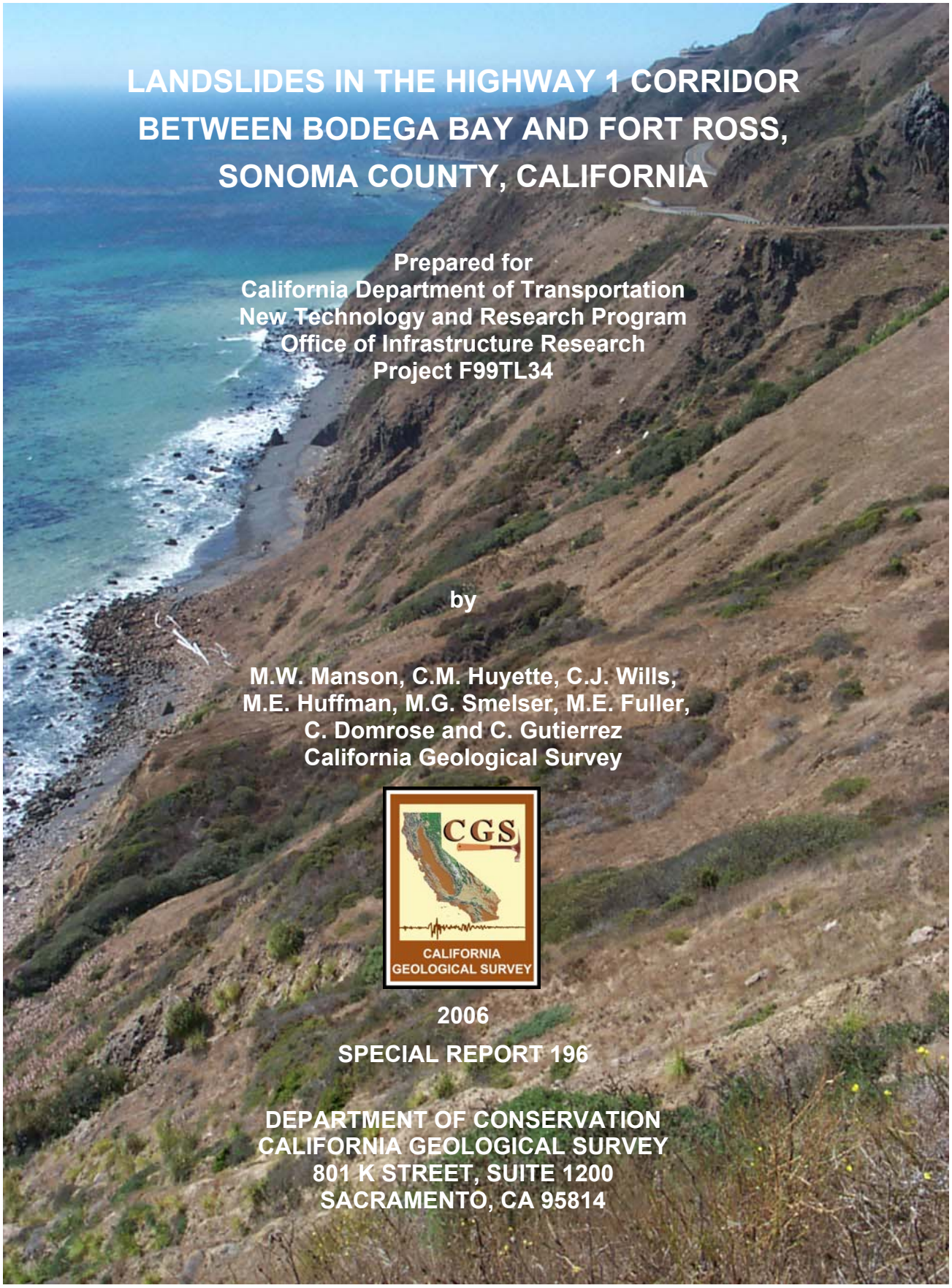

LANDSLIDES IN THE HIGHWAY 1 CORRIDOR BETWEEN BODEGA BAY AND FORT ROSS, SONOMA COUNTY, CALIFORNIA

Prepared for
California Department of Transportation
New Technology and Research Program
Office of Infrastructure Research
Project F99TL34

by

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INTRODUCTION

Highway 1 is the major North-South highway along the west coast of California. North of San Francisco Bay, the highway follows the coast along the western edge of relatively flat marine terraces bordered by near vertical sea bluffs, and on very steep slopes in rugged mountainous terrain along high cliffs overlooking the Pacific Ocean. The segment of the highway between Bodega Bay and Fort Ross crosses both types of terrain, with the coastal geomorphology greatly influenced by wave erosion, landsliding and episodic movements along the nearby historically active San Andreas fault, which roughly parallels the highway.

The Bodega Bay-Fort Ross study area includes several distinct types of landslides, and landslides that have been historically active and disrupted the highway. Movement of several deep bedrock slides in the past decades has led Caltrans to investigate landslide repair options. These repairs have included expensive retaining structures such as mechanically stabilized earth (MSE), crib walls, tieback walls, solder piles and soil nail walls.

A 4-mile-long segment of the highway, between Russian Gulch and Fort Ross, crosses very steep (typically 80 percent to near-vertical) slopes between the Pacific Ocean and the westernmost coastal ridge crest. This very steep terrain is both rugged and landslide prone. This segment (PM 26.4 to PM 30.5) consists of two-lane undivided highway that has been repeatedly affected by landslide movements, causing the highway to be closed for short periods of time and restricting the flow of traffic for days or weeks during highway reconstruction efforts. The very steep bluff location along this segment of the highway limits options for roadway location and pavement width, and has necessitated the use of Meyers Grade, Sea View and Timber Cove Roads as a temporary highway bypass route.

To place the landslides between Bodega Bay and Fort Ross in regional perspective and provide background data for proposed projects, the California Department of Transportation, Office of Infrastructure Research contracted with the Department of Conservation's California Geological Survey (CGS) to prepare maps of the Highway 1 corridor between Bodega Bay and Fort Ross. These maps were to include a geologic map and a map of landslides in the highway corridor and the surrounding area. The mapping area was to include the existing two-lane highway alignment and extend downslope to the beach and upslope to the top of the ridge. After examining the study area boundaries CGS staff expanded the study area to include Cheney Gulch on the south and Stockhoff Creek on the north, and widened the study area up to 3 miles to the east. The expansion of the study area allowed the inclusion of the previously used Meyers Grade-Sea View Road-Timber Cove Road bypass route and the two sites where the highway is close to or crosses the San Andreas fault. The maps do not indicate the probability of movement of any individual landslide or the stability of areas due to other

geologic hazards. However, the types of geologic hazard that are likely to affect the highway in the future, 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, especially the segment between Russian Gulch and Fort Ross, with the landsliding found in the surrounding region and consider the feasibility of a permanent bypass route to avoid the recurrent landslide areas that necessitate costly repairs on the unstable bluff slopes.

The maps presented here were prepared at a scale of 1:12,000 (1 inch = 1000 feet) by compilation of previous geologic mapping, interpretation of aerial photographs and original field mapping along the highway. These maps were prepared using a computer geographic information system (GIS) on scanned images of USGS 7.5-minute topographic quadrangles. Portions of the Arched Rock, Bodega Bay, Duncans Mills, Fort Ross and Plantation quadrangles form the base map of Plates 1 and 2. The geologic and landslide maps were drawn in the computer using ArcView v. 3.2®, and includes database tables describing each mapped feature.

REGIONAL OVERVIEW

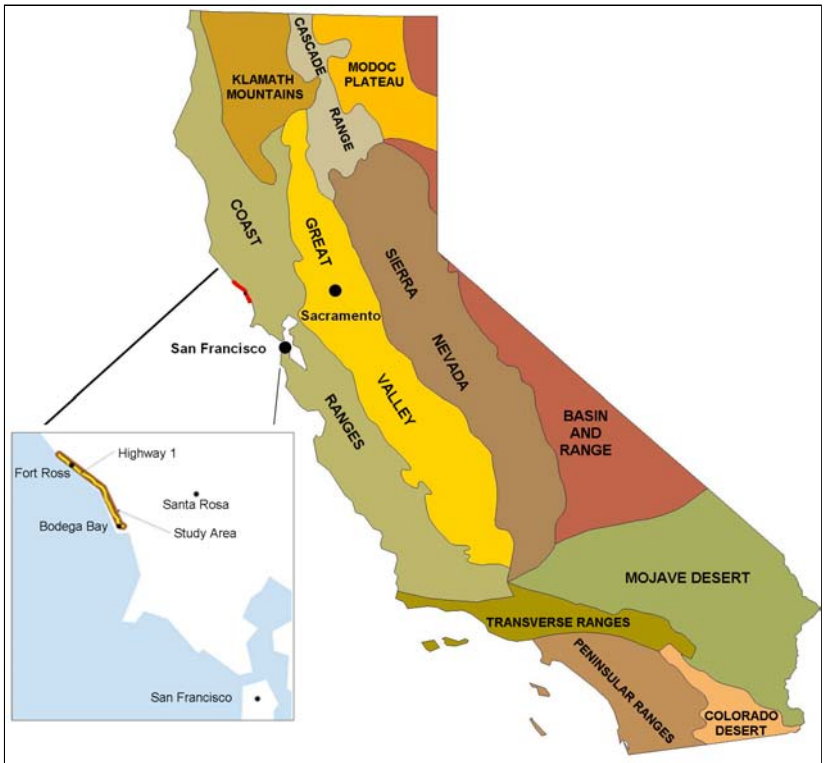


Figure 1. Geomorphic provinces of California showing the location of Highway 1 aong the Sonoma County Coast and the study area.

The Coast Ranges geomorphic province extends for about seven hundred miles within California from Santa Barbara County to the Oregon border. In the vicinity of Bodega Bay and Fort Ross the Coast Ranges province is characterized by northwest-trending mountain ranges and valleys bounded by right-lateral strike-slip faults that are part of the San Andreas fault system. The San Andreas fault lies beneath, is adjacent to, or is offshore from Highway 1 in the study area. The fault is crossed by the highway

near Fort Ross. This portion of the fault ruptured in 1906 during the San Francisco Earthquake.

The San Andreas fault system forms the complex boundary between the mostly offshore Pacific crustal plate and the onshore North American crustal plate. The faster northward-moving Pacific plate and slower northwestward-moving North American plate are colliding and sliding obliquely past each other. The active plate movements result in tectonic compression and regional uplift, on the order of 0.3 mm to 0.6 mm per year (Smelser and Reynolds, 2004). Widespread downcutting of stream bottoms and oversteepening of hillslopes follow each seismic episode that causes uplift.

Sea level is rising at about 1.5 mm per year or about 5 times faster than the current rate of tectonic uplift. At different times in the geologic past, when the rate of uplift and sea level rise were equal, wave erosion formed a broad terrace surface that was covered with alluvium. The continuous uplift associated with tectonic compression has resulted in a series of broad stair-step terraces that are higher in elevation and progressively older towards the east, away from the coastline (Smelser and Reynolds, 2004).

Most of the rocks in the vicinity of the Highway 1 study area are sedimentary rocks of Cretaceous through Tertiary ages. The most widespread unit is the Franciscan Complex, which is composed mainly of fine- to medium-grained slightly metamorphosed greywacke sandstone and highly sheared shale. Other rock types in the Franciscan include serpentine, ultramafic rocks, greenstone and chert. Conglomerate of the Cretaceous-age Great Valley Sequence is exposed on both sides of the Russian River at Jenner and Bridgehaven. Younger Tertiary sedimentary rocks overlie the Franciscan in the northern and southern portions of the study area. Numerous patches of even younger (Quaternary-age) terrace sediments were deposited on wave-cut surfaces on the bedrock that borders the coast. Oversteepened slopes are at greater risk of failure by landsliding because of the weakening of the rock units by compression and fracturing.

West of the San Andreas fault the bedrock is part of the Salinian Block, transported northwestward by innumerable earth movements along the San Andreas fault. Salinian Block bedrock in the study area includes a block of Cretaceous granitic rock at Bodega Head and Tertiary sedimentary rock of the German Ranch and Gallaway Formations in the Fort Ross area.

STUDY AREA

The Highway 1 corridor described here is 29 miles long, extending from Cheney Gulch (PM 8.2) on the south to Stockhoff Creek (PM 37.2) on the north. At each end it includes mostly broad, gently sloping coastal terraces: between Cheney Gulch and the Russian River, and between Mill Creek and Stockhoff Creek. The north-central portion of the Sonoma coast, between the Russian River and Fort

Ross, is noted for its dramatically high, steep bluff slopes, which rise to over 1,600 feet in elevation within approximately four miles. For this study we have attempted to map the geologic units, landslides or other areas of geologic hazards that may affect the stability or operation of the highway and the ridge top bypass route previously used during highway closures. Thus, we extended the original scope of the study area north of Fort Ross to include Meyers Grade, Sea View and Timber Cove Roads. Typically, our maps cover the area between the coastline and the first major ridgeline to the east, resulting in a mapped strip that is one to three miles wide.

Highway 1 was constructed through this geologically diverse landscape mostly along existing wagon roads in the early part of the 20th Century. Construction of the highway involved extensive excavations that utilized steam shovels and blasting. Fills with culvert crossings were typically placed in minor canyons. Bridges were constructed to cross the major drainage canyons located in the study area (see Figure 2). The highway route has a long history of landslides, which have both landed on the highway and undermined the roadbed. Road closures have been common, with long-term closure mainly because of large landslides in years of heavy rainfall. Earthquakes, such as the great quake of 1906 also triggered landslides that affected portions of the pre-highway wagon road between the mouth of the Russian River and Fort Ross (Lawson, 1908).

January 2006		**Log of Bridges On State Highways - District 4**			
Postmile	Bridge Number	Structure Name	Number of Spans	Year Built	Year Widened or Extended
009.16	20 0189	Cheney Gulch	2	1956	
012.49	20 0191	Salmon Creek	5	1983	
015.30	20 0198	Scotty Creek	4	1956	1959
019.72	20 0195	Russian River	6	1984	
024.50	20 0070	Russian Gulch	3	1940	

Figure 2: Caltrans list of bridges within the Highway 1 study area.

GEOLOGIC MAPPING

The Highway Corridor Geologic Map (Plate 1) was prepared by compiling previously published geologic maps (Blake and others, 1971; Blake and others, 2002; Brown and Wolfe, 1970; Huffman, 1972; Huffman and others, 1973; Huffman and Armstrong, 1980; and Smelser and Reynolds, 2004). CGS staff performed additional interpretation of aerial photographs and limited field mapping along the highway 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 Coastal Belt sandstone and "mélange." Both are composed of intensely sheared and fractured sandstone, siltstone and shale.

Coastal Belt sedimentary rocks are 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 forms steep slopes and rock fall slides of large intact blocks of rock (see Figure 3).

Figure 3: Sandstone blocks in Coastal Belt separated by eroded shear zones. All photos by M.W. Manson, CGS.

"Mélange " 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 the Coastal Belt is considered a mass of hard sandstone blocks separated by shear zones, "mélange " can be considered essentially a large shear zone containing relatively few intact blocks (see Figure 4).

There are several different criteria that can be used to distinguish areas of mélange from the more intact sandstone and shale of the Coastal Belt in an area

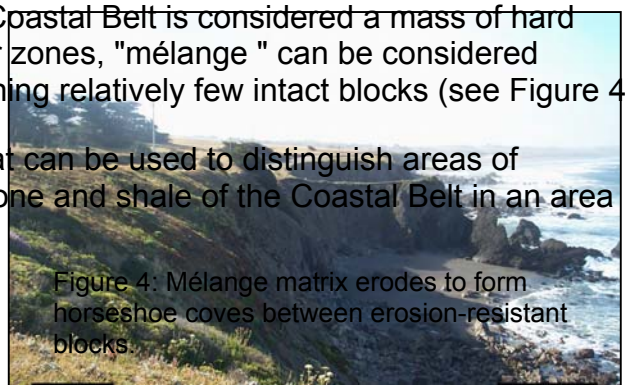


Figure 4: Mélange matrix erodes to form horseshoe coves between erosion-resistant blocks.

of sparse outcrops. Mélange 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 mélange. “Exotic” blocks near the mouth of the Russian River suggest this area is mélange. Mélange is also easily recognized because it forms distinctive terrain: the material is so weak and prone to landslides that areas of pervasive earthflow-type landslides are widespread. 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 indicative of mélange. Field mapping for this project verified that outcrops within the area mapped as mélange on previously published maps are composed mostly of sheared shale and siltstone, typically containing sandstone and “exotic” rock blocks and exhibit relatively gentle slopes.

Within the mélange unit, some blocks of different kinds of rocks are large enough to be mapped separately. These blocks may be greywacke, greenstone, chert, serpentinite, blueshist and greenshist. The blocks in the mélange unit depicted on the previously published geologic maps are generally not shown individually.

West of the San Andreas fault in the Fort Ross area, younger Tertiary sedimentary rocks of the German Rancho and Gallaway(?) Formations were deposited on basement rocks that probably include granitic rocks like those at Bodega Head. These two units consist of well-bedded sandstone, mudstone, and conglomerate containing abundant potassium feldspar.

In addition to the Franciscan Complex and Tertiary units, there are several younger surficial geologic units in the study area. These include the following units (listed in order of decreasing age):

> Wilson Grove Formation (Late Pliocene-Late Miocene): These deposits of nearshore and shallow marine sandstone and shale are found in the southeastern end of the study area, away from Highway 1. Because these rocks do not lie within the immediate area of the highway, they were not described for this study.
>
> Quaternary marine terrace deposits: Sand and some gravel deposited in a beach and shallow offshore environment is now exposed extensively on the lowest gently sloping coastal terraces between Bodega Bay and the Russian River, and in the Fort Ross - Stockhoff Creek area.
>
> Colluvium: Accumulations typically found in the upper portions of gulches and hillside swales, consists of unconsolidated to moderately consolidated clayey sand and sandy clay with varying amounts of gravel derived from the weathering of underlying bedrock.
>
> Alluvium: Stream deposits are found in the major creeks and river drainages. These deposits are unconsolidated sand and sandy gravel with some layers of finer grained materials.

Beach deposits: Bordering portions of the coastal bluffs are beach deposits, composed predominantly of sand and gravel and scattered toppled rock deposits and talus piles.

Bay Mud: Saturated estuarine mud with minor sand and silt, oyster shells and peat. Mapped only in Bodega Harbor.

Artificial fill over Bay Mud: Limited to areas of construction around Bodega Harbor.

Landslide deposits: Landslide deposits on the geologic map are the larger and deeper slides from the landslide map. For clarity the smallest slides are not shown on the geologic map. 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. Where numerous shallow landslide scars coalesce on the hillside, these areas were mapped as debris slide slopes. The materials in the landslide deposits are highly variable, depending on the source material and range from nearly intact sandstone to completely disrupted clay soils.

LANDSLIDES

More than 400 landslides were mapped in the Highway 1 corridor area between Cheney Gulch and Stockhoff Creek (Plates 1 and 2). These landslides tend to be the larger, deep-seated slides that affect large areas. Although we have attempted to show all landslides, there undoubtedly are many small shallow slides that are obscured by thick brush or forest cover and could not be seen.

The Highway Corridor Landslide Map (Plate 2) was prepared primarily by interpretation of aerial photographs, with review of previous reports and limited field checking. Landslides shown on previous maps (Blake and others, 1971; Blake and others, 2002; Brown and Wolfe, 1970; Fuller and Custis, 2002; Huffman, 1972; Huffman and Armstrong, 1980; Huffman and others, 1973), and a CGS report prepared for the California Department of Parks and Recreation (Smelser and Reynolds, 2004) were checked on aerial photos and in the field, if possible. The boundaries of landslides included in the previous work were revised as appropriate, and additional landslides were added. In addition, a topographic map of the San Andreas fault near Fort Ross was generated using LIDAR[1] data acquired from the U.S. Geological Survey. This large-scale LIDAR-based map was used to map additional landslides that are concealed by vegetation and forest canopy.

[1] LIDAR is an acronym for Light Detection and Ranging, which is an airborne remote sensing technology that can “see” the ground surface through thick brush and trees.

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 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 our map this type of slide is shown simply as a rockslide. 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 mélange commonly is "earth" because its original tectonic fabric in many places has been destroyed by pervasive landsliding.

By applying the system of Cruden and Varnes, with the criteria described above, we have identified five predominant types of landslides in this area.

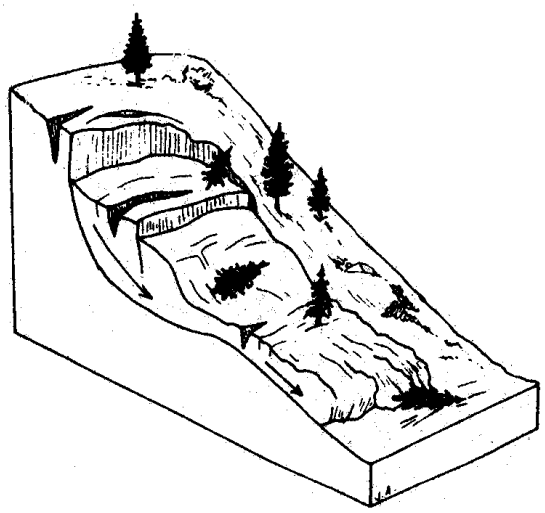


Diagram by Janet Appleby-Smith, CGS.

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 down- slope 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 in such areas, especially phreatophytic (water loving) vegetation. The increased water accumulation of these areas decreases the overall stability of the slide mass by allowing more water to infiltrate the slide, thereby increasing the unit weight of the slide mass and increasing the pore water pressure within the slide mass.

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, or even in normal rainfall years following the removal of vegetation, can decrease the overall stability. Undercutting of the base of the hillslope 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. However, movement can 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 that can move several meters in a few seconds.

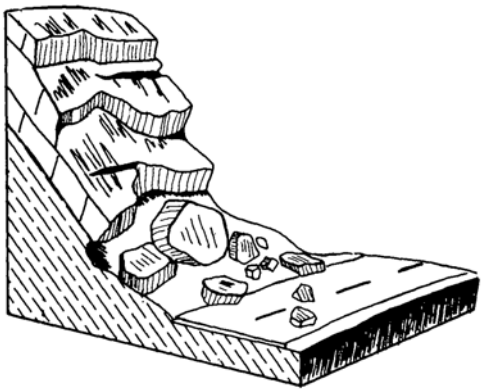


Diagram after Colorado Geological Survey, 1989

ROCK FALL: A landslide in which a fragment or fragments breaks off of an outcrop of rock and falls, tumbles or rolls down slope. Rock falls typically begin on steep slopes composed of hard rocks and result in piles of loose rubble at the base of slope.

Rock falls occur on steep slopes of hard, fractured rock. The scar left by a rock fall on the slope may be no more apparent than an area of rock that is less weathered than the surrounding rocks. Rock fall deposits are loose piles of rubble that may be easily removed by erosion. Because neither the scar nor the deposit is distinctive, and because rock falls are typically small, individual rock falls are usually not shown on regional-scale (1:24,000 and smaller) landslide maps.

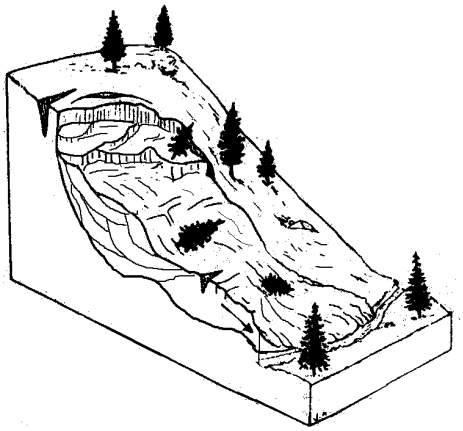


Diagram by Janet Appleby-Smith, CGS.

EARTH FLOW: A landslide composed of a 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 head scarp areas and where landslide toes are being eroded. Movement of a slide mass along numerous curved failure surfaces leads to an irregular steep head scarp at the upper boundary of the slide. Immediately below the head scarp 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 earth flow leads to a less steep slope that sometimes exhibits 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.

Earth flows 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.

