in with sediment, but still show phreatophytic vegetation.



dormant-mature: The landforms related to the landslide have been smoothed by erosion and re-vegetated. The main scarp is rounded, the toe area has been eroded and some new drainages established within the slide area. Benches and hummocky topography on the slopes are subdued and commonly obscured by dense, relatively uniform vegetation.



dormant-old: The landforms related to the landslide have been greatly eroded, including significant gullies or canyons cut into the landslide mass by small streams. Original headscarp, benches and hummocky topography are now mostly rounded and subtle. Closed depressions or ponds now filled in. Vegetation has recovered and mostly matches the vegetation outside the slide boundaries.

### Confidence of Interpretation

Each area is classified as a definite, probable or questionable landslide. Because landslides are mapped based on their landforms, the confidence of identification is dependent on the distinctness of those landforms. Confidence of interpretation is classified according to the following criteria:

DEFINITE LANDSLIDE. Nearly all of the diagnostic landslide features are present, including but not limited to headwall scarps, cracks, rounded toes, well-defined benches, closed depressions, springs, and irregular or hummocky topography. These features are common to landslides and are indicative of mass movement of slope materials. The clarity of the landforms and their relative positions clearly indicate downslope movement.

PROBABLE LANDSLIDE. Several of the diagnostic landslide features are observable, including but not limited to headwall scarps, rounded toes, well-defined benches, closed depressions, springs, and irregular or hummocky topography. These features are common to landslides and are indicative of mass movement of slope materials. The shapes of the landforms and their relative positions strongly suggest downslope movement, but other explanations are possible.

QUESTIONABLE LANDSLIDE. One or a few, generally very subdued, features commonly associated with landslides can be discerned. The area typically lacks distinct landslide morphology but may exhibit disrupted terrain or other abnormal features that strongly to vaguely imply the occurrence of mass movement.

Each landslide is also classified by a number of other factors not portrayed on the map, but listed in the accompanying database table. The records in the database table include a unique number for each landslide in each quadrangle and a listing of the quadrangle. Other factors recorded for each landslide are:

| FIELD | VALUES | NOTES |
|---|---|---|
| Depth | s,m,d | As interpreted from the geomorphology and classified into one of the following three categories: shallow <3 m, medium 3-15 m, deep >15 m. |
| Direction of movement | azimuth | |
| Primary geologic unit | KJFm, KJFbf | The geologic unit from the geologic map. In this area all landslides involve either KJFm, Franciscan melange or KJFbf, Franciscan broken formation. |
| Primary lithology | ss, sh, ss-sh | Corresponding to the unit on the geologic map. In this area the lithologies are ss, sandstone, sh, shale and ss-sh, sandstone with lesser shale. |
| Secondary geologic unit | KJFm, KJFbf | If a landslide involves two bedrock geologic units |
| Secondary lithology | ss, sh, ss-sh | If a landslide involves two bedrock geologic units |
| Strike of bedrock | azimuth | |
| Dip of Bedrock | 0-90 degrees | |

| | | |
|---|---|---|
| Source of geologic data | | Reference of previous geologic map containing strike and dip information or field locality number where strike and dip measured |
| area | Value | |
| perimeter | Value | |

## FACTORS INFLUENCING SLOPE STABILITY IN THIS HIGHWAY CORRIDOR

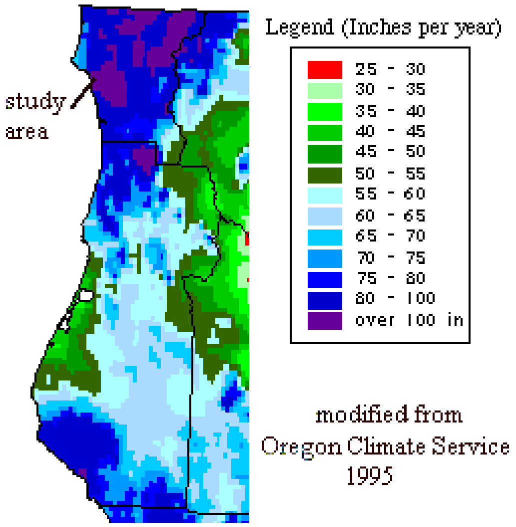
The inclination of slopes, their underlying rock types and geologic structures, landforms, and rainfall all influence the slope stability along the Highway 101 corridor between Wilson Creek and Crescent City.

