Map showing recent (1997-98 El Niño) and historical landslides, Crow Creek and vicinity, Alameda and Contra Costa Counties, California

By Jeffrey A. Coe,[1] Jonathan W. Godt,[1] *and* Pierre Tachker[2]

[1] U.S. Geological Survey, Denver Federal Center, MS 966, Denver, CO 80225
[2] Institut Des Sciences Et Techniques De Grenoble, Département Géotechnique, Grenoble, France

This report may be obtained over the Internet from: http//geology.cr.usgs.gov

Scientific Investigations Map 2859

2004

U.S. Department of the Interior
U.S. Geological Survey

Abstract

This report documents the spatial distribution of 3,800 landslides caused by 1997-98 El Niño winter rainfall in the vicinity of Crow Creek in Alameda and Contra Costa Counties, California. The report also documents 558 historical (pre-1997-98) landslides. Landslides were mapped from 1:12,000-scale aerial photographs and classified as either debris flows or slides. Slides include rotational and translational slides, earth flows, and complex slope movements. Debris flows and slides from the 1997-98 winter modified 1 percent of the surface of the 148.6 km^2 study area. Debris flows were scattered throughout the area, regardless of the type of underlying bedrock geology. Slides, however, were concentrated in a soft sandstone, conglomerate, and clayey group of rock units. Digital map files accompany the report.

Introduction

As early as the summer of 1997, the 1997-98 El Niño weather phenomenon was predicted to be one of the most intense in the past 100 years (Monteverdi and Null, 1997; Leetmaa and Higgins, 1998). In the San Francisco Bay region of California, above-average rainfall predicted for the 1997-98 winter season was also expected to increase slope instability (San Francisco Bay Landslide Mapping Team, 1997; Godt and others, 1997). Throughout the fall of 1997, the general public in the region experienced an uneasy anticipation of possible severe winter storms and associated flooding and landslides (Diaz, 1997; Perkins, 1997; Perkins and Whetzel, 1997; Richards, 1997; Rogers, 1997). By the end of January 1998, the region had received more than 170 percent of normal rainfall, but experienced only scattered, and relatively minor, landslide activity. The largest storm of the 1997-98 winter season occurred on February 2 and 3, 1998 (National Climatic Data Center, 1998). This storm affected the entire Bay region (Wilson, 1998) and dropped as much as about 150 mm of rain in about 30 hours (Coe and Godt, 2001). Following this storm, landslides were extensively reported by the news media (for example, Akizuki, 1998; Bailey and others, 1998; Buel, 1998; Tucker, 1998). Landslides triggered by the February storm prompted the U.S. Geological Survey (USGS) to mobilize field teams to assess damage and cleanup costs in the region. Results from these assessments indicated that costs of landslide damage totaled approximately $150 million (Highland and others, 1998; Godt, 1999). Damage costs from landslides in Alameda and Contra Costa Counties were about $20 million (Coe and others, 1999; Godt and others, 2000) and $27 million (Graymer and Godt, 1999), respectively.

In March and April of 1998, during ground and air reconnaissance to assess landslide damage in Alameda County, we identified two main areas of moderate to abundant landslide activity (fig. 1a and Coe and others, 1999). The southern area, in the vicinity of Walpert Ridge east of Hayward (fig. 1a), was the subject of a separate report (Coe and Godt, 2001). That report documented the distribution, geomorphic setting, and triggering rainfall for 531 debris flows. The northern area, which is the subject of this report, encompasses 148.6 km^2 and is northeast of Castro Valley, in the vicinity of Crow Creek (figs. 1a and 1b). This area contains abundant debris flows, rotational and translational slides, and earth flows triggered by 1997-98 winter rainfall, as well as many pre-1997-98 landslides. The purpose of this report is to document the distribution of landslides in the northern study area. Detailed information regarding the rainfall that caused the 1997-98 landslides in this area is contained in Coe and Godt (2001).

