

Overview of the Ground and Its Movement in Part of Northwestern California¹

Stephen D. Ellen,² Juan de la Fuente,³ James N. Falls,⁴ and Robert J. McLaughlin⁵

Abstract

The Eureka area of northwestern California is characterized by a variety of terrain forms that reflect a variety of geologic materials, most of which are components of the highly disrupted and heterogeneous Franciscan Complex. Recent regional geologic mapping by McLaughlin and others (2000) has delineated the distribution of contrasting materials within the principal recognized units of the Franciscan, and so has revealed for the first time the intricate distribution of materials in much of the area.

This geologic mapping was used by a mass-wasting review panel to select areas for detailed geomorphic mapping of landslide processes. Three study areas were chosen to represent the geologic and topographic diversity of timberlands in the broader area. In addition to abundant debris sliding, this mapping revealed that as much as 70 percent or more of this landscape shows evidence of large landslides of diverse scales and styles, ranging from fresh features produced by recent movement to subdued features suggestive of ancient movement followed by long quiescence. Several lines of evidence suggest that large landslide deposits in this area warrant monitoring for movement, as sediment contribution from subtle movement of these large masses in some areas could be comparable to that from debris sliding.

Key words: California, debris slides, geology, landslides, sediment, terrain mapping

Introduction

This paper describes results from two projects that in recent years have shed light on the nature of the ground and its movement in the Eureka area of northwestern California. The first, geologic mapping by McLaughlin and others (2000), describes the geologic materials and their relation to the varied topography of the region. The second, geomorphic mapping conducted for a mass-wasting scientific review panel, describes the kinds and abundance of landslides that have occurred in study areas representative of these materials and topographies. Together the projects clarify relations relevant to timber harvest in the area.

Below we describe these two studies in sequence: first, the geologic mapping of bedrock materials, which permitted the panel to choose geologically representative

¹ This paper was presented at the Redwood Science Symposium: What does the future hold? March 15-17, 2004, Rohnert Park, California.

² Retired from U.S. Geological Survey, 116 Huckleberry Trail, Redwood City, CA 94062. email: sdellen@comcast.net

³ USDA Forest Service, Klamath National Forest, 1312 Fairlane Road, Yreka, CA 96097. email: jdelafuente@fs.fed.us

⁴ California Geological Survey, 2120 Campton Road, suite D, Eureka, CA 95503. email: james.falls@conservation.ca.gov

⁵ U.S. Geological Survey, 345 Middlefield Road MS-973, Menlo Park, CA 94025. email: rjmcl@usgs.gov

study areas; then the geomorphic mapping that revealed landslide processes within the study areas.

Geologic Mapping of Earth Materials

Methods

Geologic mapping by McLaughlin and others (2000) began by delineating the major geologic units at regional scale (1:100,000). Two principal bedrock sequences underlie the area (*fig. 1*): the generally older (Jurassic to Miocene) assemblage of disrupted and dismembered geologic materials that constitute the Franciscan Complex; and the Wildcat Group of Ogle (1953), which consists of poorly lithified, young (Miocene to Pleistocene) sedimentary rocks. The Franciscan rocks reflect a history of deformation as severe as any in the world. The Wildcat strata, which were deposited atop the late Eocene and older rocks of the Franciscan, in many places have been folded and faulted, but because their deposition post-dates the severe deformation of the underlying Franciscan rocks, they remain largely intact as flat-lying or tilted sequences of layered rock.