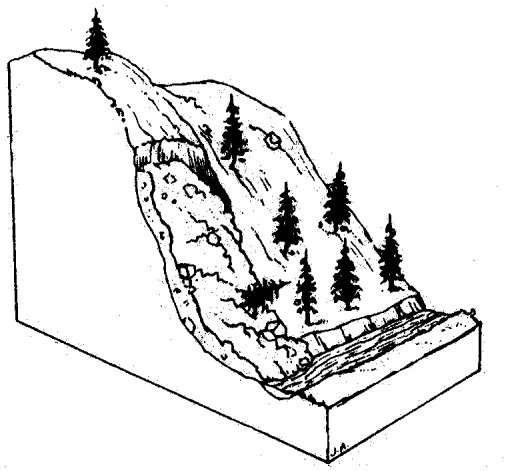


Diagram by Janet Appleby-Smith, CGS.

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 small changes that 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 second. 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. Excavating into the base of a debris slide scar 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.

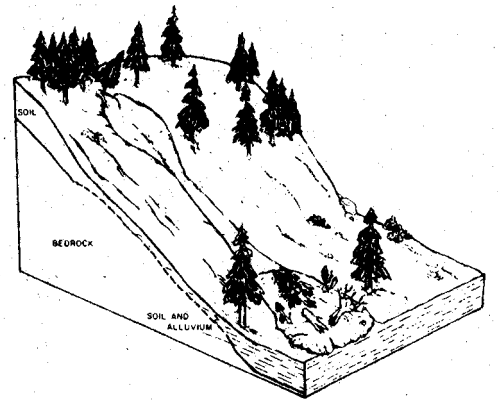


Diagram by Janet Appleby-Smith, CGS.

DEBRIS FLOW: A landslide in which a mass of coarse-grained soil flows downslope as a slurry similar to ready-mixed concrete. Material involved is commonly a loose combination of surficial deposits, rock fragments, and vegetation, including trees. 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 pore water pressure changes that are smaller and occur over shorter time frames than those that affect deeper slides. Debris flows 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, and can be extremely dangerous. Works of man that tend to concentrate water on steep slopes or that may increase pore water pressures on those slopes have to be carefully designed and constructed to avoid increasing the potential for debris flows.

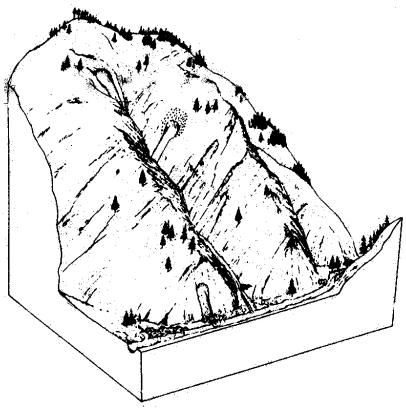


Diagram by Janet Appleby-Smith, CGS.

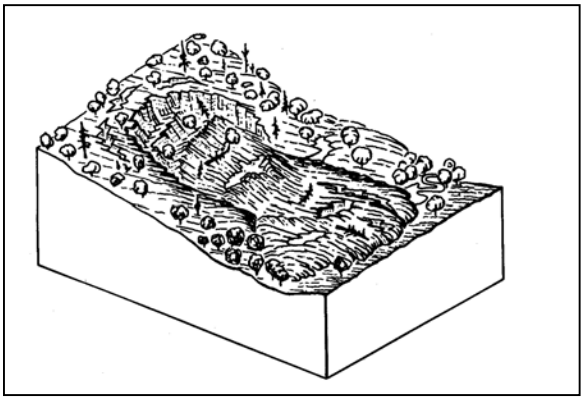
DEBRIS SLIDES and DEBRIS FLOWS are commonly found on a landform called a DEBRIS SLIDE SLOPE, which represents the coalesced scars of numerous landslides that are too small to depict on a map of this scale. These landforms are generally very steep, and have developed in areas of weak bedrock mantled with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

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

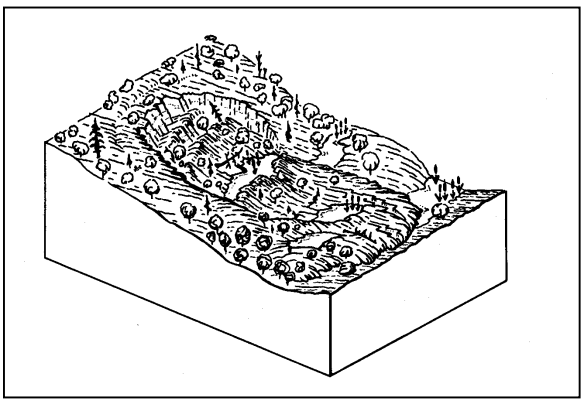
DEBRIS FLOW FANS consist of coalescing debris flows or debris slides, or both.

Activity of landslides

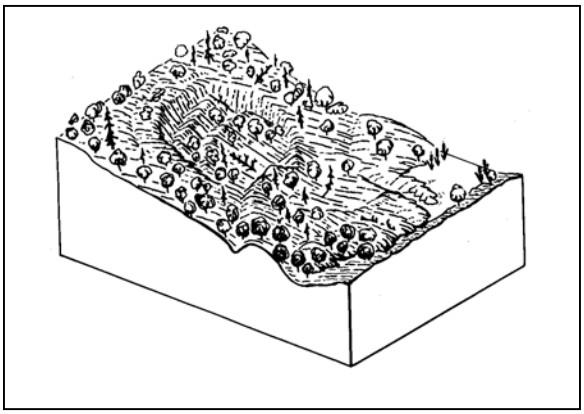
Each landslide is classified based on the recency of activity into one of three categories based on the system of Keaton and DeGraff (1996). The diagrams below illustrate levels of activity (diagrams from Wieczorek, 1984).



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.

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 the following:

FIELD	VALUES	NOTES
Depth	s,m,d	As interpreted from the geomorphology and classified into one of the following three categories: **s**hallow <3 m, **m**edium 3-15 m, **d**eep >15 m.
Scarp or Deposit	s,d	As interpreted from the geomorphology and classified into one of the following two categories: **s**carp or **d**eposit.
Direction of movement	Azimuth	Generally estimated in 45° increments, rotating clockwise from Due North (0°).
Photo year	Date	Date of earliest photography showing landslide feature, or publication date of reference.
Primary geologic unit	KJfm,TKfs, Tgr, Tg	The geologic unit from the geologic map. In this area most landslides involve either KJfm, Franciscan melange or TKfs, Franciscan Coastal terrane. A limited number of landslides near Fort Ross originate in the German Rancho or Gallaway (?) Formations.
Primary lithology	ss, sh, ss-sh, ms, cg	Corresponding to the unit on the geologic map. In this area the lithologies are ss - sandstone, sh - shale, ss-sh - sandstone with lesser shale, ms - mudstone, and cg - conglomerate.
Source of geologic data	CGS, USGS	Reference of previous geologic map containing strike and dip information or field locality number where strike and dip measured
Source of landslide data	MWM, CMH, MGS, MEH, MEF	CGS geologist who mapped the landslide.
Comments		Comments concerning the landslide, if any.
Quadrangle	Name	Arched Rock, Bodega Bay, Duncans Mills, Fort Ross, Plantation
Symbol	Qls, Qols, Qef, Qdf	Geologic unit symbol, if applicable.
Initial Movement & Activity	RSH, RSY, RSM, DSY, RFH, RFY, EFH, EFY, DGY,DSSY, KJfmY	Combination of Initial Movement and Activity; used for application of landslide legend file in Arc View.
Area	Value	Calculated by ArcView
Acres	Value	Calculated by ArcView
Perimeter	Value	Calculated by ArcView

FACTORS INFLUENCING SLOPE STABILITY IN THIS HIGHWAY CORRIDOR

The inclination of slopes, their underlying rock types and geologic structures, landforms, rainfall, wave or river erosion and seismicity all influence the slope stability along the Highway 1 corridor.

Slopes along the Highway 1 corridor range from gentle terraces adjacent to near-vertical bluffs a few tens of feet high, to extremely steep slopes, up to 1,600 feet high, between the rocky coastline and the first ridge back from the ocean. The steepest slopes have numerous rock falls, wedge failures and slumping along them. Slopes between Russian Gulch and Fort Ross range from 600 to about 1,600 feet high and average steeper than 65% slope, with many areas over 100%. Slopes that are this steep are characterized by bare rock outcrops and landslide scars. Most landslides on these very steep slopes involve dormant young deep-seated rock slides with numerous more recent shallow soil and loose rocks, moving as debris slides and rock falls. Some relatively large portions of the dormant young deep-seated rock slides have become reactivated, typically after periods of prolonged or intense rainfall. Stream canyons that cut into the ridge from both the west and east are relatively steep. The short drainages of Meyer, Jewel, Timber, Mill and Kolmer Gulches and Fort Ross and Timber Cove Creeks 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 Russian Gulch and Wheatfield Fork of the Gualala River have side slopes averaging 65% to over 80%. Highway 1 between Cheney Gulch and Jenner and between Fort Ross and Stockhoff Creek generally follows the gentlest slopes in the area: along the gently sloping terrace edge. To reach the terraces north of Fort Ross however, the highway must traverse very steep slopes between Russian Gulch and Mill Gulch.

Bedrock geology also has a very strong influence on the types and activity of landslides. Sandstone and shale of the Coastal Belt of the Franciscan Complex, 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 rockslide type landslides are characteristic of the more intact sandstone and shale but not as common in the mélange. In much of the northern Coast Ranges, mélange bedrock forms a distinct set of landforms, commonly called “mélange terrain”. The features of mélange 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 mélange terrain between Bodega Bay and Jenner contains a greater distribution of blocks than the mélange found along the ridge north of Russian Gulch. The areas mapped as mélange with abundant blocks do not appear to have landslides that are as numerous and the landslides are typically shallow debris slides, resulting in canyons of debris slide slopes. North of Russian Gulch the mélange terrain has a lower abundance of blocks in the matrix. As a result, the terrain is “soft” with

relatively gentle slopes and broad ridges. The mélange consists predominantly of weak sheared clay with little remaining rock-like structure and it typically fails as earthflows.

In some cases the landforms created by landslides help to perpetuate the slides. Closed depressions, troughs and benches that commonly form near the head scarps of landslides allows increased percolation of water into the slide mass and along the slide plane, tending to destabilize the slide by increasing the unit weight of the slide mass and increasing the pore water pressure. Shallow debris slides and rock falls, 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.

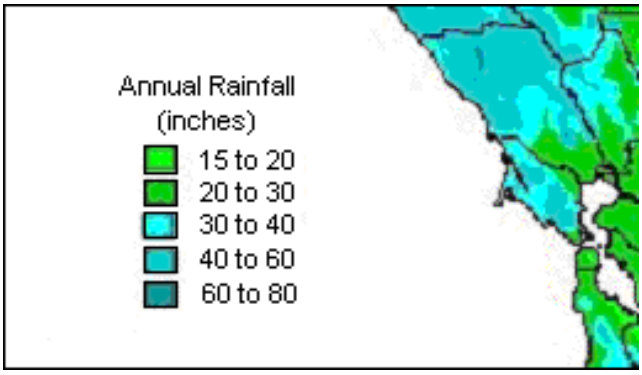


Figure 5: Average rainfall for Sonoma County and surrounding areas from 1961-1990. Source: Oregon Climate Service (1995).

Precipitation is a major factor influencing landslides. The segment of Highway 1 between Jenner and Fort Ross passes through one of the highest rainfall areas in California. According to the Oregon Climate Service the area averaged over 40 inches of rainfall per year between 1961 and 1990 (Figure 5). 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 Bodega Bay - Fort Ross corridor, landslides are most abundant in three main zones. Along the sea cliffs, wave erosion helps to maintain extremely steep slopes and causes landslides. In Coastal Belt and mélange bedrock, weak rocks and abundant planes of weakness lead to landslides. In areas affected by the San Andreas fault zone, shearing has weakened the rock mass further, resulting in a lowered internal shear strength making it more susceptible to landslide movement. Where the Franciscan Complex or mélange intersects the coastline, at or near the San Andreas fault zone, virtually the entire slope from the shore to the ridge is an active landslide, as is the case between

Russian Gulch and Fort Ross. High rainfall totals increase the ground water level within a slide mass, further destabilizing the slides.

Liquefaction and lateral spreading were triggered in the Russian River, Salmon Creek and Bodega Bay by the 1906 San Francisco earthquake (Lawson, 1908, p. 191 and Plate 142A). Liquefaction-induced deformations contributed to the severe damage of the Struve Slough bridges on Highway 1 in Santa Cruz County during the 1989 Loma Prieta earthquake (Chieruzzi and Lew, 1990, p. 105). The design of the destroyed Struve Slough bridges appears similar to the existing bridges at Salmon Creek and may cross similar liquefiable or soft deformable sediments.

POTENTIAL GEOLOGIC HAZARDS ALONG HIGHWAY 1

Landslides can and do damage and close roads, resulting in significant repair and maintenance costs. Economic losses due to increased travel distance and time 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 and other geologic hazards along Highway 1 between Bodega Bay and Fort Ross may help Caltrans plan for future landslide mitigation projects and prioritize more detailed studies of individual landslides and other areas prone to geologic hazards. A thorough evaluation of the probabilities of ground 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, bluff failure, liquefaction, lateral spread or lurching, nor the economic data to measure their consequences. We can, however, assess the types of geologic hazards that are likely to affect the highway within the study area, and the general consequences of induced land movement. In the table below are the locations of the highway that may be affected, hazard type, the probable *velocity of movement*[*] that is typical of a type of hazard for a triggering event, and the type of triggering event causing the hazard to effect 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.

[*] Moderate – centimeters to meters per day; Rapid – meters per hour to meters per second

GEOLOGIC HAZARDS BY HIGHWAY SEGMENT				
SEGMENT (PM-PM)	HAZARD TYPE	PROBABLE RATE OF MOVEMENT	POSSIBLE CONSEQUENCES	EVENT
8.2 – 8.7	Landslide	Moderate Rapid	Lane Closure Highway Closure	Rainfall Seismic
9.1 – 9.2	Liquefaction	Rapid	Bridge Closure	Seismic
9.2 – 9.4	Lateral Spread Lurching	Moderate to Rapid	Highway Closure	Seismic
9.8 – 10.0	Bluff Failure	Rapid	Lane Closure	Seismic
10.2 – 10.5	Bluff Failure	Rapid	Lane Closure	Seismic
12.4 – 12.6	Liquefaction	Rapid	Bridge Closure	Seismic
12.9 – 13.4	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
13.5	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
13.6	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
13.8 – 13.9	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
14.1	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
14.2 – 14.4	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
14.5 – 14.6	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
14.8	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
14.9 – 15.0	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
15.3 – 15.4	Liquefaction	Rapid	Bridge Closure	Seismic
15.4 – 15.6	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
15.7 – 15.9	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
16.3	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
19.8 – 20.1	Liquefaction	Rapid	Bridge Closure	Seismic
20.1 – 20.7	Lateral Spread Lurching	Moderate to Rapid	Highway Closure	Seismic
20.3 – 21.0	Landslide	Moderate Rapid	Lane Closure Highway Closure	Rainfall Seismic
20.7 – 21.1	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
21.1 – 21.2	Lateral Spread Lurching	Moderate to Rapid	Highway Closure	Seismic
21.3 – 24.5	Landslide	Moderate Rapid	Lane Closure Highway Closure	Rainfall Seismic

21.3 – 21.7	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
21.9 – 22.4	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
22.5 – 22.6	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
23.2	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
23.3 –23.4	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
23.5 – 23.6	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
23.9 – 24.1	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
24.5 – 24.6	Lateral Spread Lurching	Moderate to Rapid	Bridge Closure	Seismic
24.6 – 26.0	Landslide	Moderate Rapid	Lane Closure Highway Closure	Rainfall Seismic
26.4 – 31.9	Landslide	Moderate Rapid	Lane Closure Highway Closure	Rainfall Seismic
32.5 – 32.9	Landslide	Moderate Rapid	Lane Closure Highway Closure	Rainfall Seismic
34.1 – 34.3	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
34.4 – 34.5	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
35.0 – 35.1	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
35.3	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
36.5	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic
37.1 – 37.2	Bluff Failure	Moderate Rapid	Lane Closure Highway Closure	Erosion Seismic

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 within a slide 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 traveling public. Movement of large, deep landslides is less likely to occur rapidly, but could have particularly severe consequences. Large displacements of deep-seated landslides may result in the roadway being closed for repair, or in the worst case closed for long periods for reconstruction or rerouting. Highway 1 has been closed between Meyers Grade Road and Fort Ross on several occasions in the last decade due to landside damage and road reconstruction.

SUMMARY

Highway 1, the main transportation corridor along the coast in northern California, traverses a particularly rugged and landslide-prone area between Bodega Bay and Fort Ross in Sonoma County. Within this corridor, landslides on the high steep slopes between Russian Gulch and Fort Ross have been an ongoing problem for decades. Movements in the 1990's necessitated construction of several large structures to attempt to stabilize landslides. In order to evaluate the relative hazards of the landslides along the highway on the high bluffs 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.

Approximately 400 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 100% 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 mélange bedrock. This weak, pervasively sheared rock tends to fail on gentler slopes than the surrounding sandstone and shale of the Coastal Belt. The mélange 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 high steep sea cliffs converges with the belt of landslides along the weak mélange bedrock, near the San Andreas fault zone between Russian Gulch and Fort Ross. Seismicity has also trigger bluff and slope failures in the early part of the 20th century. Within the study area, likely locations of highway embankment and structure support failures caused by liquefaction or lateral spread/lurching during future nearby large magnitude seismic events in the Bodega Bay region have been identified for Caltrans evaluation.

ACKNOWLEDGEMENTS

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State of California
The Resources Agency

California Department of Conservation
Bridgett Luther, Director

Geology of the Highway 1 Corridor between Bodega Bay and Fort Ross, Sonoma County, California

prepared for the
California Department of Transportation

by
M.W. Manson, C.M. Huyette, C.J. Wills, M.G. Smelser,
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California Geological Survey

2006

Geologic Units

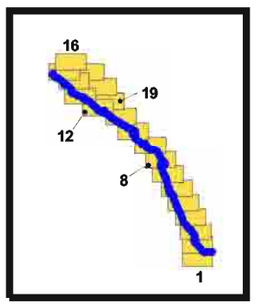
Quaternary	Holocene	af	Artificial fill
		afbm	Artificial fill over Bay Mud
		Qhc	Modern stream channel deposits
		Qhbs	Latest Holocene beach sand
		Qhds	Holocene dune sand (<10,000 years)
		Qhbm	Holocene Bay Mud
		Qha	Holocene alluvium, undivided
		Qdf	Holocene debris fan
		Qls	Landslide
		Qef	Earth flow
		Qac	Alluvium & Colluvium
	Pleistocene	Qc	Colluvium
		Qols	Older landslide
		Qa	Latest Pleistocene to Holocene alluvium, undivided
		Qmt	Pleistocene marine terrace deposits (10,000 to 1.6 million years)
		Qoa	Early to Late Pleistocene alluvial deposits, undivided (30,000 to 1.6 million years)
Tertiary	Miocene	Tb	Basalt
		Tgr	German Rancho Formation
	Eocene & Paleocene	Tw	Wilson Grove Formation
		Tg	Gallaway Formation (?)
Mesozoic	Jurassic - Cretaceous	TKfs	Franciscan Coastal Belt sandstone and shale
		KJfs	Franciscan Central Belt sandstone
		KJfm	Franciscan Central Belt "melange"
		KJfch	Franciscan chert
		KJfgs	Franciscan greenstone
		sp	Franciscan serpentinite
		KJgvc	Great Valley Sequence conglomerate
		Kgr	Granitic rocks at Bodega Head

Geologic Structure Symbols

- Fault, well located
- Fault, approximately located
- Fault, concealed
- Fault, inferred
- San Andreas Fault 1906, well located
- San Andreas Fault 1906, inferred
- San Andreas Fault 1906, concealed
- San Andreas Fault, pre-1906, approximately located
- Salmon Creek Fault Zone boundary
- Salmon Creek Fault Zone boundary, concealed
- 60 — Inclined Strata
- Spring

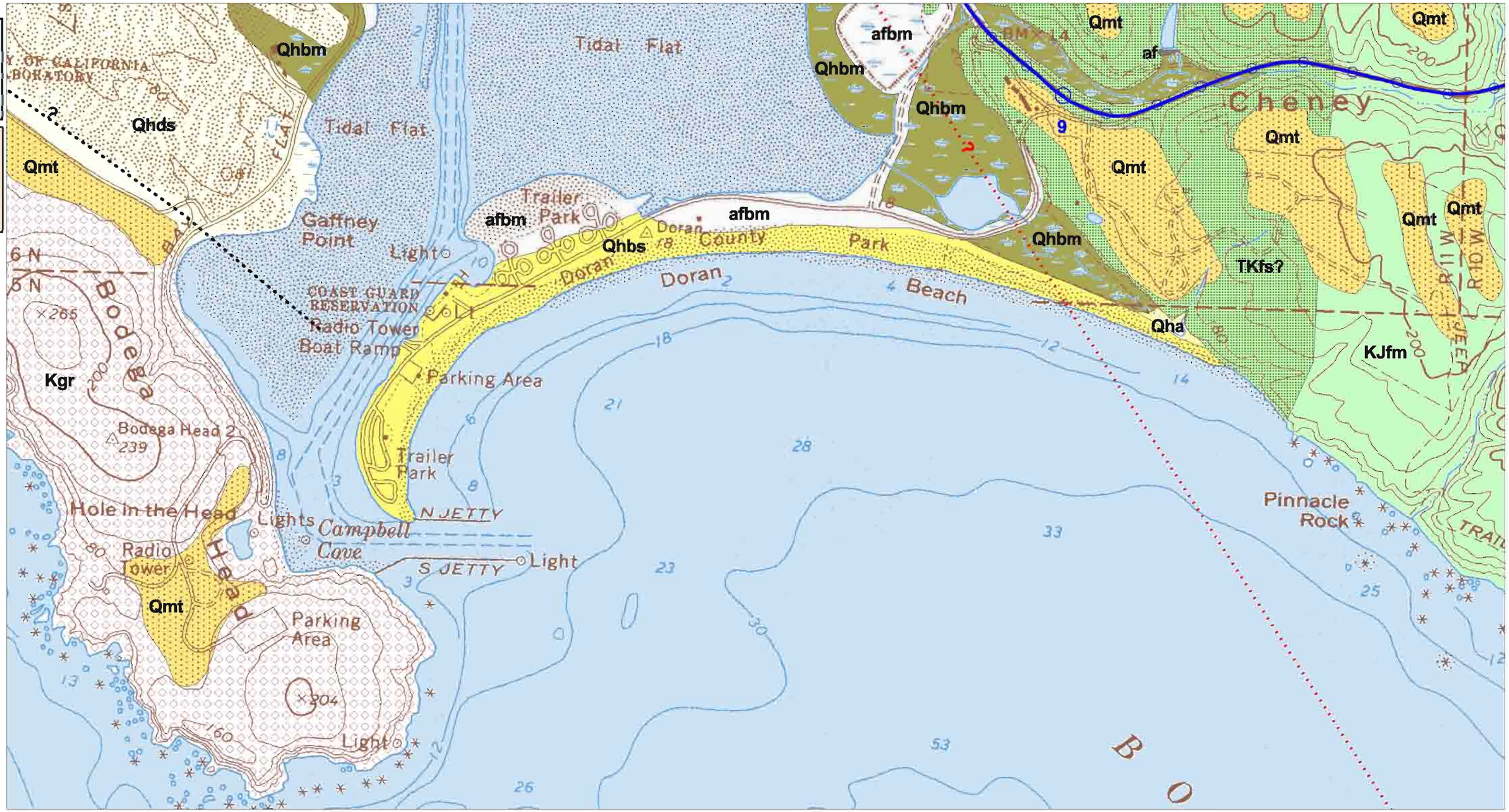
The geologic map is divided into 19 map sheets as shown at right, arranged from south to north. Postmiles are shown along Highway 1 as above; each mile is labeled and tenths are shown by unlabeled circles.

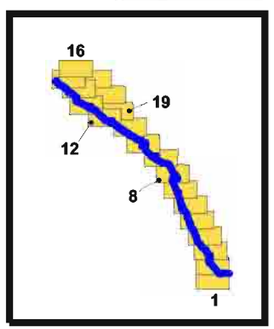
Project Location Map



Corridor Map Sheet Index
Highway 1 in blue.