Terminology

Throughout this report, “landslide” is used as the general term for all types of slope movement. The term “slide” designates generally slow-moving rotational and translational slides, earth flows, and complex slope movements as classified by Varnes (1978) and Cruden and Varnes (1996). Rotational and translational slides generally lack any appearance of flowing movement. Earth flows have the appearance of flowing movement, but move primarily by sliding on discrete slip surfaces (Keefer and Johnson, 1983; Baum, 2003). Earth flows have a distinctive morphology that includes an overall tongue or tear-drop shape (with the widest part of the tear usually at the bottom of the flow) that is elongate in the direction of downslope movement, a depleted source area, distinct lateral and basal shear boundaries, and a bulging toe (Keefer and Johnson, 1983). Complex slope movements combine two or more types of movement. The term “debris flow” designates fast-moving flows of mud, gravel, and organic material (Pierson and Costa, 1987) that commonly mobilize

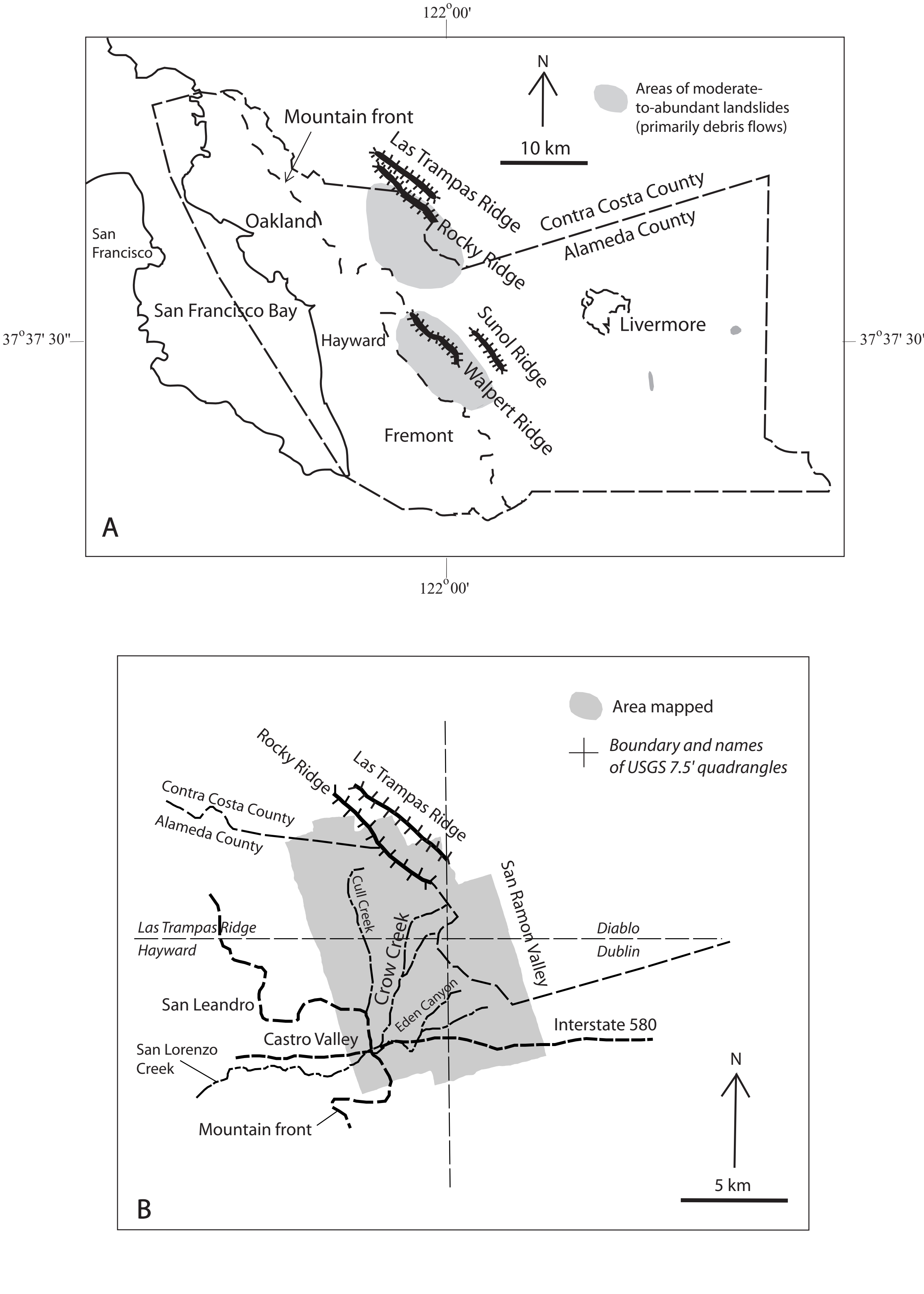

Figure 1. Maps showing location of study area. A, Map showing San Francisco Bay, Alameda County, and areas of moderate to abundant landslides resulting from the February 2-3, 1998 storm. The northern shaded area is the Crow Creek study area, the subject of this report. The southern shaded area is the Walpert Ridge study area of Coe and Godt (2001). B, Map showing the Crow Creek study area.

from slides (Campbell, 1975; Ellen and Fleming, 1987; Reid and others, 2003).

Setting and Previous Work