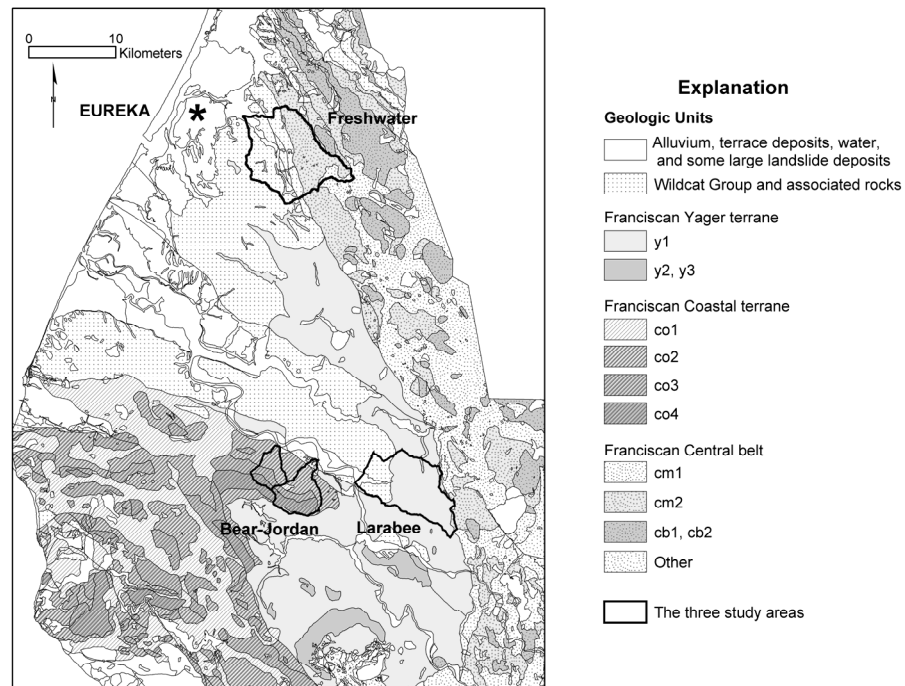


Figure 1—The Eureka area of northwestern California, showing geologic units (modified from McLaughlin and others 2000) and the three areas of detailed study. Shades of gray in the Franciscan distinguish subunits mapped by topographic form; darker tones within each group indicate the “harder” topographies.

The Franciscan Complex in this area includes three major units—the Central belt, Yager terrane, and Coastal terrane. Each of these units consists dominantly of sandstone and clayey rock (mudstone, siltstone, and shale) that have been deformed to varying degrees. Shearing and disruption tend to be concentrated in the clayey rocks. Style and overall degree of deformation differ among these units, but bedrock in each unit ranges from more-or-less intact sandstone-dominated sequences to clayey, intensively sheared shale.

To map the distribution of these disparate materials within the major Franciscan units, McLaughlin and others (2000) used a form of terrain mapping, in which contrasts in topographic form, as viewed in high-altitude aerial photographs, were systematically mapped as a reflection of the mechanical character of the underlying bedrock (see Ellen and Wentworth 1995, McLaughlin and others 2000). The Franciscan displays strong contrasts in topographic form (*fig. 2*), and the use of these contrasts for distinguishing bedrock materials is widely recognized (for example, Kelsey 1980).