Plate 1
Explanation





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

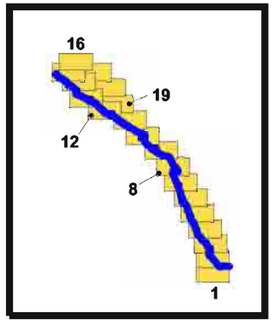
0.5 0 0.5 1 Miles

0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 1 of 19



Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

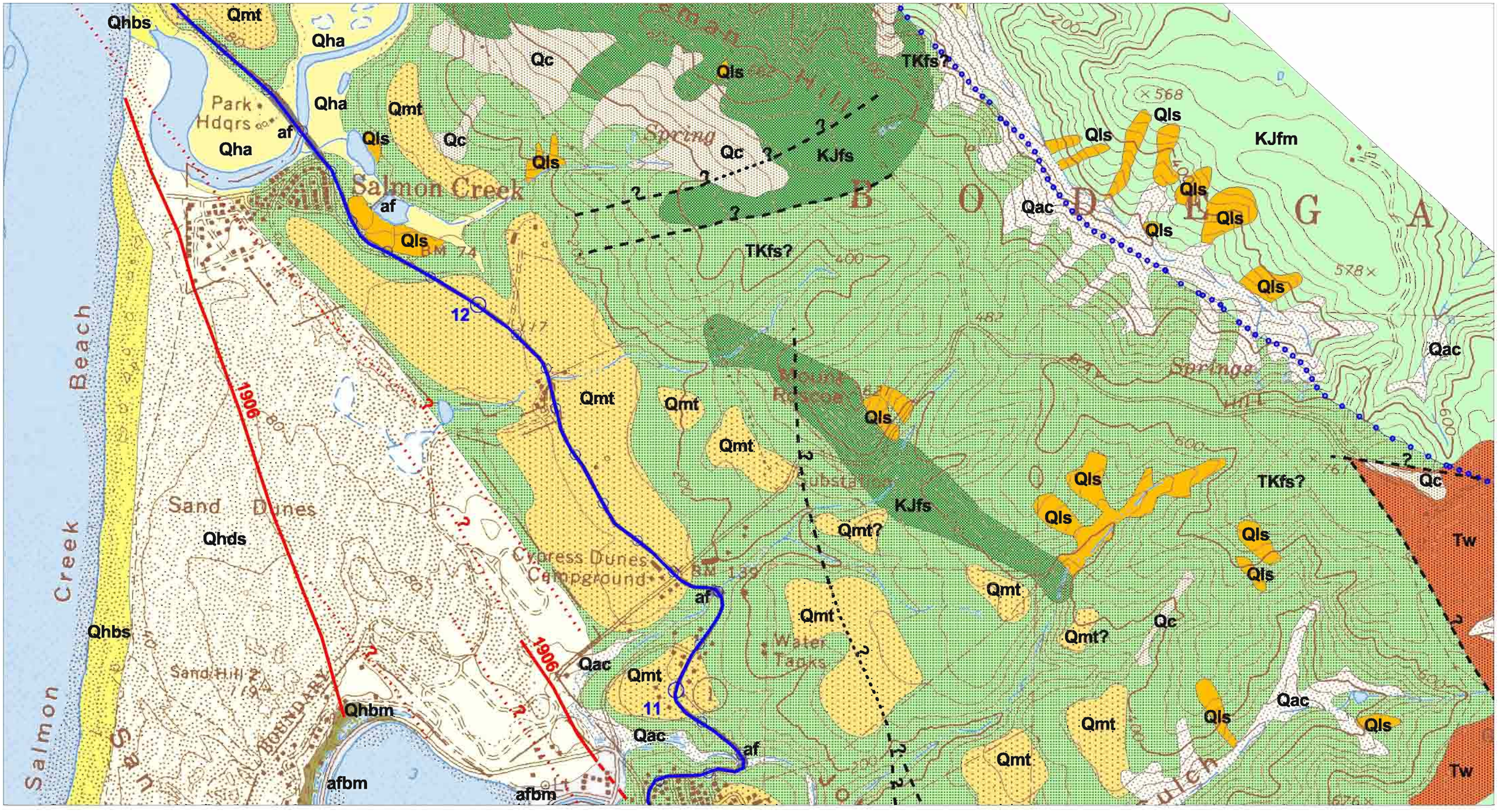
0.5 0 0.5 1 Miles

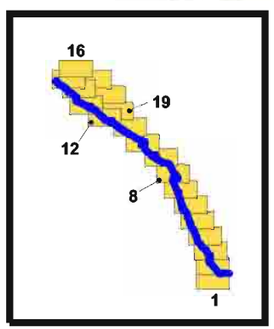
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 2 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

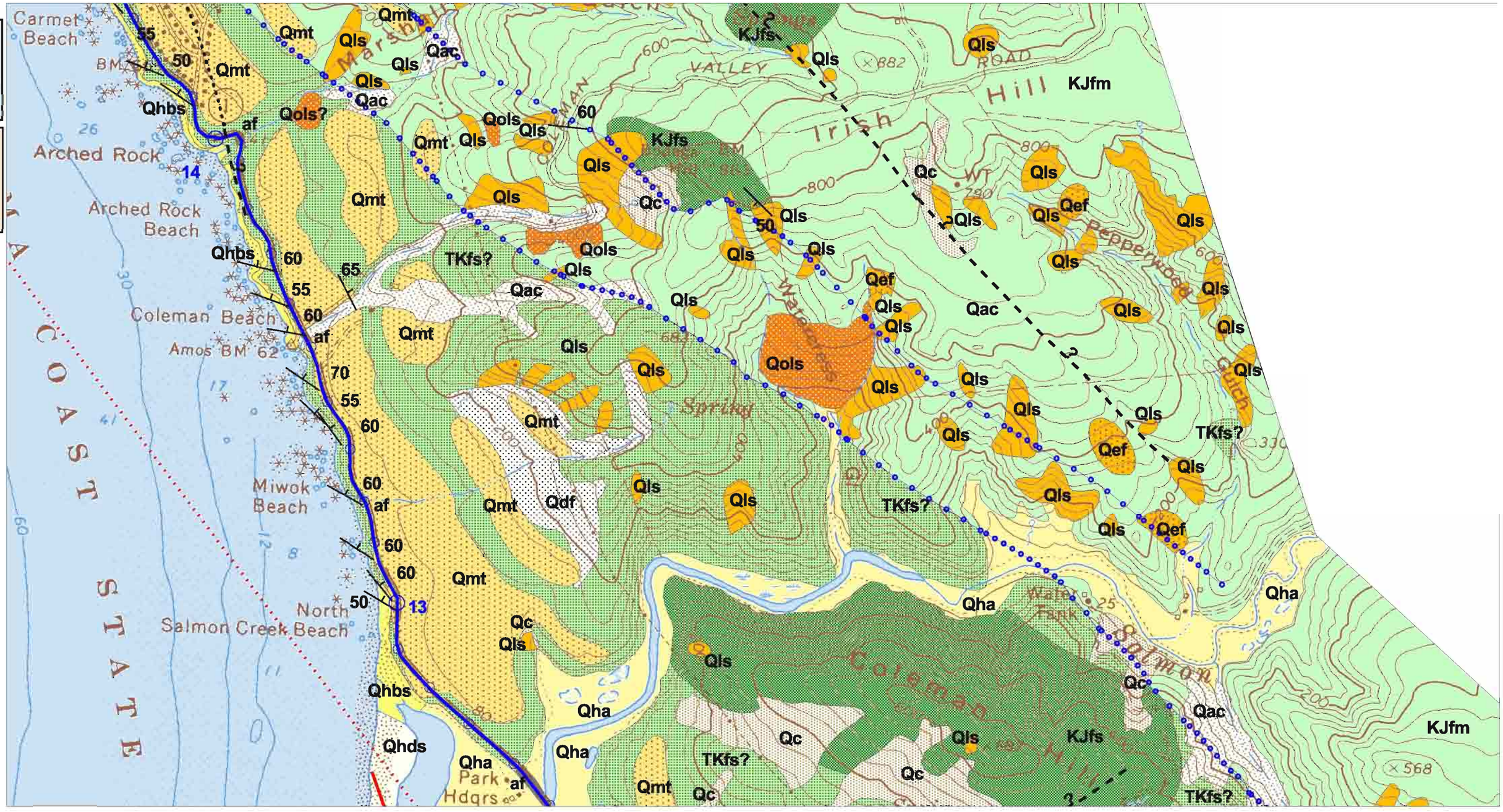
0.5 0 0.5 1 Miles

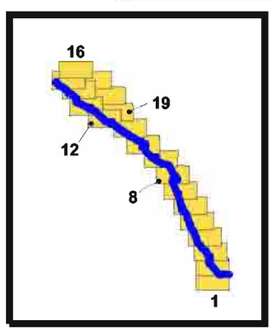
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 3 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

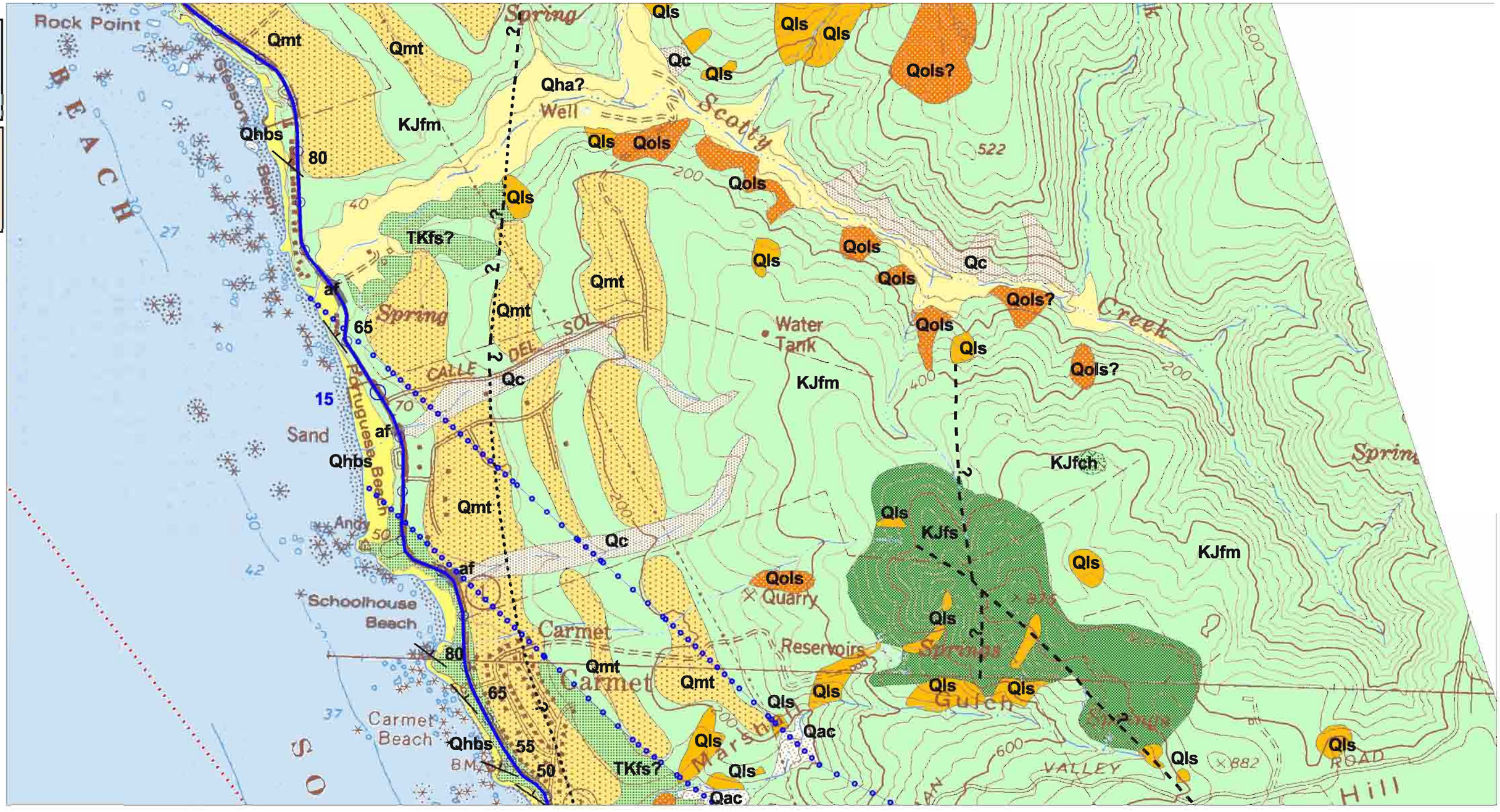
0.5 0 0.5 1 Miles

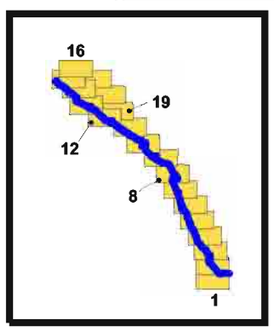
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 4 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

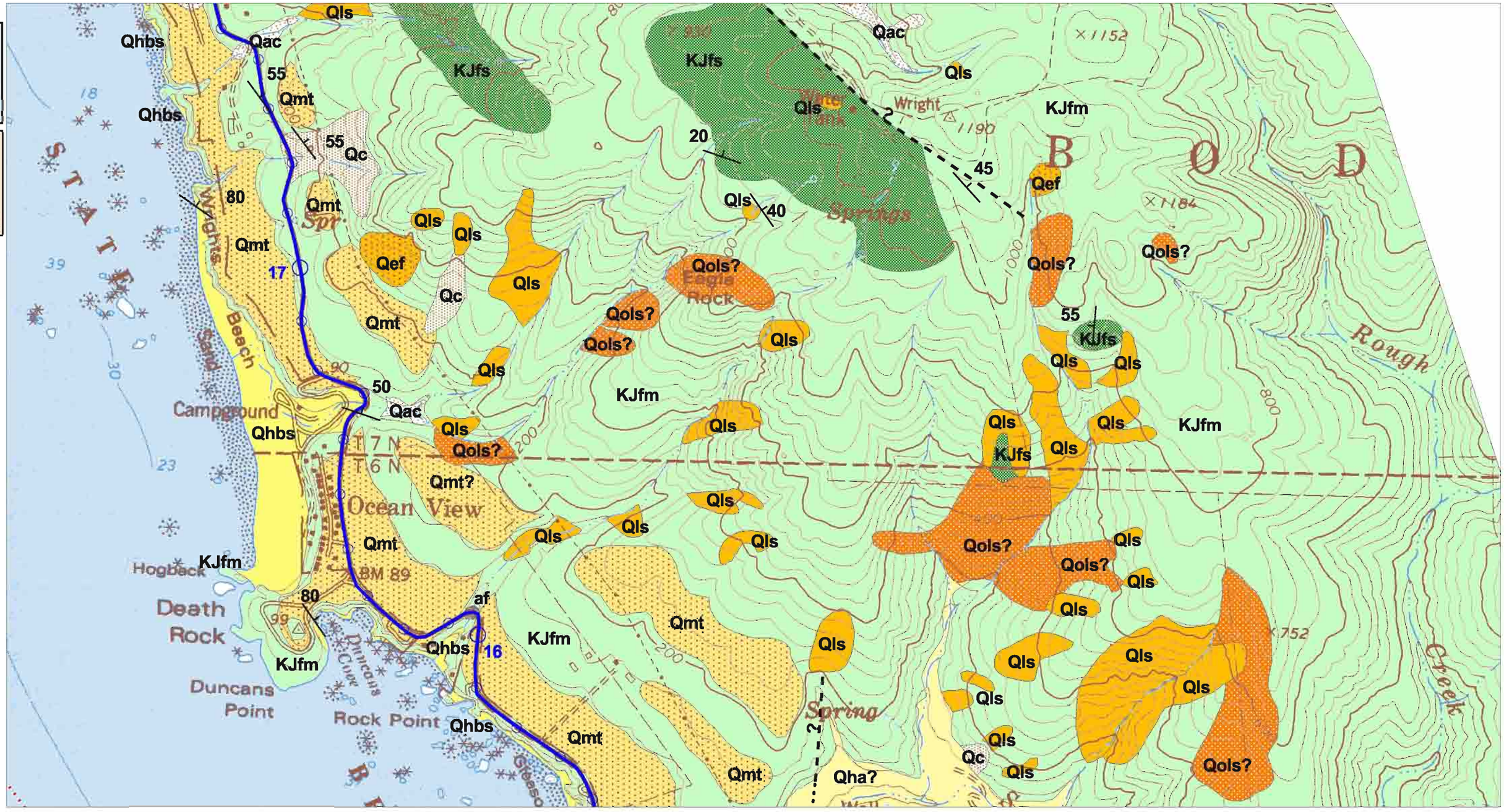
0.5 0 0.5 1 1.5 2 Kilometers

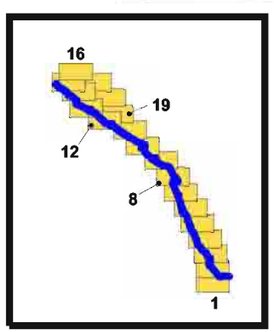
Base Map from USGS
Bodega Bay & Duncans Mills
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 1
Map 5 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

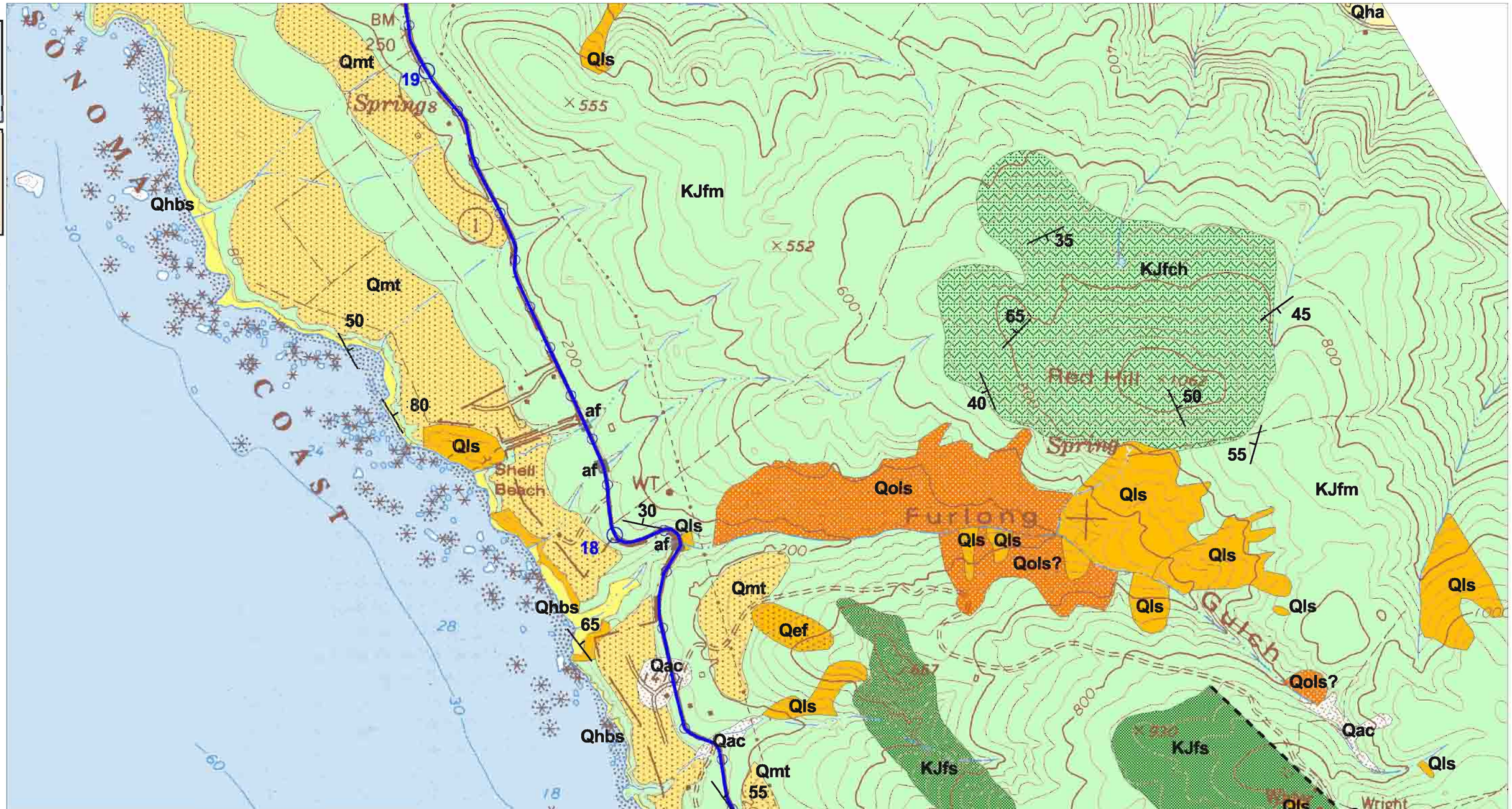
0.5 0 0.5 1 1.5 2 Kilometers

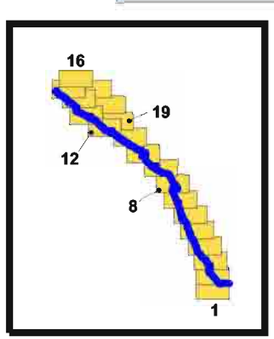
N W E S

Base Map from USGS
Duncans Mills
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 6 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

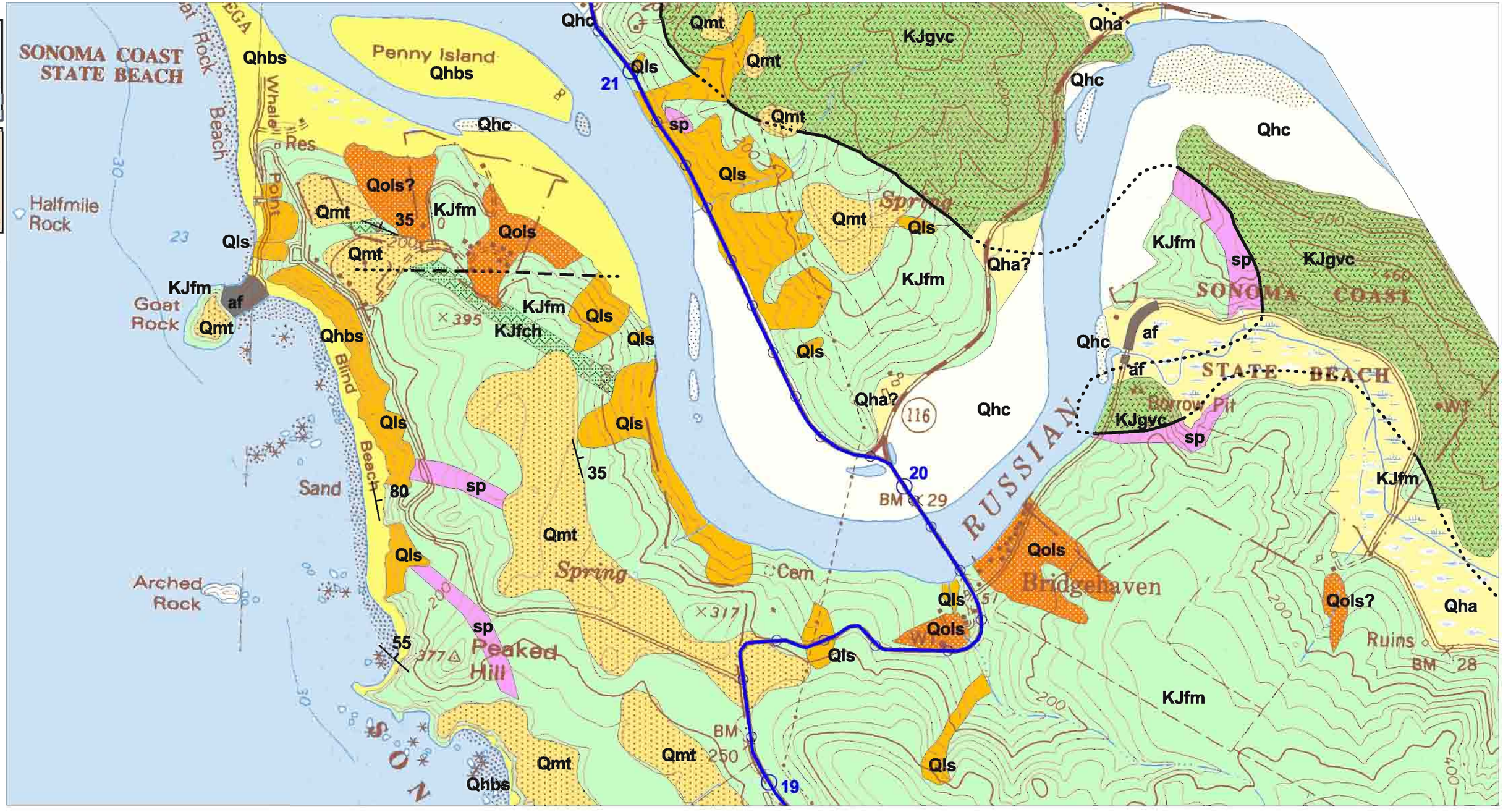
0.5 0 0.5 1 Miles

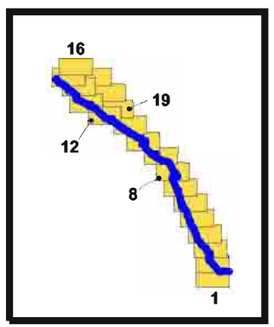
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Duncans Mills
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 7 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