Hillslopes in the study area (fig. 2) have moderate to steep gradients (10°-50º) and are mantled by colluvial soil that is as much as several meters in thickness. Vegetation is mostly grass but includes some shrubs and deciduous trees. Land use is predominantly livestock grazing, but some areas are being converted to residential use because of the areas location at the urban margin. Mean annual precipitation in the area is about 460 mm in valleys, but can be as much as 610 mm along upper flanks of the prominent northwest-trending ridges in the area (Rantz, 1971a and b). The most prominent ridges are Rocky Ridge, and an unnamed ridge with a steep west face referred to on the Hayward 7.5-minute topographic map as "The Knife" (see map). Both ridges are located along the Alameda and Contra Costa Counties border. Elevations in the area reach a maximum of about 600 m on Rocky Ridge. The study area is transected from northeast to southwest by southwest flowing Crow Creek.

The study area is underlain by Cretaceous and Tertiary sedimentary rocks of marine and non-marine origin that have been extensively folded and faulted by multiple oblique-slip faults (Dibblee, 1980a, b, c, d; Graymer and others, 1994; Graymer and others, 1996; Helley and Graymer, 1997). Geologic units in the area (fig. 3) have been assembled into 5 geologic groups: (1) alluvium; (2) soft sandstone, conglomerate, and clayey rock; (3) firm sandstone and clayey rock; (4) siliceous rock; and (5) well-bedded, hard to firm sandstone and clayey rock (Ellen and Wentworth, 1995; Wentworth, 1997). Most of these units (with the exception of siliceous rocks) release abundant clay as they are weathered (Ellen and Wentworth, 1995); therefore, much of the colluvial soil mantling the hillslopes is clay rich and particularly susceptible to