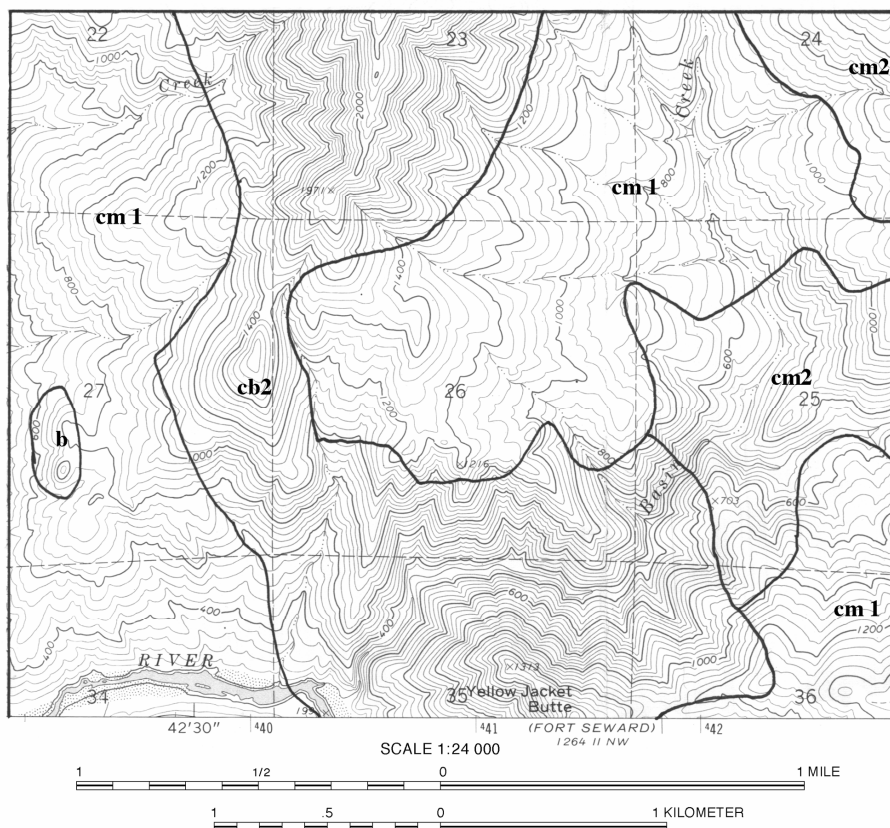


Figure 2—Contrasting topographies in the Franciscan Central belt. Subunits cm1, cm2, cb1 (not shown), and cb2 constitute a spectrum from gently sloping and poorly incised topography (cm1), characterized by a large proportion of weak, highly sheared clayey material, to steep and regularly incised topography (cb2) underlain largely by strong, clay-free materials. Area illustrated is near Fort Seward, California. From McLaughlin and others (2000). Contour interval 12.2 m.

Results

The terrain mapping distinguished 1) steep, angular, and deeply dissected “hard” topography, which tends to develop in rockmasses that lack clayey materials, or in which clayey materials are not mobilized in slope processes, from 2) gently sloping, rounded, shallowly dissected, and more irregular “soft” topography, which tends to develop in clayey sheared materials (Ellen and others 1988). Intermediate topographies, reflecting intermediate conditions, were also distinguished. Subunits are designated by numbers that increase with “hardness” of the topographic form, as shown in the explanation of *figure 1*. Thus, subunits of the Coastal terrane are labeled co1, co2, co3, and co4. In the Yager terrane, which lacks exceedingly “soft” topography, only three subunits (y1, y2, and y3) were distinguished. For the Central belt, the accepted terms “mélange” (for highly sheared rocks) and “broken formation” (for more intact materials) were used in the naming system, so that cm1 and cm2 (for melange), and cb1 and cb2 (for broken formation), form a sequence that corresponds to co1, co2, co3, and co4 of the Coastal terrane (see *fig. 2*).

Discussion

The logic behind the terrain-mapping method is that contrasts in topographic textures evident in small-scale imagery (1:80,000-scale and smaller) arise largely from the different slope processes that characterize clayey and granular materials. Clayey and granular material properties constitute the principal distinctions in engineering behavior and slope stability (Kenney 1984, Mitchell 1976). Granular materials, such as crushed rock or clay-poor fractured rockmasses, are strong and tend to support steep slopes; clayey materials tend to be weaker and can support only gentler slopes (Kirkby 1987). These material properties also result in different landslide behaviors once the ground fails and in different propensity for soil creep, both of which may further affect topographic form. Thus, the systematically mapped spectrum of topographic form (*fig. 2*), expressed by the numbered subunits, depicts a spectrum of landslide processes and also of engineering materials. The mapping may consequently be useful in reconnaissance planning of conventional engineering activities, such as grading, as well as in considerations of landsliding.

This geologic mapping permitted the mass-wasting review panel to select study areas representative of the geologic and topographic diversity of timberlands in the Eureka area (*fig. 1*). The watershed of Freshwater Creek, east of Eureka, is underlain principally by the Wildcat Group and by subunits of the Central belt of the Franciscan Complex. The contiguous watersheds of Bear and Jordan Creeks, located well south of Eureka, are underlain dominantly by a spectrum of Franciscan Coastal terrane. The lower part of the Larabee Creek watershed is underlain in part by the most abundant subunit of the Franciscan Yager terrane and in part by the Wildcat Group. The Wildcat Group in Larabee dips sufficiently to provide the possibility of landsliding along weak layers and bedding planes, whereas in Freshwater layering generally is close to horizontal. Thus, these three study areas sample the principal geologic units and configurations of the area (*fig. 1*).

Geomorphic Mapping of Landsliding

Methods

To determine the kinds of landslides and their distributions, the review panel conducted new geomorphic mapping in the Bear-Jordan and Larabee study areas (de

la Fuente and Hicks 2001, Ellen 2001) and updated recent mapping in the Freshwater study area (Falls 2001). The mapping was accomplished principally by interpretation of aerial photographs. It made use of multiple sets of photographs in order to gain the fullest possible description, in contrast to previous mapping of the region (for example, Spittler 1982, 1983) which was constrained by a single set of aerial photographs. Field checking of landslides and other geologic conditions was limited to about a week in Bear-Jordan and in Larabee; Freshwater had received periodic field visits over the course of five years.