Slopes along the Highway 101 corridor range from moderate to extremely steep. The steepest slopes are along the sea cliffs. Slopes at Last Chance Grade are almost 1000 feet high and average steeper than 60% slope. Other sea cliffs between Enderts Beach and Damnation Creek are as steep as 75%. Slopes that are this steep are characterized by bare rock outcrops and landslide scars. Most landslides on these very steep slopes involve shallow soil and loose rocks, moving as debris slides and rock falls. The ridge between the coast and the Mill Creek and Wilson Creek drainages has a broad, gently sloping crest. The relatively low slopes are what make the location of the highway on the crest of the ridge feasible. Stream canyons that cut into the ridge from both the west and east are relatively steep. The short drainages of Nichols Creek, Cushing Creek, and Damnation Creek have cut steep canyons between the main ridge and the ocean. Side slopes of these canyons are typically 30 to 50 %. East of the ridge, the canyons of the West Branch of Mill Creek and Wilson Creek have side slopes ranging up to 65%. Highway 101 between Wilson Creek and Crescent City generally follows the gentlest slopes in the area: along the ridge crest between the ocean and the Mill Creek and Wilson Creek drainages. To reach that ridge, however, the road must traverse relatively steep slopes in the Cushing Creek drainage on the north and sea cliffs at Last Chance Grade to the south.

Bedrock geology also has a very strong influence on the types and activity of landslides. Broken Formation, with hard blocks of bedrock separated by weak beds and shear zones, tends to have large, deep masses of rock that slide on narrow zones of weakness. These rock slide type landslides are characteristic of the broken formation but not as common in the melange. Where melange consists of weak sheared clay with little remaining rock-like structure, it typically fails as earthflows. In much of the northern Coast Ranges, melange bedrock forms a distinct set of landforms, commonly called “melange terrain”. The features of melange terrain include hummocky topography, closed depressions and benches on hillslopes, and gullying, all characteristic of downslope movement by earthflows and creep. In the study area, the slopes immediately north of Wilson Creek have many of the features of melange terrain. Farther north the areas mapped as melange do not appear to have landslides that are as abundant or as active. As a result, the terrain is “soft” with relatively gentle slopes and broad ridges.

The northwest trend of geologic structure, and similar orientation of bedding, shear zones and faults controls the general trend of ridges and stream valleys. Bedding and shear zones dip to both northeast and southwest, leading to planes of weakness that favor landslides that move in those directions. The overall structural grain and orientation of common planes of weakness leads to relatively common large landslides on slopes that face northeast and southwest.

The landforms created by landslides, in some cases, help to perpetuate the slides. Closed depressions, troughs and benches that commonly form near the headscarps of landslides allow increased percolation of water into the slide mass and along the slide plane, tending to destabilize the slide. Shallow debris slides, which tend to occur in response to streams or waves under cutting a slope may destabilize the adjacent area upslope when they move. This leads to successive landslides that fail progressively up slope.



modified from
Oregon Climate Service
1995

Figure 3. Average annual precipitation in northern coastal California.

Precipitation is a major factor influencing landslides. The segment of Highway 101 between Wilson Creek and Crescent City passes through one of the highest rainfall areas in California. According to the Oregon Climate Center the area averaged over 100 inches of rainfall per year between 1961 and 1991 (Figure 3). This amount of rainfall adds to the level of saturation of the landslide masses, decreasing their stability. Long term steady rain leads to deep saturation of landslide masses and tends to de-stabilize the larger, deeper types of landslides. Shorter term, but very intense rain tends to de-stabilize the shallower types of landslides, such as debris slides and debris flows.

Landslides are most abundant where several factors that negatively influence stability converge. In the Wilson Creek to Crescent City corridor, landslides are most abundant in two main zones. Along the sea cliffs, wave erosion helps to maintain extremely steep slopes and landslides. In melange bedrock, weak rocks and abundant planes of weakness lead to landslides. Where the melange intersects the coastline, virtually the entire slope from the shore to the ridge is an active landslide.

## POTENTIAL FOR LANDSLIDES ALONG HIGHWAY 101

Landslides can and do damage and close roads, resulting in significant repair and maintenance costs. Economic losses can be significant to an entire region of the state if a major route is closed for a significant period. Besides the costs associated with landslide damage, some types of landslides pose a risk to the safety of the traveling public. None of these risks can be eliminated. If roads are to pass through regions like the northern coast ranges where landslides are common, they will be exposed to some risk.