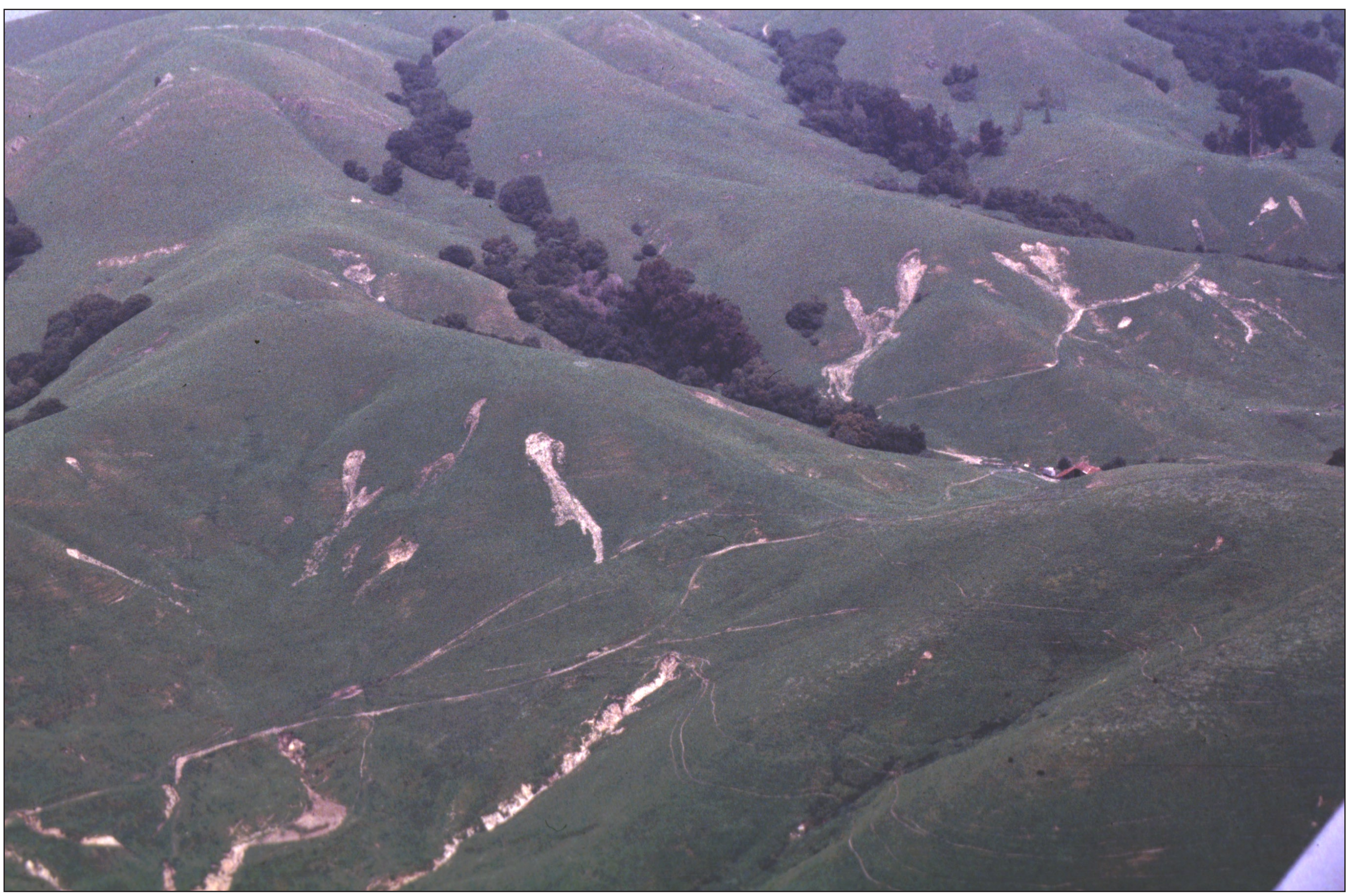

Figure 2. Hillslopes and 1997-98 landslides in the study area. View is to the east. See map for location of photograph. Photograph taken April 22, 1998.

