LANDSLIDES IN THE HIGHWAY 299 CORRIDOR BETWEEN BLUE LAKE AND WILLOW CREEK, HUMBOLDT COUNTY, CALIFORNIA

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by

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INTRODUCTION

Highway 299 is the major east-west highway in north coastal California. Located north of Eureka, the highway traverses the Coast Ranges through rugged, mountainous terrain. The segment of the highway between Blue Lake and Willow Creek crosses terrain that is particularly landslide prone, especially the area west of Berry Summit. Many types of mass wasting are present within the study area. The roadway crosses numerous landslides and many these have been active historically and have disrupted the highway. Reactivation of numerous slides over the past 10 years has led the California Department of Transportation (CalTrans) to evaluate the feasibility of long-term landslide repair options for some of the most problematic sites.

The CalTrans New Technology and Research Program within the Office of Infrastructure Research contracted with the Department of Conservation's California Geological Survey (CGS) to prepare landslide inventory maps of the Highway 299 corridor between Blue Lake and Willow Creek in order to give the slides along the corridor a regional perspective and provide background information for current and future projects. The map series includes a map of landslides within the study area along highway corridor superimposed on a bedrock geologic map, paying particular attention to those landslides most likely to directly affect the highway.

Mapping landslides in heavily forested terrain by traditional field mapping methods can require an extraordinary effort. In many cases, where the time and money for mapping is limited, the acceptance of maps that are less complete and less accurate than those on un-forested land may occur. This is because landslides are mapped based on their geomorphology. The distinctive landforms created by landsliding are commonly obscured in heavily forested terrain. Neither aerial photos nor photogrammetrically prepared topographic maps accurately depict the ground surface beneath the forest canopy. In view of the fact that the typical reconnaissance techniques are less effective, either extra effort is spent on the ground or a less accurate map is produced.

Since CGS anticipated difficulties in preparing an accurate landslide inventory map of this corridor using traditional techniques, CGS proposed an additional project where CGS would develop detailed specifications for a LiDAR survey, contract with LiDAR vendors for the survey and evaluate the product. The initial conclusions regarding the value of the LiDAR surveys to landslide mapping were presented in a preliminary report to CalTrans in 2002. In this report, the results of the LiDAR survey have been used to prepare landslide maps in the same format as other highway corridor maps. This report also presents conclusions on the effectiveness of the LiDAR survey in improving the accuracy and completeness of the landslide mapping.

The mapped area extends up to 1½ miles either side of Highway 299, encompassing 41 sq. mi (26,000 acres). Each landslide in the area is described in terms of the materials involved, the dominant type of movement, the interpreted recency of movement, and other factors as described below. The descriptions of each landslide allow some general conclusions regarding the potential for future movement, but do not allow for detailed evaluation of the movement potential of any specific landslide or areas outside of the mapped landslides.

The geometry of each landslide and physical properties of the geologic units in which they have formed can be used by engineers and geologists at CalTrans in the planning of more detailed specific roadway improvement projects. These maps are intended to allow CalTrans to compare the scale and activity of landsliding immediately adjacent to, and underlying, the highway with the landsliding found in the surrounding region. Plans for landslide mitigation and the evaluation of possible bypass routes can also be considered.

STUDY AREA

The portion of the Highway 299 corridor in this study extends approximately 18 air miles (29 km) and 32 highway miles (52 km) between the towns of Blue Lake and Willow Creek (Figure 1). The roadway starts at an approximate elevation of 280 feet near Blue

Lake and follows the canyons of the North Fork of the Mad River and Long Prairie Creek until it reaches 2,200 feet at Lord Ellis Summit. The highway then drops to 880 feet at the O'Kane Bridge as it traverses the Redwood Creek canyon, then climbs to 2,800 feet at Berry Summit on the eastern side. The roadway then drops 2,100 feet over approximately nine miles as it parallels Willow Creek to its confluence with the Trinity River at the town of Willow Creek.

Green Diamond Resource Company owns most of the North Fork Mad River and Long Prairie Creek watersheds. Green Diamond, Barnum Timber and numerous other small landowners own property in the Redwood Creek watershed. Six Rivers National Forest is located immediately east of Redwood Creek and contains the headwaters of Willow Creek.

The route now followed by Highway 299 between Blue Lake and Willow Creek was established as a pack train, then a wagon road handling freight between the coast and the Klamath gold mines in the 1850's.

Construction of the modern roadway started in mid-1960's, coming west from Willow Creek. Portions of the old roadway alignment were abandoned and turned over to the County of Humboldt and local landowners. Only Chezem Road in Redwood Creek is still open to the public and is a County road. Green Diamond uses the old roadway west of Lord Ellis Summit as a main haul road for that portion of their ownership.

REGIONAL OVERVIEW

The Highway 299 study area traverses the Coast Ranges geologic province and enters the Klamath Mountains province (Figure 1). The Coast Ranges extend for about 700 miles within California from Santa Barbara County to the Oregon border, and continue through Oregon into Washington.

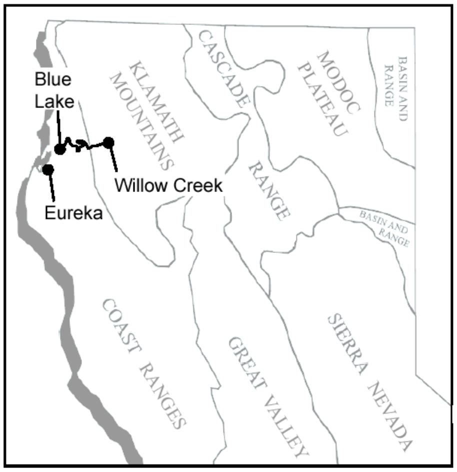


Figure 1, Location of the Highway 299 corridor with respect to the geomorphic provinces of California.

South of Cape Mendocino, the province is characterized by northwest-trending valleys and mountain ranges bounded by right lateral strike slip faults where sections of the earth's crust have slid horizontally past one another. North of Cape Mendocino, compressional tectonic forces dominate where the Gorda plate (Figure 2), is colliding with and being driven (subducted) beneath the North American continent.

The regional structure and tectonics in this part of California are extremely complex and the geology of the study area is typical of that complexity. During past subduction processes, oceanic sediments were scraped off the descending plates and "welded" (accreted) onto the western edge of the North American plate. In California, this accreted material is named the Franciscan Complex. This unit consists primarily of marine sandstone and shale, and contains occasional blocks of limestone, basalt, serpentinite and exotic metamorphic rocks. The rocks in the Franciscan Complex generally are slightly metamorphosed, and are often highly disrupted, with broad zones of pervasively sheared shale matrix containing relatively intact blocks of varying rock types and sizes. This tectonicly created mélange is highly variable in its physical characteristics and susceptibility to landsliding, depending on the relative proportion of sheared matrix and intact rock, and the orientation of the blocks in the matrix (Medley, 2005).

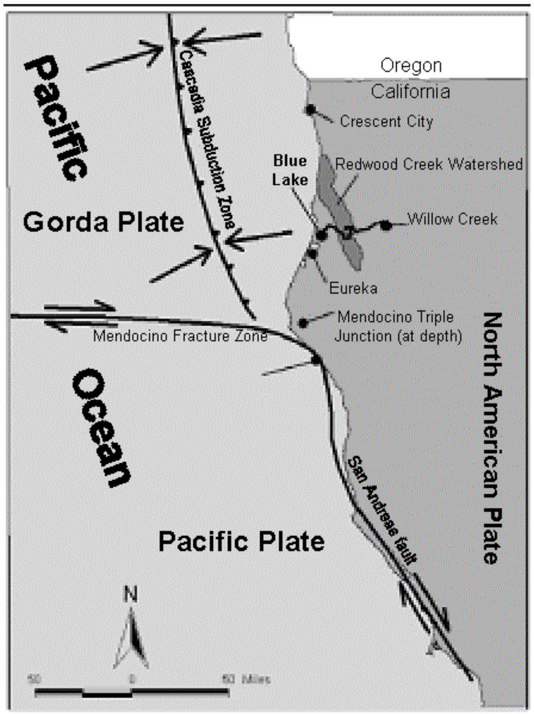


Figure 2. Location of the Highway 299 corridor with respect to major plates and plate boundaries.

The compressional tectonics of the area have lead to rapid uplift of these sedimentary rocks in recent geologic time. This uplift is thought to be in part due to a broad regional warping related to northeast-southwest-oriented compression along the North American and Pacific plates boundary. The study area has some of the highest uplift rates in North America (1 to 4 mm/year near the Mendocino triple junction, Figure 2; McLaughlin and others, 1983; Merritts and Bull, 1989; Merritts, 1996). River terraces observed along the highway alignment in Redwood Creek indicate that relatively high rates of uplift persist well inland from the plate boundary (CGS-NCWAP, 2003). Rapid uplift leads to naturally high rates of erosion and abundant landslides (Montgomery and Brandon, 2002).

The region experiences a high level of seismic activity, with common earthquakes large enough to damage structures, as well as infrequent extreme events of magnitude 8.5 or greater (Dengler and others, 1992). At least 60 damaging earthquakes have occurred near the coastal portion of Humboldt County since the mid 1800's (Dengler and others, 1992). Major earthquakes often trigger or reactivate existing landslides, so the high rate of seismicity in the region probably contributes to the high natural rate of landsliding observed.

Highway 299 leaves the Coast Range and enters the Klamath Mountains province where it crosses the Coast Range Thrust, immediately east of Berry Summit (Figure 1). This fault defines the eastern limit of Coast Range rocks. The Klamath Terrane rocks are part of an accretionary complex similar to the Franciscan, but are significantly older and consist of a discrete sequence of relatively competent east-dipping “packages” of related rocks ranging from mid-Paleozoic age (360 MY) in the east to Jurassic-Cretaceous (144 MY) in the west. The Klamath Terrane and Franciscan Complex provide a record of over 350 million years of episodic, subduction-related accretion along the ancient boundary of western North America (Metcalfe and Barrow, 2002).

The northern Coast Ranges do not have the broad northwest-trending valleys that make natural transportation corridors as are found in the southern Coast Ranges. This is partly because of this difference in tectonic styles. Highway 299 north of Blue Lake follows the valleys of several minor streams and rivers but is forced to climb and traverse several steep-sided ridges before it reaches Willow Creek. Most of these slopes are naturally prone to landslides, so maintaining this part of the roadway is a continuing challenge.

GEOLOGIC MAPPING

To prepare the geologic map of the Highway 299 corridor, previous published regional maps by CGS-NCWAP (2003), Harden and others (1982), Kelley (1985), Ristau (1979) and Young (1978) were compiled. The geologic maps were assembled from existing GIS data and augmented with in-house digitizing of the paper geologic map (Young, 1978). Landslides were mapped by interpreting the shaded relief images derived from the Digital Elevation Models (DEMs) of the study area (three illumination directions per DEM for a total of 12). DEM-based slope and topographic maps were used to check and fine-tune the mapping. More typical review of aerial photographs and field reconnaissance were also employed. Selected historical aerial photographs dating back to 1941 were analyzed. Site-specific field mapping conducted during this study and during earlier timber harvest inspections throughout the study region were used to check several areas.

There were gaps in coverage between some of the previously published geologic maps and differences in the identification and location of geologic units at the map boundaries. Focused field reconnaissance augmented with analysis of topography helped resolve the differences between the map sources and modify the geographic locations of several geologic contacts.

Surficial units

Fluvial and man-made deposits are present throughout the study area and are described in the following section. Quaternary units are mapped based on their age and environment of deposition as revealed by their composition, geomorphic expression and relative position to other units. The types of mass wasting features shown on the maps are described in the “Landslide Types and Associated Geomorphic Features” section that follows.

Artificial fill (af): Man-made, highly variable assemblages of sand, silt, clay and gravel.

Undifferentiated Alluvium (Qal): Holocene-Pleistocene. Interbedded boulders, cobbles, gravel, sand, silt and clay within active stream channels, flood plains and lower river terraces. These deposits typically are located within 40 vertical feet of the active channel (see river terrace discussion following).

Alluvial fans (Qf): Holocene. Characteristically seen as broad fan/cone shapes at the mouths of actively eroding stream canyons; includes debris flow deposits typically consisting of poorly sorted silt, sand, gravel, cobbles and some boulders.

Lacustrine deposits (Ql): Holocene. Lake deposits consisting of unconsolidated clay, silt and fine sand that have accumulated within undrained depressions on landslides. Some small artificial ponds for livestock watering are included in this category.

A large lake deposit was mapped south of milepost R15.900 by Kilbourne (1985). Kilbourne’s interpretation that this material is a lake deposit, rather than artificial fill spoils, appears to be most likely because: a) the area lies on a broad bench that appears to be landslide related; b) field observations that the surface has a uniform, meadow-like appearance that slopes very gently to the south-southwest at approximately 3 percent without an obvious surface drainage system; c) the watercourse along the west side of the flat has an irregular, sinuous channel that has been modified by minor bank sloughing; and, d) in contrast, the drainage system and surface of the large fill spoils site at the target range (milepost R12.400) has a series of very regular benches and an orthogonal pattern to its surface drainage system .

A small portion of the roadway fill may overlie this lacustrine material, but it does not appear to be a potential landslide threat. No pavement problems were observed there.

Erosion in the existing gully on the west side of the lacustrine deposits could accelerate if runoff increases or the outer edge of the old lakebed is breached but this would probably not be a sudden, catastrophic phenomenon.

Old Alluvium (Qoal$_1$, Qoal$_2$): Holocene-Pleistocene. Interbedded boulders, cobbles, gravel, sand, silt and clay underlying uplifted river terraces. Most of these deposits are adjacent to Redwood Creek. All the relatively younger terraces lying between 40 and approximately 140 vertical feet above of the active channel are grouped into Qoal$_1$. This elevation range is qualitative and based on observations by archaeologists that many terraces in this elevation range contain the remains of numerous aboriginal settlements (Mark Gary, CDF Archaeologist, personal communication, 1999). The assumption is that lower terraces were either reworked periodically by large floods and/or were not occupied permanently by native peoples.

The older terraces (those located 150 vertical feet or more above the active channel) are designated Qoal$_2$; possibly Pleistocene-age. The oldest terraces are located as much as 500 to 900 feet above the valley bottom, high on the canyon walls. These deposits have relatively well-developed soils where observed in the field. These units represent the ancient valley bottom and are seen as relatively small, scattered erosional remnants that have been left behind as the active channel incised into the landscape in response to the regional uplift.