An evaluation of the potential consequences of landslides along Highway 101 between Wilson Creek and Crescent City may help Caltrans plan for future landslide mitigation projects and prioritize more detailed studies of individual landslides. A thorough evaluation of the probabilities of landslide movement, or of the economic consequences of that movement is beyond the scope of this study. We do not have the detailed geotechnical data to evaluate the probability of movement of landslides, nor the economic data to measure their consequences. We can, however, assess the types of landslides and the general consequences of movement of those types of landslides. In the table below are the size, movement type, materials and activity level of a landslide, the velocity of movement that is typical of a type of landslide, and the proximity to the highway. One can assume that those landslides that have moved most recently are the most likely to move in the future, and that the types of movement that have occurred in the past will continue.

The consequences of landslide movement are related to the size of a landslide, and the amount and velocity of movement. Larger slides may displace more of a roadway, resulting in greater repair costs. Larger displacements also translate to greater repair costs. If large movements accumulate slowly, over years or decades, they may be a continuing maintenance problem where cracks are filled and pavement re-leveled frequently. Large, rapid, displacements of even small volumes of material may undermine the road or deposit material on the road sufficient to close or partially close the roadway. These smaller volume but rapidly moving slides are the most likely to pose a safety risk to the travelling public. Movement of large, deep landslides is less likely to occur rapidly, but could have particularly severe consequences. Large displacements of large, deep landslides may result in the roadway being closed for repair, or in the worst case closed for long periods for reconstruction or rerouting.

|  | NAME | TYPE | RECENCY OF MOVEMENT | SIZE | DEPTH | PROBABLE RATE OF MOVEMENT | POSSIBLE CONSEQUEN-CES | COMMENTS |
|---|---|---|---|---|---|---|---|---|
| 1 | SR-2 | RS | m | 165 ac | d | slow | Road damage- cracks and grade offsets | No evidence of current movement |
| 2 | SR-4 | RS | y | 4 ac | d | moderate | Hwy closure | repaired |
| 3 | SR-6 | RS | m | 85 ac | d | slow | Lane closure |  |
| 4 | SR-7 | DS | y | 0.5 ac | s | moderate | Lane closure | repaired |
| 5 | CH-12 | RS | m | 15 ac | m | slow | None initially | Future movement could de-stabilize road |
| 6 | CH-11 | RS | m | 26 ac | d | slow | " | " |
| 7 | CH-16 | RS | m | 13 ac | m | slow | " | " |
| 8 | CH-17 | RS | m | 15 ac | m | slow | " | " |
| 9 | CH-22 | RS | m | 45 ac | d | slow | " | " |
| 10 | CH-46 | RS | a | 200 ac | d | slow-moderate | Lane -road closure, closure for extended period in worst case scenario. | Very large slide has moved recently. Potential to displace 4000+ feet of road by several meters or more |
| 11 | CH-45 | DS | a | 5 ac | s | rapid | ", risk to public | Debris slide below road stabilized by wall, scars above road. |
| 12 | CH-44 | DS | a | 35 ac | d | slow-moderate | Lane - hwy closure | Smaller slide within # 10. |
| 13 | CH-42 | DS | a | 4 ac | s | rapid | ", risk to public | Debris slides below road |
| 14 | CH-43 | DS | a | 3 ac | s | rapid | " | Debris slides below road |
| 15 | CH-61 | RS | a | 18 ac | d | slow-moderate | Lane - hwy closure | Smaller, deep slide within # 10. |
| 16 | CH-47 | EF | a | 105 ac | d | slow | Small, frequent movement, damage | Slow movement likely to continue, periodic repair needed |