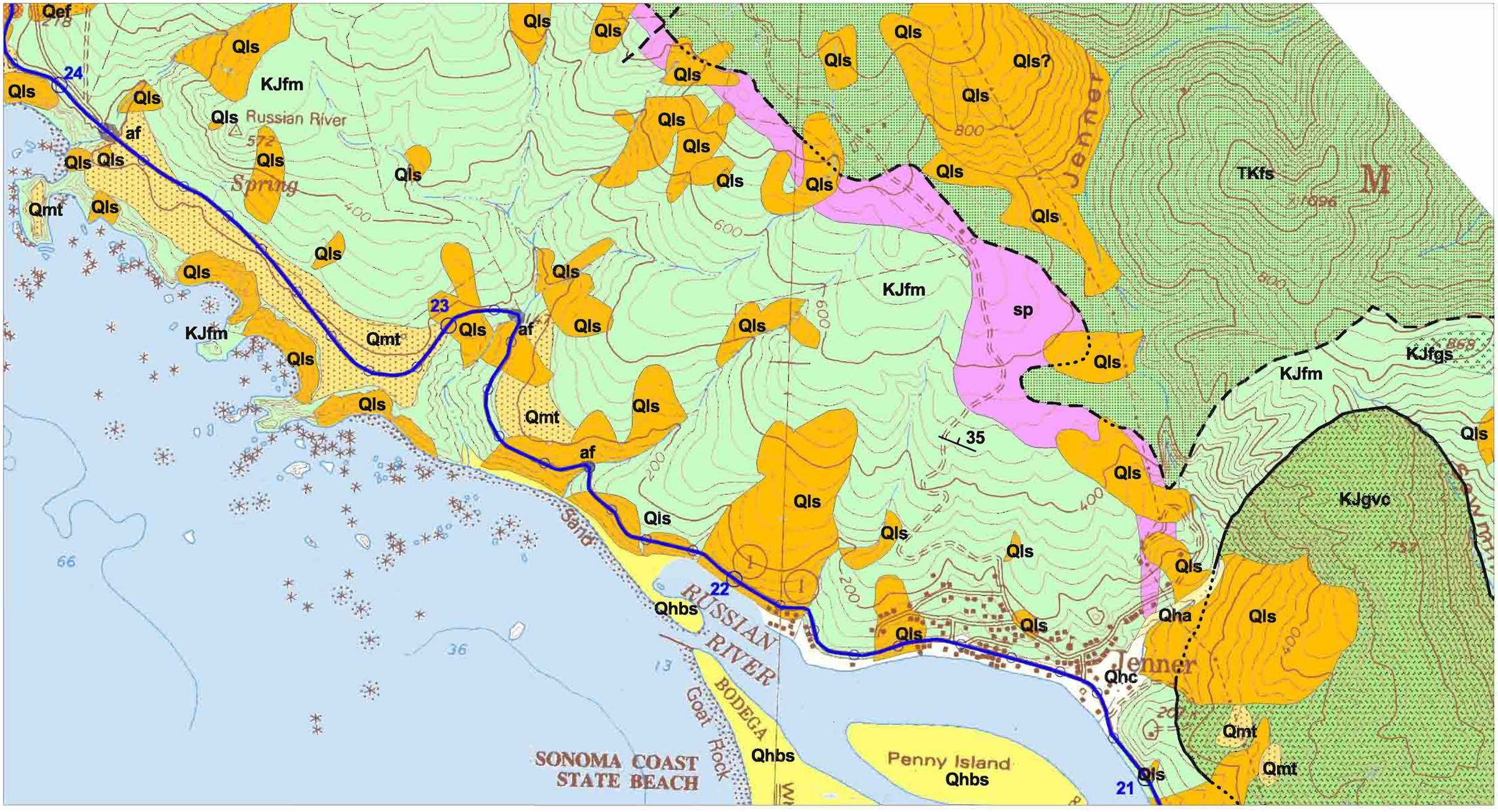
0.5 0 0.5 1 1.5 2 Kilometers

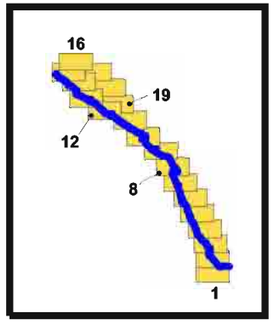
Base Map from USGS
Arched Rock & Duncans Mills
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 1
Map 8 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

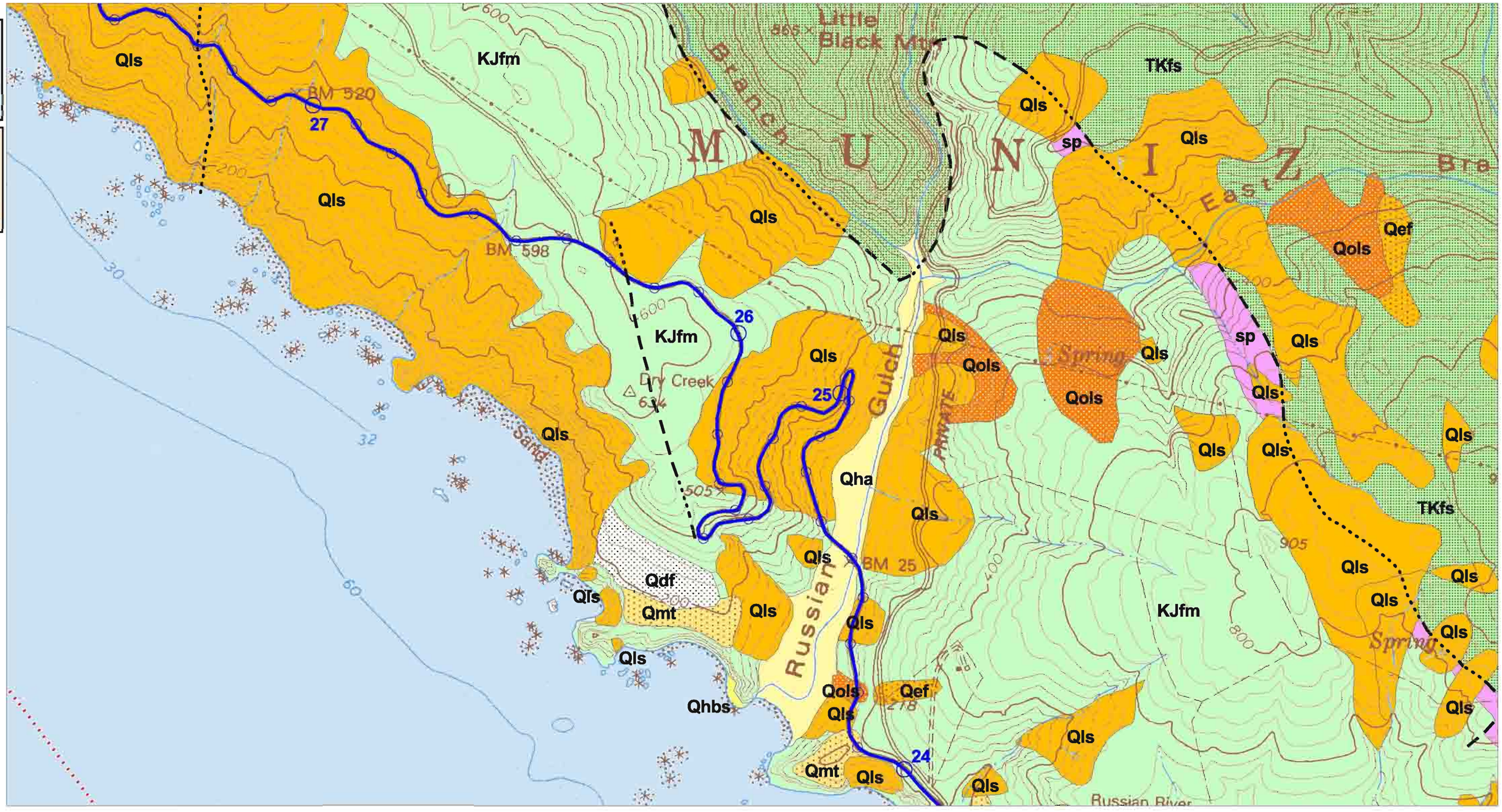
0.5 0 0.5 1 Miles

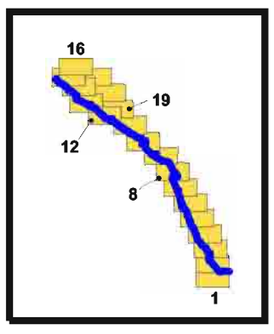
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Arched Rock & Duncans Mills
7.5 minute Quadrangles

January 1, 2006

Plate 1
Map 9 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

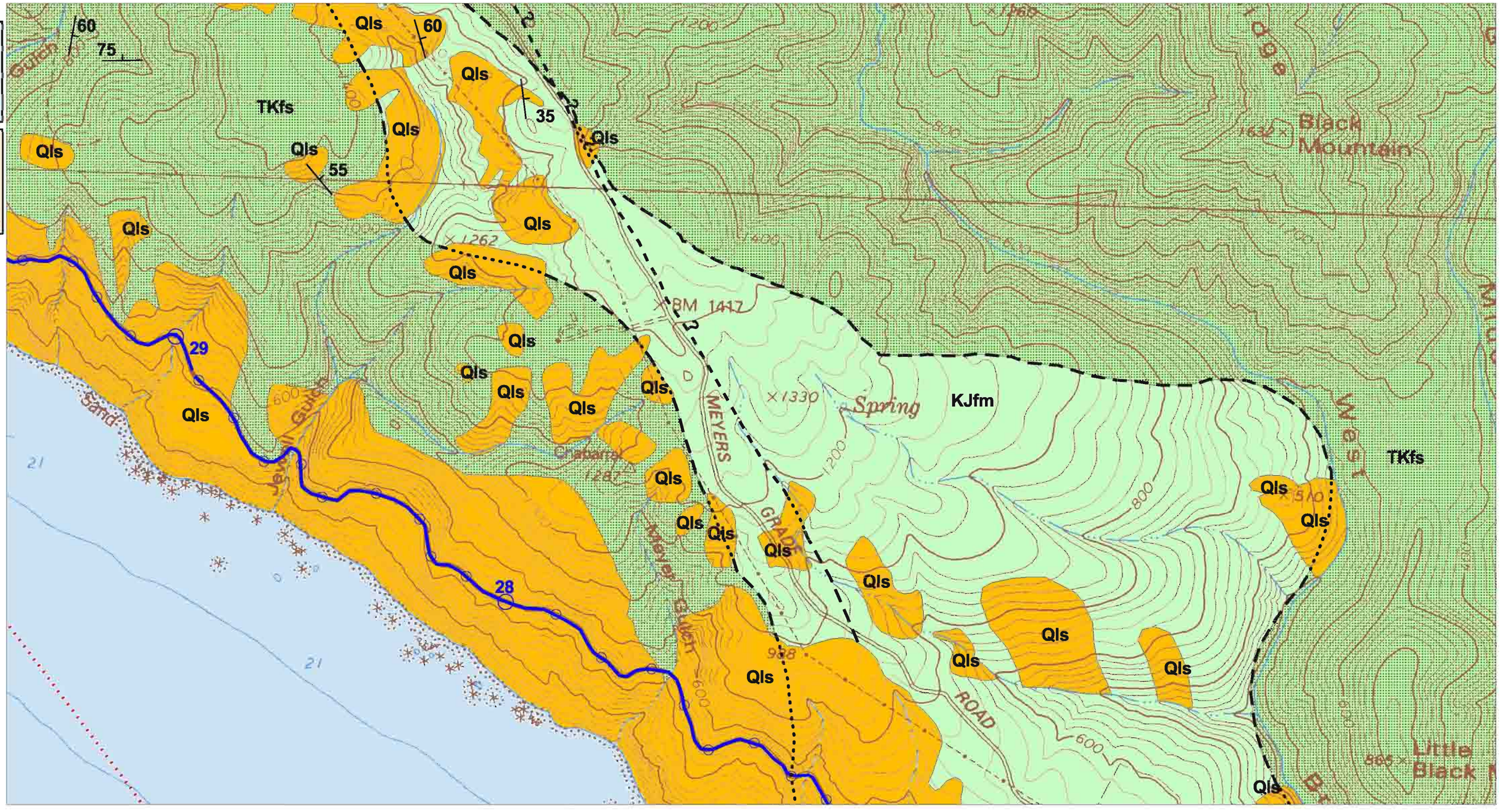
0.5 0 0.5 1 Miles

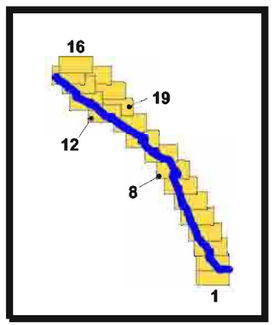
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Arched Rock
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 10 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

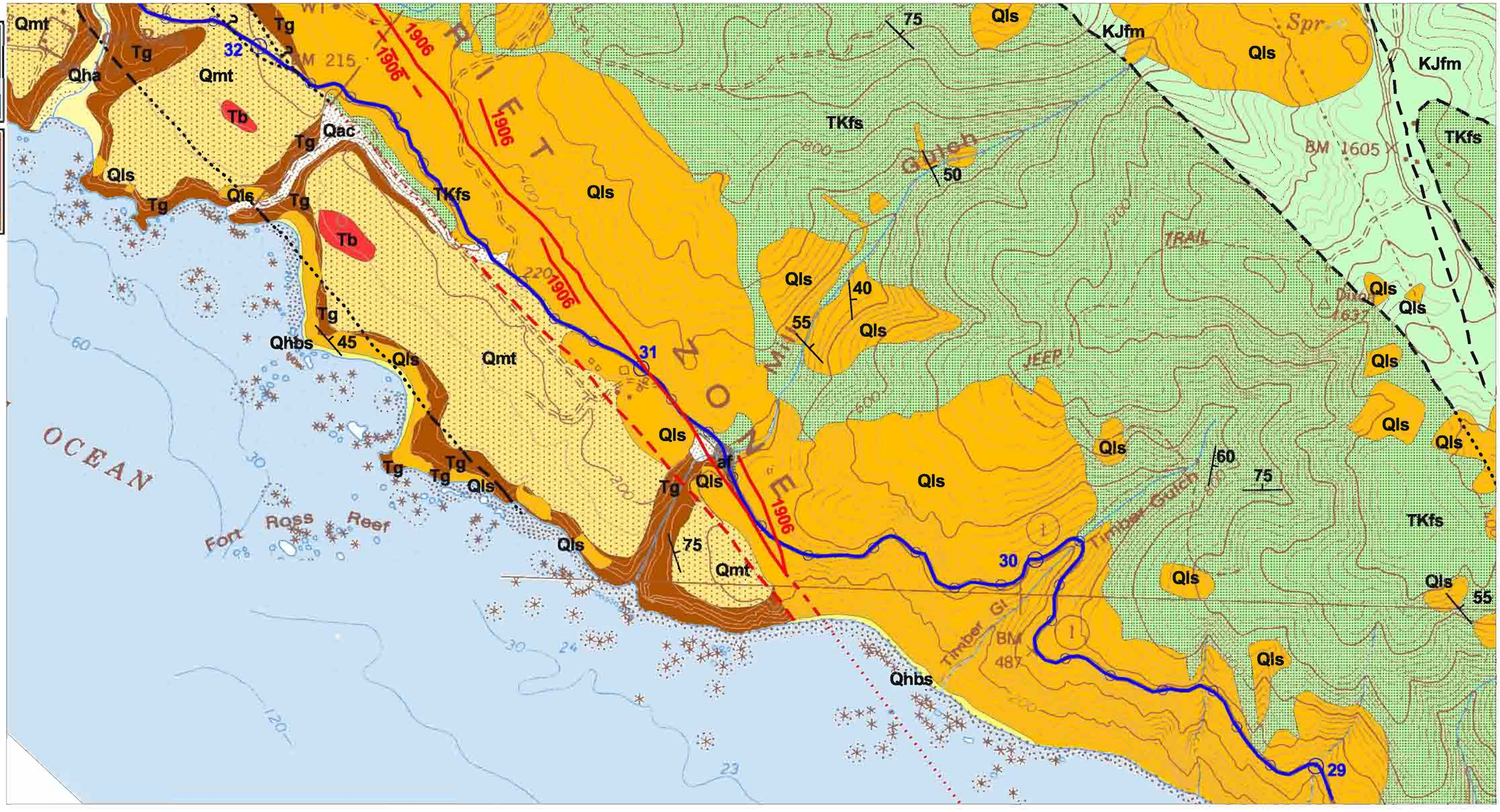
0.5 0 0.5 1 Miles

0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Arched Rock & Fort Ross
7.5 minute Quadrangles

January 1, 2006

Plate 1
Map 11 of 19


Qmt
Tg
Qha
Tb
Qac
Qls
TKfs
KJfm
1906
OCEAN
Fort Ross Reef
Qhbs
Qmt
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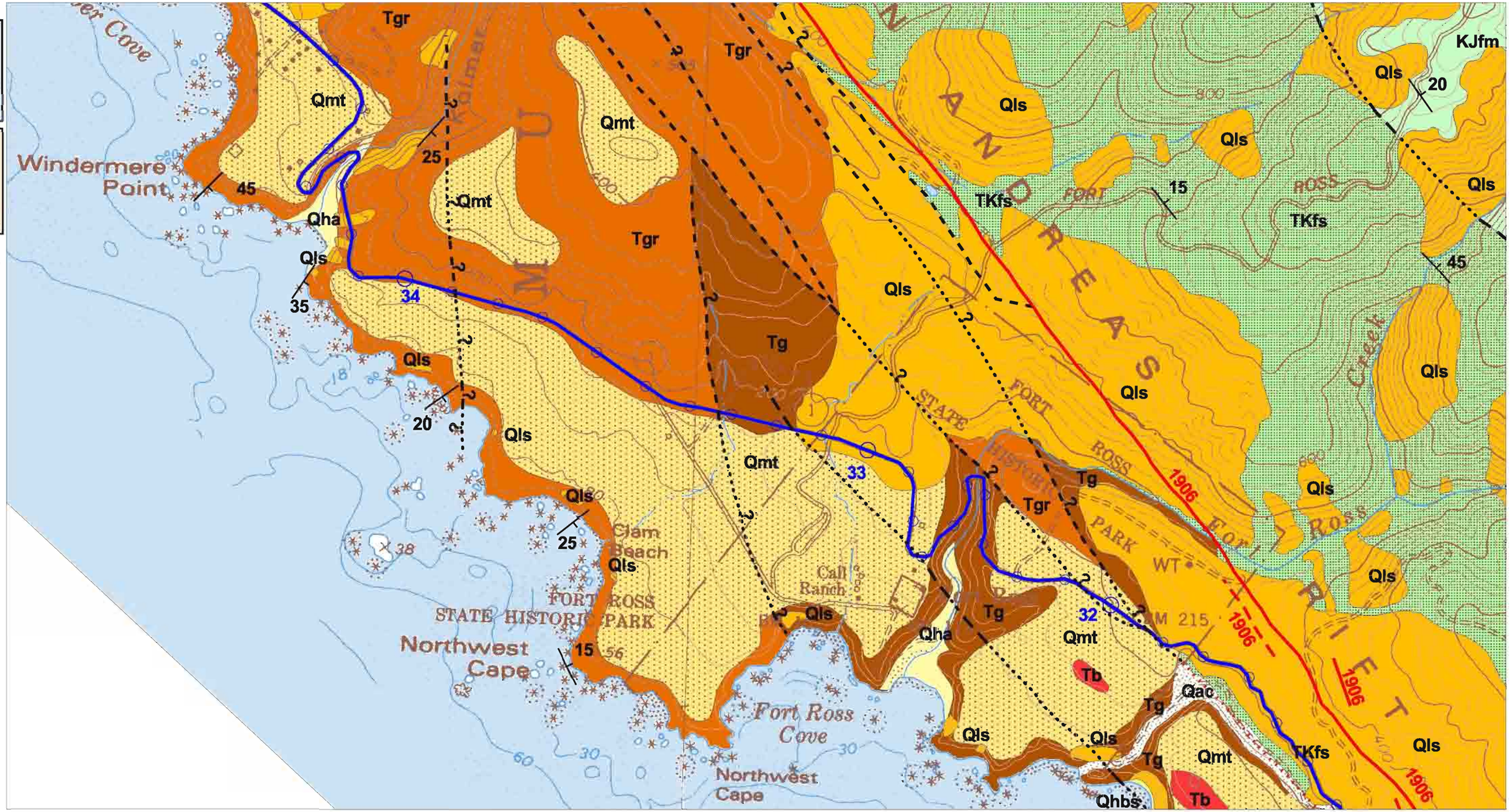
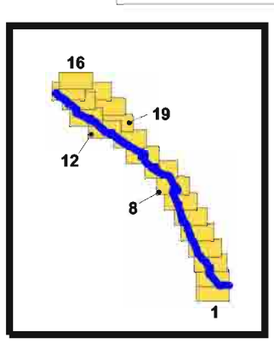
TKfs
Qls
Qls
Qls





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

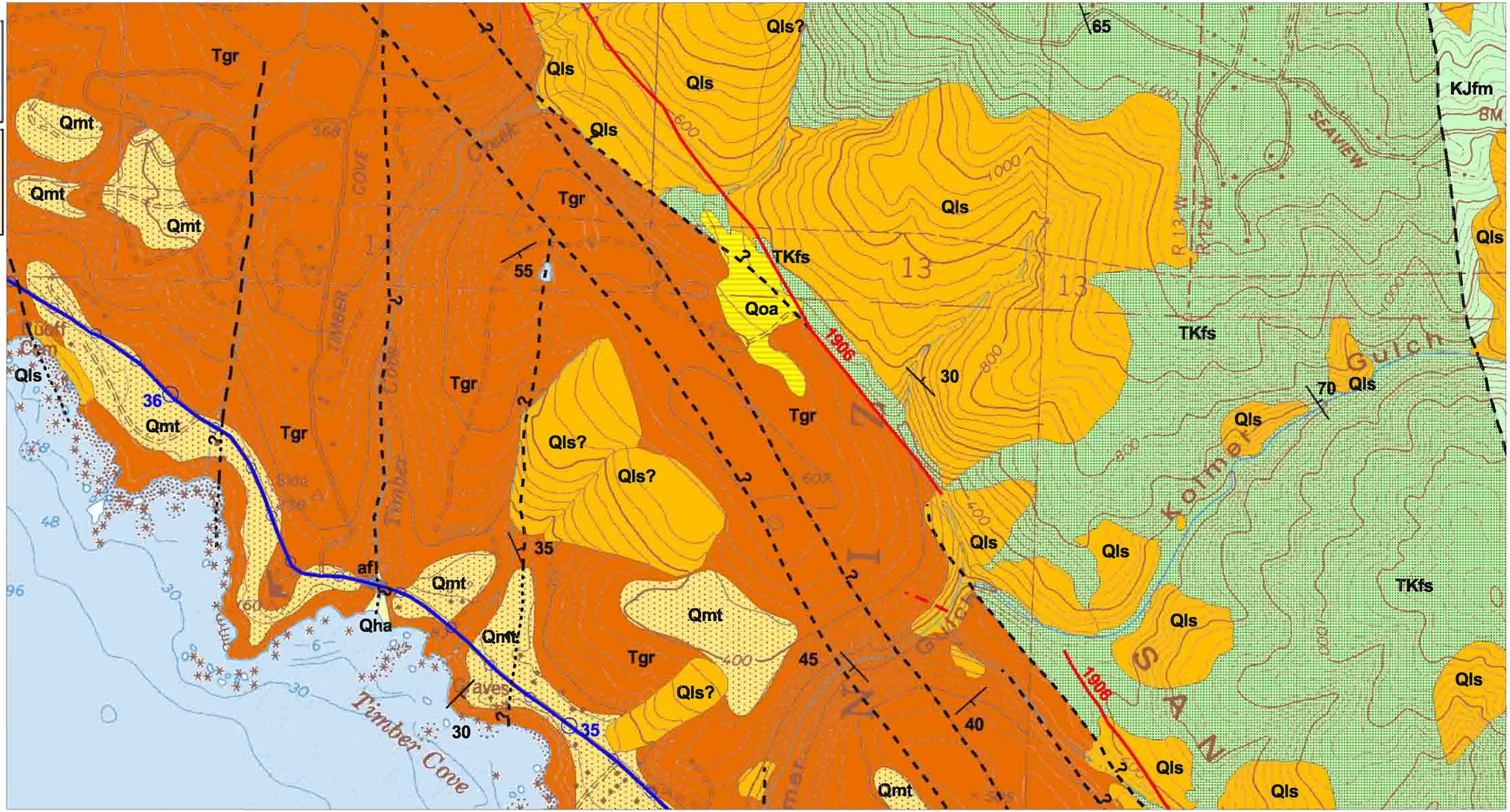
0.5 0 0.5 1 1.5 2 Kilometers

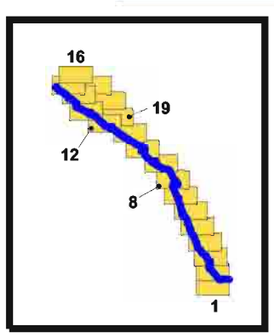
Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 1
Map 13 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