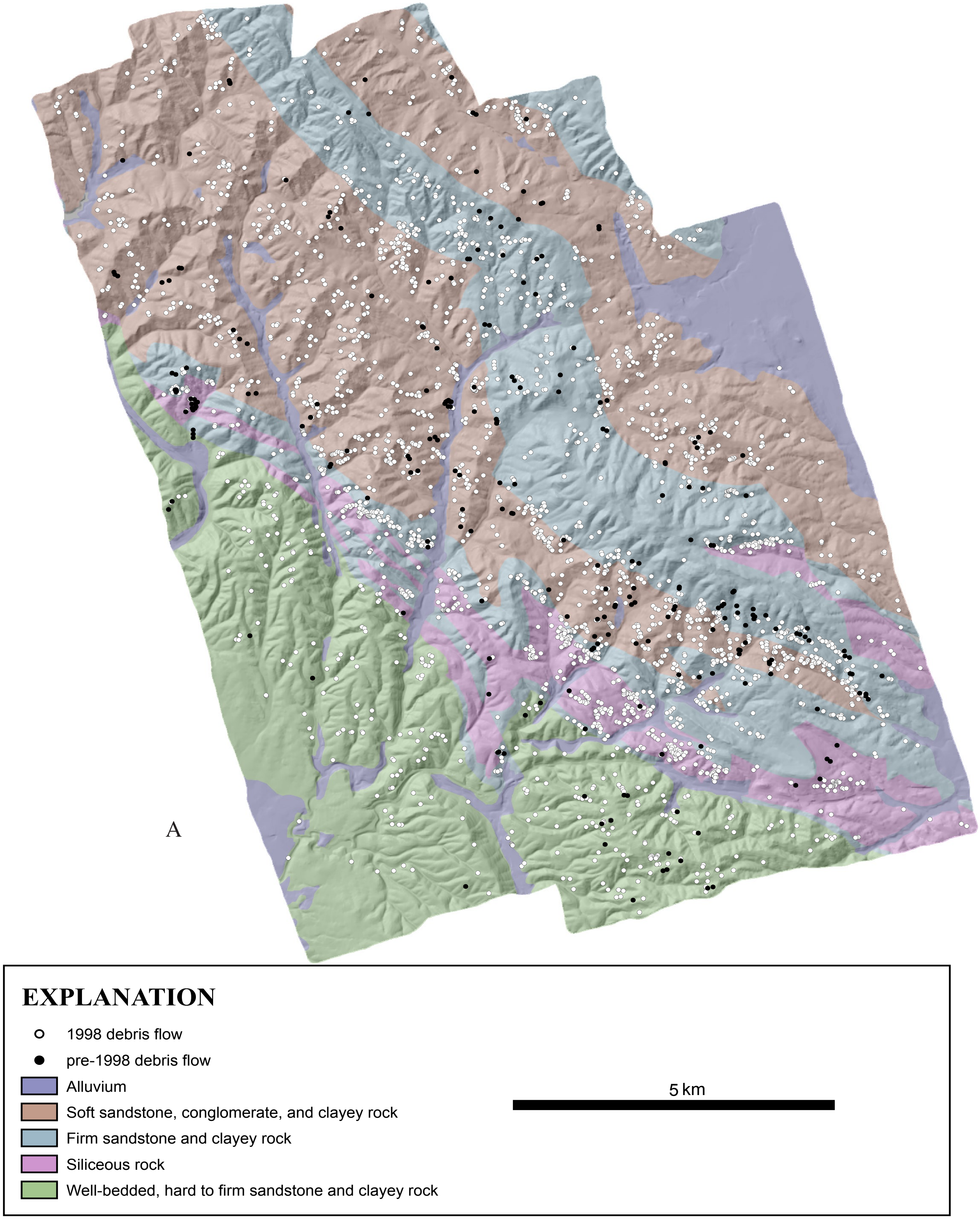

Figure 3. Geologic map of the study area (from Ellen and Wentworth, 1995, and Wentworth, 1997) shown on shaded relief derived from USGS 10-m Digital Elevation Models. Landslides are shown by dots. (See text for additional explanation.) A, Geologic map with debris-flow locations shown at the upslope end of each flow. B, Geologic map with slide locations shown at the center point of each slide.

EXPLANATION

- ○ 1998 slide
- ● pre-1998 slide
- Alluvium
- Soft sandstone, conglomerate, and clayey rock
- Firm sandstone and clayey rock
- Siliceous rock
- Well-bedded, hard to firm sandstone and clayey rock

5 km

landslides. Numerous reports and inventory maps have documented Quaternary and historical landslides in the area (Waltz, 1971; Nilsen, 1971; Taylor and Brabb, 1972; Nilsen, 1973a and b; Nilsen and others, 1975; Taylor and others, 1975; Keefer and Johnson, 1983; Wieczorek and others, 1988; Wentworth and others, 1997). Some of these data have been used to produce landslide susceptibility maps within Alameda County (Majmundar, 1996a and b; Ellen and others, 1997; Pike and others, 2001). Most of the currently available inventory and susceptibility maps are at scales of 1:50,000 or smaller (exceptions are 1:24,000-scale maps by Nilsen and others, 1975, and Majmundar, 1996a and b).