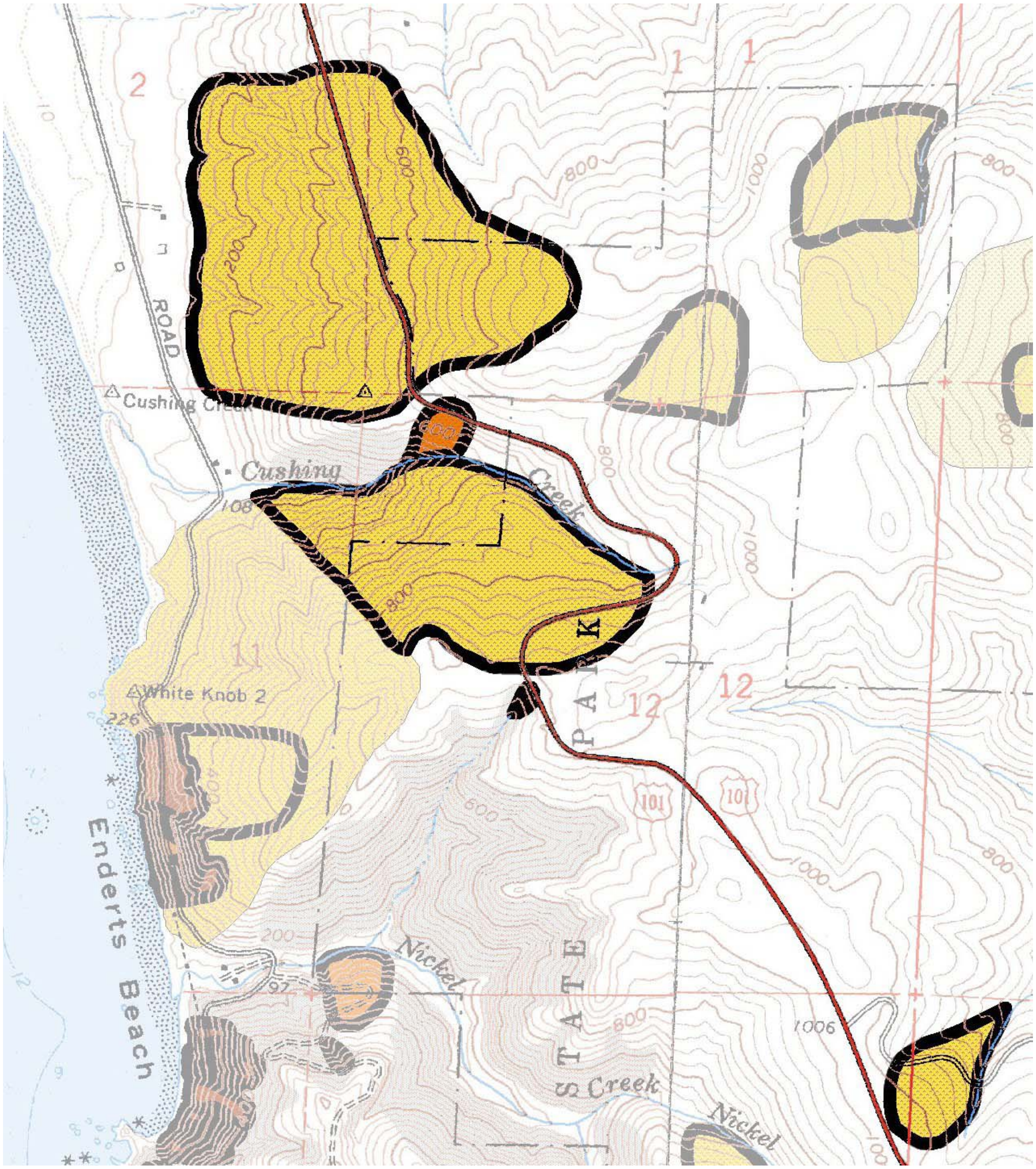


Figure 4a. In the Cushing Creek area the Highway crosses two very large landslide masses and two smaller ones on steep slopes just below the road. The northern of the two large landslides does not appear to have caused any distress to the roadway, nor does it show other evidence of recent movement. The southern large landslide may have had recent movement, and has been the site of smaller slides during the recent roadway widening project. The two smaller slides have moved and damaged the road. Both of these have been repaired and appear to be unlikely to re-activate. If they were to re-activate, however, they would almost certainly displace part of the roadway.