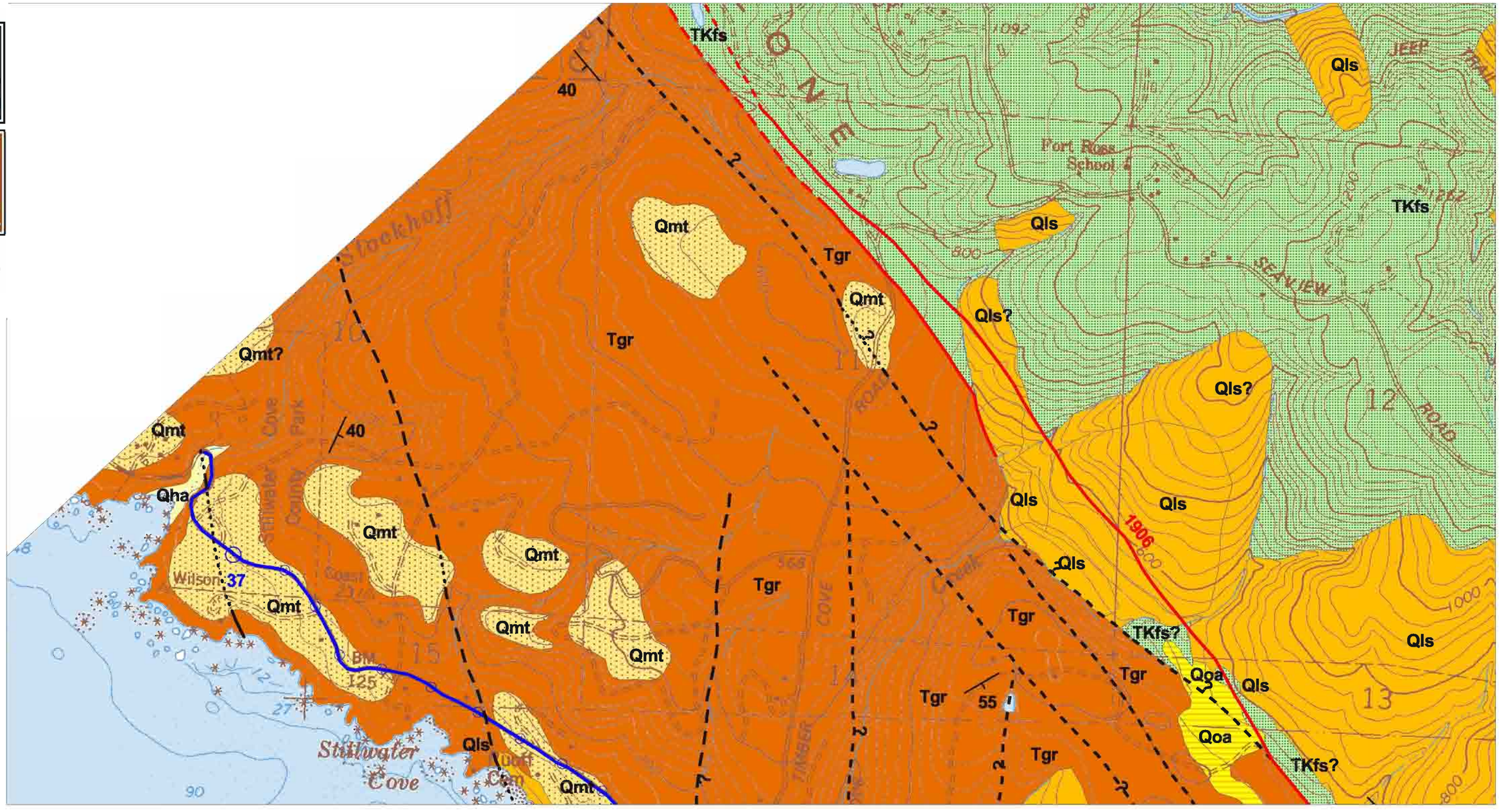
0.5 0 0.5 1 Miles

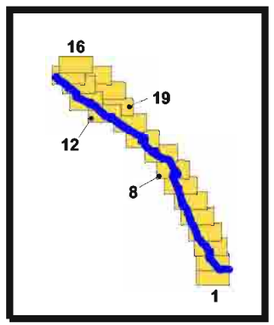
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

Plate 1
Map 14 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

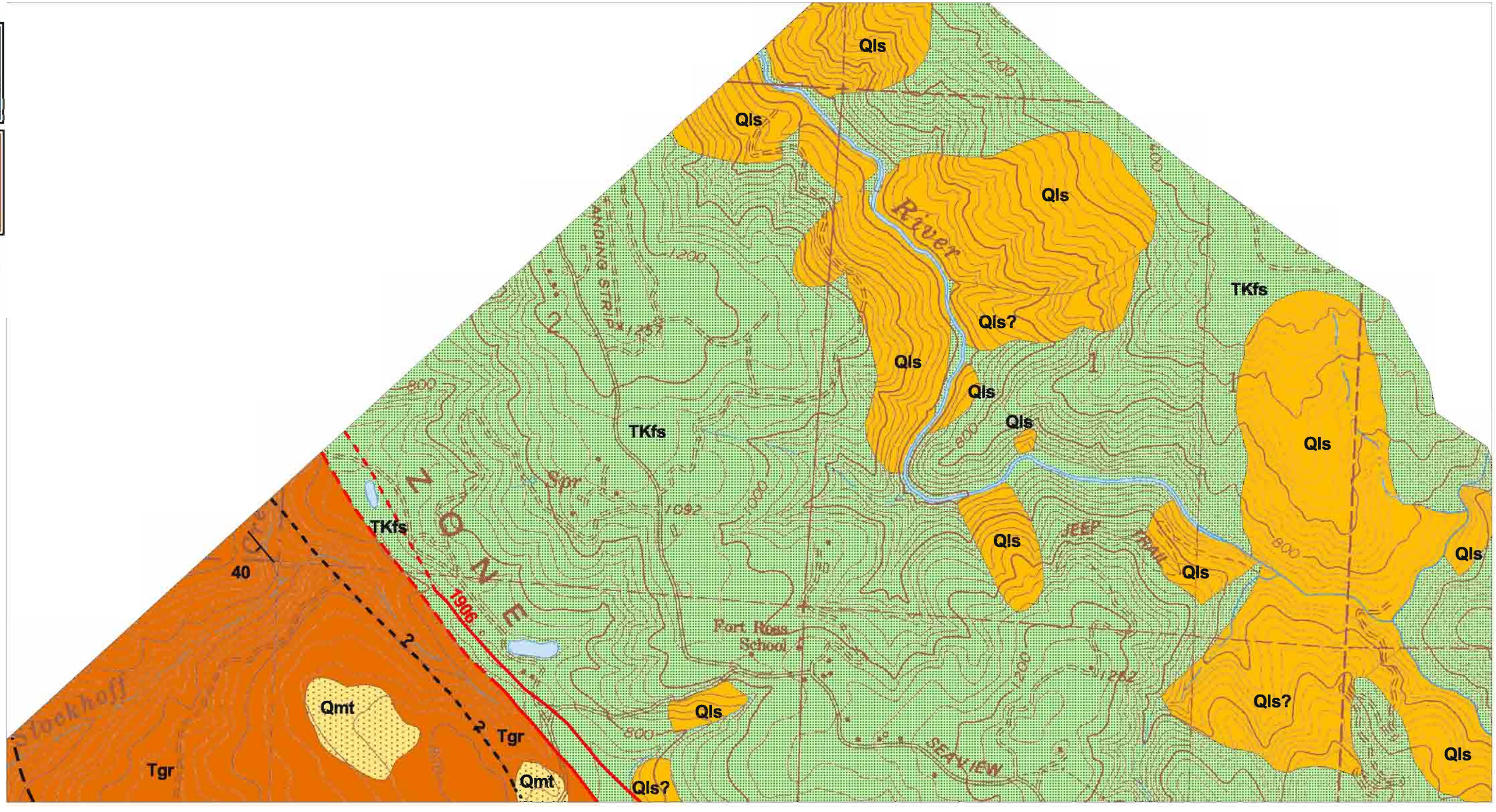
0.5 0 0.5 1 Miles

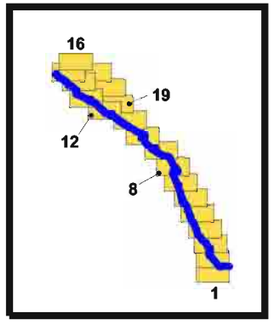
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Plantation
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 15 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

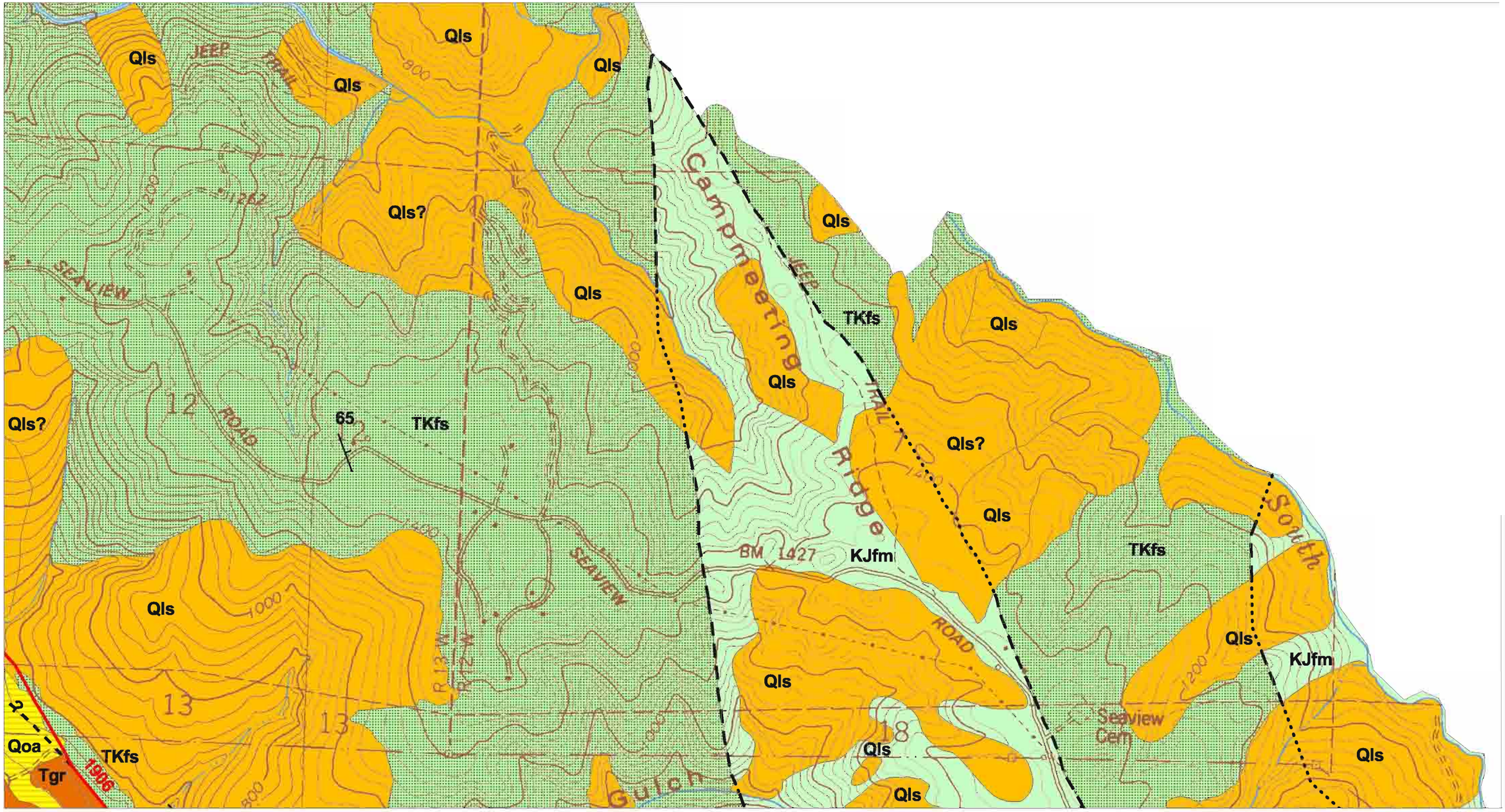
0.5 0 0.5 1 1.5 2 Kilometers

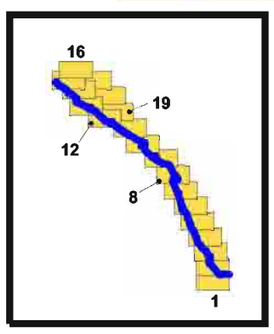
Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 1
Map 16 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

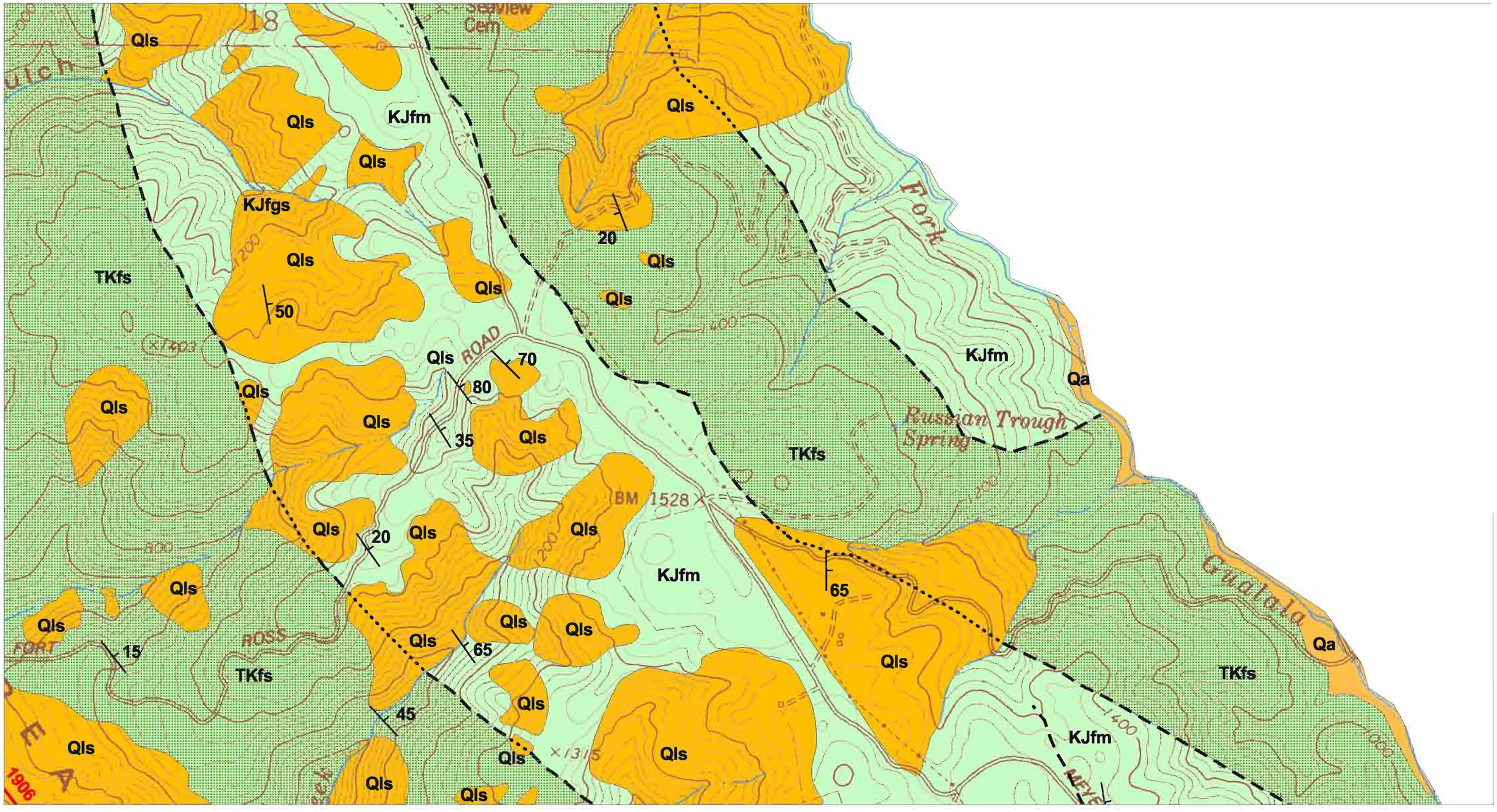
0.5 0 0.5 1 1.5 2 Kilometers

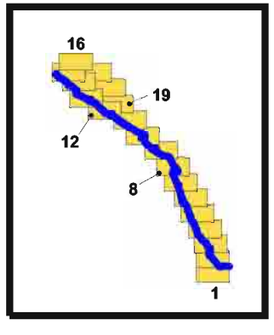
N W E S

Base Map from USGS
Fort Ross
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 17 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Geologic Map

Map Scale 1:12,000

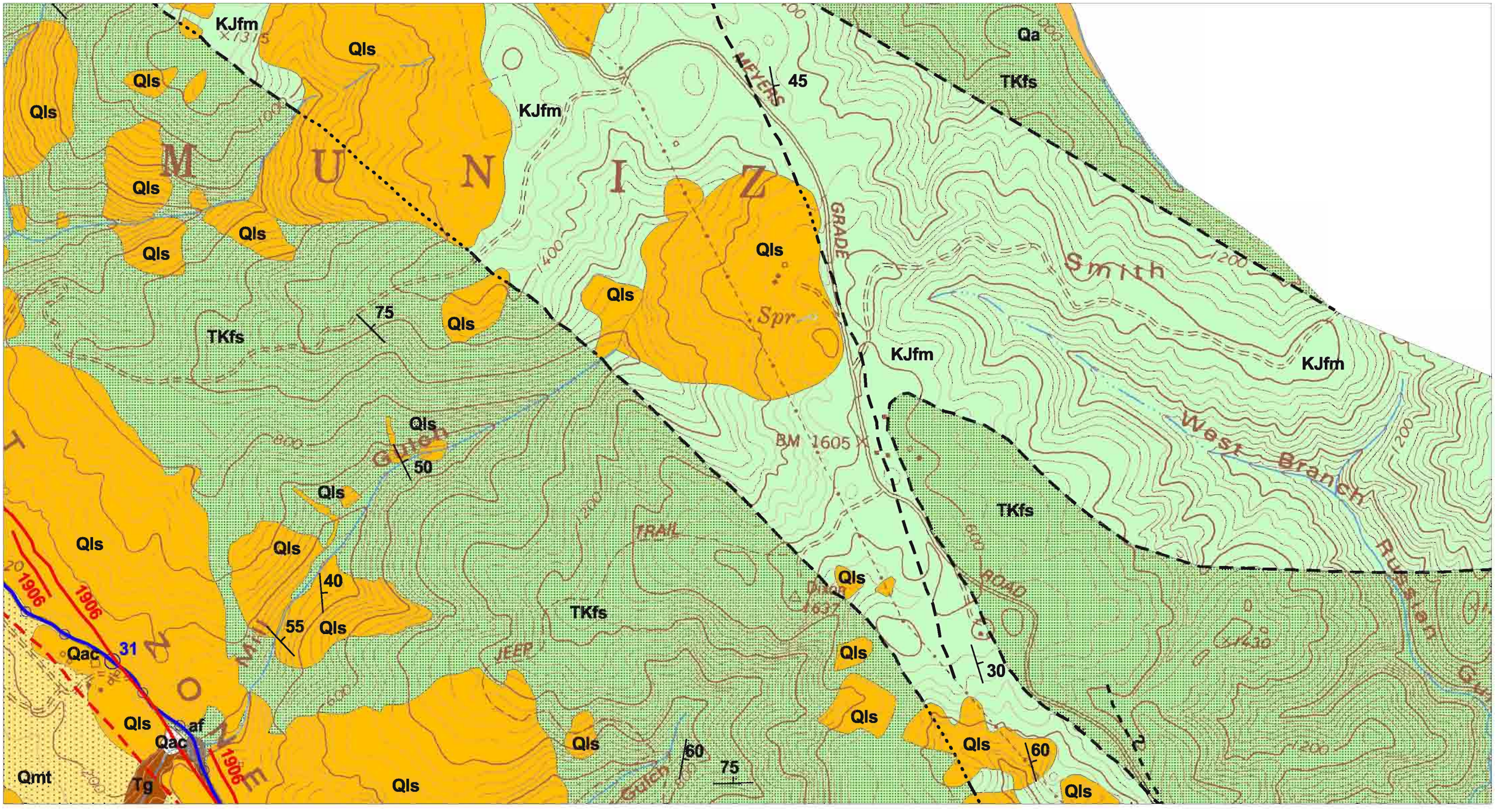
0.5 0 0.5 1 Miles

0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross
7.5 minute Quadrangle

January 1, 2006

Plate 1
Map 18 of 19


KJfm
Qls
Qls
Qls

Landslides along the Highway 1 Corridor between Bodega Bay and Fort Ross, Sonoma County, California

prepared for the
California Department of Transportation

by
M.W. Manson, C.M. Huyette, C.J. Wills, M.G. Smelser,
M.E. Fuller, C. Domrose and C. Gutierrez
California Geological Survey

2006

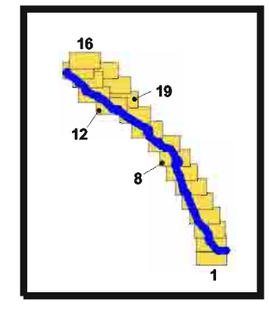
	Active or Historic The landslide appears to be currently moving or movements have been recorded in the past	Dormant Young The landforms related to the landslide are relatively fresh, but there is no record of historic movement	Dormant Mature The landforms related to the landslide have been smoothed by erosion and re-vegetated
Debris Flow: A landslide in which a mass of coarse grained slil flows downslope as a slurry			
Debris Flow Fan: A landslide mass consisting of an accumulation of debris flows			
Debris Slide: A landslide of coarse grained soil, commonly consisting of surficial deposits, rock fragments and vegetation			
Rock Fall: A landslide in which a fragment, or fragments, breaks off of an outcrop and falls, rolls or tumbers downslope			
Rock Slide: A landslide involving bedrock that moves as an intact block or blocks on a slide plane			
Earth Flow: A landslide involving fine-grained soil or deeply weathered bedrock in which the material flows by movements on many ephemeral slide planes			
Debris Slide Slope: A landform representing the coalesced scars of debris flows and debris slides, an area largely shaped by shallow landslides			
Franciscan Central Belt Melange: A geologic unit consisting of highly sheared sandstone and shale, with few intact blocks			

Landslide Confidence

- Definite
- Probable
- Questionable

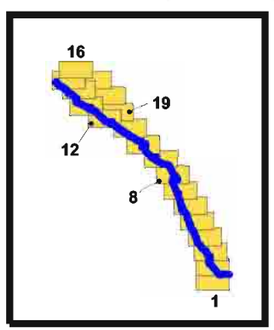
The geologic map is divided into 19 map sheets as shown at right, arranged from south to north. Postmiles are shown along Highway 1 as above; each mile is labeled and tenths are shown by unlabeled circles.