Bedrock units

The distribution of bedrock and mass-wasting styles along the highway alignment are discussed in three general sections for clarity (Blue Lake, Lord Ellis and Willow Creek). These sections proceed from west to east along the highway using the CalTrans milepost GIS coverage tags for general location references. Note that the sections also correspond very closely with transitions between the three major bedrock packages between Blue Lake and Willow Creek. This is a reflection of the strong regional “grain” in the bedrock along the alignment. There may be a labeling problem on the milepost coverage at Lord Ellis Summit between adjacent mileposts R17.400 and R18.359

(0.859 mile gap indicated by the labeling, 0.1 mile observed on the ground between milepost markers). The mileages as labeled on the Caltrans GIS file were used for simplicity.

Several unit descriptions have been repeated between sections because they overlap section boundaries. Other units repeat within the same section because of complex faulting. Text descriptions of every unit are not repeated in these cases. Please refer to the prior descriptions in the text.

Blue Lake R6.500 – R17.250

Three bedrock units underlie the North Fork Mad River watershed (Plate 1, Sheet 1). Two of these are associated with the Central and Eastern Belt of the Franciscan Complex and underlie the bulk of the watershed. The Franciscan bedrock within the watershed is divided into fault-bounded units. Progressing to the northeast through the watershed are the Falor Formation, Sandstone and mélange unit of Snow Camp Mountain and Redwood Creek schist.

R7.050 – 7.250: Falor Formation (QTfa): This is a pebbly conglomerate, sandstone and siltstone that contains abundant animal and plant remains locally. The unit was deposited in a fluvial and shallow marine environment. The contact between it and underlying Franciscan complex unit is an erosional unconformity. This unit does not appear to contribute to the landslides affecting the highway. The Falor Formation appears to be relatively competent and forms debris slide slopes northwest of Korbel near the highway. Gully erosion can be a problem where runoff is concentrated on slopes below the road.

R6.500 - R7.050, R7.250 – R18.359: Sandstone and mélange unit of Snow Camp Mountain (KJfsc) Central Belt Franciscan Complex: This unit underlies the bulk of the North Fork Mad River watershed and consists of bodies of dense, intact sandstone intermixed with a pervasively sheared shale-rich mélange containing smaller blocks of metagraywacke, metachert, volcanic breccia, metabasalt, metatuff, metavolcanic rocks, greenstone and glaucophane-lawsonite blueschist.

Areas dominated by mélange generally form rounded hilltops with gentle slopes and complex side hill drainage patterns. Sharp-crested ridges with moderately steep slopes and well-defined drainage systems tend to develop where the upper edges of earthflow complexes meet. Intact tectonic blocks (usually sandstone) stand out from the surrounding landscape as steep-sided, rocky knobs that tend to be elongated in a northwest-southeast direction parallel to the structural grain.

Active earthflows and large deep landslides are the main modes of mass wasting in the Snow Camp Unit. Debris slides typically occur on oversteepened slopes created through stream erosion or grading. Mélange matrix typically underlies the grassland and lightly wooded areas present in the northeast portion of the Long Prairie Creek watershed. Well-developed gully networks are common within the more active portions of earthflow complexes and are considered significant sediment sources because they are directly connected to the drainage system.

Based on aerial photograph interpretation and mapping, this material appears to be similar mechanically to the incoherent unit of Coyote Creek (see R23.209 – R29.009, Lord Ellis section following), but appears to be more resistant to active mass-wasting. Most of the Snow Camp Mountain unit supports dense, healthy tree cover, compared to large expanses of prairie in the Coyote Creek unit. The geomorphology is varied with steep slopes forming in areas underlain by relatively competent sandstone, and more subdued hummocky terrain in areas underlain by mélange.

Kilbourne (1985) mapped a large ancient slide complex heavily modified by erosion and later mass wasting occupying much of the Pine Creek / Long Prairie Creek watershed. Our observations support Kilbourne's interpretation. The feature is seen as a series generally concordant, gently sloping benches enclosed within a large, relatively steep amphitheater containing the drainages of both creeks. The roadway between Pine

Creek and Long Prairie Creek makes use of these broad benches as it climbs toward Lord Ellis Summit. This part of the drainage is mapped as underlain by Redwood Creek schist, which was confirmed in the field, but the schist probably is not in-place. It may have been transported down slope by mass-wasting, forming a veneer of sorts covering Franciscan Complex materials.

The heads of Long Prairie and Pollock Creeks are formed by large earthflow amphitheaters. These features are seen as broad, bowl-shaped depressions in the hillsides that extend from the creek to the ridge top. The large features do not appear to be recently active, but rather contain isolated areas of localized activity. Careful field reconnaissance is necessary to evaluate the relative stability of specific areas on these slopes.

<u>13.800 – 14.550 Bald Mountain shear zone:</u> Rocks within this shear zone in the Snow Camp unit appears to be particularly weak compared to the surrounding Snow Camp unit because there are many relatively recent slides along this side of Pine Creek. Most of the slides the highway crosses appear to be young or historically active (Cruden and Varnes, 1995) and begin at or near Kilbourne's (1985) mapped western boundary of this zone.

Lord Ellis R17.250 – R29.009

Five fault-bounded, bedrock units associated with the Franciscan Complex underlie the Redwood Creek watershed. Progressing to the northeast across the watershed are the sandstone and mélange unit of Snow Camp Mountain, Redwood Creek schist, altered rocks within the Grogan fault zone along Redwood Creek, the incoherent unit of Coyote Creek, and the coherent unit of Lacks Creek (Plate 1, Sheets 1 and 2).

The age of the Franciscan rocks in the basin is not well constrained because few fossils have been found. Those that have been found indicate an Cenomanian to Tithonian age (Cashman and others, 1995) (approximately 94 to 151 million years old using the USGS geologic time scale presented by Topinka, 2001). General descriptions of all the bedrock units within the watershed follow below in order of their occurrence along the roadway. The following descriptions are from NCWAP (2003).

17.250 – 18.359: Sandstone and mélange unit of Snow Camp Mountain (KJfsc) Central Belt Franciscan Complex: (note that there is a labeling problem on the milepost coverage as discussed earlier).

R18.359 – R21.659: Redwood Creek schist (KJfr) Eastern Belt Franciscan Complex: This unit is mostly light green to dark gray fine-grained foliated and crenulated (numerous small folds) quartz-mica schist and underlies the western half of the watershed from Lord Ellis Summit to the O'Kane Bridge. The unit is distinctive because of its strongly developed platy (metamorphic) textures and high quartz/mica content. The Redwood Creek schist and South Fork Mountain Schist seen in the Willow Creek section appear nearly identical at hand-sample scale. Several other types of rocks occur locally within the Redwood Creek schist, including meta-sandstone, greenstone (altered basalt) and tuff. Large variations in texture, composition and degree of deformation are seen within this unit (Cashman and others, 1995). Outcrops occasionally contain minor amounts of epidote, actinolite, lawsonite and graphite.

Large dormant landslide complexes and earthflows are common along the main channel of Redwood Creek and its western tributaries underlain by this unit. These features typically are seen as broad, bowl-shaped depressions in the hillsides that often extend from Redwood Creek to the ridge top.

The large features do not appear to be recently active from a geomorphic perspective, but rather contain occasional areas of localized activity. Careful field reconnaissance is necessary to evaluate the relative stability of specific areas on these slopes.

R21.659 – R23.209: Transitional rocks of the Grogan fault zone (KJfg) Eastern Belt Franciscan Complex: This unit is composed of phyllitic sandstone and mudstone with minor greenstone, metaconglomerate and exotic blocks of blueschist.

Metaconglomerates exhibit alignment, deformation and shattering of clasts. Grogan fault zone rocks are described as intermediate in texture and degree of metamorphism between the Redwood Creek schist and the sandstone and mudstone units (Harden and others, 1982). These rocks crop out along the trace of the Grogan fault and underlie much of the inner gorge of Redwood Creek. Most of the mapped near-channel debris slides along the inner gorge of Redwood Creek are found in this unit. Debris slides are the dominant mode of mass wasting and occur 400 to 500 percent more often in this unit than any other in the basin, based on CGS-NCWAP (2003) analyses. This predisposition to debris slides is tied to the presence of relatively weak rock within the unit and its location within the inner gorge.

Earthflows are also an important mode of transport within this unit, but the earthflows have probably started upslope of the Grogan fault zone in weak units and have simply flowed across the fault zone on their way to Redwood Creek.

R23.209 – R29.009: Incoherent unit of Coyote Creek (KJfc) Eastern Belt Franciscan Complex: The Coyote Creek unit consists dominantly of a fine-grained sandstone and shale assemblage that has been pervasively sheared into a mélange by tectonic processes. The Coyote Creek unit is further characterized by the presence of greenstone, chert and minor conglomerate. Greenstone blocks are found as “floaters” in pervasively sheared mudstone matrix. Soils developing on the bedrock are typically clay rich and highly susceptible to erosion and sliding.

Areas dominated by mélange generally form rounded hilltops with gentle slopes and poorly developed side hill drainages. Sharp-crested ridges with moderately steep slopes and well-defined drainage systems tend to develop where the upper edges of earthflow complexes meet. Intact tectonic blocks (usually sandstone) within the Coyote Creek Unit stand out from the surrounding landscape as steep-sided, rocky knobs that tend to be elongated in a northwest-southeast direction parallel to the structural grain.

Active earthflows are the main modes of mass wasting in the mélange matrix of the

Coyote Creek unit. Mélange matrix typically underlies the expansive grassland and lightly wooded areas present in the southeastern portion of the watershed. Well-developed gully networks are also common within the more active portions of these earthflow complexes.

Several large topographic amphitheaters along the east side of the watershed appear to have formed in the Coyote Creek unit over time from the long-term episodic action of numerous earthflows (Figure 3).

As in the case of the Redwood Creek schist, the amphitheaters do not appear to be active throughout their entirety, but rather contain areas of localized activity at any given time. Careful field reconnaissance is necessary to evaluate the relative stability of specific areas within the amphitheaters.

Such ”earthflow amphitheaters” appear to represent surfaces that have been created over time through the actions of thousands of small earthflows occurring throughout the amphitheater. This is analogous to the process that forms alluvial fans at the base of hillsides. Alluvial fans develop when watercourses exit hill-fronts and migrate back and forth across valley floors, depositing sediment as they go. The eventual result is a broad cone of sediment with its apex at the base of the hill-front. “Earthflow amphitheaters” form over time by material being removed from the system by earthflow activity, resulting in a broad, bowl-like slope.

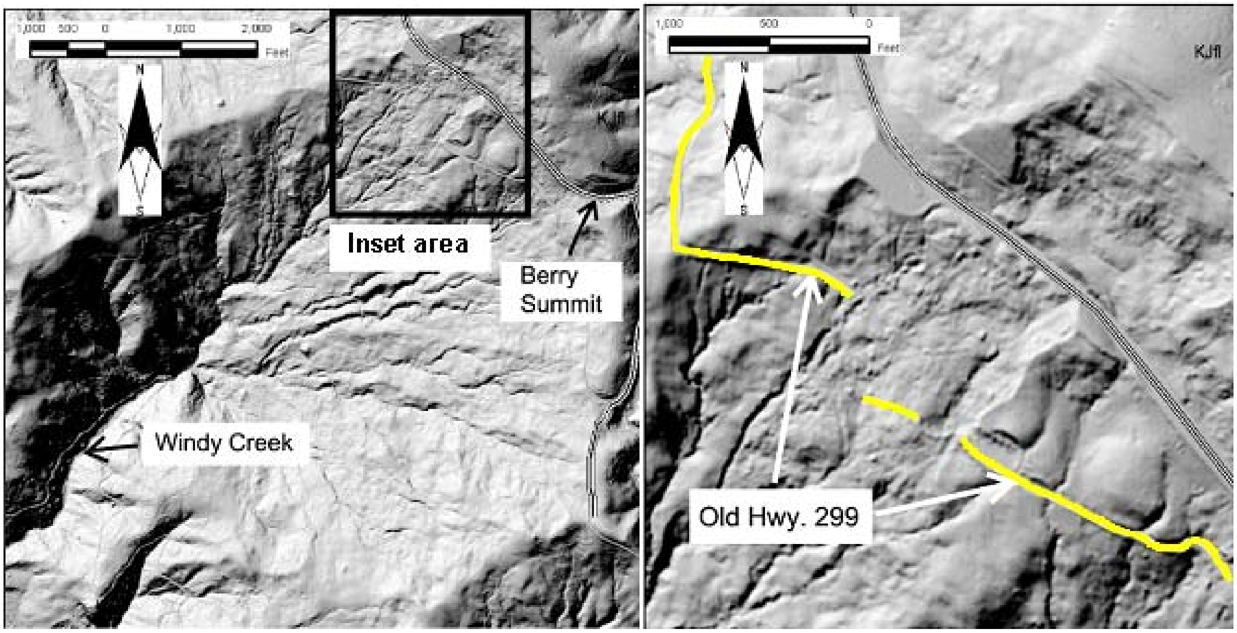


Figure 3, Earthflow amphitheater in Eastern Belt Franciscan Complex, Incoherent unit of Coyote Creek (KJfc). Inset shows sections of the old roadway of Highway 299 transported downslope by the earthflow.

A large earthflow complex in the incoherent unit of Coyote Creek forms the headwaters of Windy Creek (Figure 3). An active earthflow in the complex has progressively disrupted and displaced the old highway downhill several hundred feet at Berry Summit. Several sections of the old roadway are visible in the LiDAR image (Figure 3, Inset).

WILLOW CREEK R29.009 – R39.978

This portion of the alignment has the most variable mix of bedrock because major thrust fault systems have created repeated packages of rock (Plate 1, Sheet 2). Most of the rock descriptions in this section are from Young (1978).

R29.009 – R29.059. Incoherent unit of Coyote Creek (KJfc) Eastern Belt Franciscan Complex: This unit continues a short distance beyond the crest of Berry Summit as mapped by Harden (1982).

R29.059 – R30.578: Coherent unit of Lacks Creek (KJfl) Eastern Belt Franciscan Complex: This unit underlies the western edge of the Willow Creek watershed and consists of a resistant assemblage of sandstone and mudstone. Intact sections of interbedded sandstone and mudstone show rhythmic bedding and sedimentary structures characteristic of turbidites (repeating sequences of sandstone and siltstone deposited underwater by density currents). Sandstones are composed of lithic greywacke and quartzofeldspathic greywacke (Cashman et al., 1995). Massive sandstone beds are up to 10 m thick but are typically 0.1 - 3 m thick where interbedded with mudstone.