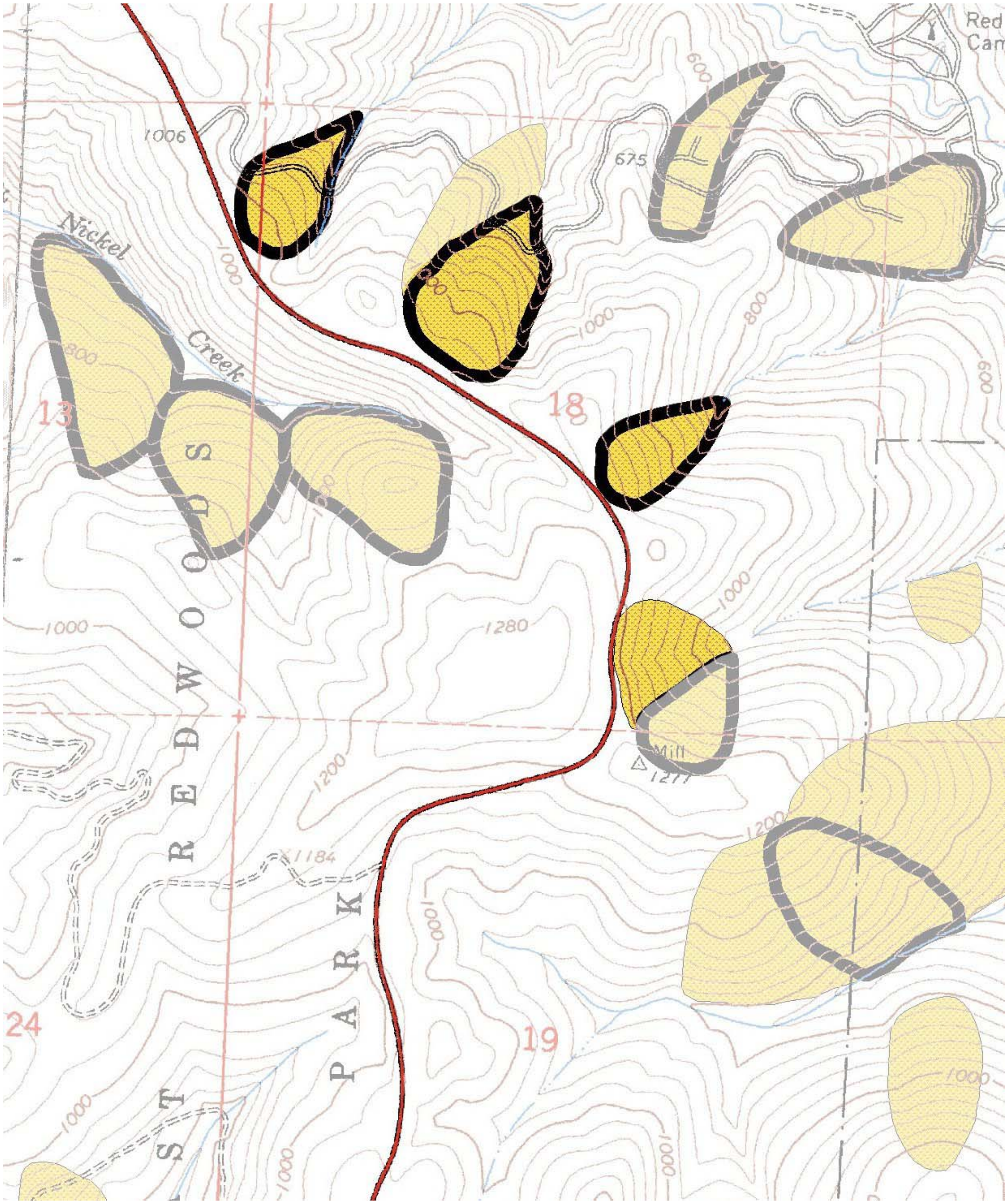


Figure 4b. Several large landslides in the area around the state park campground road are on moderate slopes below the highway. Movement of any of these slides would remove support from the roadway area, potentially decreasing the stability of the area..