Project Location Map



Corridor Map Sheet Index
Highway 1 in blue.

Plate 2
Explanation



Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

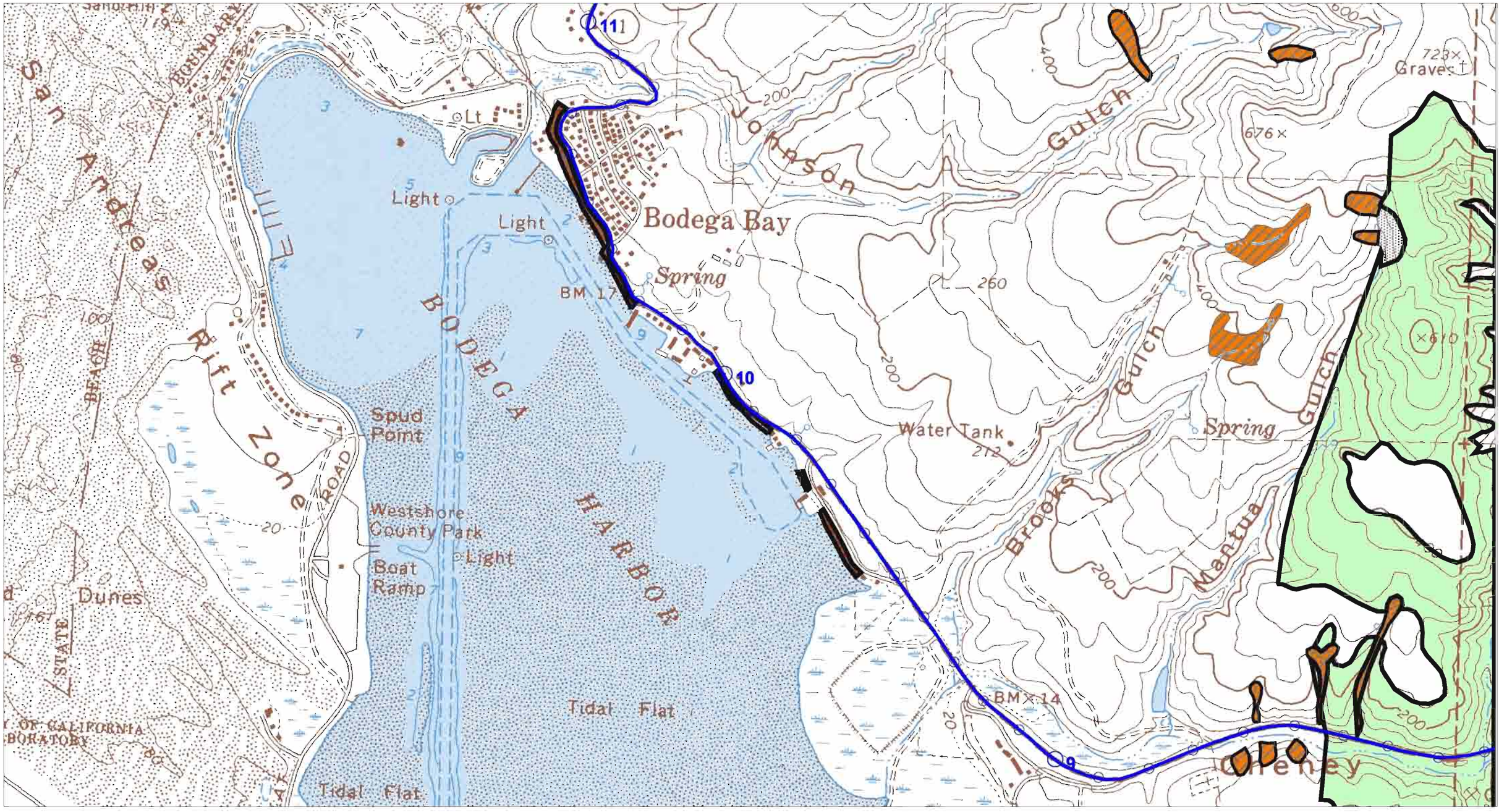
0.5 0 0.5 1 Miles

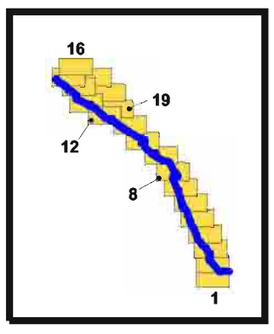
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 1 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

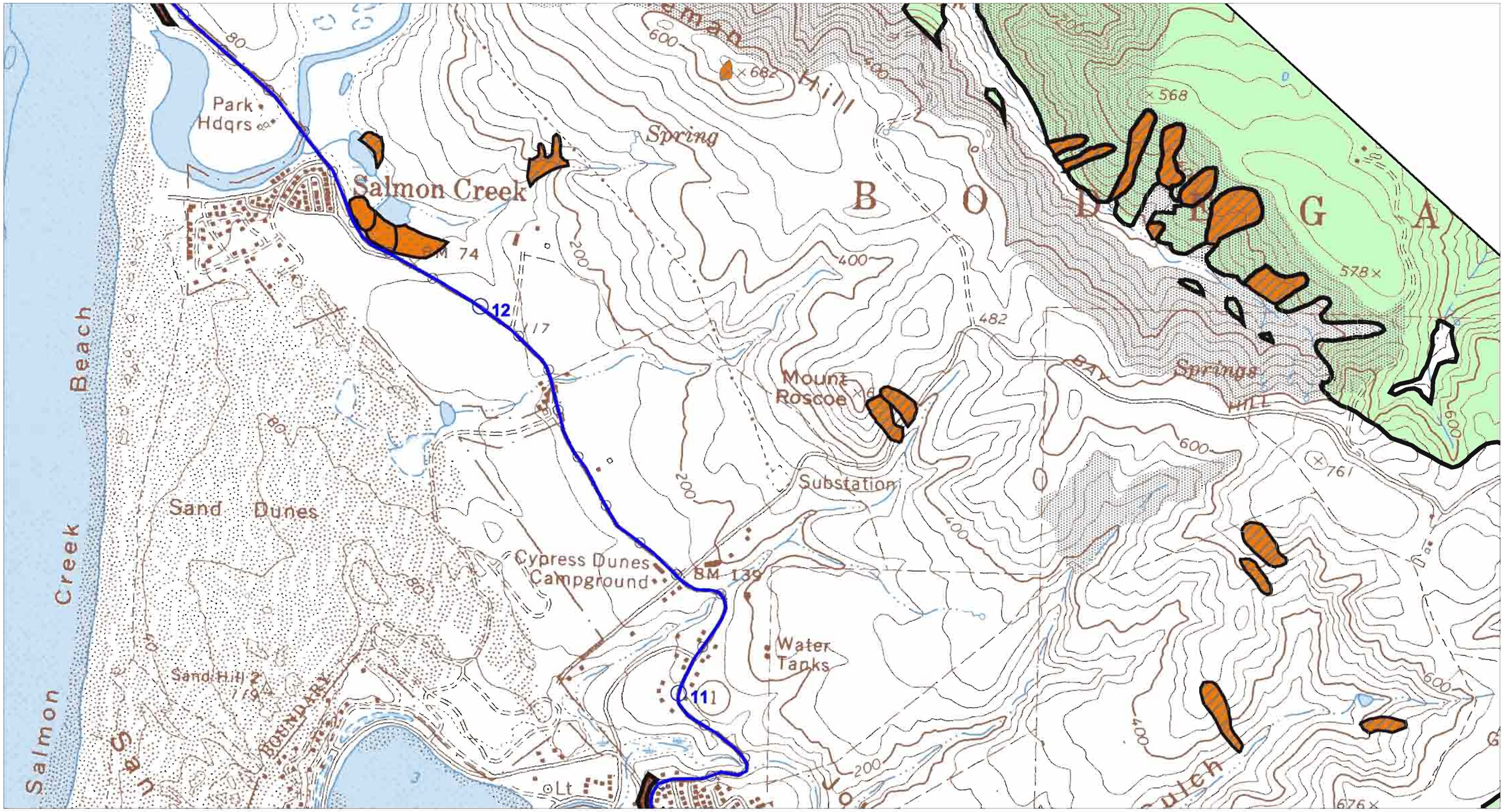
0.5 0 0.5 1 1.5 2 Kilometers

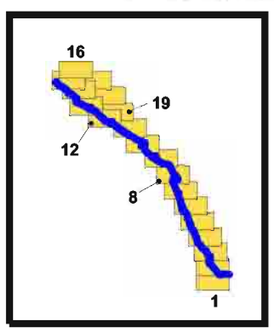
N W E S

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 2 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

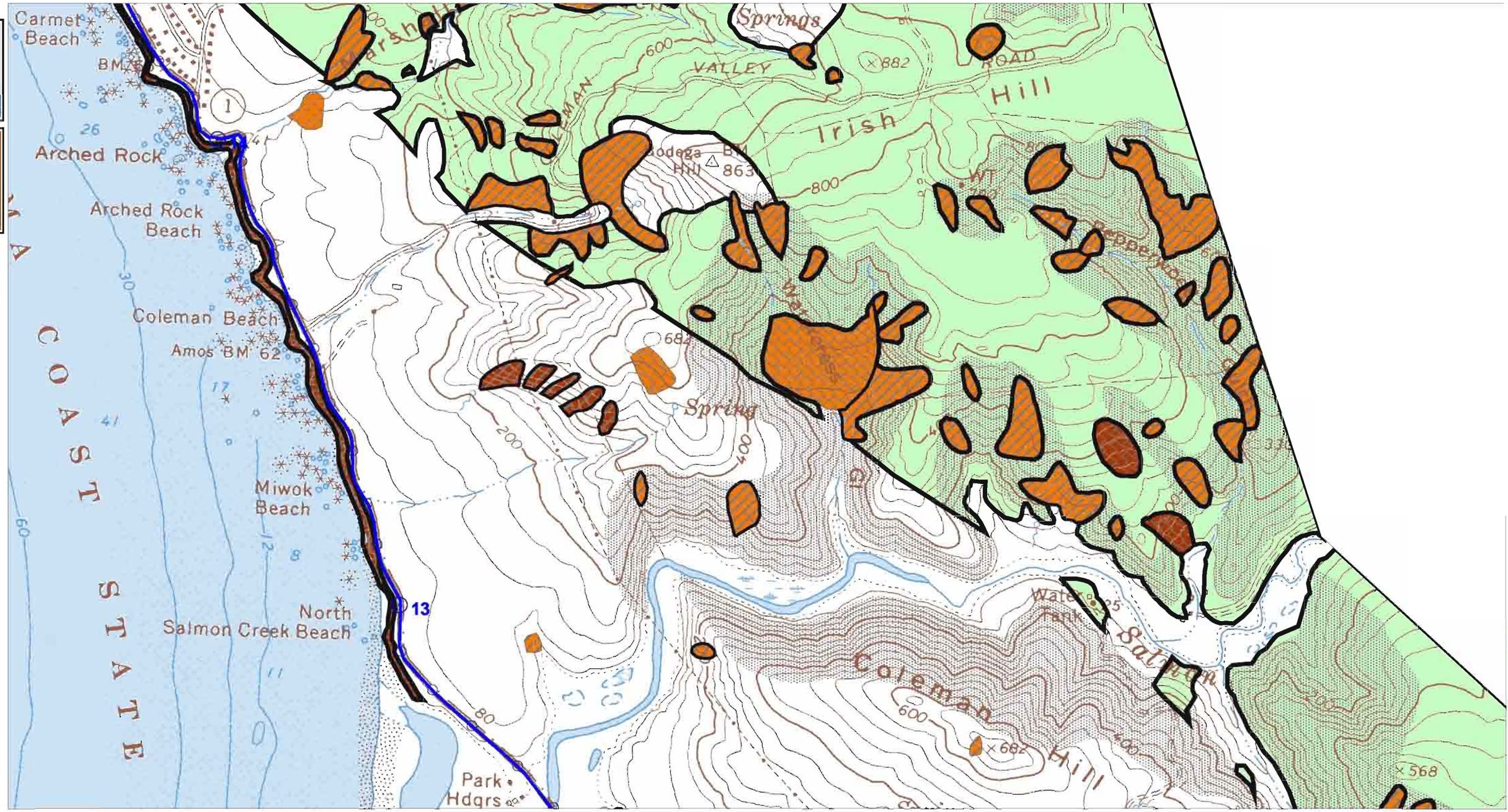
0.5 0 0.5 1 Miles

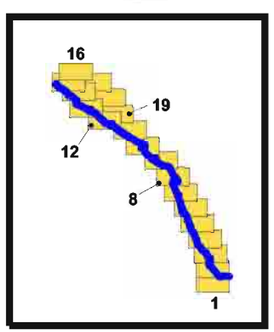
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 3 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

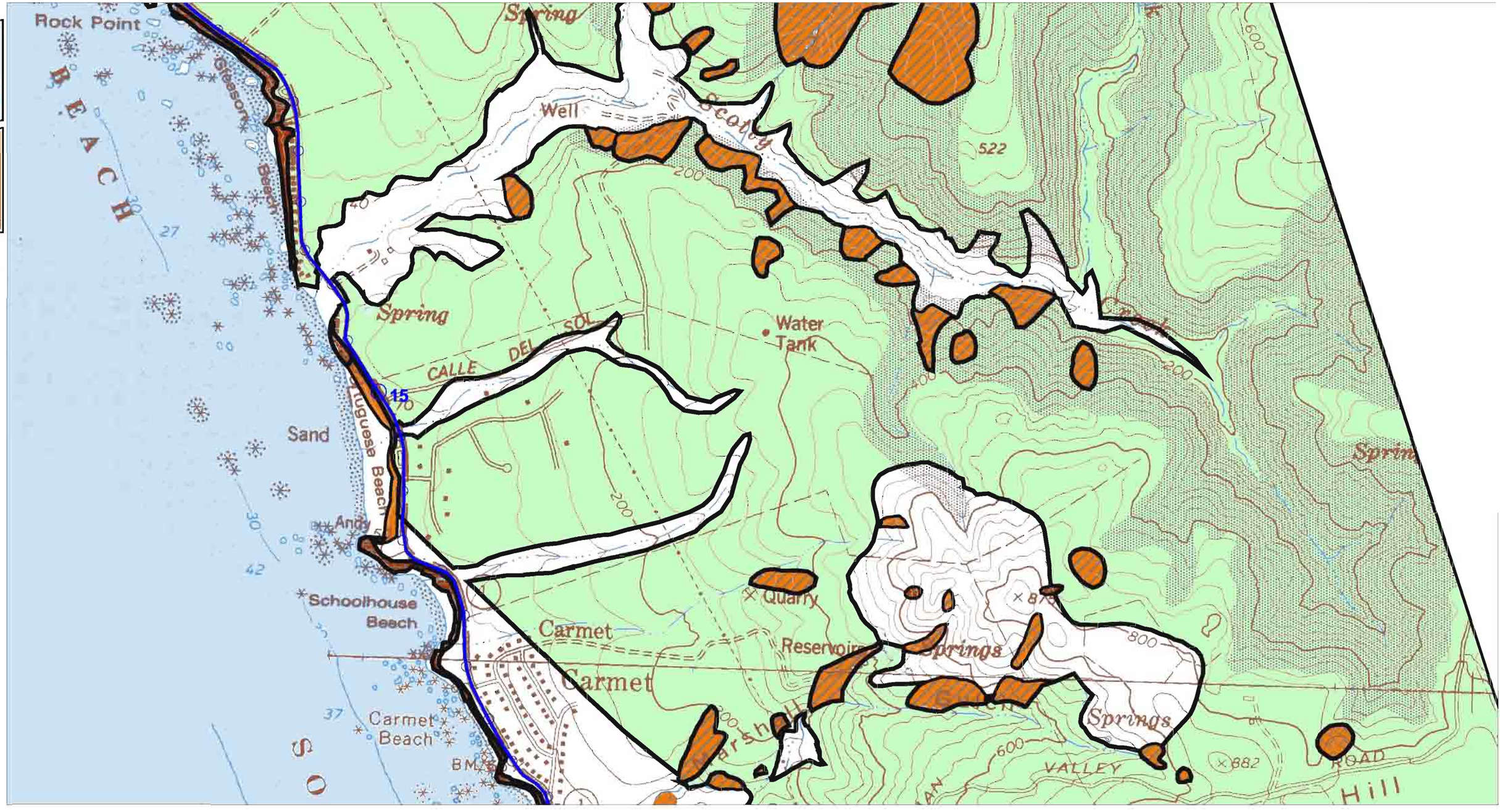
0.5 0 0.5 1 Miles

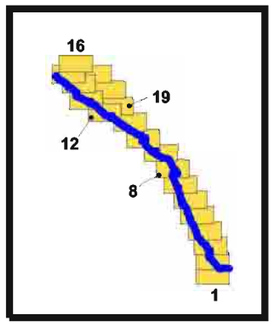
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Bodega Bay
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 4 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

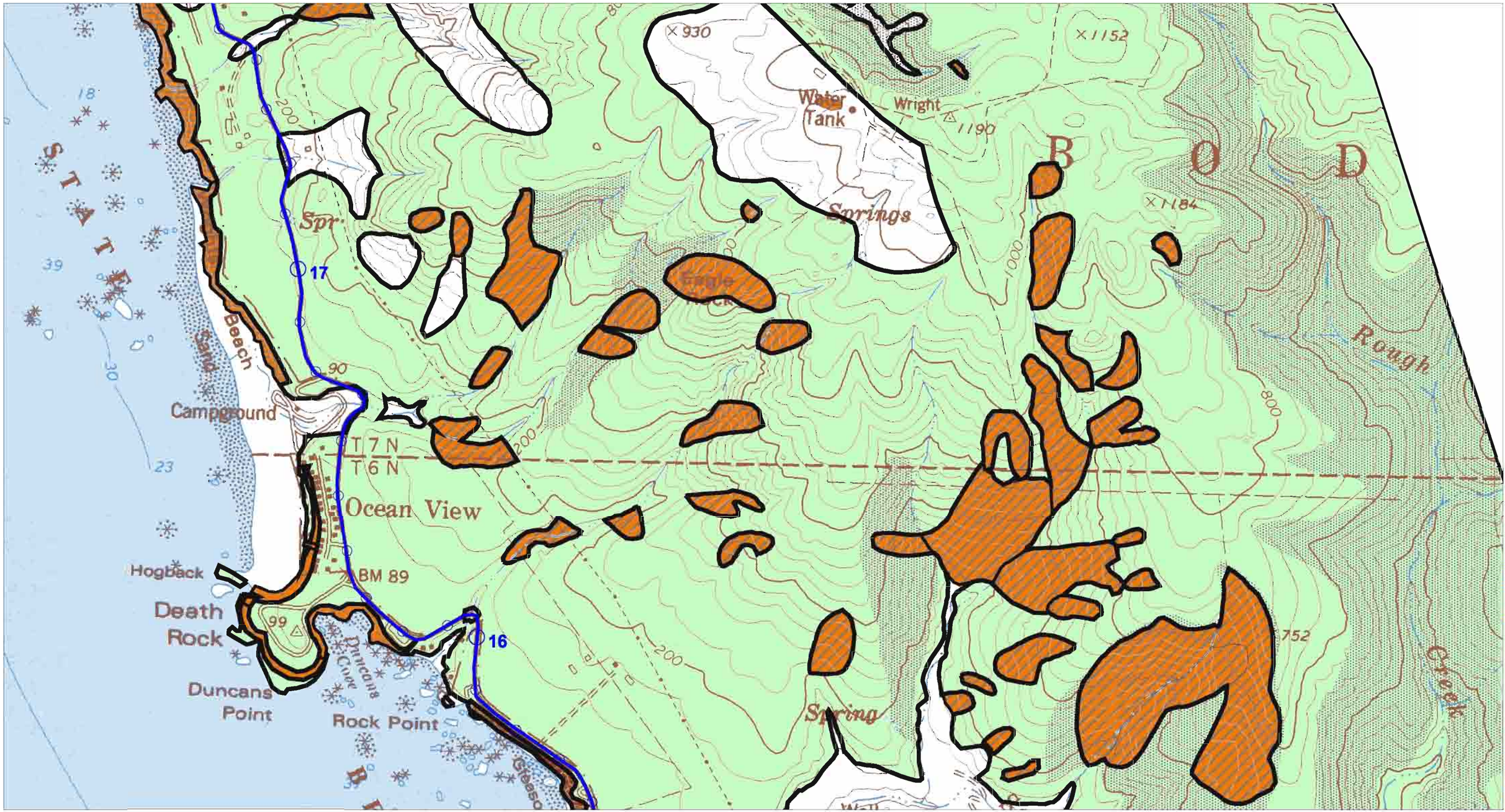
0.5 0 0.5 1 1.5 2 Kilometers

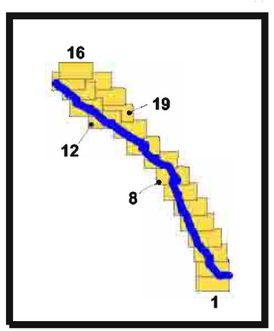
Base Map from USGS
Bodega Bay & Duncans Mills
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 2
Map 5 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

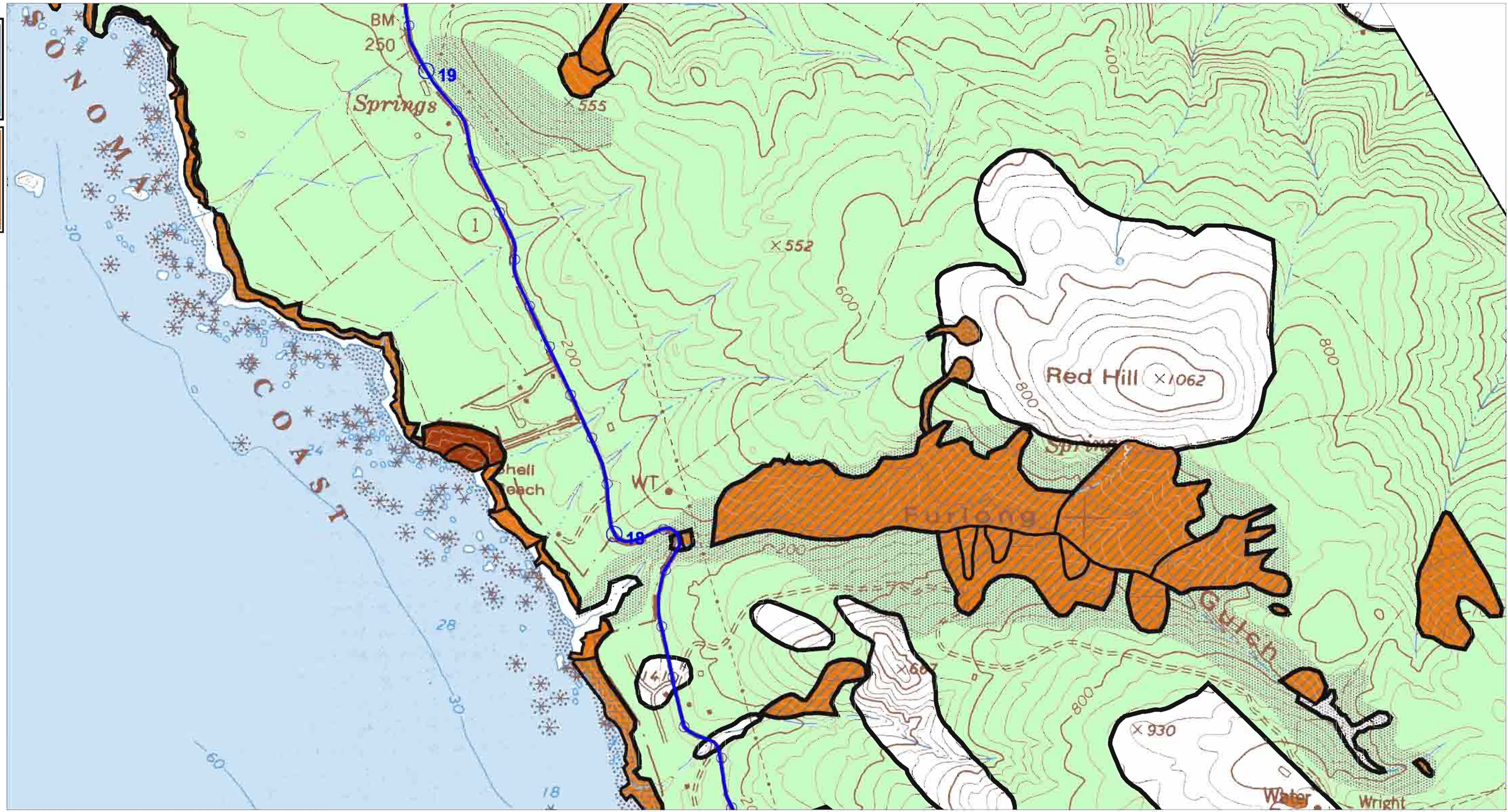
0.5 0 0.5 1 Miles

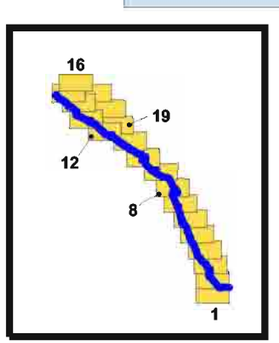
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Duncans Mills
7.5 minute Quadrangles