Topography characteristically is steep and rugged and contains many debris slide amphitheaters (steep, funnel-shaped drainages formed by numerous debris slides over a long period of time). Debris slides and occasional deeper landslides are the dominant modes of mass wasting. This unit is best seen along the alignment in the Mason Gulch and Low Gap Creek drainages immediately beyond Berry Summit.

R30.578 –R31.028: Incoherent unit of Coyote Creek (KJfc) Eastern Belt Franciscan Complex. See prior description.

R31.028 – R31.228: South Fork Mountain Schist (KJfs) Eastern Belt Franciscan Complex: The dominant rock is dark gray to green quartz-albite-muscovite-chlorite schist and has similar mineralogical characteristics to the Redwood Creek schist. It includes foliated greenstone and quartz-gneissic rocks. The surface expression is geomorphically variable. It has a well-developed foliation (platy texture), is fine-grained and typically has quartz veins oriented parallel to the foliation based on field examination of hand specimens and outcrop exposures. The dominant modes of mass wasting in this unit appear to be large, dormant landslide complexes, active earthflows, and large rotational landslides as seen along the highway alignment and elsewhere in the region. Most of these large features appear to be dormant at this time.

R31.228 - R31.528: Friday Camp gneiss (gn): This is a weakly foliated hornblende-diorite gneiss. The dominant modes of mass wasting in this unit are large rockslides and debris slides as seen along the alignment and elsewhere in the region. Most of these large features appear to be dormant at this time. Young (1978) mapped foliation planes dipping to the east and northeast. This foliation does not appear to be strongly developed enough to create a preferred failure direction.

R31.528 – 31.578: Willow Creek Pluton (wc): The Willow Creek Pluton is coarse granite composed almost entirely of crushed and altered quartz and feldspar. Young (1978) maps the contact of this unit as extending from the north side of the Willow Creek canyon and pinching out under the roadway. A large rockslide underlies the south side of the canyon here, so the presence of the Willow Creek Pluton near or under the roadway is unclear.

R31.578 – R31.628: Rogue Formation (Jr): The Rogue Formation cosists of mafic (high in magnesium and iron) to intermediate volcanic flows and tuffs that have been altered to greenstone. Some volcanic conglomerates are reportedly present in the upper portion of the unit. This unit appears to be relatively competent. Young (1978) mapped foliation planes dipping to the east and northeast along the Willow Creek canyon. This foliation this does not appear to be strongly developed enough to create a preferred failure direction. Several mature rockslides were mapped in this unit, but they do not directly affect the roadway. Based on the topographic expression of the unit, the dominant mode of mass wasting appears to be debris sliding. Most of the large landslide features appear to be dormant at this time.

R31.628 – R32.078: Undifferentiated Ultramafic rocks (ps): This unit is dominated by a single, large, old dormant rockslide that underlies the roadway for a distance of approximately 4,600 feet. The slide, which is approximately 3,200 feet wide and 6,200 feet long, is one of the largest along the highway corridor. The feature is heavily modified by erosion and appears to have been dormant for a very long period of time.

R32.078 – R32.128; R32.578 - R32.628: Small igneous plugs, dikes and sills (i): Only the largest masses were shown on the map. The unit stands very steeply and appears to be competent because no significant mass-wasting features were observed in the small area it occupies south of the road.

<u>R32.128 – R32.428: Rogue Formation (Jr):</u> A possible member of the Rogue Formation underlies this section. It is a greenstone composed of altered volcanic flows, tuffs and volcanic conglomerates. See prior description.

<u>R32.428 – R32.8; R32.628 – R34.478: Galice Formation (Jg):</u> This is a gray, silvery phyllitic metagraywacke, slate and phyllitic slate (see Figure 4). Numerous exposures along stream channels show graded bedding. Scattered metamorphic-felsite dikes and sills intrude the unit. Areas underlain by slate and phyllitic slate are described as especially subject to slope failure. Young (1978) mapped foliation planes dipping steeply to the north-northeast at 35 to 50 degrees. Three large rotational landslide complexes occupy east facing slopes in this unit. These failures appear to be structurally controlled. West facing slopes tend to be very steep and the occupied by debris slides and smaller rotational landslides (Figure 4). One relatively young rockslide centered between mileposts 35.6 and 35.8 has the potential to block the roadway should it move significantly. The toe of this feature has several active debris slides on it and is being actively eroded by the creek.

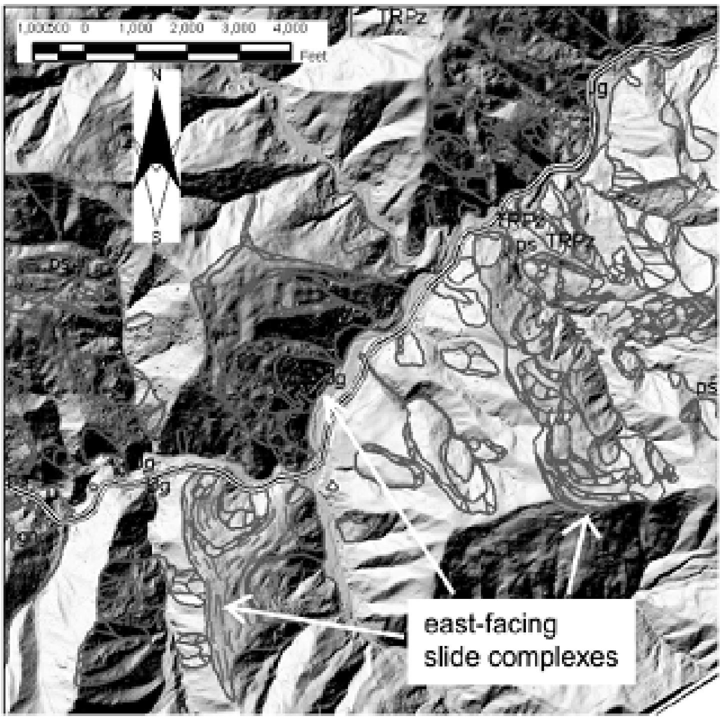


Figure 4, Landslide complexes in the Galice Formation.

<u>R34.478 – R34.978: Western Paleozoic and Triassic belt mélange (TRPz):</u> The unit consists of fine-grained volcanic rocks, fine- to medium-grained greywacke, chert and siliceous argillite, lenses of serpentinite, local limestone and conglomerate and small

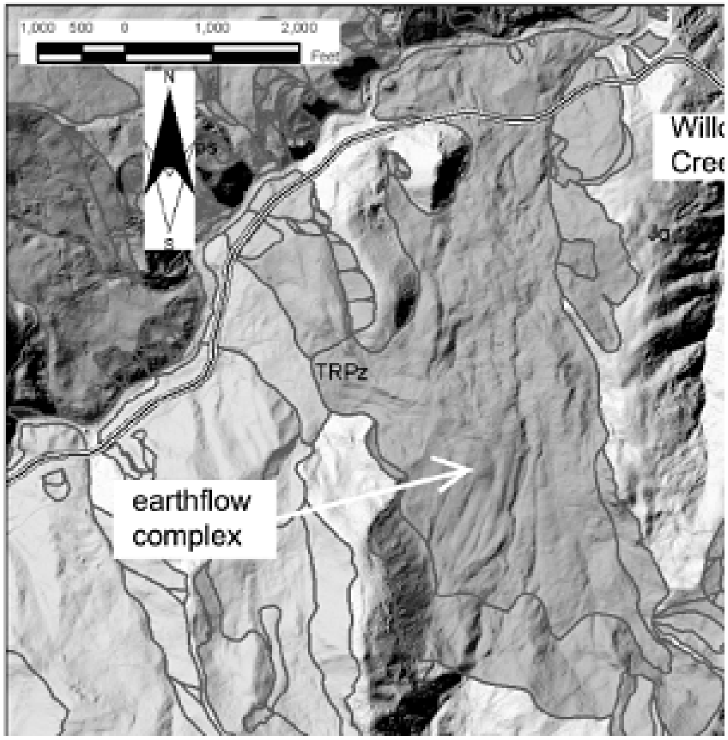


Figure 5, Earthflow complex in the Western Paleozoic and Triassic belt mélange (TRPz),.

intrusive igneous bodies. Individual rock units are discontinuous. The unit appears to fail initially as large, deep-seated rockslides and earthflows, and subsequently fails as smaller debris slides and rockslides where they toe out into Willow Creek.

The largest earthflow complex in the study area (Figure 5) occurs in this unit and crosses the roadway between mileposts R37.128 and R37.328. The main body of the earthflow is 1,000 to 2,200 feet wide and 8,000 feet long. Young (1978) mapped several much larger slides north of the river, but they fall largely out of the study area. The toes of these slides are moving into Willow Creek as a pair of active rockslide complexes between mileposts 36.0 - 36.2 and 36.7 – 36.9. These will threaten the roadway if they encroach into the Willow Creek channel, forcing the channel against the south bank.

R34.978 – R35.678: Galice Formation (Jg)

R35.678 – R36.178: Western Paleozoic and Triassic belt mélange (TRPz)

R36.178 – R36.778: Undifferentiated Ultramafic rocks (ps)

R36.778 – R37.278: Western Paleozoic and Triassic belt mélange (TRPz)

R37.278 –R38.678: Galice Formation (Jg)

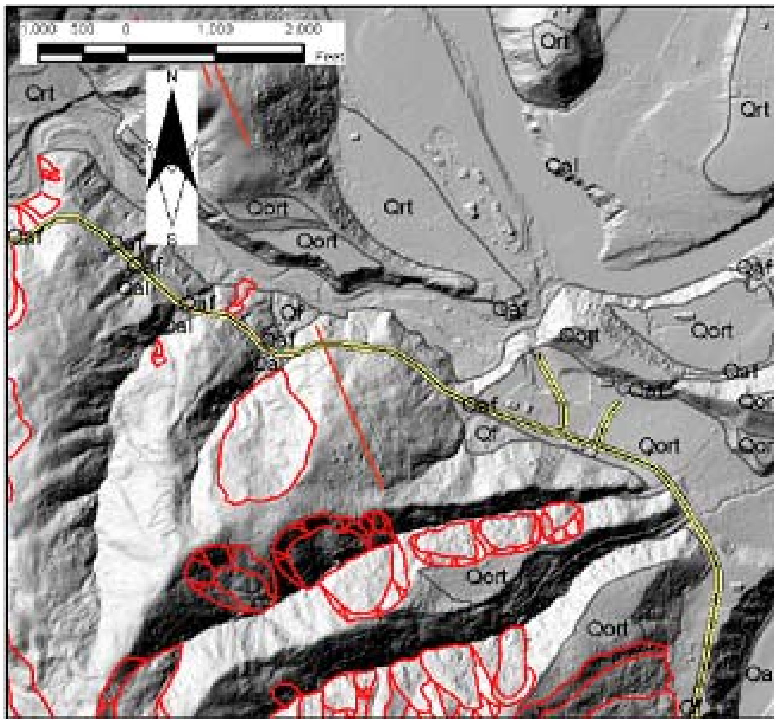


Figure 6. Older River Terraces (Qort) along Willow Creek and the abandoned older channel of Willow Creek.

R38.678 - R39.978: Older River Terraces (Qort atop Jg): These deposits consist of interbedded boulders, cobbles, gravel, sand, silt and clay underlying uplifted river terraces eroded into bedrock (Figure 6). The surface represents the ancient channel of Willow Creek before it cut through the bedrock platform at the Highway 96 bridge and abandoned its old course. The high level of debris slide activity along the Willow Creek canyon suggests that this channel may still be down cutting as it tries to reach equilibrium with its surroundings.

LANDSLIDES

More than 1,600 features related to mass wasting were mapped in the study area between Blue Lake and Willow Creek. These landslides tend to be the larger, deep-seated slides that affect large areas. Although we have attempted to show all landslides, there probably are many small shallow slides that fall below the resolution of the DEM or are obscured by thick forest cover and could not be seen in the aerial photographs. The relative resolution of LiDAR is slightly higher than that seen in some of the low altitude (1: =1,000’) aerial photographs used for mapping portions of the highway corridor. However, the issue of dense vegetation obscuring the ground surface remains. Accurate and precise location of landslide features is difficult in densely forested terrain. Without LiDAR, accuracy and completeness of landslide identification and location requires extensive detailed on-ground field mapping. The location issue is magnified if time and funding are limited. Although the LiDAR data made possible the preparation of a much more detailed and accurate landslide map than would have been possible using aerial photos alone, the accuracy and level of detail is still less than is achievable in unvegetated or grassland terrain.

The landslide map (Plate 1) was prepared by interpretation of the DEM shaded relief images augmented by aerial photograph evaluation, the review of previous reports and limited field reconnaissance. Landslides depicted on previously published maps were compared with those landforms seen on the Lidar images and aerial photos. Landslide boundaries from previous work were revised and additional landslides were added based on geomorphic interpretation.

Landslides are classified and mapped based on their geomorphology. Landslides form distinctive topography depending on their mode of movement. The resulting landforms show the extent and characteristics of the landslide. Recognition of these landforms (scarps, troughs, benches and other subtle topographic features) enables geologists to recognize, map and classify most landslides.

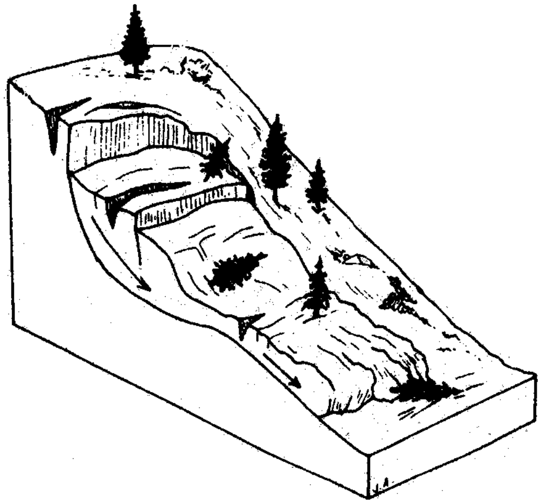
The characteristics of the slide are recorded, generally following the recommendations of Wieczorek (1984). Portrayal of landslides on the maps includes a symbol, which designates the type of slide (materials and type of movement). The color of the slide area signifies its level of activity, and the thickness of the outline signifies the confidence of interpretation as described below.