Results

Kinds of Landsliding

The study areas provided a fresh look at the kinds of landslides and their abundance. Two basic types are recognized. Debris slides are shallow (typically 0.5 to three m thick) landslides that carry vegetation and soils rapidly from steep hillslopes. Debris slides may be called debris avalanches if they are especially fast-moving, and they may become fluid and travel far downslope or down channels as debris flows, mud flows, or debris torrents. Debris slides leave behind barren scars that can be easy to recognize in the field or in aerial photographs until vegetation covers the bare soil or rock, typically after a few years.

The other basic type of landslide that has occurred in the area is generally larger, slower, and deeper (Swanson and Swanson 1977). These are less commonly recognized because their movement typically is more gradual, they largely retain forest cover or other vegetation, and they can remain dormant for many years. These landslides tend to move progressively and intermittently, often in seasonal increments, over periods of years, decades, or longer. They may range in size from a few acres up to the scale of a mountainside (several square kilometers). Movement may be dominantly rotational in profile (called rotational sliding or slumping), in which back-rotation of the sliding ground results in hillside benches or depressions; dominantly translational, where movement parallels the ground surface; or more fluid in character, where moving materials form elongate tongues called “earth flows” that tend to move slowly and persistently. In this paper, we call ground that has moved by any of these larger, slower, and deeper processes “large landslide deposits.” These are commonly bordered by landslide scarps, the steep slopes left behind by displaced ground.

Abundance

Debris slides and large landslide features are more abundant in the study areas than shown in earlier published mapping. *Table 1* shows the comparison for the Bear-Jordan study area. The contrast is especially pronounced for large landslide deposits. The new mapping shows large landslide deposits and scarps occupying 18 percent of the ground in Freshwater, 66 percent in Bear-Jordan, and 76 percent in Larabee.

Table 1—Abundance of mapped debris slides and large landslide deposits in Bear-Jordan study area.

	Debris slides		Landslide deposits and scarps	
	Count	Percent of area	Count	Percent of area
Previous mapping (Spittler 1982, 1983)	121	4	25	2
New mapping (de la Fuente and Hicks 2001)	776	6	377	66

Landslide styles in the study areas

Landslides in the three study areas show different styles and distributions

Freshwater (fig. 3)—Large landslide deposits here chiefly occur as discrete masses surrounded by unslid ground, especially in the western half of the study area underlain by the Wildcat Group. Here large landslide deposits typically have moved by rotational or translational sliding. In the Franciscan Central belt of the eastern part of the study area, large landslide deposits typically result from earth flows and tend to be larger and more elongate than landslide deposits in the Wildcat Group.

Debris slides and related phenomena occur scattered about the study area. In the Wildcat Group, most originate high in the landscape in low-order drainage basins, and few occur along major streams. In the Franciscan, most occur low in the topography along major streams.

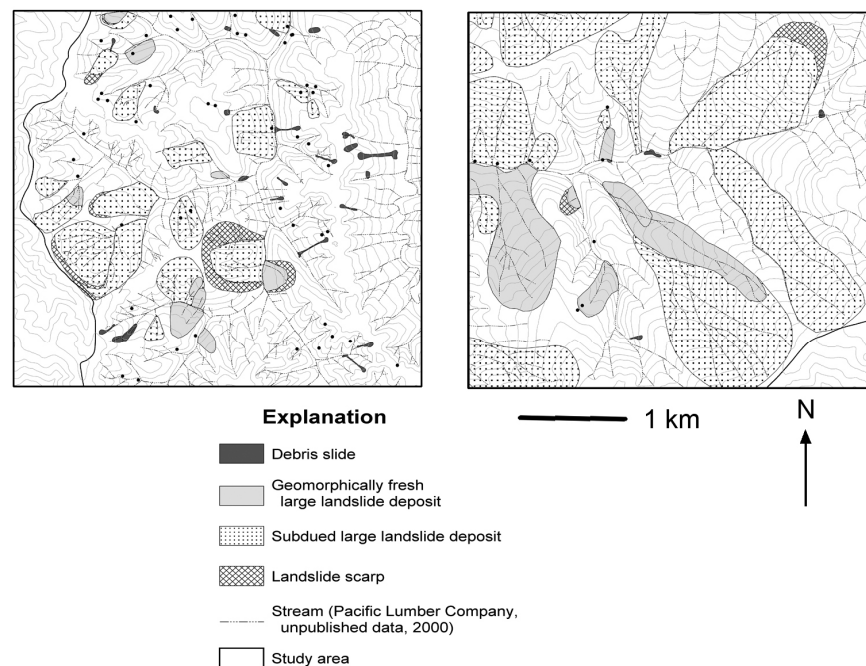


Figure 3—Landslide features in Freshwater study area (Falls 2001). A, Part of western side of study area, underlain by Wildcat Group; B, Part of eastern side of study area, underlain by Franciscan Central belt (mostly unit cm2). Contour interval 25 m.