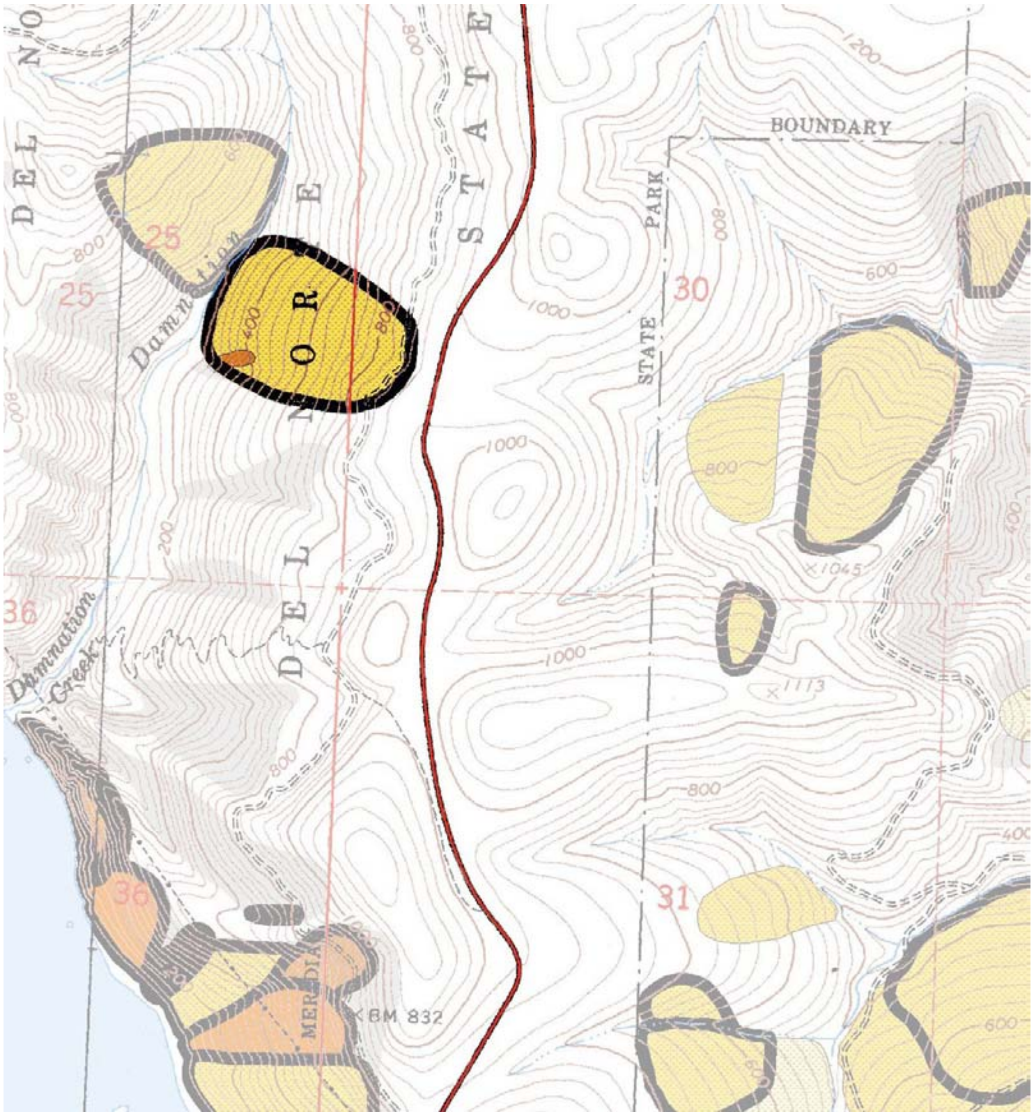


Figure 4c. One large landslide on the slopes above Damnation Creek is in a position to destabilize the area that the highway is built on. A large amount of renewed movement on this landslide would have to occur if it were to undermine the highway.