Types of landslides

Each landslide is classified according to the materials involved and the movement type, as interpreted 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 create a series of names that closely describe the dominant materials and processes involved in a landslide. The terms and definitions of Cruden and Varnes are simplified by listing only the primary classification of a given landslide. For example, the example diagram of a rockslide, (see following section), is a rotational rock slide/flow in which the upper part of the feature has moved by sliding, but the lower part has disaggregated and is flowing like a very viscous fluid. On this map this type of slide is shown simply as a rockslide. The various vague and overlapping meanings of “rock” and “soil” in common usage also complicate use of the Cruden and Varnes system. 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. In this report, the 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 pervasive tectonic shearing and landsliding have destroyed its original rock fabric in many places.

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

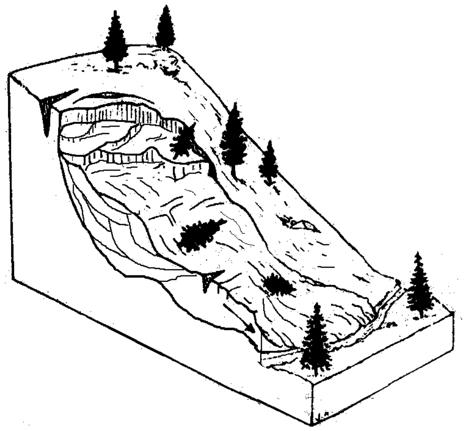


ROCK SLIDE: A slide involving bedrock in which much of the original rock structure is preserved. Zones of weakness such as bedding planes, joints and foliation, usually control the strength of the rock. Movement occurs primarily by sliding on a narrow zone of weakness as a relatively intact block. Typically, 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 referred to as slumps, while those with planar failure surfaces are called block glides.

Rock slides commonly start on relatively steep slopes in competent rocks. Slopes are commonly from 35 percent to as steep as 70 percent. Movement of an intact rock mass along a curved slide plane leads to a steep head scarp at the upper boundary of the slide. Immediately below the head scarp is a block or bench that is commonly rotated so that it is less steep than the surrounding hill slopes. 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 slides may bulge outward in a lobate form 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 in aerial photographs is aided if the accumulated water leads to significantly different vegetation, especially phreatophytes (water loving vegetation) in such areas. The improved water holding capacity of these areas also decreases the overall stability of the slide mass by providing 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 a slope or the addition of fill to an upper slope also tends to reduce the stability of 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.

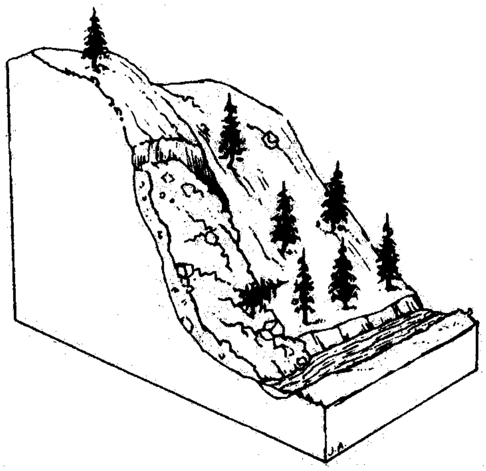


EARTH FLOW: A landslide composed of a mixture of fine-grained soil, consisting of surficial deposits and deeply weathered, disrupted bedrock. The material strength is low through much of the slide mass, and movement occurs on many discontinuous shear surfaces throughout the landslide mass. Although the 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 pervasively disrupted rock units. Slopes are commonly from 10 percent to as steep as 30 percent, 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 commonly are rotated so they are less steep than the surrounding hill slopes. 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 that sometimes holds closed depressions. These areas may accumulate and hold water more than the surrounding slopes as discussed above.

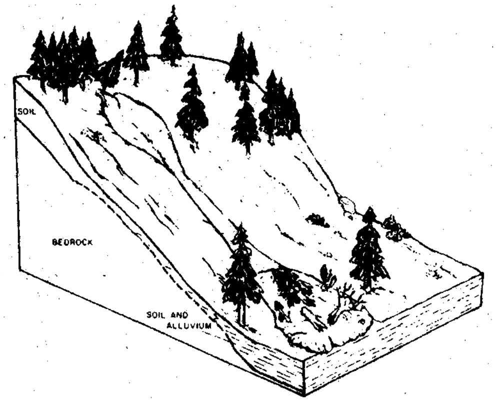
Earthflows are sensitive to conditions that affect the entire slope and to disturbances of any part of the slope. A rise in the water table that may occur in high rainfall years may decrease the overall stability. High water pore pressures, typically following a sustained period of heavy rains, may trigger earth flows, which then may continue to move for a period of days to weeks. Undercutting of the base of a slope or the addition of fill to an 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, often as steep as 60 percent to 70 percent, 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 shallow amphitheater shape of many scars as well as their even steep slopes.

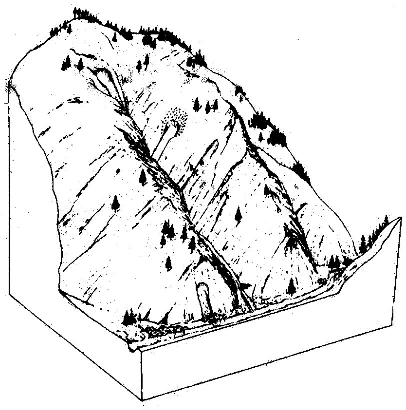
Because debris slides are relatively shallow, they are sensitive to changes that are smaller in magnitude and may occur over shorter times than those that affect deeper slides. A single heavy rainstorm or series of storms may deliver enough rain to trigger debris slides. Individual debris slides may move at rates ranging from meters per day to meters per minute. Debris slide scars are sensitive to renewed disturbance because they are extremely steep. Natural erosion at the base of debris slide scars may trigger additional slides. Cutting into the base of a debris slide scar may also trigger renewed slides. Even without additional disturbance, debris slide scars tend to 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 down slope as a slurry. Material involved commonly is 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 down slope.

Debris flows often begin as relatively small (several tens to hundreds of cubic yards) slides of shallow masses of soil and weathered rock. Once initiated, they may “bulk up” and collect material from the bed and banks of the channel they flow down by mechanical scour (Corominas, 1995; Robison, E.G., et al., 1999). Deposits can sometimes be tens of thousands of cubic yards as a result. Their distinctive signature in the landscape is the scar and runout track left by the slide. The path of a debris flow often is marked by a riparian zone that has been stripped of vegetation and soil down to bedrock. The debris flow may not leave any deposit if it empties into a large enough watercourse and is immediately eroded away. Debris flow deposits often are ephemeral, but in some cases numerous debris flows may deposit material in the same area creating a debris fan, which resembles a small, relatively steep alluvial fan.

Debris flows are sensitive to relatively short, intense weather phenomena because they are shallow. Debris flows are especially sensitive to rapid increases in the water level in slopes. They are triggered under natural conditions by factors that increase the pore pressures in the shallow subsurface, commonly at the soil - bedrock contact. A single heavy rainstorm or series of storms may deliver enough precipitation to trigger numerous debris flows. Individual debris flows may move at rates ranging from meters per hour to many meters per second. Construction and land-use activities that may concentrate water on steep slopes must be carefully designed to avoid increasing the potential for debris flows.

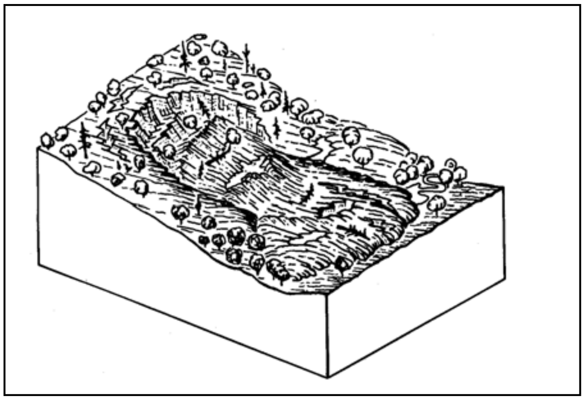


DEBRIS SLIDES and DEBRIS FLOWS are commonly found on, and help create, a landform called a **DEBRIS SLIDE SLOPE**. The overlapping scars of numerous debris slides have sculpted this type of topographic feature over a long period of time. The scars and slides are usually too small to depict on a map of this scale. These landforms are generally very steep, and have developed in areas of relatively competent bedrock mantled with loose, thin soils. Vegetation can be patchy and thin depending on the level of slide activity.

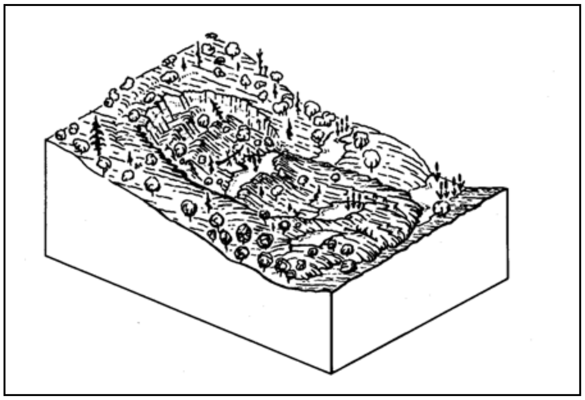
Debris slide slopes typically are very steep, 60 percent and steeper is common. Very steep slopes characterize areas in which the dominant form of erosion is by debris slides and debris flows, commonly with each small canyon having rounded amphitheater-shaped heads. Mason Gulch is one example noted in the study area.

Activity of landslides

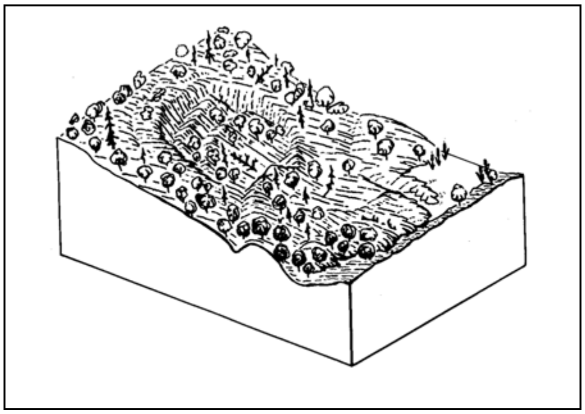
Landslide activity is classified based on its geomorphic "freshness" into one of four categories based on the system of Keaton and DeGraff, (1996). The diagrams below illustrate levels of activity (diagrams from Wieczorek, 1984).



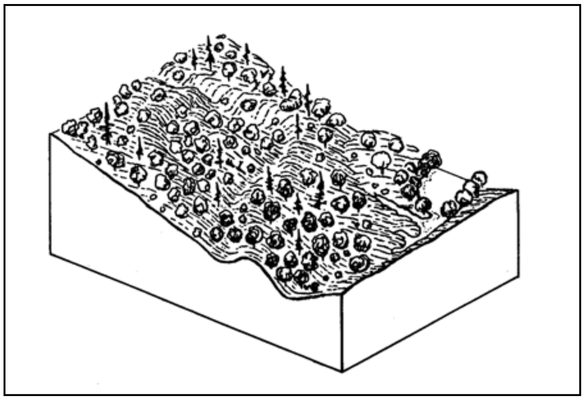
Active or **historic**: The landslide appears to be currently moving or movements have been recorded in the past. Fresh cracks, disrupted vegetation or displaced or damaged man-made features indicate recent activity. Water may pond in depressions created by rotation of the slide mass or blockage of stream 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 generally are 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 head scarp, benches and hummocky topography are now mostly rounded and subtle. Closed depressions or ponds have been breached or filled. Vegetation has recovered and mostly matches the vegetation outside the slide boundaries.

Confidence of Interpretation

Confidence of interpretation of each landslide is classified as definite, probable or questionable. Because landslides are mapped based on their landforms, the confidence of identification is dependent on the clarity and freshness 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 down slope movement.

PROBABLE LANDSLIDE. Some 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 down slope 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 imply the occurrence of mass movement.

Each landslide also is 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 noted in Table 1, Shapefile Database Attributes.

FIELD	**VALUES**	**NOTES**
ACTIVITY	H, Y, M, O	Historic, young, mature, old per Cruden and Varnes (1996)
CONFIDENCE	D, P, Q	Definite, probable, questionable
INITIAL_MVMT	RS, EF, DS, DF, DSS	Initial movement mode: rock slide, earthflow, debris slide, debris flow, debris slide slope
DIR_MVMT	Value	Direction of movement by azimuth
DEPTH	S, M, D	As interpreted from the geomorphology and classified into one of the following three categories: shallow <3 m (10 feet), medium 3-15 m (10 to 50 feet), deep >15 m (>50 feet).
SCARP_DEP	S, D	Scarp or deposit. Scarp areas were mapped as discreet entities.
SYMBOL	H, Y, M, O	Historic, young, mature, old per Cruden and Varnes (1996)
PHOTO_YR	Value	Aerial photographs
QUADRANGLE	Name	USGS 7.5 minute series name
AREA	Value	Calculated by ArcMap
ACRES	Value	Calculated by ArcMap
PERIMETER	Value	Calculated by ArcMap
LIDAR_ID	Y, N	Was LiDAR primary source of identification?
Comments		
CONFI_LBL	D, P, Q	Confidence label: definite, probable, questionable
SOURCE		Source of geologic data: LiDAR, aerial photograph, reference of previous geologic map, THP report, field reconnaissance
SOURCE_YR		Not used

Table 1. Shapefile Database Attributes

LIDAR DATA ACQUISITION

Several of the highway corridors mapped for CalTrans by the California Geological Survey are in the densely wooded northern Coast Ranges. Mapping landslides in heavily forested terrain can require an extraordinary effort to recognize landslides by field methods. In many cases where the time and money for mapping are limited, the resulting maps are less complete and less accurate that those in un-forested land. This is because landslides are mapped based on their geomorphology. The distinctive landforms created by landsliding must be recognized on aerial photographs, topographic maps, or in the field. In heavily forested terrain, neither aerial photos nor photogrammetrically-prepared topographic maps depict the ground surface. Photos, of course, show the tops of the trees, but topographic maps also are prepared from photos showing the tops of the trees, with some assumption of tree height factored in so ground elevations can be approximated. The typical reconnaissance techniques are less effective, resulting in either extra effort being spent on the ground or a less accurate map being produced. Work on the first corridor, along Highway 101 in Del Norte County (Wills, 2000) also made it apparent that the 1:24,000, 7.5 minute topographic maps, and more detailed photogrammetric maps obtained from CalTrans, contained substantial errors and did not show many of the landforms related to landsliding. It was anticipated that the Highway 299 corridor would be difficult and time-consuming to map accurately at the scale requested by CalTrans.