Bear-Jordan (fig. 4)—Large landslide deposits occupy most of the ground in these watersheds except ridge crests and sidehill ridges. In the steep headwaters area shown in *figure 4*, which constitutes “hard” topography of the Coastal terrane, large landslide deposits occupy the steep hillsides and sidehill draws of this landscape. “Softer” units of the Coastal terrane, which underlie middle and lower parts of these watersheds, include at least one large earth flow in addition to numerous large landslide deposits of less distinctive style, some of which are interrelated as parts of landslide complexes.

Debris slides are abundant and occur dominantly along the main stream channels. Many are large, and some of these large debris slides appear to represent detached pieces of preexisting large landslide deposits.

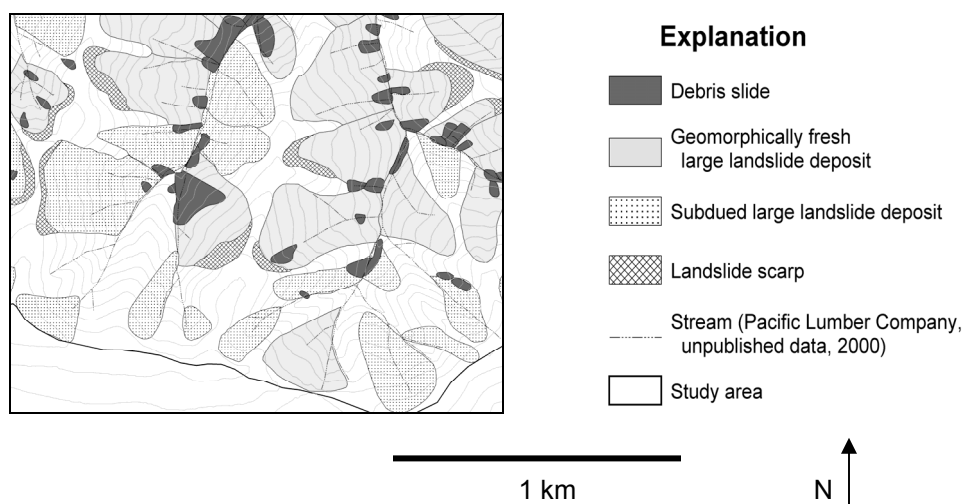


Figure 4—Landslide features in part of Bear-Jordan study area largely underlain by Franciscan Coastal terrane (unit co4). Contour interval 25 m. From de la Fuente and Hicks (2001).

Larabee (fig. 5)—The western part of this study area (*fig. 5A*) is underlain by strata of the Wildcat Group that appear to dip toward Larabee Creek from both north and south. Much of this ground consists of large landslide deposits, on the order of 300 to 1200 m across and as much as 1200 m long, which appear to have been facilitated by the dip slopes. Sometime prior to 1941 (the date of the earliest aerial photographs examined), one of these large landslides transformed into a debris avalanche that extended across Larabee Creek and apparently dammed it temporarily to a depth of about 20 to 30 m. Some steep hillslopes underlain by the Wildcat Group are free of large landslide deposits but show abundant debris slides high in the landscape, as in Freshwater.