January 1, 2006

Plate 2
Map 6 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

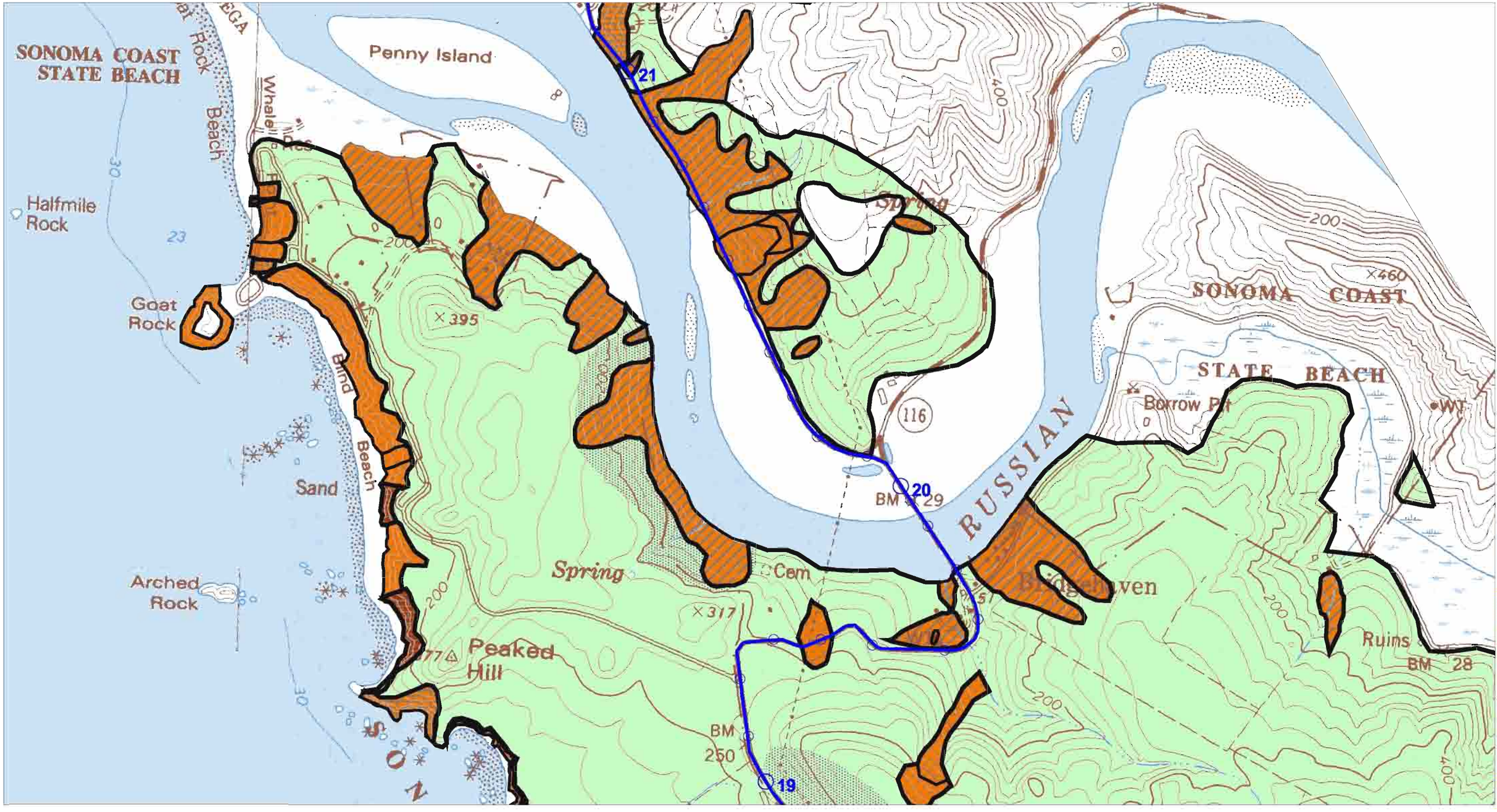
0.5 0 0.5 1 1.5 2 Kilometers

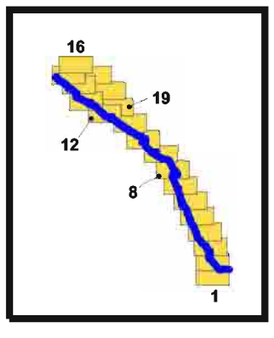
N W E S

Base Map from USGS
Duncans Mills
7.5 minute Quadrangles

January 1, 2006

Plate 2
Map 7 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

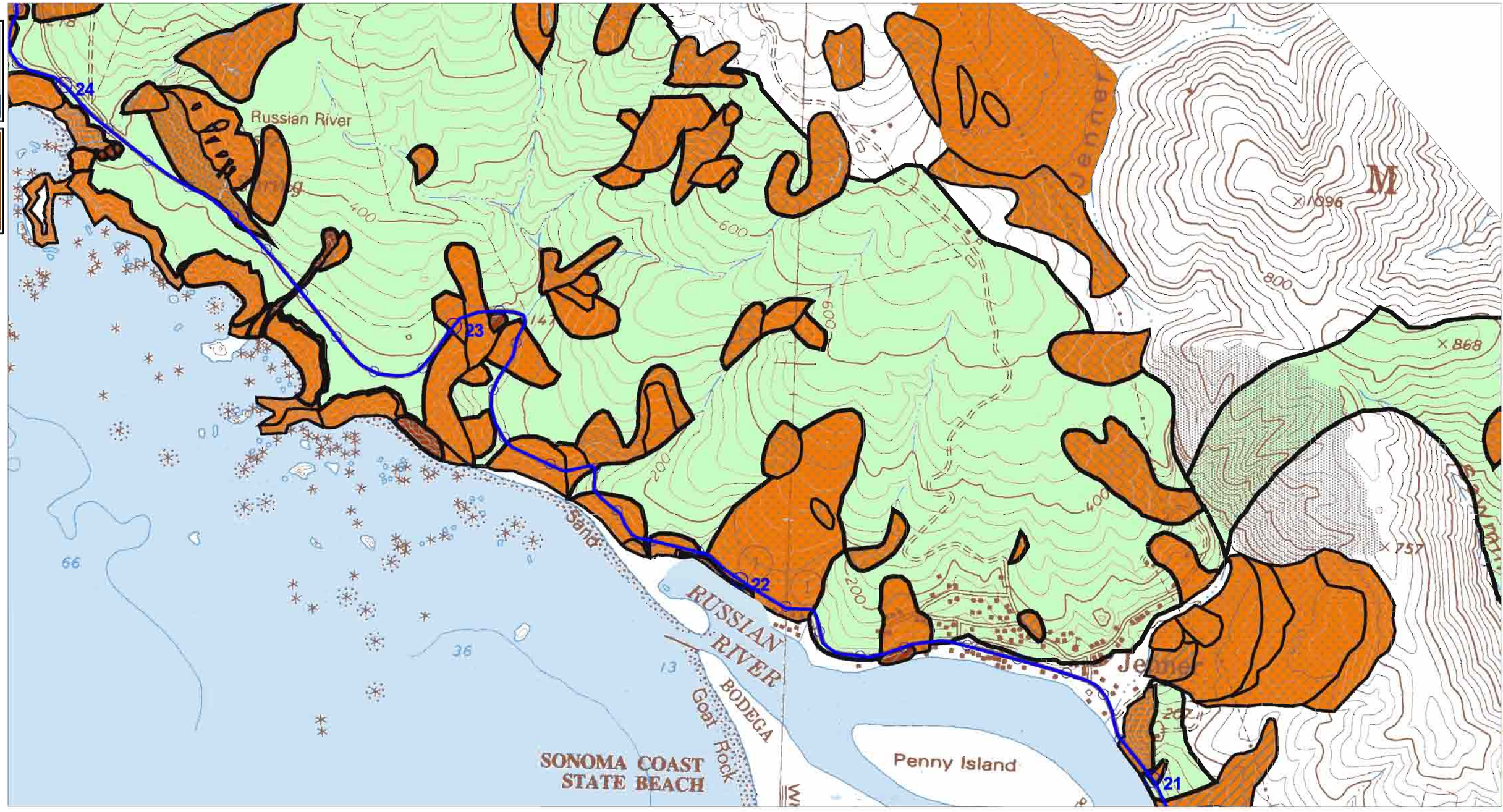
0.5 0 0.5 1 1.5 2 Kilometers

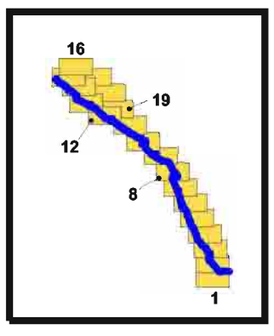
Base Map from USGS
Arched Rock & Duncans Mills
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 2
Map 8 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

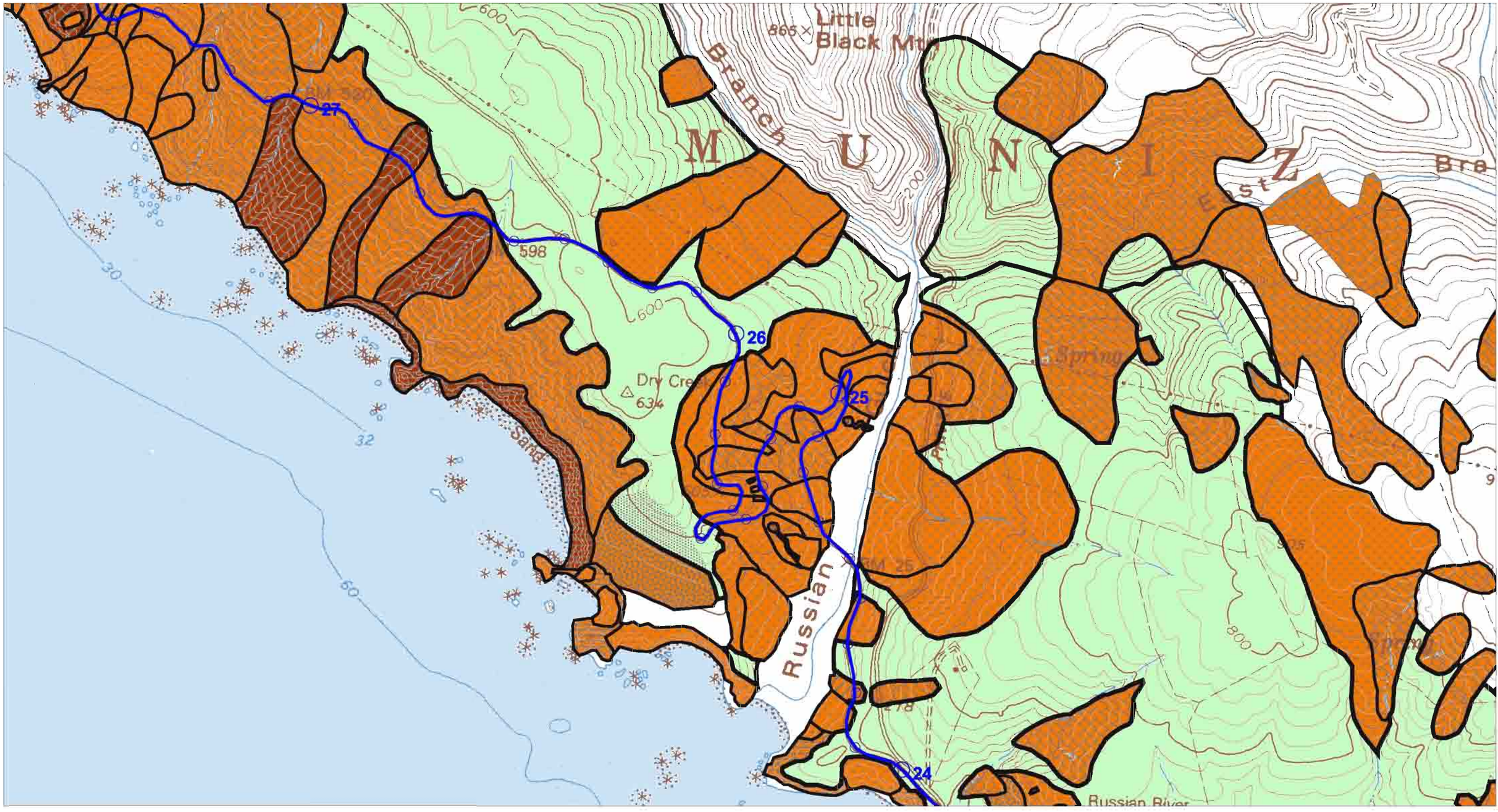
0.5 0 0.5 1 1.5 2 Kilometers

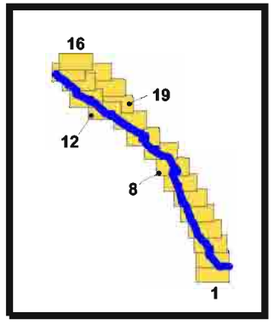
Base Map from USGS
Arched Rock & Duncans Mills
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 2
Map 9 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

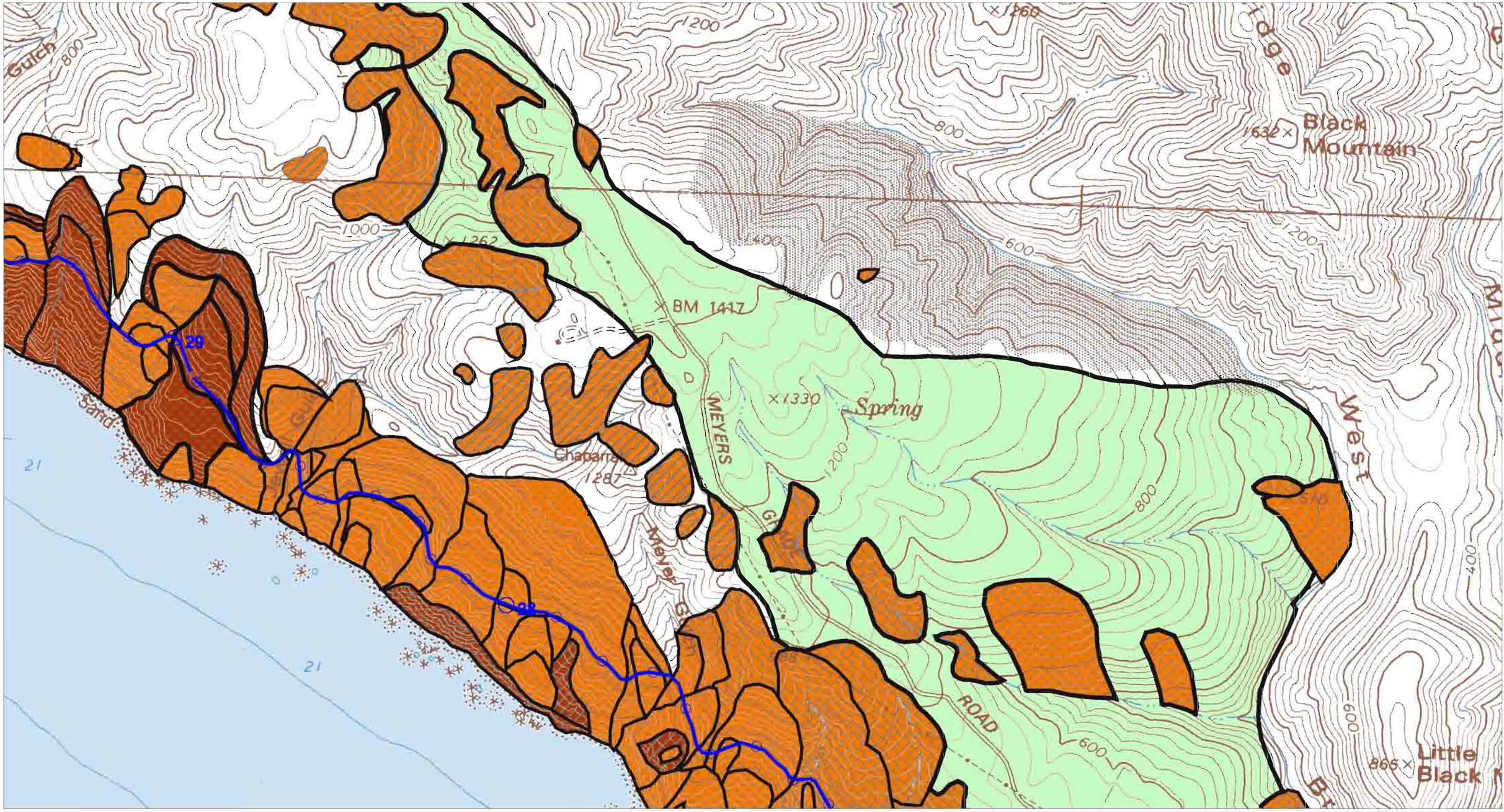
0.5 0 0.5 1 Miles

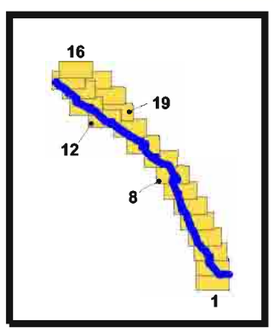
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Arched Rock
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 10 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

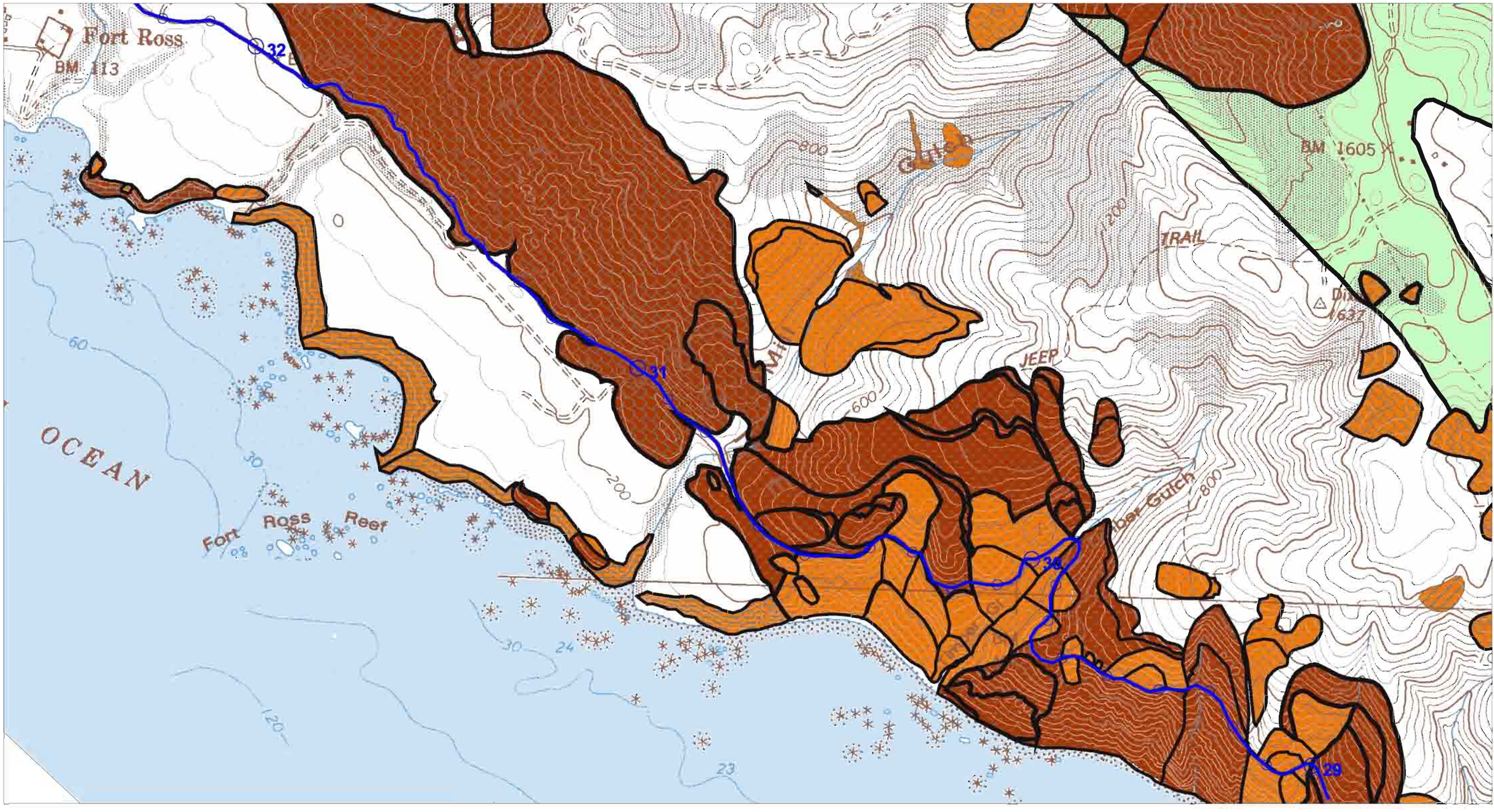
0.5 0 0.5 1 1.5 2 Kilometers

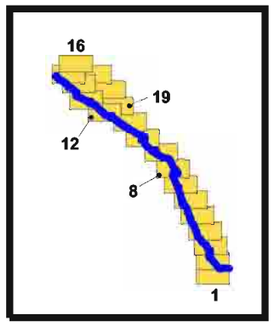
Base Map from USGS
Arched Rock & Fort Ross
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 2
Map 11 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