Recognizing the difficulty in preparing an adequate landslide map with traditional techniques, the potential for LiDAR to acquire a more detailed and accurate image of the ground beneath the forest was investigated. LiDAR, light detection and ranging, uses a system that is essentially a laser rangefinder, which pulses rapidly and scans an area from an aircraft. Airborne GPS and inertial navigation on the aircraft allow for the precise location of each reflection off of the ground or other surfaces. A computer system can “filter” the distance measurements, retaining those that reach the ground and rejecting reflections from trees. The result can be detailed digital elevation model (DEM) of the treetops, or of the ground surface (Figure 7). The DEM can be processed in a Geographic Information System (GIS) to make a traditional topographic contour map or a shaded relief map to aid interpretation. The DEMs can be much more detailed and more accurate than either the available UGSS topographic DEMs or photogrammetric topographic maps.

In developing specifications for a LiDAR survey, it was learned that in order to obtain the amount of detail desired for landslide mapping - the level of detail typically found on

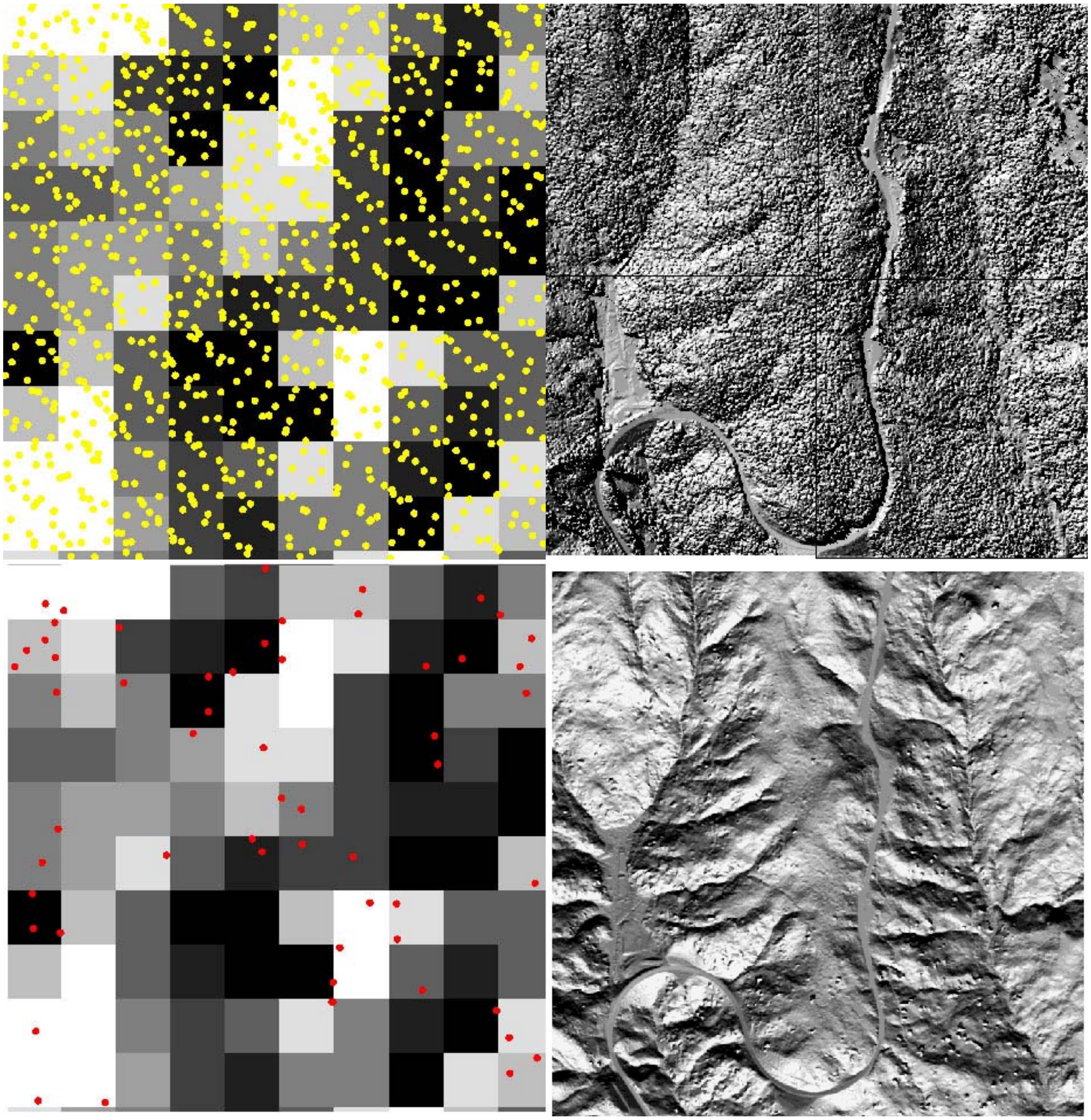


Figure 7. Comparison of laser reflection “first return” points in a 100 foot square area (top left) with points interpreted to be “bare earth” reflections (bottom left). Processed shaded relief images of a 2 km square area show the topography that can be calculated from the first returns (top right) and from the “bare earth” reflections (bottom right).

a topographic map with a 10-foot contour interval - a DEM with a minimum 10-foot pixel size would be required. All LiDAR vendors contacted indicated that the precision of the LiDAR point locations would be well under 1 meter, which is better than needed for a map of the scale specified. Caltrans requested that CGS obtain LiDAR surveys from more than one contractor. The draft contract asked for separate bids on the western part of the Highway 299 corridor (Area A), and the eastern part of the Highway 299 corridor (Area B).

Contracts were finalized in March, 2002 and the surveys flown in May, 2002. One contract called for coverage of Area A, while the other called for coverage of Areas A and B. Finished products were received from both contractors for Area A, and complete coverage of the corridor from one contractor. Both contractors delivered data samples as xyz points in ASCII format and processed all the data into first return and bare earth DEMs. CGS specified data in xyz format and the processed DEMs in order to evaluate the differences between the data sets from the two vendors. For this analysis, CGS examined the density of bare earth reflections and processed the xyz data using Arc View Spatial Analyst to obtain a bare-earth DEM (Figure 7). Subsequent evaluations compared the bare earth DEMs prepared through Arc View with those supplied by the vendors, and with what was considered a realistic depiction of the ground surface.

COMPARISON OF DEMS

The initial evaluation of the DEMs from the xyz data and from the vendors consisted of a visual evaluation of three different views of the DEM. Maps of the data were visually inspected to check how well the vegetation had been filtered out of the DEMs. Although the figures included here show the slope maps (Figure 8), the differences are inherent in the DEMs and can also be seen in the shaded relief and contour maps. Four “bare earth” DEMs wre reviewed, the two delivered by the vendors under the contract and two that CGS prepared from the contractors’ “bare earth” reflections delivered as points with xyz coordinates. This comparison enables us to look at the density of the point data acquired by the two vendors and to compare the results of the processing by the

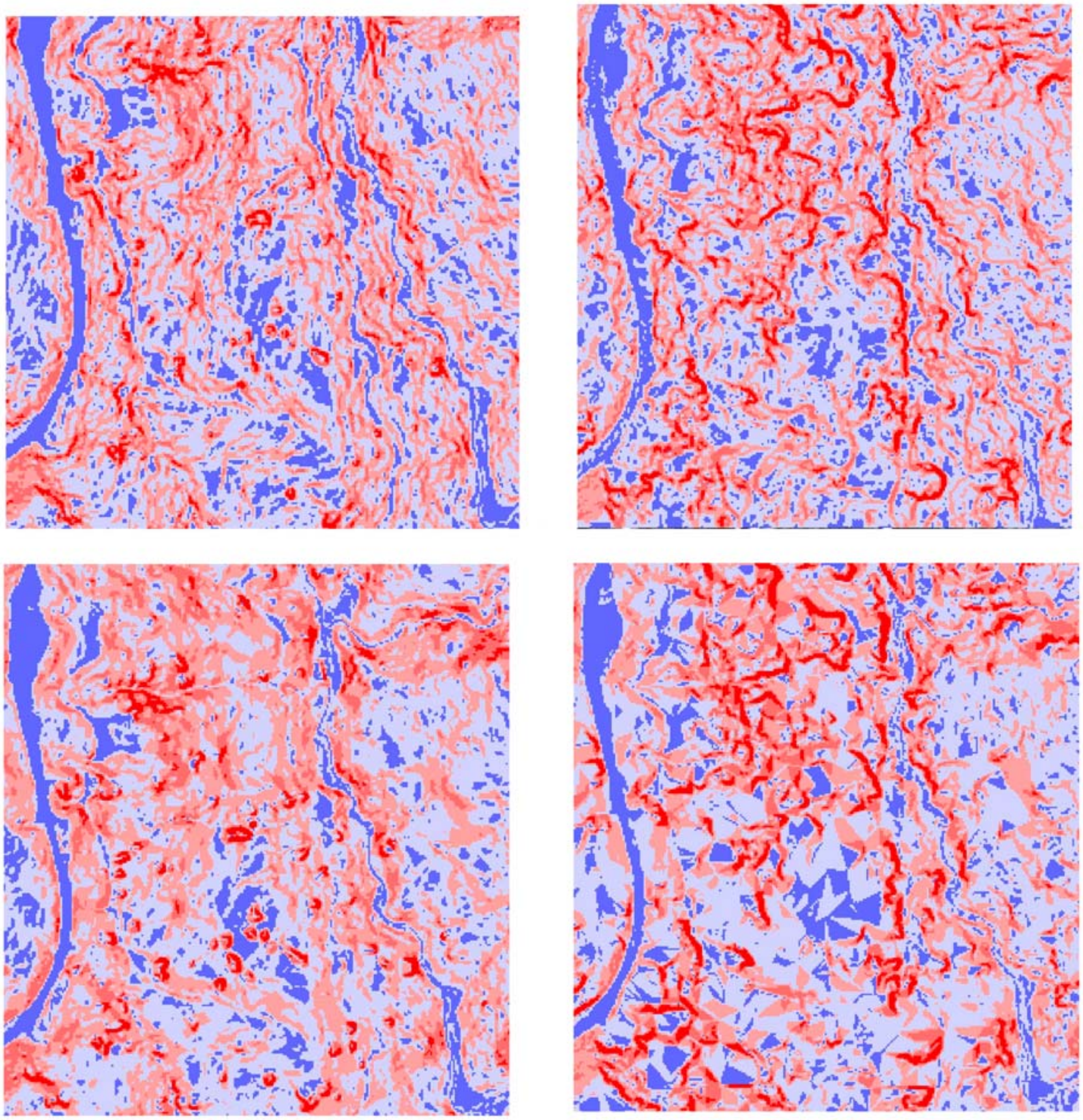


Figure 8. Slope maps of a part of the Highway 299 corridor showing the differences between DEMs processed through Arc View (top) and by the LiDAR vendors (bottom) and between the results of "bare earth" data from the two vendors. Note the north south banding (parallel to slope) in the DEMs processed through Arc View, suggesting a terraced pattern in the DEM. Also note the large triangular facets in the DEM processed by one vendor (bottom left).

vendors with the results of the default processing provided with Arc View Spatial Analyst.

The DEM created from the raw data through Arc View is somewhat rougher in forested areas than in areas that had been clear-cut, indicating that the relatively sparse ground reflections from heavily forested areas does affect the quality of the DEM. It is also apparent from the slope map that most slopes appear to have alternating steeper and gentler slopes, almost a terraced appearance. This terraced appearance does not look natural, it is likely to be an artifact of the processing method. Since this terraced appearance is seen in the data from both vendors is is likely to be an artifact of the default processing method in Arc View Spatial Analyst. The point data from one vendor did not record nearly the number of “bare earth” reflections per area as the other vendor, particularly in densely vegetated areas. The result of fewer point data used in the DEM is a much rougher appearing surface, as visualized as either a shaded relief map or as a slope map (Figure 9).

The DEMs received from the vendors showed neither the smoother appearance in clear-cut areas nor the terraced appearance. Apparently the vendors’ processing did not generate the same artifacts as Arc View’s default methods. The LiDAR DEM from one vendor shows areas containing blocks of many small triangular facets, 10 to 40 feet on a side, that project above the adjacent smoother ground surface. Several of these features were field checked, and were dense clusters of large trees. In processing the LiDAR data to remove all but the “bare earth” reflections, the vendor evidently was not able to remove all of the reflections from the vegetation in these areas. The DEM therefore is not completely free of artifacts. Interpretation of any depiction of the DEM must account for the possibility that the DEM does not uniformly depict the ground surface. These blocks however, are relatively easy for a geologist to ignore in interpreting the geomorphology.

The DEM from the second vendor did not show these blocks, but did show areas where the DEM was made up of large triangular facets. Some individual facets were over a hundred feet on a side. Examination of the xyz data provided by this vendor revealed that large triangular areas that had single “bare earth” reflections at the corners typified the DEM in the most densely forested areas (Figure 9). As a result, the “bare earth” DEM from the second vendor was very difficult to interpret and was not used in preparing the landslide inventory maps. Fortunately, the first vendor provided the DEM for the entire Highway 299 corridor and the more useful DEM were employed in the interpretation and landslide mapping.