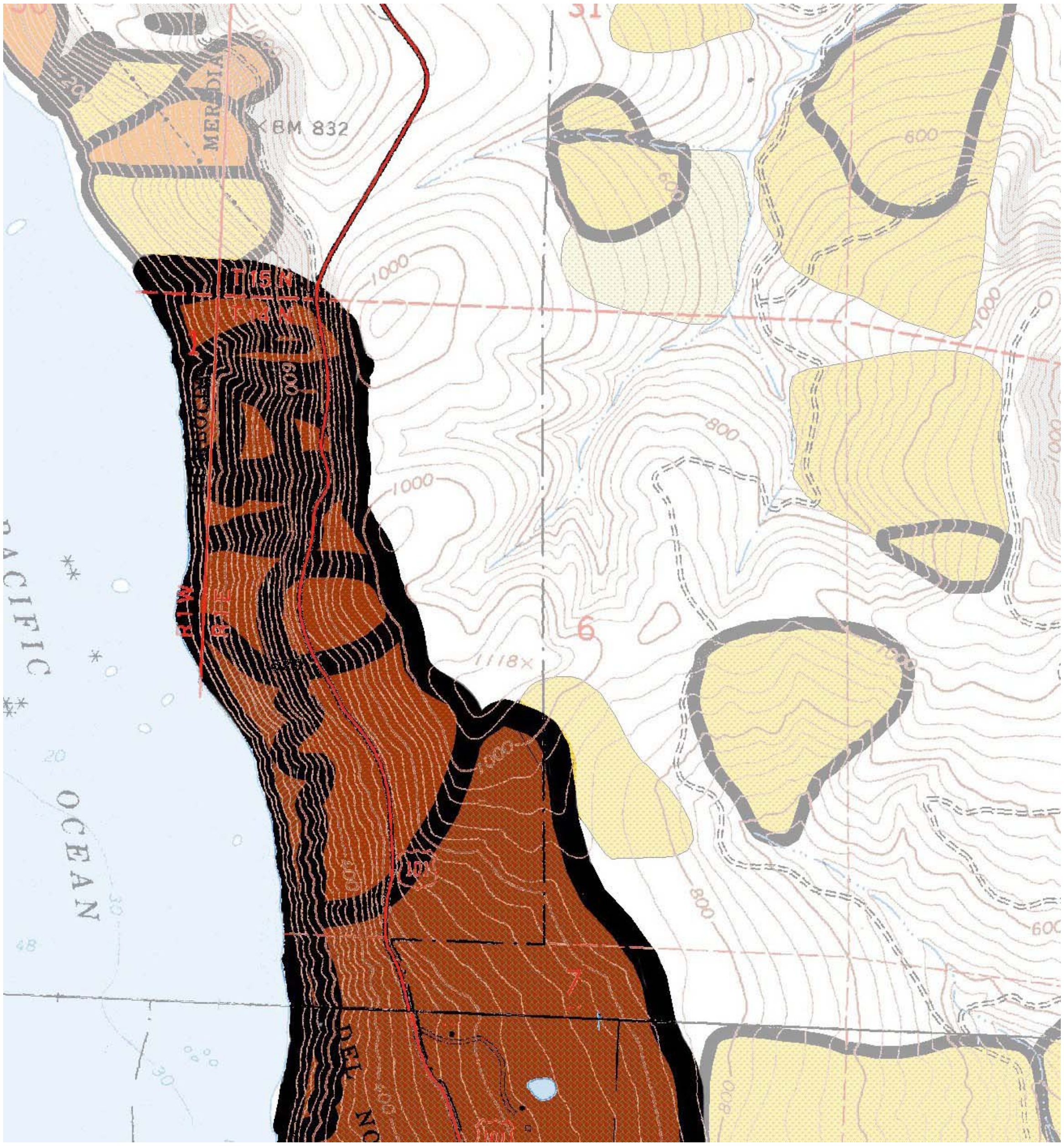


Figure 4d. As Highway 101 leaves the ridge and begins to traverse the Last Chance Grade, it enters a series of landslides. These landslides are both large, deep-seated slides and shallower debris slides. The shallow debris slides affect the area below the road and have the potential to undermine the road. Slopes above the road also show scars of past debris slides and debris flows. As a result, the entire segment of roadway classified could be affected by large deep landslides and shallow fast-moving slides such as debris flows and rock falls. Caltrans has constructed retaining walls in the past several years to mitigate the risk from the smaller slides below the road. The deep rock slides have the potential to move several feet to tens of feet rapidly in response to exceptionally wet seasons or earthquake shaking.