Map Description

Landslides shown on the map were mapped from 1:12,000-scale, natural-color, stereo aerial photographs onto parts of four USGS 7.5 minute quadrangles (fig. 1b) using a Kern PG-2 photogrammetric plotter (Pillmore, 1989). The photographs were taken on May 18, 1998. Landslides were initially mapped on 2X enlargements (1:12,000 scale) of the base maps. The scale of the photography allowed us to accurately identify landslides as small as about 0.5 m in width, but the scale of the base map only allowed us to map landslides greater than about 3 m wide. The smallest mapped landslides covered an area of about 10 m^2, whereas the largest covered about 788,720 m^2 (table 1). Each landslide on the map (4,358 total, table 2a) includes the source area, travel path (typically present for debris flows, but not slides), and deposit. The mapped landslides cover about 1.7 percent of the 148.6 km^2 study area (table 1). In addition to landslides, the map shows areas of recently (within the last 40 years) modified land. These areas are housing developments containing zones of both cut and fill. These graded areas were mostly unaffected by landslides during the winter of 1997-98 (see map; Coe and others, 1999; Godt and others, 2000). We did not systematically field check the maps, but used observations made during our ground and air reconnaissance in March and April, 1998 (Coe and others, 1999), to calibrate our photogrammetric mapping. Once mapped, landslides were digitized from the 1:12,000-scale maps into an ArcInfo Geographic Information System (GIS). The final map is presented at a scale of 1:18,000. The topographic base for the final map is a seamless digital representation of the study area that is available on CD-ROM from the National Geographic Society. ArcInfo export files containing landslide polygons accompany this map report.

As part of the mapping, landslides were classified according to relative age and type of movement. Landslides were classified as 1997-98 winter season landslides if they appeared fresh; that is, non-vegetated. These landslides were typically light brown or white areas that contrasted strongly with adjacent darker, vegetated ground. The landslides generally displayed at least two of the following morphologies: curvilinear scarps; flow-path scars or deposits; lateral scarps; fan or tear-drop shaped deposits; or hummocky deposits. Examples of landslides attributed to the 1997-98 season are visible in figures 2 and 4. These landslides are labeled on the map as “1998” landslides (3,800 total, table 2a), because all available evidence suggests they occurred sometime during or shortly after the February 2-3, 1998, rainstorm. Landslides were classified as pre-1998 landslides (558 total, table 2a) if they had distinct landslide morphology but were covered by vegetation that varied in color or texture from surrounding vegetation. We do not know the exact age of these landslides, but estimate that they are historical. These landslides are labeled on the map as “pre-1998” landslides. An example of a pre-1998 landslide is shown in figure 4. We also observed large areas of fully vegetated, hummocky topography throughout the study area. We did not map these areas because they have been included in previous mapping by Nilsen (1971, 1973a, 1973b), Nilsen and others (1975), and Majmundar (1996a and 1996b).

We classified each mapped landslide as a debris flow or slide on the basis of surface characteristics and morphology. Debris flows were identified on the basis of their tear-drop shape (the widest part of the tear commonly at the top of the flow) and/or the gradual thinning of deposits in the downslope direction (figs. 2 and 4). Most mapped debris flows (3,091 total, table 2a) were mobilized from small, shallow slides (also known as soil slips, Campbell, 1975). Although these debris flows initiated as slides, we designated the entire feature, including landslide, flow path, and deposit, as a “debris flow” and show the entire feature on the map. In some locations, pre-1998 slides or parts of these slides mobilized as debris flows. At many locations, mobilized mud and debris