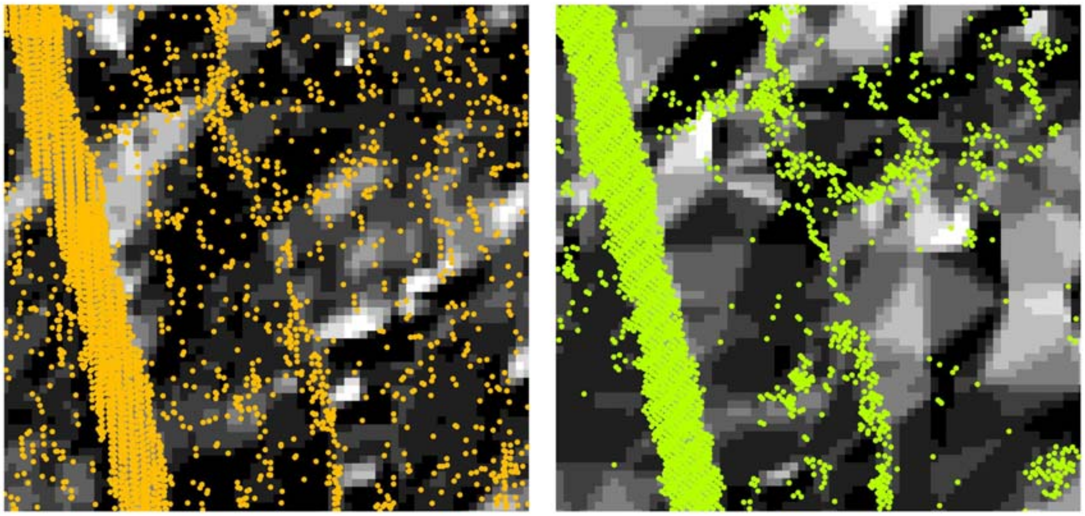


Figure 9. Comparison of the density of “bare earth” reflection points from the LiDAR surveys by two vendors for a part of the Highway 299 corridor including the highway (wide band of dense points at left), a trail or old logging road (thin band of points in center) and dense forest (sparse points in right center). Area of view is approximately 670 feet across, 10-foot pixels are from shaded relief images from the DEMs by the two vendors. Note how the sparse points in the image on the right and their processing leads to triangular facets that are up to 100 feet across in the densely forested area.

INTERPRETATION OF LANDSLIDES FROM LIDAR DEMS

The three-dimensional DEM surface can be displayed and analyzed in various manners to map landslides. In this study, the “bare earth”, DEM was used to interpret the landforms that may be related to landsliding. The LiDAR DEMs are much more detailed and more accurate than the USGS topographic map-based DEMs and similar maps developed using traditional photogrammetric methods. Figure 10 compares shaded relief images of two portions of the project area based on DEMs from the LiDAR survey and the USGS topographic maps. Model “illumination” is from the upper left. The greater detail visible in the images based on the Lidar DEMs is apparent. Additionally, there is a marked change in the images based on the USGS DEM across the boundary between the Blue Lake and Lord Ellis Summit 7.5 minute topographic maps. This

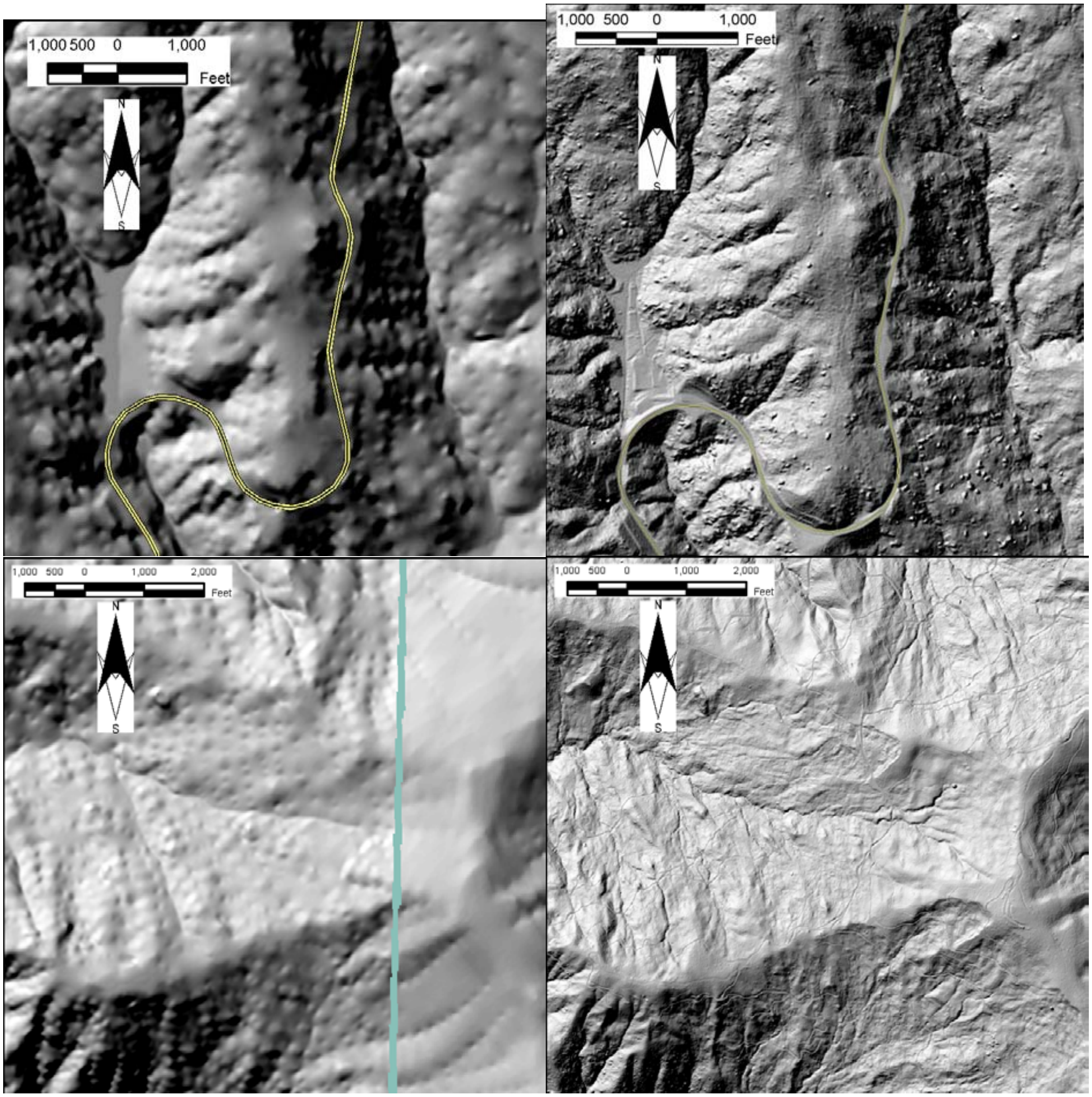


Figure 10: Comparison of shaded relief images from 10m USGS DEMs (left) and from the LiDAR DEM (right) for the Pine Creek (top) and Pollock Creek (bottom) areas.

difference is shown on the bottom left image in Figure 10 for the Pollock Creek area. The blue line marks the boundary between the quadrangles, and also a small gap between the DEMs. The difference within the USGS DEM of this area appears to be the result of the original 1970's topographic maps that were used to develop that DEM. Both maps have a contour interval of 80 feet, but the topography on the Lord Ellis Summit quadrangle appears to be generalized and smoothed compared to the adjacent Blue Lake quadrangle. The smoothing was likely introduced during the initial map editing process. The smooth, generalized appearance of the topography on the Lord Ellis Summit quadrangle makes interpretation of landslide-related geomorphology more difficult.

Slope maps showing the angle of slope between the elevation points were prepared from the DEM, (Figure 11). A DEM tool provided with ArcMap 8 produces images in a variety of formats. Images showing average slopes in green, steeper than average slopes in shades of red and gentler than average slopes in shades of blue were found to be simple to interpret visually. The colored image provides geologists additional information to help pick out some of the geomorphic features related to landsliding.

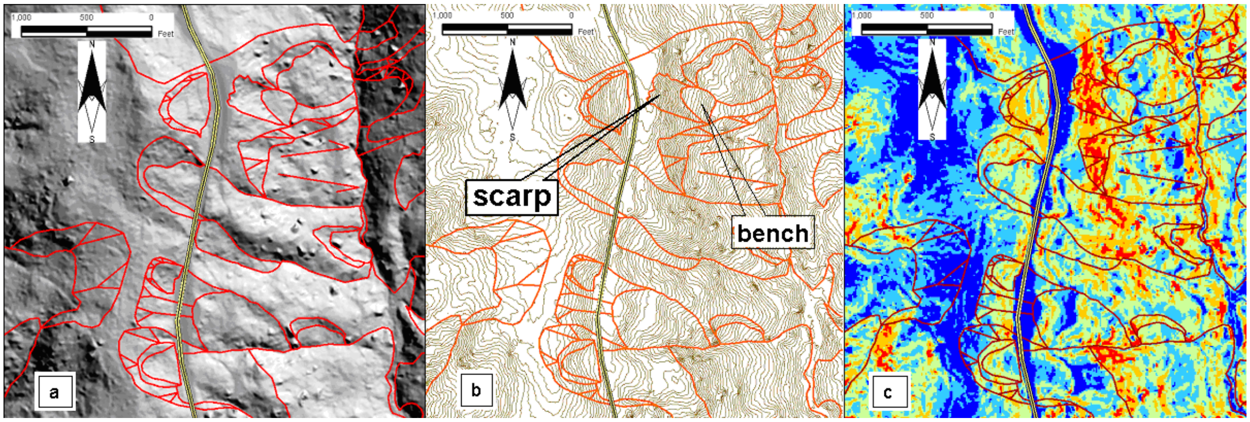


Figure 11. (a) Shaded-relief; (b) contour; and, (c) slope maps of a part of the Highway 299 corridor showing how some representative landslide features are expressed in those maps. Red outlines on the maps are mapped landslides as indicated by the features labeled on the contour map.

Topographic maps with a 10-foot contour interval were also generated from the DEMs. Compared to the level of detail shown the detail shown in the current 7.5-minute topographic map available from the USGS, these contours provide much more detail. Therefore landslide-related topography is much more readily apparent (Figure 12).

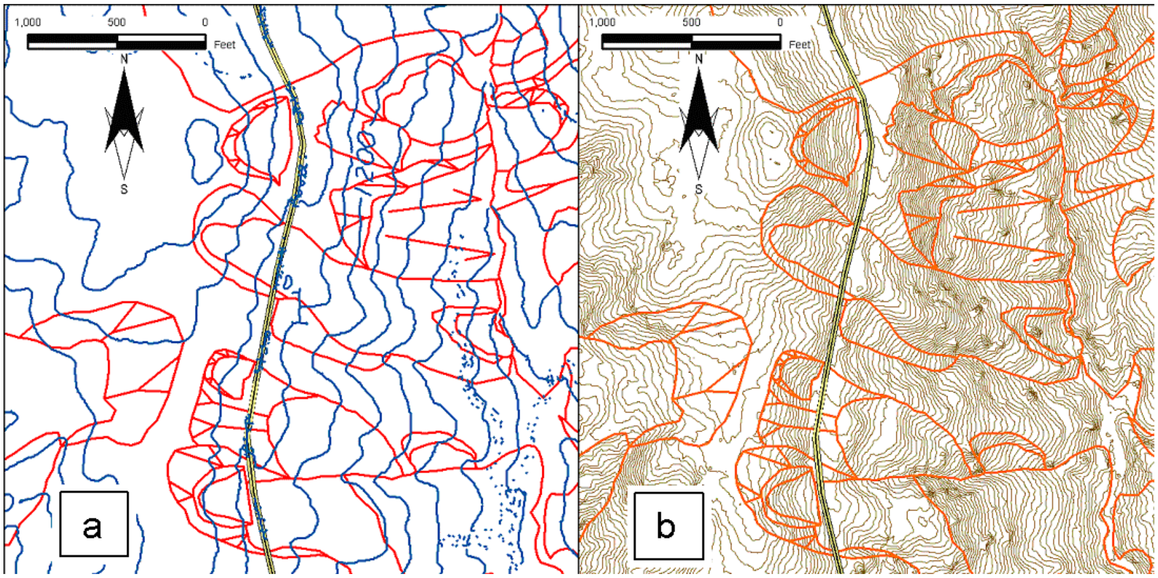


Figure 12. Comparison of USGS photogrammetrically derived topographic map with 80-foot contour intervals (a) and LiDAR-derived topographic map with 10-foot contour intervals (b)

Geomorphic features suggesting landslides are evident each of the three views of the DEM (Figure 11). The shaded relief, contour and slope maps all show features suggesting landslides and were used individually and in combination to map landslides in considerable detail.

This method of identifying landslides is similar to photogrammetric techniques using aerial photos as the basis of the mapping. Geologists typically will evaluate as many sets of aerial photographs as possible in an effort to view the study area at a variety of scales in different years and different times of year (varying sun angles) in order to identify subtle changes in the topography that may indicate the presence of landslides. Land use patterns and dense vegetation are the biggest impediment to the interpretation of the landscape and the best interpretations can be made if the site in question has recently been cleared of vegetation through the action of fire, development, or timber harvest.

LiDAR has the advantage of not containing significant vegetation or land-use patterns that create visual “noise” for the observer. The effect of these shaded relief maps is to provide a view of the ground surface as if all the vegetation had been removed from the surface. The landforms on the shaded relief images are interpreted from the same patterns of sunlight and shadow seen in aerial photographs, with the difference that if the lighting is not well oriented to highlight a particular feature on one image, the geologist can “move the sun” by changing the direction and angle of the lighting and create another image that better portrays the feature of interest. The scale of the image is easily manipulated by zooming in and out. Large features can be mapped by panning across the image as one maps. A significant advantage is that the mapping is done directly on the screen in “heads-up” mode. Landslides also can be mapped to the limit of DEM resolution (10 feet, or approximately 3m for this project), thereby minimizing the amount of potential mapping error introduced when transferring data from aerial photograph overlays or paper maps into the GIS.

The colored slope maps visually assist in landslide identification by highlighting those slopes that are steeper or gentler than the surrounding slopes. Steeper slopes, when juxtaposed with gentler slopes may represent landslide scarps with adjacent benches formed by the slide mass. Topographic maps help to highlight the same features of steeper and gentler slopes in a more traditional format that geologists and engineers are more familiar with. This more traditional format allows a quick check of the geologist’s geomorphic interpretation by users less experienced with colored slope maps and shaded relief images.

The maps in this report are presented at a scale of 1:12,000 (1 inch = 1000 feet). These maps were prepared using a computer geographic information system (ArcMap 8.0 GIS). Portions of the Blue Lake, Lord Ellis, Willow Creek and Salyer quadrangles form the initial bases for Plates 1 and 2. The landslide maps include attribute tables containing factors such as relative age (per Cruden and Varnes (1996), mode of mass-wasting and approximate depth of slide deposit (see Table 1, Shapefile Database Attributes). Landslide head scarps and source areas were also mapped separately whenever possible.

Test Area Comparisons.