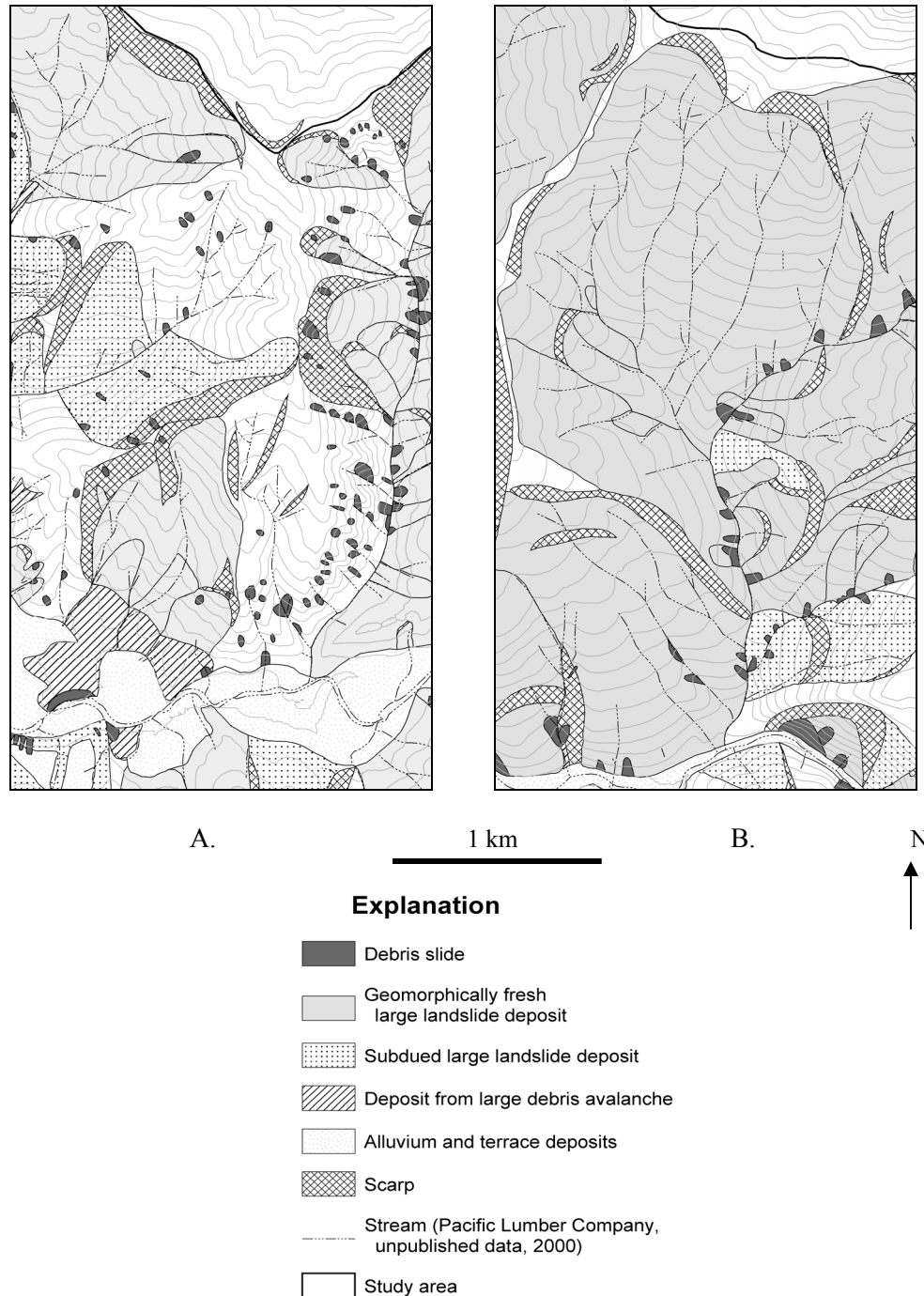


Figure 5—Landslide features in Larabee study area (Ellen 2001). A, Part of western side of study area, underlain by Wildcat Group; B, Part of eastern side of study area, underlain by Franciscan Yager terrane (unit y1). Contour interval 25 m. Larabee Creek crosses southern part of maps.

The eastern part of the study area (*fig. 5B*) is underlain by unit y1, the most common subunit of Yager terrane. Unit y1 displays an intermediate topography that includes 1) gently to moderately sloping ground (<35 percent slope) that appears underlain largely by clayey rock, and 2) steep ground that appears underlain largely

by more resistant rock dominated by sandstone and lesser conglomerate. The gently to moderately sloping ground is irregular in form and consists of landslide complexes that cover areas as large as several square kilometers and commonly extend from major streams almost to the ridgecrests. In such areas, debris slides are not abundant and occur mainly along creeks. The steep parts of the Yager include more discrete large landslide deposits, large debris slides along Larabee Creek, and unslid ground.

Activity

Debris slides are well documented in the study areas by mapping from multiple generations of aerial photographs. In each study area, the mapping indicates that debris slides have occurred throughout the period of record, most abundantly during photo intervals that include major rainstorms.

Activity of large landslide deposits is not so easily detected because field evidence for movement may be subtle and easily overlooked. During field reconnaissance, we found some evidence for historical activity, such as fresh scarps and displaced roads. Reliable detection of current activity, however, generally requires instrumental monitoring. The absence of all but minimal monitoring in the immediate area of this study leaves major questions for any attempt to quantify sediment sources: Are enough large landslide deposits sufficiently active to constitute significant sources of sediment? Or alternatively, can the large landslide deposits be considered relict, that is, "...clearly developed under different geomorphic or climatic conditions, perhaps thousands of years ago" (Cruden and Varnes 1996)?