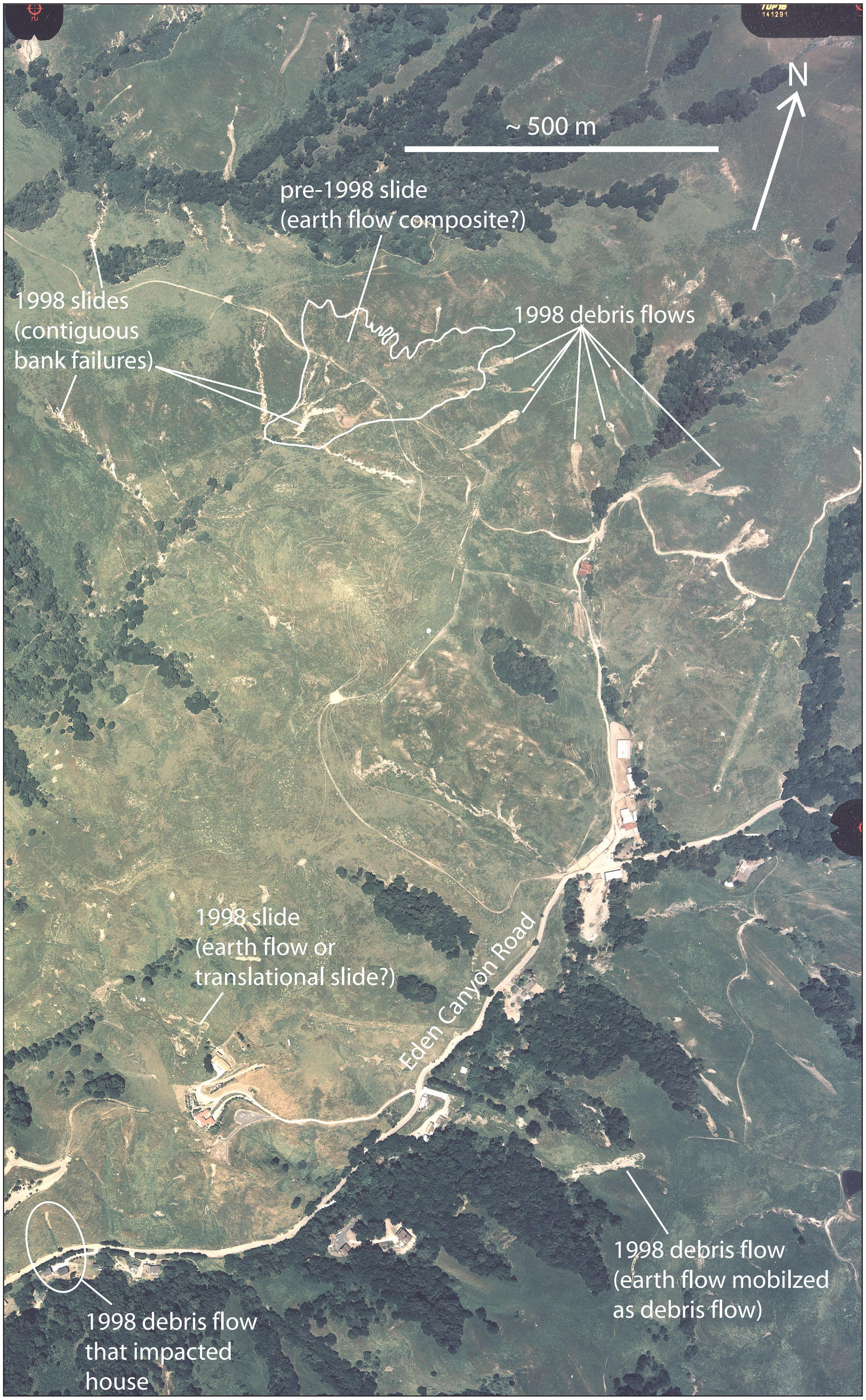

Figure 4. Aerial photograph showing landslides in the vicinity of the eastern part of Eden Canyon Road. Some of the smaller debris flows that were visible in the PG-2 photogrammetric plotter (stereoscopically at 2, 4, and 8x magnification) and shown on the map, are not readily visible here because of the lack of significant magnification. See map for location of photograph. Photograph is part of 1:12:000-scale USGS photograph 3-10, which was acquired for the USGS by Hammon, Jensen, Wallen, and Associates, Inc., on May 18, 1998.

Figure 5. Debris flow that did not erode the hillside, near the intersection of Palo Verde Road and Interstate 580. See map for location of photograph. Photograph taken on February 3 or 4, 1998, by Julie Cannon.