Three CGS geologists mapped the same five square mile area along the Highway 299 corridor to compare the numbers, types, and sizes of landslides interpreted from the LiDAR DEMs with those that could be interpreted from aerial photographs (Figure 13). Each geologist used aerial photographs, existing topographic maps at a scale of 1:24,000, and USGS 10 m DEMs to interpret the area without using the LiDAR data. This effort was intended to produce landslide maps using methods similar to others produced by CGS. For the second phase of the study, each geologist used the LiDAR shaded relief images with several illumination directions to interpret landslides in the test area that they had previously mapped using aerial photos.

Figure 14 shows a portion of the final map. The geologists re-examined some of the aerial photographs for the area, compared their LiDAR mapping and evaluated selected landslides on-screen using several hillshade DEMs to clarify the features of interest. They also compared the level of confidence they had for individual slides. Apparent “false positives” and large landslides mapped using the aerial photographs were later extensively modified, subdivided and/or deleted using the higher resolution LiDAR in the final version of the map.

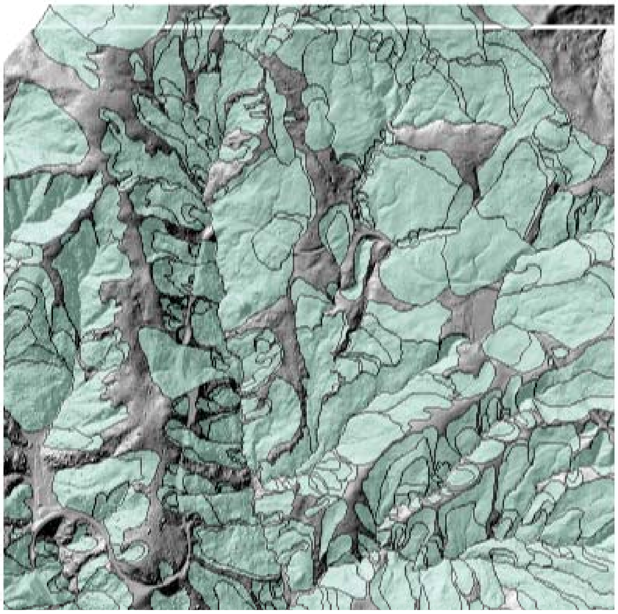


Figure 14, Final map of test area.

Comparison Results

With respect to accuracy, precision, repeatability and confidence of interpretation, CGS geologists were able to produce a more detailed landslide inventory using the LiDAR DEMs, with a higher level of confidence.

LiDAR significantly improves the identification and location of the margins and internal features of large, deep-seated rockslides and earthflows when compared with aerial photographs. However, traditional aerial photographs were found to be more useful in identifying recently active landslides, particularly shallow debris slides and debris flows, because of the contrast differences between bare soil and vegetated slopes. Additionally, evidence of recent landslide movement as evidenced by pavement patches on roadways is not apparent using LiDAR, but often is readily visible on aerial photographs. This study found that LiDAR and supplemental aerial photographic interpretation, used concurrently, greatly improve the quality of the final product.

This study also found that the amount of time each geologist needed to map the study area using either system was approximately the same. Most of the time needed for aerial photograph interpretation involves evaluating the first set of photographs. Review of subsequent sets of aerial photographs takes less time because the user becomes progressively more familiar with the area being studied. The main time-consuming factor affecting the use of LiDAR appears to be in identifying and drawing the much greater landslide detail, including internal structure, and the related time involved with attributing this detail in the GIS. As a result, the LiDAR mapping takes almost the same amount of time as detailed aerial photo interpretation, but results in a more detailed depiction of the ground surface (see Figure 14).

The use of LiDAR technology in mapping landslides, in addition to the more traditional aerial photograph and ground-based reconnaissance studies appears to have a number of immediate advantages. The user can readily create:

1. Accurate and precise existing road and watercourse locations.
2. Detailed topographic maps at a wide range of scales or contour intervals. The vegetation-penetrating capabilities of LiDAR enable the preparation of detailed maps of the ground surface that would be very expensive to generate with survey crews on the ground.
3. Rapid as-built documentation of cut and fill slope configurations and volumes.
4. On-screen evaluation and design of new roadway alignments.
5. Landslide mapping, evaluation and mitigation triage.
6. Statistics regarding style and amount of mass-wasting; and preferred failure orientation for particular geologic units (for example, see discussion of the Galice Formation in the Willow Creek portion of the Geologic Mapping section).
7. For bridge and culvert design, one can evaluate channel conditions such as: thalweg orientation, channel profiles and cross-sections, and identify flood plains.

In summary, LiDAR is a very effective multi-purpose tool for the rapid, precise and accurate identification and mapping of landslides and other features across large areas of densely forested terrain. However, CGS recommends that this process include an aerial photograph component to identify smaller, recent features such as debris slide-debris flow scars and pavement damage that are not expressed in the topography. Using both of these methods concurrently aided the creation of a detailed set of maps to aid in the long-term management of this highway corridor.

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 stability of the slopes along the Highway 299 corridor between Blue Lake and Willow Creek. Bedrock geology also has a very strong influence on the topography and the types of landslides. Slopes along the Highway 299 corridor range from moderate to extremely steep. The steepest slopes are within the Willow Creek portion of the study area. Older, generally more competent rocks underlie this portion of the alignment and this is reflected in the mode and distribution of mass-wasting (see Plate 1, Sheet 2). Natural hillsides and road cuts between Berry Summit and Willow Creek can be as steep as 100 percent and often exceed that locally. Slopes this steep are typically characterized by bare rock outcrops and debris slide scars. Most small landslides on these very steep slopes involve shallow soil and loose rocks, moving as debris slides and rock falls. Rock slides and earthflows tend to be deeper-seated and larger than their counterparts to the west in Redwood Creek and Blue Lake.

Weaker rocks to the west of Berry Summit control the mode and distribution of mass-wasting. For example, the mélange of the Franciscan Complex in Blue Lake and the incoherent unit of Coyote Creek in the Redwood Creek watershed tend to develop large topographic amphitheaters populated with numerous, relatively shallow earthflows. The Redwood Creek schist also forms topographic amphitheaters, but the earthflows and rock slides in this unit are larger and appear to be deep seated. Attempts by Redwood National and State Parks Geologists to install inclinometers through some of the larger earthflows were inconclusive because the researchers were not confident they had penetrated the slides even at depths exceeding 200 feet (Robert Ziemer, personal communication, 1998).

In much of the northern Coast Ranges, mélange bedrock forms a distinct landform, commonly called “mélange terrain”. The features of mélange terrain include rolling hummocky topography, closed depressions and benches on hill slopes, and susceptibility to gullying where water is concentrated. As a result, the terrain appears to be “soft” with relatively gentle slopes and broad ridges. Long Prairie is an example of this topography.

The northwest trend of the regional 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 on slopes similarly oriented. The overall structural grain and orientation of common planes of weakness leads to large landslides on slopes that face northeast and southwest. Slopes north and west of the North Fork campground (milepost R33.278) underlain by Galice Formation are excellent examples in the Willow Creek section of this study (see Figure 4). The foliation of the bedrock dips to the northeast and deep-seated landslides complexes are located on these slopes. Slopes facing west and southwest in this unit cut “across the grain” of the foliation and are much steeper and more competent by comparison. Debris slides are the dominant mode of slope failure on these slopes.

Landforms created by landslides, in some cases, can help to perpetuate movement of the slides. Closed depressions, troughs and benches that commonly form near the head scarps of landslides trap water and deliver additional 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 undercutting a slope may remove support and destabilize the adjacent area upslope. This can lead to landslides that propagate up slope over time.

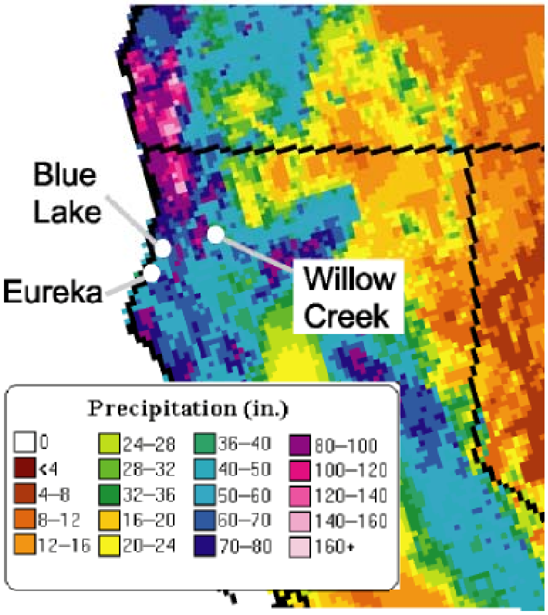


Figure 15, Average annual precipitation in Northern California

Precipitation is a major factor influencing landslides. The segment of Highway 299 between Blue Lake and Willow Creek passes through one of the higher rainfall areas in California (Oregon State University, 2004). According to the Spatial Climate Analysis Service at Oregon State University, the area averaged from 50 to 100 inches of rainfall per year between 1971 and 2000 (Figure 15). This amount of rainfall adds to the ground water level in the landslide masses, decreasing their stability. Long term steady rains lead to deep saturation of landslide masses and tends to de-stabilize the larger, deeper types of landslides. Shorter term, intense rains tend to de-stabilize shallower types of landslides, such as debris slides and debris flows.

POTENTIAL FOR LANDSLIDES ALONG HIGHWAY 299

Landslides can and do damage and close roads, resulting in significant repair and maintenance costs. Economic losses can be significant to an entire region if a major route is closed or impaired 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 entirely eliminated. If roads are to pass through regions like the northern Coast Ranges where landslides are common, they will be exposed to some hazard.

An evaluation of the potential consequences of landslides along Highway 299 between Blue Lake and Willow Creek 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. However, assessment of the types of landslides and the general consequences of movement of those types of landslides can be made. Table 2 lists the size, movement type, materials and activity level of a landslide, the velocity of movement that is common for a type of landslide, and the landslide's proximity to the highway. It is assumed 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 magnitude and velocity of movement. Large, single event slides may remove or displace more of a roadway, resulting in a high repair cost. However, smaller, chronic displacements or "sinks" also translate to high, long-term repair costs. If large movements accumulate slowly, over years or decades, they may be a continuing maintenance problem where cracks are filled and pavement frequently re-leveled. This process can sometimes add to the problem by increasing driving forces within the slide. Large, rapid, displacements of even small volumes of material may undermine a road or deposit material on a road sufficient to obstruct 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 large, deep landslides may result in the roadway being closed for repair, or in the worst case, closed for long periods for reconstruction and/or rerouting.

Highway 299 crosses well over two hundred slides having all modes of movement and levels of activity on its course from Blue Lake to Willow Creek. It would not be productive to attempt a detailed discussion of all of them in this summary report. As an alternative, the characteristics of some of the most active slides along the corridor associated with recent pavement damage are listed along with their probable rate of movement and consequences should they fail (Table 2). Figures 17 through 20 show areas of recurrent pavement damage and the associated slides. There are numerous areas where the outboard edge of the roadway is settling in response to creeping fill installed at the upper reaches of slides. These slides have been a continuing maintenance problem for years, and probably have been active most years long before both generations of the modern roadway were built.

APPX MILE-POST	**TYPE**	**ACT.**	**APPX AREA (Ac)**	**DEPTH**	**PROBABLE RATE OF MOVEMENT**	**POSSIBLE IMPACTS**	**COMMENTS**
R7.700	EF	H	12	M	Moderate	Hwy closure, closure for extended period in worst-case scenario, risk to public.	Rolling pavement surface, involves approximately 500 feet of roadway
R8.530	EF	H	12	M	Slow	Grade offset – Lane closure	New AC, rolling pavement surface
R8.950	EF	H	15	M	Slow	Lane closure	Hump in roadway, past pavement work
R9.150	EF	H	4	M	Slow	Grade offset, lane closure	Rolling pavement surface
R9.700	DS	H	2	M	Fast	Outboard lane slid out, risk to public	Failed subdrain, repaired, no subsequent movement noted
R11.000	EF	H	4	M	Moderate	Lane closure	Encroaching on roadway
R13.500	RS	H	13	M	Slow	Grade offset, lane closure	
R16.300	DS	H	2	S	Moderate	Lane closure	Encroaching on roadway
R18.959	EF	H	83	D	Slow	Grade offset, lane closure if active zone moves uphill	No recent roadway damage, Redwood Valley road immediately below has rolling surface
R19.959	EF	H	33	D	Moderate	Lane -road closure, closure for extended period in worst-case scenario.	Fill prism within earthflow complex. Potential to displace 500+ feet of road
R20.259	EF	H	18	M	Slow	Grade offset, lane closures	Fill prism within earthflow complex.
R23.259	EF	H	11	M	Slow	Grade offset, lane closure if active zone moves uphill	300-400 foot section of Chezem Road below has dropped 10-15 feet
R23.859	EF	H	67	D	Slow	Grade offset, lane closures	Chezem Road below has rolling pavement surface

R24.359	EF	H	81	D	Slow	"	Roadway has rolling surface
R26.059	EF	H	80	M	Slow	Lane closure	Fill prism within earthflow complex. Outer edge of the road dropping, could extend uphill.
R27.010	EF	H	22	M	Slow	Small, frequent movement, damage	Fill prism within earthflow complex. Slow movement likely to continue, periodic repair needed.
R27.959	EF	H	63	D	Slow	"	Fill prism within earthflow complex. Roadway has rolling surface.
R28.259	EF	H	25	D	Slow	"	Roadway has rolling surface
R28.459	EF	H	61	D	Moderate	Grade offset, lane closures, risk to public	Roadway has rolling surface for 1,000-1,100 ft

Table 2, Selected Slides with evidence of recent movement affecting Highway 299.

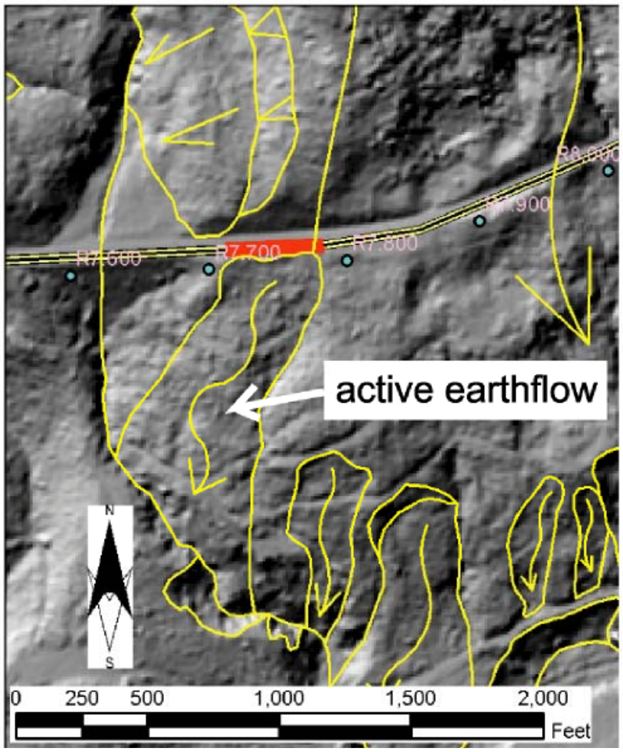


Figure 16, Landslides and area of recent roadway damage at R7.7 east of Blue Lake.