Several lines of evidence bear on these questions. 1) Significant activity during the current geomorphic and climatic regime is suggested by the fact that the vast majority of large landslide deposits in the study areas toe along stream channels. These streams are active geomorphic agents responding to the high degree of tectonic activity that characterizes the area (Clarke and Carver 1992). 2) Large landslide deposits display a broad range of geomorphic freshness, as rated during the authors' systematic appraisal of landslide features in the study areas (*figs. 3 through 5*). Differences in freshness suggest differences in recency, rather than a scenario in which movement is confined to the distant past. 3) Monitoring of hillslope movement in other parts of northern California and adjacent areas reveals significant movement under current climatic conditions and in the absence of earthquake shaking. 4) As reported by Reid and others (2006), debris sliding in the Bear-Jordan and Larabee study areas is significantly more abundant in geomorphically fresh large landslide deposits than in other parts of these study areas. This observation suggests that these fresher large landslide deposits have moved recently enough that shallow materials remain destabilized. These several lines of evidence, taken together, suggest that most large landslide deposits are not relict but rather hold the potential for movement and delivery of sediment to the streams at their toes.

Discussion

Whereas debris slides in the study areas were easily recognized and mapped, and their sediment production tallied routinely during other local studies, the potential for movement of large landslide deposits in this area has been hindered by lack of monitoring. Even modest efforts, such as inventories of displacements along roads following wet winters or sequences of wet winters, would go a long way toward clarifying this issue. Note that even slight movement of these enormous deposits could generate large volumes of sediment. Calculations indicate that 10 cm of yearly movement on six to 15 percent of the large landslide deposits in places like

the Larabee study area could provide annual sediment inputs comparable to the impressive contributions from debris sliding documented by Pacific Watershed Associates (1998, 1999) in the Bear Creek and Jordan Creek watersheds.

Another tool mentioned for investigation of large landslide deposits is site-specific stability analysis. Such quantitative analysis, which is common in urban areas, typically is based on borings and engineering testing aimed at determining the geometry, strength, and ground-water conditions at a site. Such methods may be difficult to justify in timberlands, and they may be especially difficult in timberlands underlain by Franciscan rocks because the heterogeneity and disruption of these materials would diminish confidence in subsurface determinations of landslide geometry and material properties. Interrelation of landslides in complexes, which is common in much of the area, would add to the difficulty of stability analysis and diminish its effectiveness.

Conclusions

The ground in much of the region is a mixture of variably deformed materials, and regional geologic mapping by McLaughlin and others (2000) has revealed for the first time the intricate distribution of engineering materials in much of this terrain. These materials are further modified by more recent movement of large landslides, which cover as much as 70 percent or more of the landscape and range from fresh features produced by recent movement to subdued features suggestive of ancient movement followed by long quiescence. In three study areas chosen to be representative of geologic materials in the Eureka area, both debris slides and large landslide deposits are common, and both kinds of landslides show variation in scale, style, and abundance among the different materials represented in the study areas. Debris slides have been shown to be an important source of sediment; movement of large landslide deposits has not been adequately monitored, and even slight movement of a small proportion of these large masses could contribute significant sediment to streams.

Acknowledgments

Much of this work was undertaken for the Mass Wasting Scientific Review Panel, which was convened by the National Marine Fisheries Service, the U.S. Fish and Wildlife Service, the California Department of Fish and Game, and the Pacific Lumber Company as part of the Headwaters agreement. Work was facilitated by Paul Vincent, Alan Foreman, Todd Flackus, and Tim Spear of the GIS Department at the Pacific Lumber Company. Eric Johnson of VESTRA Resources, Inc., also assisted in GIS map preparation and analysis, as did D.L. Brien, J.B. Barnes, J.D. Cecil, and K.A. Cyr of the U.S. Geological Survey. Aerial photographs were provided by the Pacific Lumber Company, the California Geological Survey, and the U.S. Geological Survey Library. The Pacific Lumber Company also provided base maps and access to the ground.