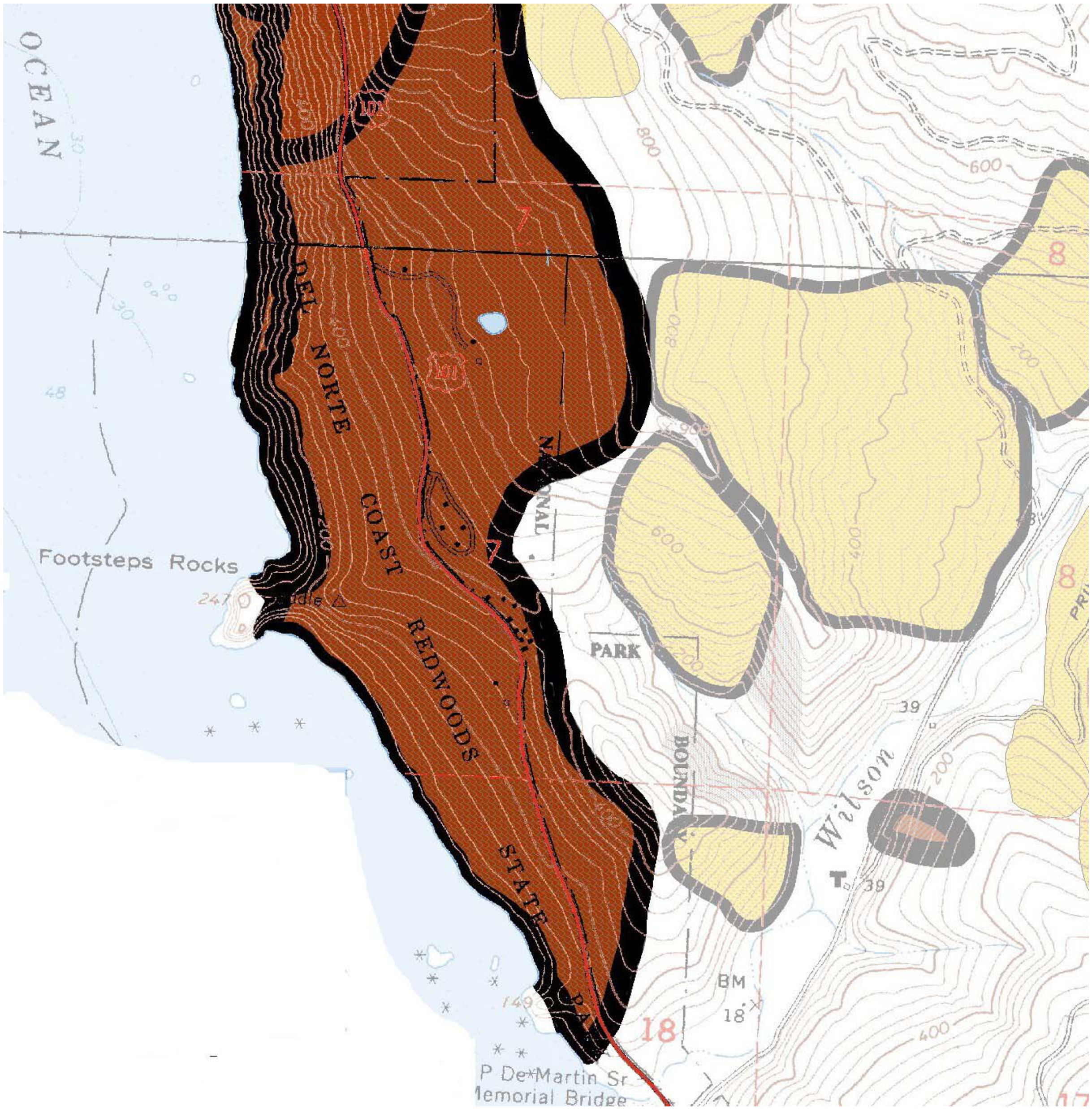


Figure 4e. The large earthflow complex north of Wilson Creek has been active in the past several years, resulting in “wavy” uneven pavement. This slide mass will continue to move in the future, moving more in response to wet years and slowing down in dry years. The properties of the melange bedrock in this area and the active erosion at the toe of the slide make mitigation of this slide extremely difficult, if not impossible. Very rapid large movements that would close the road for extensive periods is also unlikely because of the properties of the melange bedrock.

## SUMMARY

Highway 101, the main transportation corridor in northern coastal California, traverses a particularly rugged and landslide-prone area between Crescent City and Wilson Creek in Del Norte County. Within this corridor, landslides at Last Chance Grade have been an ongoing problem for decades. Movements in the 1990's necessitated consideration of several large and complex mitigation options. In order to evaluate these options, and the relative hazards of the landslides at Last Chance Grade compared with other landslides in the area, Caltrans contracted with the California Geological Survey to map the geology and landslides of the corridor. This mapping will help Caltrans plan landslide mitigation along the existing roadway and evaluate potential means of avoiding the most severe hazards.

Over 200 landslides have been mapped within the corridor area. The type and activity of the slides, the level of confidence of our interpretation and several other factors are recorded for each slide. Landslides within the corridor are concentrated in two belts, controlled by the steepness of the slopes and the bedrock geology. Along the sea cliffs, active wave erosion leads to very steep slopes, as steep as 75% for hundreds of feet vertically. These steep slopes tend to fail as shallow debris slides and rock falls. Larger masses of relatively intact bedrock fail along weak bedding planes or shear zones as rock slides. The other belt of abundant landslides follows the area mapped as melange bedrock through the center of the area. This weak, pervasively sheared rock tends to fail on gentler slopes than the surrounding "broken formation". The melange also tends to fail as earth flow type landslides due to the pervasive shearing of the material. The greatest concentration of landslides is found where the belt of abundant landslides along the steep sea cliffs converges with the belt of landslides along the weak melange bedrock, near the mouth of Wilson Creek.

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