R7.700, Blue Lake. This section of roadway crosses the head of an active earthflow in the sandstone and mélange unit of Snow Camp Mountain northwest of Korbel (Figure 16). All lanes appear to have been involved based on CGS staff observations of chronically rolling and hummocky pavement surface while traversing the highway during evaluation of timber harvest plans in the region. The pavement appears to be affected for a distance of approximately 500 feet. Slow movement and pavement disruption should be expected to continue until mitigation is devised for this slide.

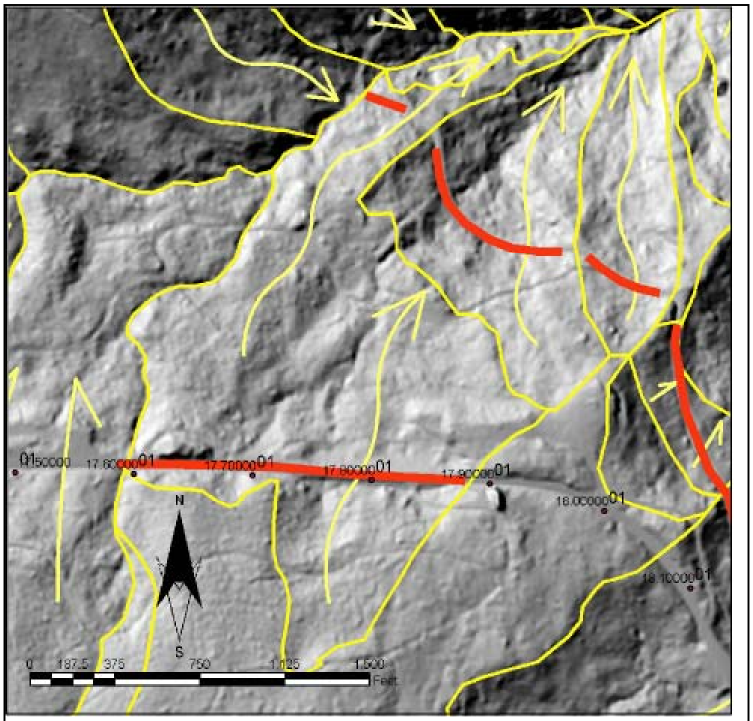
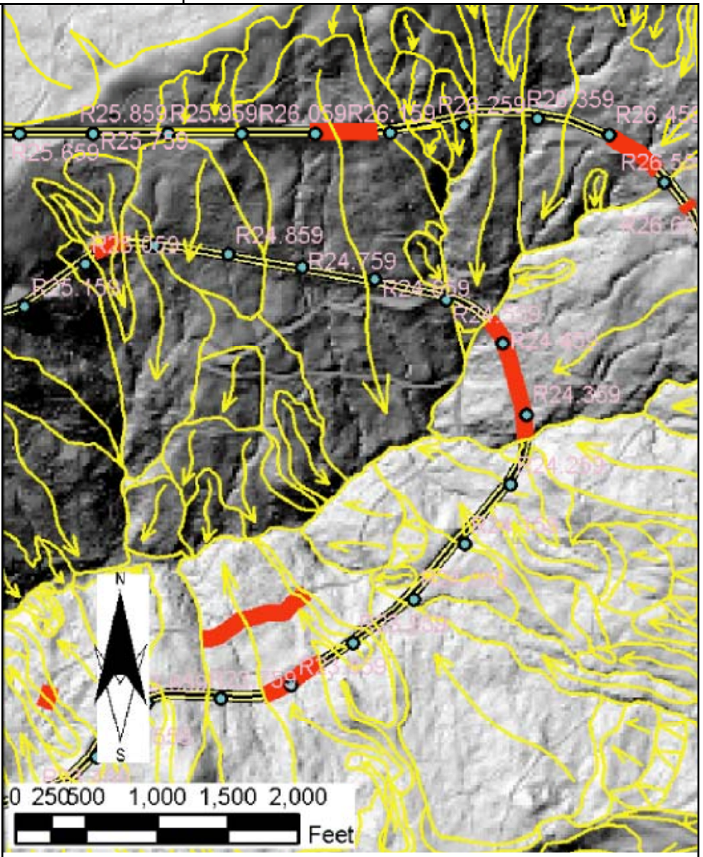


Figure 17, Landslides and areas of recent roadway damage in the Green Point Grade area.

<u>R17.600 to R17.900, Green Point grade</u>. The highway crosses an active deep-seated earthflow as it descends from Lord-Ellis Summit and enters the Redwood Creek basin (Figure 17). As before, all lanes appear to have been involved based on observations of rolling and hummocky pavement surface. The pavement appears to be affected for approximately 1,500 feet (1/4 mile). Slow movement and pavement disruption should be expected to continue until mitigation is devised for this slide.

<u>R23.700 to R26.500, Circle Point</u> area. The highway crosses several active earthflows while passing through this part of Redwood Creek (Figure 18). Roadway sections at approximate mileposts R23.659 and R24.359 are rolling and hummocky in response to earthflow movement. Earth materials observed in road cuts appear to be pervasively sheared shale. An active earthflow at R25.059 is affecting the outer edge of the



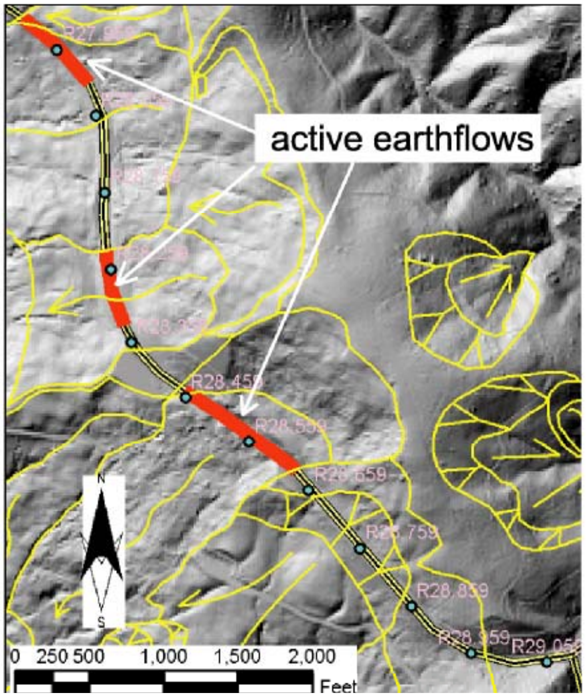


Figure 19, Landslides and areas of recent roadway damage near Berry Summit.

road. The westbound lane appears to have been involved.

R28.459 to R28.659, Berry Summit. Approximately 1,000 feet of roadway have been threatened by the earthflow crossing the highway (Figure 19). The old highway traversed this earthflow further down the slope and the new alignment was relocated near the head of the slide. However, moderate movement of the slide has continued and this location is a continuing maintenance problem. The roadway still appears to be founded on slide debris and this should be expected to continue moving until a mitigation is devised for this feature. There also appear to be a series of tension cracks on the hillside immediately above the head scarp of this feature, implying that deep seated bedrock failure may be involved.

SUMMARY

Highway 299 is a major transportation corridor in northern coastal California and traverses a particularly rugged and landslide-prone area between Blue Lake and Willow Creek in Humboldt County. Within this corridor, landslides at Berry Summit 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 compared with others 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 1,600 features related to landsliding have been mapped within the study area. The type and activity of the slides, the level of confidence of interpretation and several other factors are recorded for each slide. Landslides within the corridor are concentrated in two major belts, controlled by the bedrock geology and the steepness of the slopes.

Active earthflows lead to recurrent roadway disruption and are the dominant mode of mass wasting along the western 2/3 of the alignment underlain by Franciscan complex rocks. This weak rock tends to fail on gentler slopes and also tends to fail as earth flow type landslides because of the pervasive shearing of the material.

Debris slides and rock falls are the main hazards in the Willow Creek canyon as the road passes through Klamath Terrane rocks on its course to the Trinity River. The Klamath Terrane rocks are more competent relative to the Franciscan complex and form very steep slopes locally, as steep as 75 percent to 100 percent for hundreds of feet vertically above the roadway. 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 deep-seated rock slides.

ACKNOWLEDGEMENTS

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Andrew Frazier of Green Diamond Resource Company arranged for us to have access to portions of his company's property near Lord-Ellis Summit. Dave Murphy of the California Department of Forestry and Fire Protection provided ownership information for the Redwood Creek to Willow Creek portion of the alignment.

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AERIAL PHOTOGRAPHS BY YEAR AND REGION

BLUE LAKE

1941 U.S. Department of Agriculture, Agricultural Adjustment Agency, 1941, black and white photographs, flight CVL, frames 7B-120 and 121, 7B-138 through 141, nominal scale 1:24,000, dated November 26, 1941.

1942 U.S. Department of Agriculture, Agricultural Adjustment Agency, 1942, black and white photographs, flight CVL, frames 10B-139 through 41 (dated March 3, 1942), 11B-68 through 74 (dated March 3, 1942), 14B-118 through 120 (dated July 31, 1942), nominal scale 1:24,000.

1948 U.S. Forest Service, 1948, black and white photographs, flight CDF2, frames 17-121 through 125, 18-163 through 166, 19-66 and 67, 19-149 through 151, 19-177 through 183, nominal scale 1:26,400, dated June 22, 1948.

1962 Humboldt County Assessor, 1962, black and white photographs, flight HCN-2, frames 21-38 through 40, 22-33 through 36, 23A 34 through 37, 24-32 through 40, nominal scale 1:12,000, dated August 27, 1962.

1965 U.S. Department of Agriculture, Soil Conservation Service, 1965, black and white photographs, flight CVL, frames 19FF-110 through 112 (dated August 29, 1965), 20FF-58 through 61 (dated August 30, 1965), 20FF-139 through 143 (dated August 30, 1965), nominal scale 1:20,000.

1984 WAC Inc., 1984, black and white photographs, flight WAC-84C, frames 22-139 through 131 (dated May 6, 1984), nominal scale 1:31,680.

1988 WAC Inc., 1988, black and white photographs, flight WAC-88CA, frames 22-27 through 29 (dated July 19, 1988), nominal scale 1:31,680.

1996 WAC Inc., 1996, black and white photographs, flight WAC-96CA, frames 22-163 through 165, 23-54 through 58, nominal scale 1:24,000, dated June 5, 1996

2000 WAC Inc., 2000, black and white photographs, flight WAC-00-CA, frames 4-132 through 135, 4-212 through 216, nominal scale 1:24,000, dated April 1, 2000

LORD ELLIS

1962 Humboldt County Assessor, 1962, black and white photographs, flight HCN-2, frames 25-35 through 38, 26-35 through 38, 27-34 through 37, 28B-14 through 18, 29B-17 through 21, 30-36 through 41, 31-34 through 36, nominal scale 1:12,000, dated August 27, 1962.

1965 U.S. Department of Agriculture, Soil Conservation Service, 1965, black and white photographs, flight CVL, frames 22FF-177 and 178 (dated September 2, 1965), 24FF-119 through 122 (dated September 4, 1965), nominal scale 1:20,000.

1984 WAC Inc., 1984, black and white photographs, flight WAC-84C, frames 24-202 and 203 (dated May 6, 1984), 25-116 through 119 (dated May 7, 1984), nominal scale 1:31,680.

1988 WAC Inc., 1988, black and white photographs, flight WAC-88CA, frames 20-155 and 156 (dated July 15, 1988), 24-50 through 53 (dated July 28, 1988), nominal scale 1:31,680.

1996 WAC Inc., 1996, black and white photographs, flight WAC-96CA, frames 28-125 through 128, 28-219 through 221, nominal scale 1:24,000, dated September 8, 1996**.**

2000 WAC Inc., 2000, black and white photographs, flight WAC-00-CA, frames 5-131 through 134, 5-213 through 216, nominal scale 1:24,000, dated April 1, 2000.

WILLOW CREEK

1948 U.S. Forest Service, 1948, black and white photographs, flight CDF2, frames 14 140 through 142 (dated June 22, 1948), 15-153 through 155 (dated June 23, 1948), 17-205 through 207 (dated July 11, 1948), 33-98 through 100 (dated July 11, 1948), nominal scale 1:26,400.

1962 Humboldt County Assessor, 1962, black and white photographs, flight HCN-2, frames 32-37 through 40, 33-36 through 38, 34-33 through 36, 35-34 through 37, 36-35 through 37, 37A-37-39, 38-37 through 39, nominal scale 1:12,000, dated August 27, 1962.

1965 U.S. Department of Agriculture, Soil Conservation Service, 1965, black and white photographs, flight CVL, frames 5FF-146 through 149 (dated July 21, 1965), 23FF-94 through 97 (dated September 3, 1965), 23FF-115 through 119 (dated September 3, 1965), nominal scale 1:20,000.

1984 WAC Inc., 1984, black and white photographs, flight WAC-84C, frames 22-178 through 180 (dated May 7, 1984), 31-18 and 19 (dated August 8, 1984), 31-80 through 82 (dated August 8, 1984), nominal scale 1:31,680.

1988 WAC Inc., 1988, black and white photographs, flight WAC-88CA, frames 21-95 and 96 (dated July 19, 1988), 22-112 through 114 (dated July 19, 1988), 22-188 and 189 (dated July 19, 1988), nominal scale 1:31,680.

1996 WAC Inc., 1996, black and white photographs, flight WAC-96CA, frames 29-59 through 61, 29-145 through 147, 29-236 through 238, nominal scale 1:24,000, dated September 8, 1996**.**

2000 WAC Inc., 2000, black and white photographs, flight WAC-00-CA, frames 5-292 through 294, 8-53 through 55, 8-133 through 136, 8-208 through 210, nominal scale 1:24,000, dated April 2, 2000.