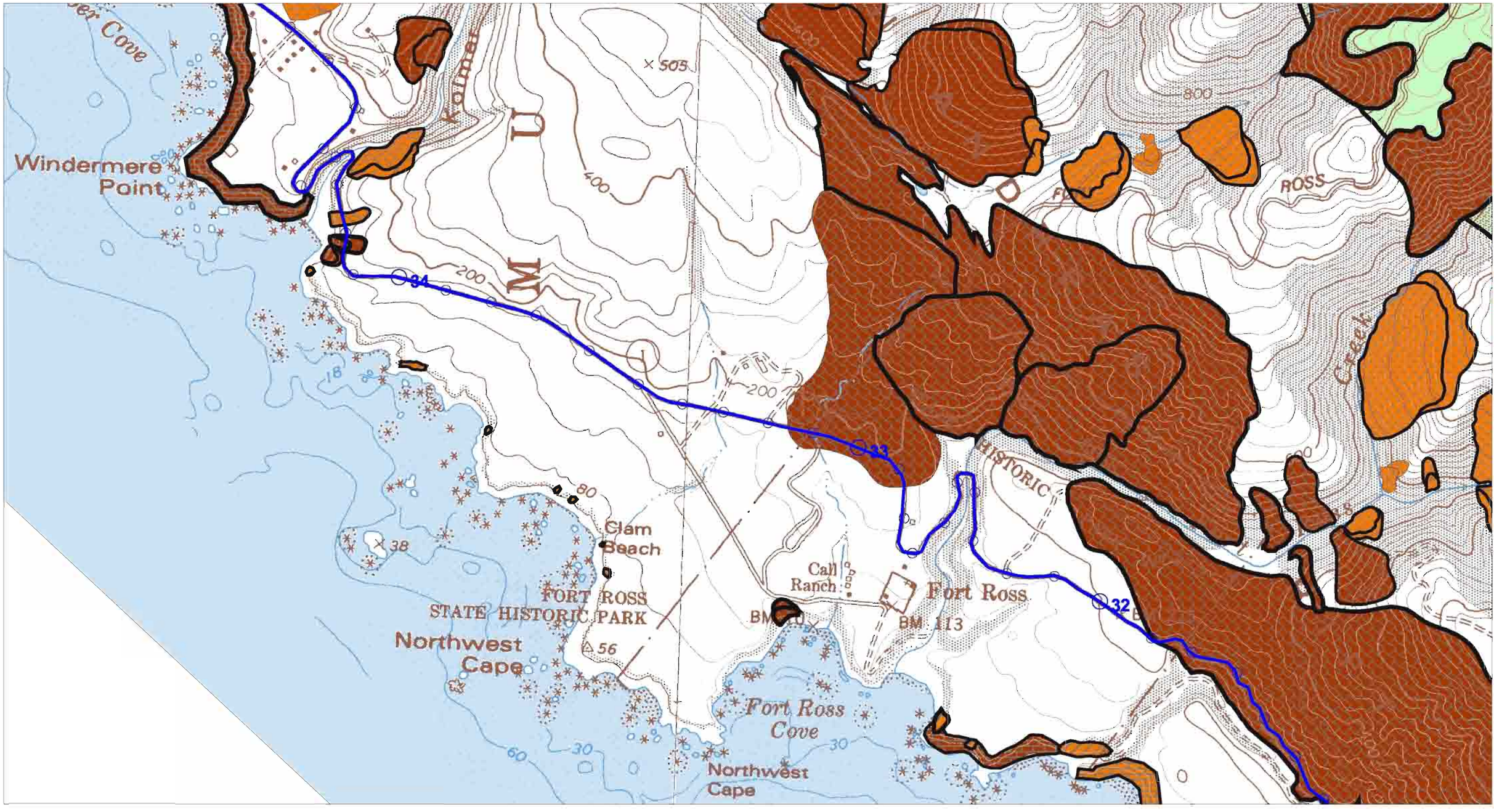
0.5 0 0.5 1 1.5 2 Kilometers

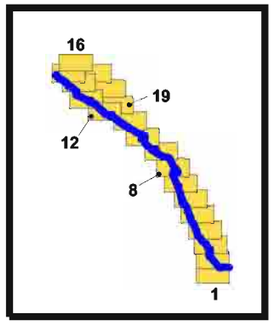
Base Map from USGS
Arched Rock & Fort Ross
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 2
Map 12 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

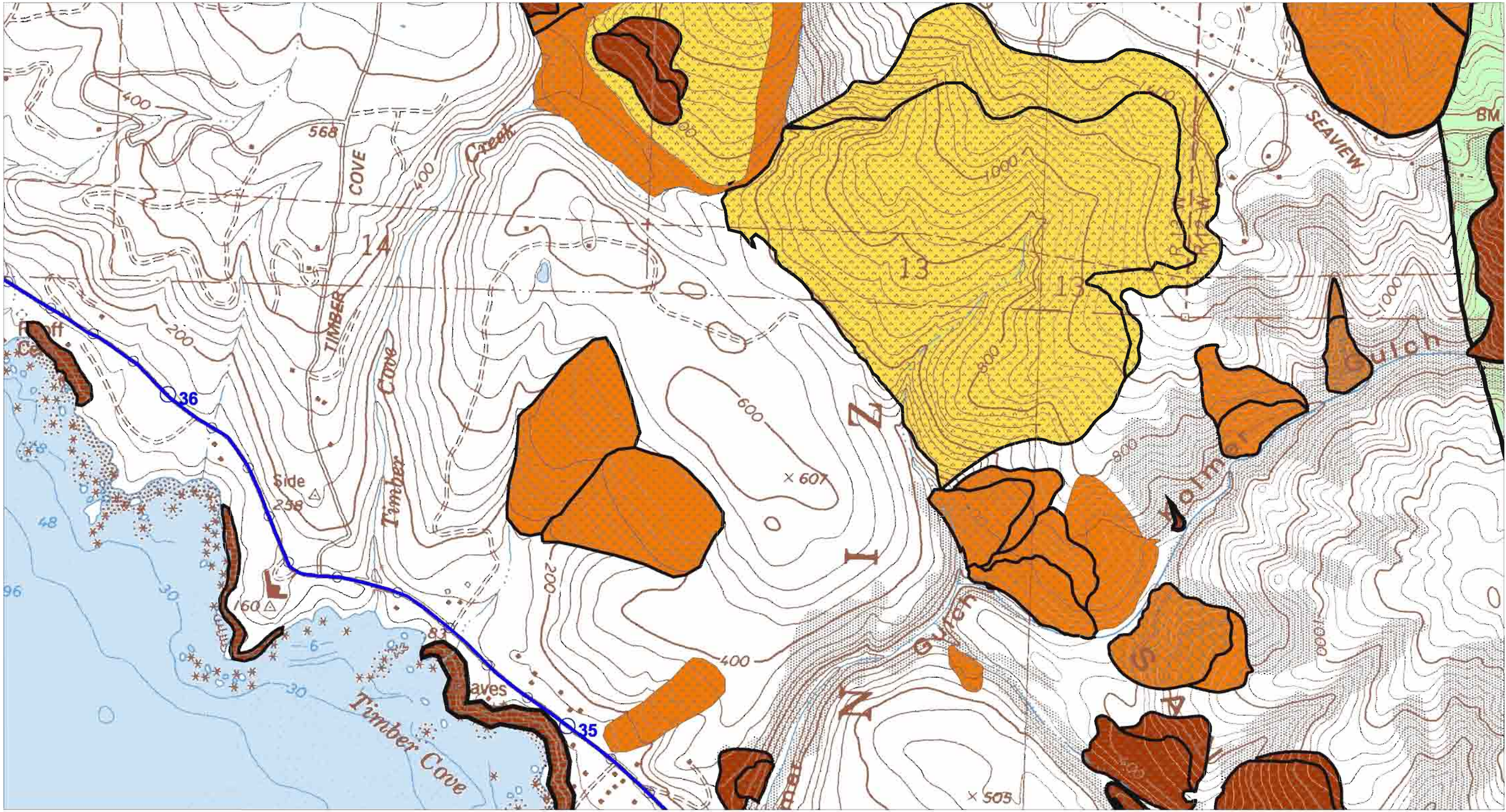
0.5 0 0.5 1 Miles

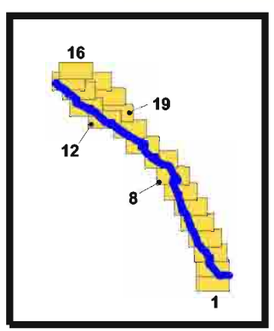
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

Plate 2
Map 13 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

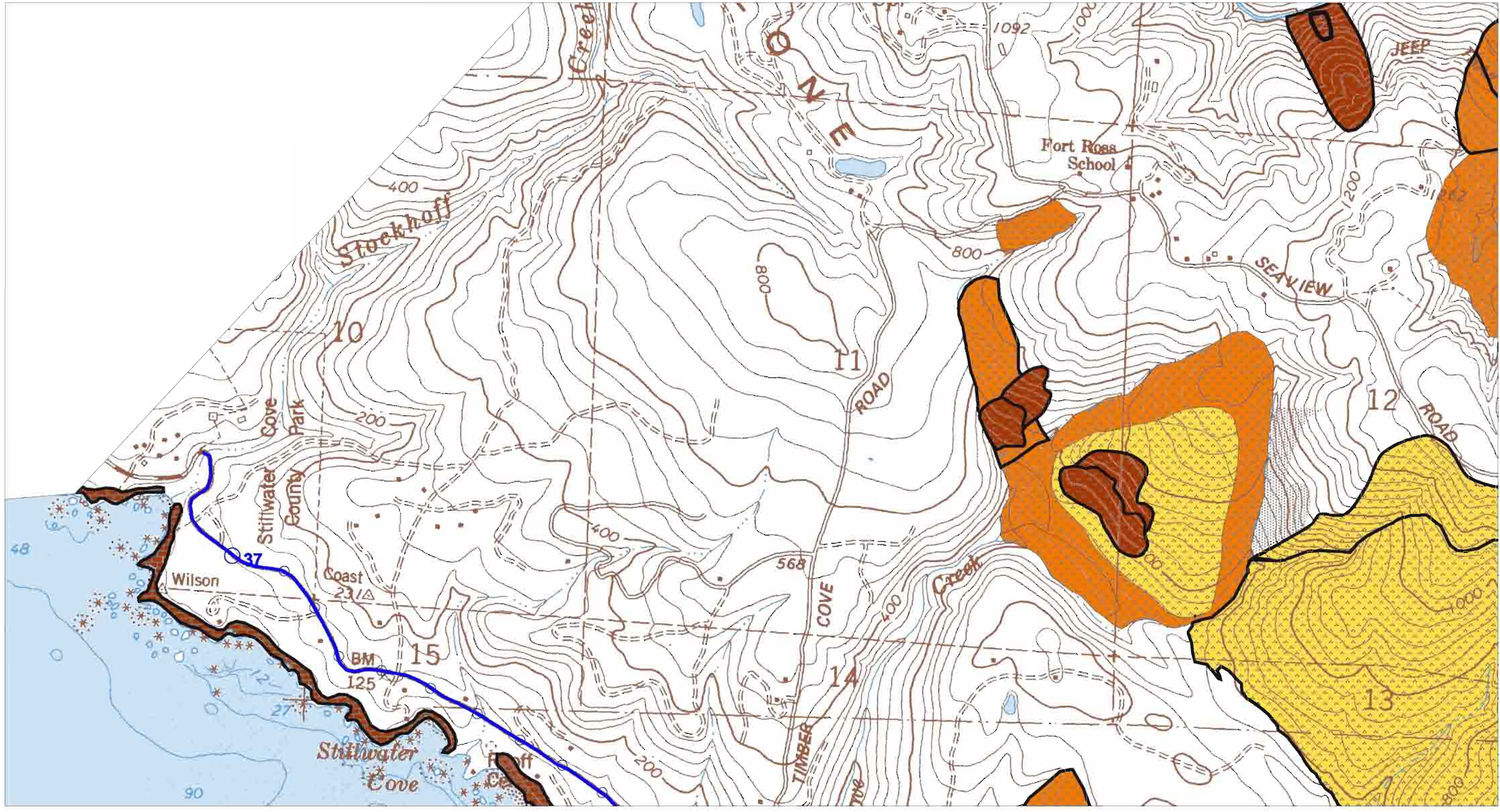
0.5 0 0.5 1 Miles

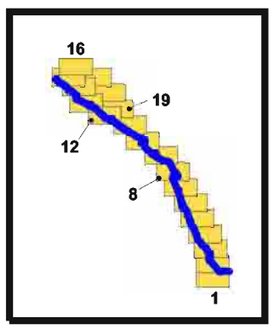
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

Plate 2
Map 14 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

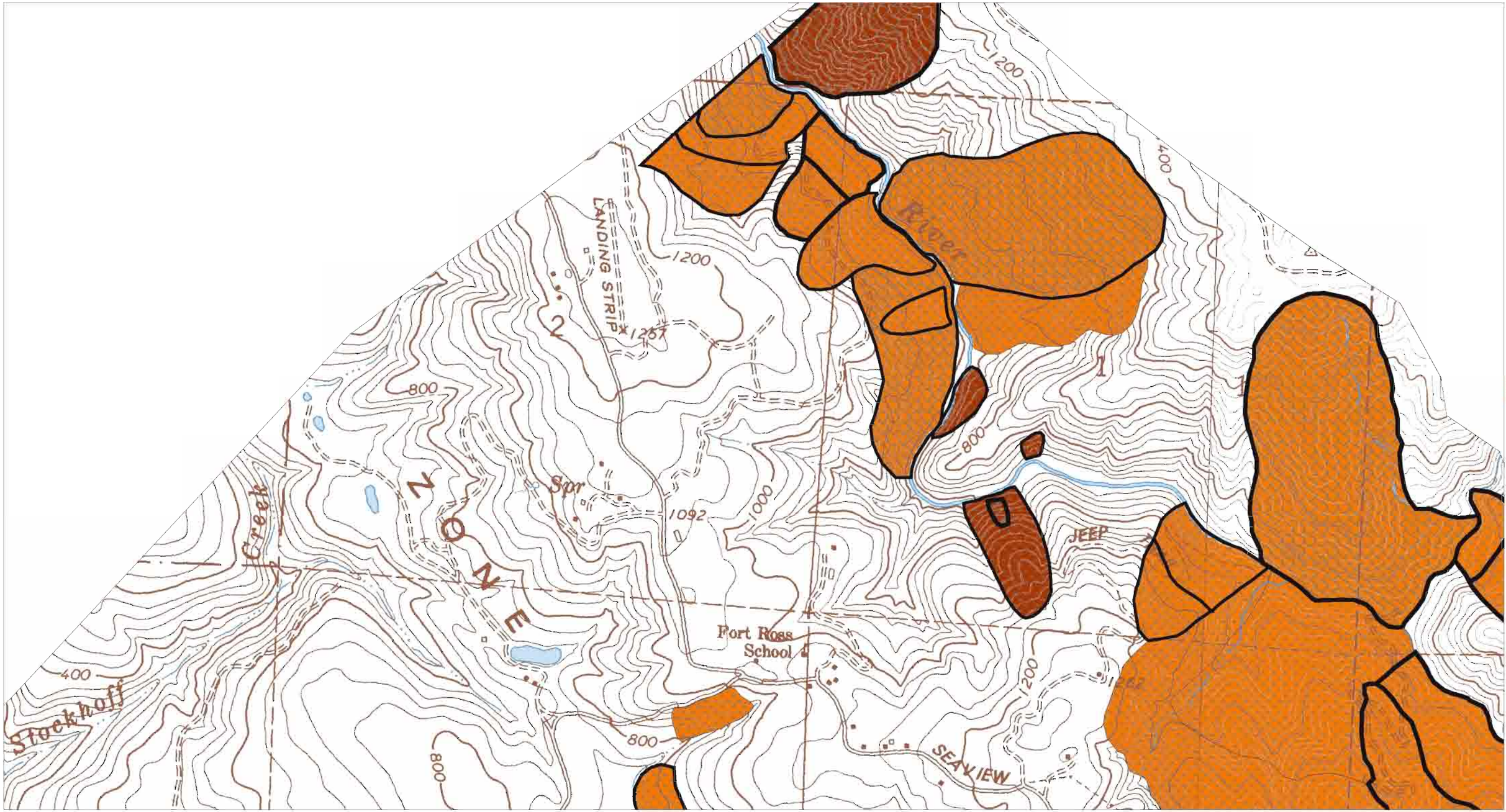
0.5 0 0.5 1 Miles

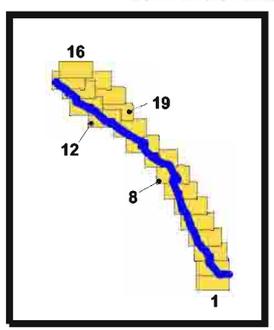
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Plantation
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 15 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

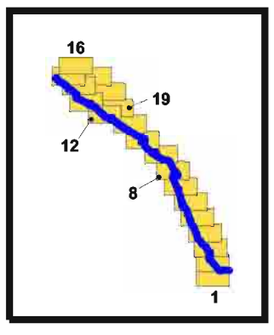
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

N W E S

Plate 2
Map 16 of 19



Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

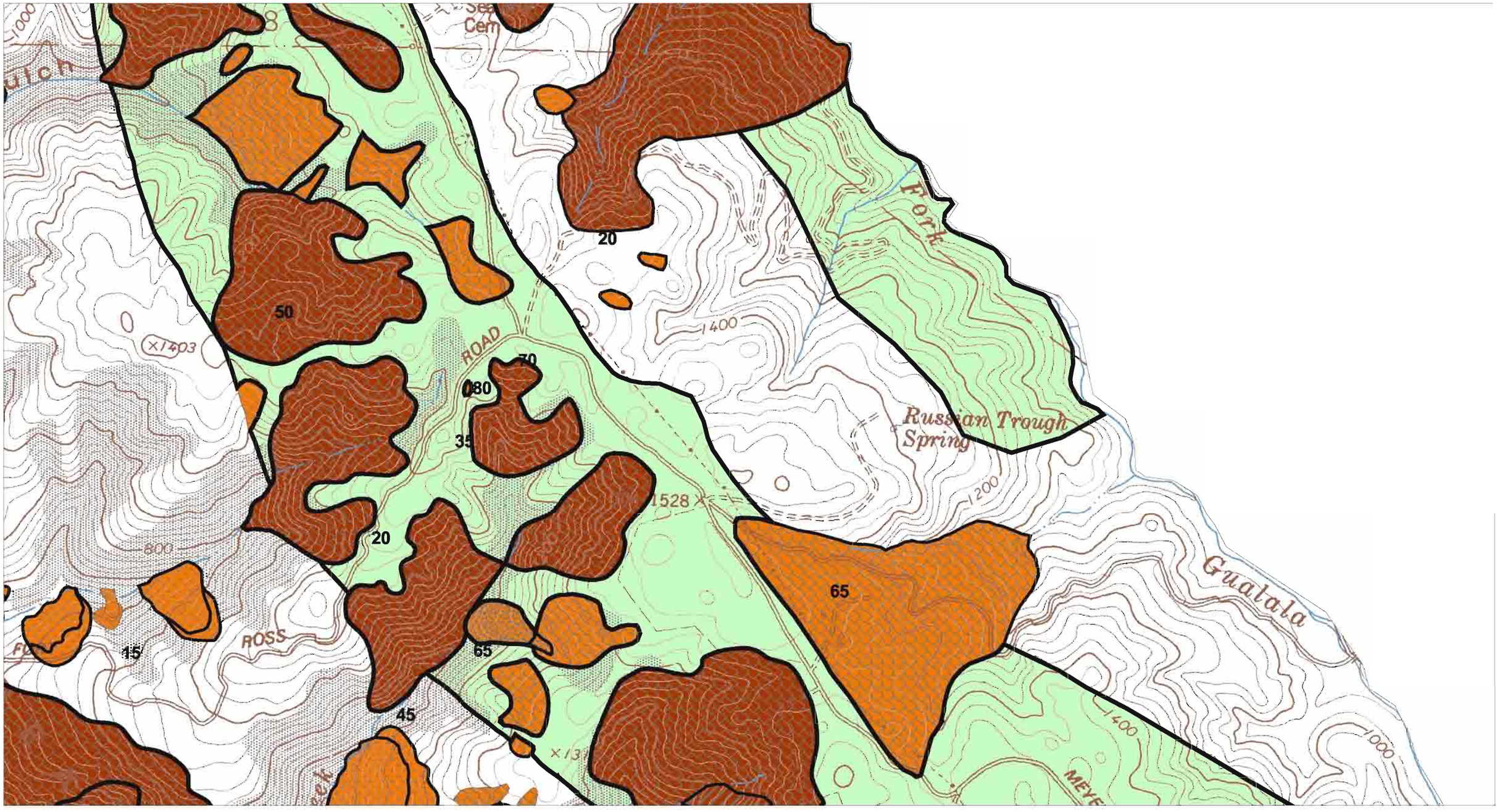
0.5 0 0.5 1 1.5 2 Kilometers

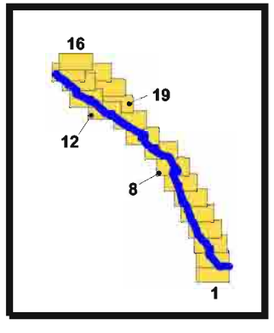
N W E S

Base Map from USGS
Fort Ross
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 17 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

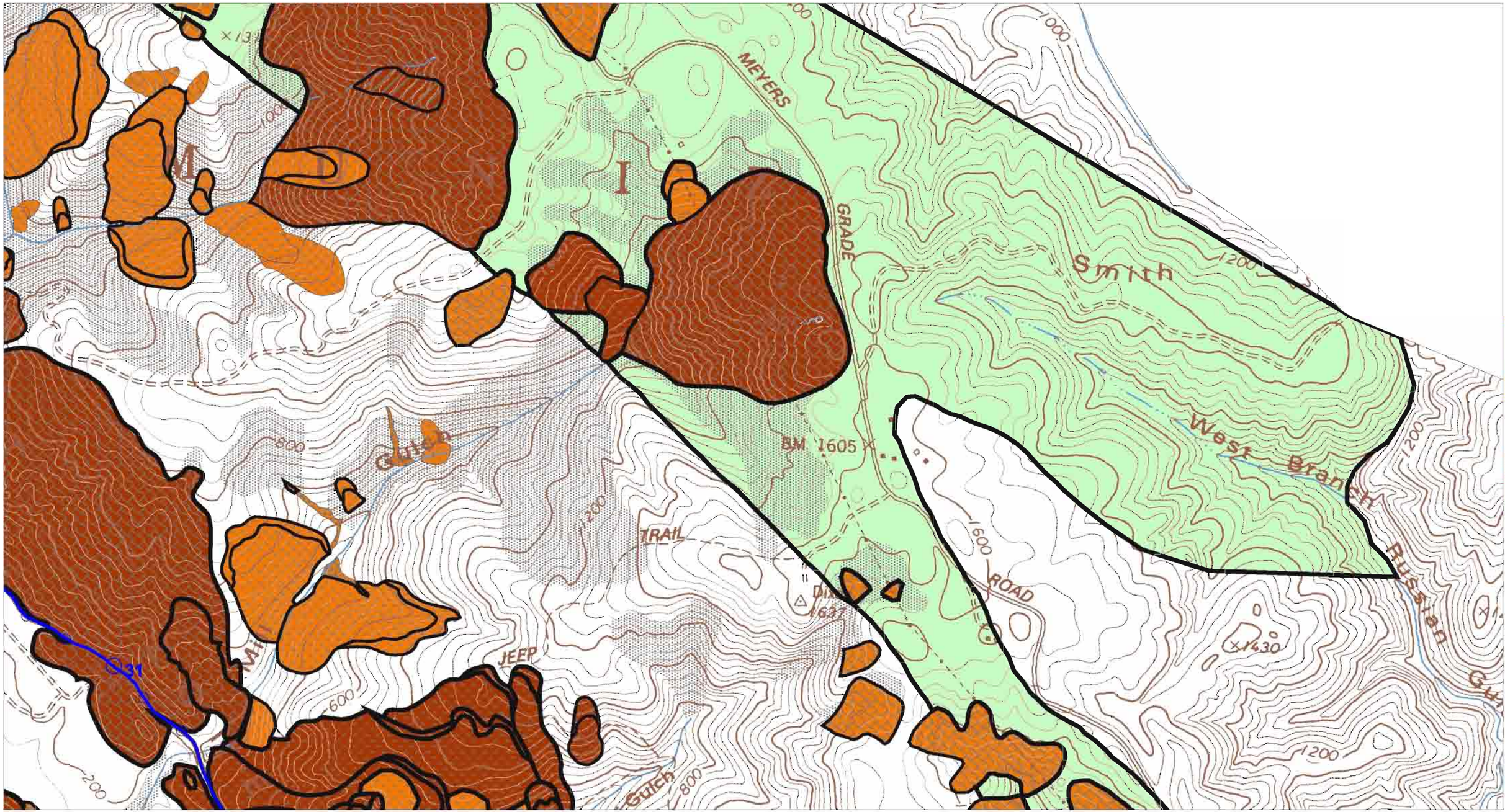
0.5 0 0.5 1 Miles

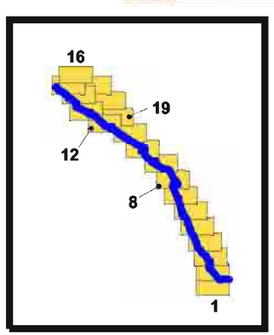
0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross
7.5 minute Quadrangle

January 1, 2006

Plate 2
Map 18 of 19





Geology and Slope Stability Along the Bodega Bay - Fort Ross Highway Corridor

Highway Corridor Landslide Map

Map Scale 1:12,000

0.5 0 0.5 1 Miles

0.5 0 0.5 1 1.5 2 Kilometers

Base Map from USGS
Fort Ross & Plantation
7.5 minute Quadrangles

January 1, 2006

Plate 2
Map 19 of 19