References

- Clarke, S.H., Jr.; Carver, G.A. 1992. **Late Holocene tectonics and paleoseismicity, southern Cascadia subduction zone.** Science 255: 188-192.
- Cruden, D.M.; Varnes, D.J. 1996. **Landslide types and processes.** In: Turner, A.K.; Schuster, R.L., eds. Landslides: investigation and mitigation. Transportation Research Board Special Report 247. Washington, DC: National Academy Press; 36-75.
- de la Fuente, J.; Hicks, B.G. 2001. **Landslide features in the Bear Creek and Jordan Creek study area.** Unpublished mapping for Mass Wasting Scientific Review Panel.
- Ellen, S.D. 2001. **Landslide features in the Larabee Creek study area.** Unpublished mapping for Mass Wasting Scientific Review Panel.
- Ellen, S.D.; Cannon, S.H.; Reneau, S.L. 1988. **Distribution of debris flows in Marin County.** In: Ellen, S.D.; Wieczorek, G.F., eds. Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California. U.S. Geological Survey Professional Paper 1434; 113-131.
- Ellen, S.D.; Wentworth, C.M. 1995. **Hillside materials and slopes of the San Francisco Bay region.** U.S. Geological Survey Professional Paper 1357; 215 p.
- Falls, J.N. 2001. **Landslide features in the Freshwater Creek study area.** Unpublished mapping for Mass Wasting Scientific Review Panel.
- Kelsey, H.M. 1980. **A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941-1975: Summary.** Geological Society of America Bulletin 91: 190-195.
- Kenney, C. 1984. **Properties and behaviors of soils relevant to slope instability.** In: Brunsden, D.; Prior, D.B., eds. Slope instability. Chichester, UK: John Wiley and Sons; 27-65.
- Kirkby, M.J. 1987. **General models of long-term slope evolution through mass movement.** In: Anderson, M.G.; Richards, K.S., eds. Slope stability. Chichester, UK: John Wiley and Sons; 359-379.
- McLaughlin, R.J.; Ellen, S.D.; Blake, M.C., Jr.; Jayko, A.S.; Irwin, W.P.; Aalto, K.R.; Carver, G.A.; Clarke, S.H., Jr. 2000. **Geology of the Cape Mendocino, Eureka, Garberville, and southwestern part of the Hayfork 30 × 60 minute quadrangles and adjacent offshore area, northern California.** U.S. Geological Survey Miscellaneous Field Studies Map MF-2336, version 1.0; 26 p., 6 plates. With digital database by Barnes, J.B.; Cecil, J.D.; Cyr, K.A.; 16 p.
- Mitchell, J.K. 1976. **Fundamentals of soil behavior.** New York: John Wiley and Sons; 422 p.
- Ogle, B.A. 1953. **Geology of the Eel River Valley area, Humboldt County, California.** California Division of Mines Bulletin 164; 128 p., 6 plates.
- Pacific Watershed Associates. 1998. **Sediment source investigation and sediment reduction plan for the Bear Creek watershed, Humboldt County, California.** Report prepared for The Pacific Lumber Company, dated April 1998; 42 p. plus maps and appendices.
- Pacific Watershed Associates. 1999. **Sediment source investigation and sediment reduction plan for the Jordan Creek watershed, Humboldt County, California.** Report prepared for The Pacific Lumber Company, dated January 1999; 63 p. plus maps and appendices.
- Reid, M.E.; Ellen, S.D.; Brien, D.L.; de la Fuente, J.; Falls, J.N.; Hicks, B.G.; Johnson, E.C. 2006. **Predicting debris-slide locations in northwestern California.** In: Standiford,

R.B.; Giusti, G.A.; Valachovic, Y.; Zielinski, W.J., technical coordinators. Proceedings of the Redwood Region Forest Science Symposium; 2004 March 15-17; Rohnert Park, CA Gen. Tech. Rep. PSW-GTR-194. Albany, CA: Pacific Southwest Research Station. USDA Forest Service; [this volume].

Spittler, T.E. 1982. **Geology and geomorphic features related to landsliding, Scotia 7.5' quadrangle, Humboldt County, California.** California Department of Conservation, Division of Mines and Geology, Open-File Report OFR 82-20 S.F.

Spittler, T.E. 1983. **Geology and geomorphic features related to landsliding, Redcrest 7.5' quadrangle, Humboldt County, California.** California Department of Conservation, Division of Mines and Geology, Open-File Report OFR 83-17 S.F.

Swanson, F.J.; Swanson, D.N. 1977. **Complex mass-movement terrains in the western Cascade Range, Oregon.** In: Coates, D.R., ed. Landslides. Geological Society of America Reviews in Engineering Geology 3: 113-124.