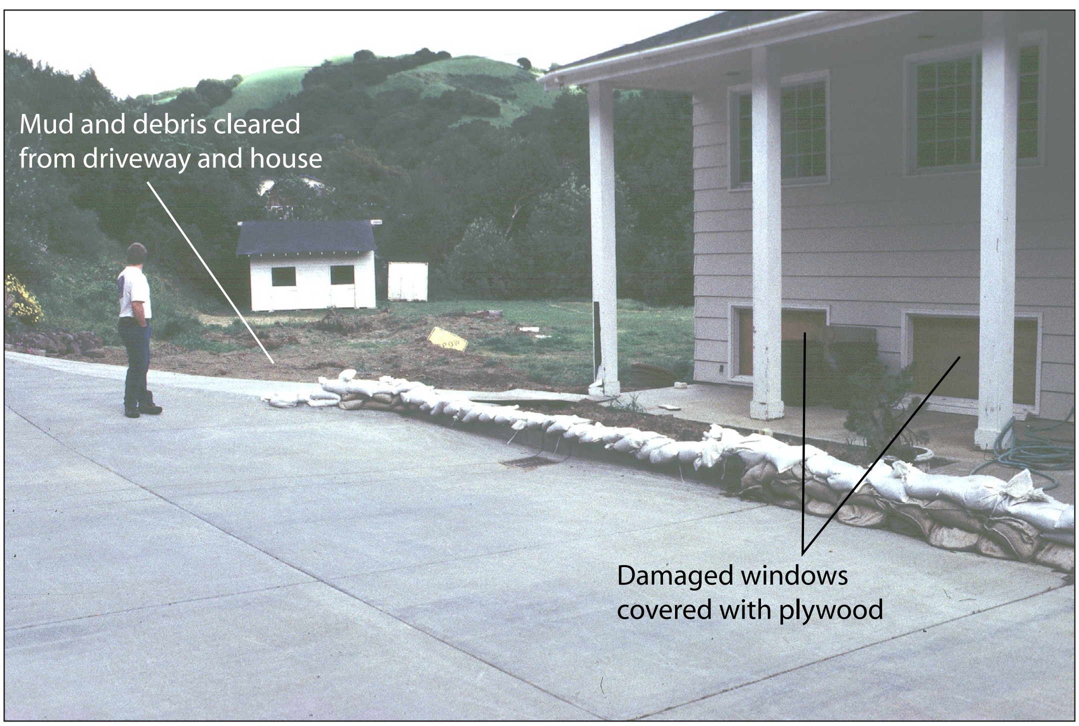

Figure 6. House at 21780 Eden Canyon Road impacted by debris flow and condemned by Alameda County. View is to the east. See map and figure 4 for location of photograph. Photograph taken April 23, 1998.

flowed downslope across the grass surface, without eroding the hillslope (fig. 5). Although many debris flows did not erode into the hillslope, the volumes of debris typically mobilized were capable of damaging anything in their path. One house damaged by a debris flow is located at 21780 Eden Canyon Road (figs. 4 and 6). This house was impacted by part of a debris flow, with a volume of about 30 m^3, between 2:00 and 2:30 am on February 3, 1998. The debris flow initiated as a slide near the head of a small gulley (fig. 4 and map) and flowed across Eden Canyon Road before damaging an automobile in the driveway and breaking windows in the house. When we visited the site in April 1998, the owner told us that Alameda County inspectors had red-tagged the house and wanted them (the owners) to move it to another location on the property. The estimated cost for the move, including a new septic system and foundation, was $250,000.

The “slide” category is a broad designation that includes individual and composite translational slides, rotational slides, and earth flows; complex slope movements; and isolated or contiguous stream bank failures. Landslides classified as slides had one characteristic in common; they moved primarily by sliding at relatively slow velocities. We designated landslides as slides if they displayed landslide morphology, but did not have characteristics indicative of debris flows. We did not distinguish types of slides (for example, translational slides from earth flows) because the aerial photographs did not consistently provide enough information to verify such a distinction (for example, see fig. 7). We are confident, however, that most of the landslides classified as slides (1,267 total, table 2a) had earth-flow morphology as described by Keefer and Johnson (1983). Mapped slides that are narrow and parallel to streams are contiguous stream-bank failures that were too small to map individually (fig. 4).

The relation between the spatial distribution of debris flows and slides and the underlying bedrock geology was challenging to assess. Sizes (areas and volumes) of the two types of landslides varied

Figure 7. Slide behind houses with frontage along Eden Canyon Road. See map and figure 4 for location of photograph. Photograph taken April 22, 1998.

widely. Debris flows tended to have relatively small areas and volumes compared to slides. Volume data represent the actual size of landslides, whereas area data provide an estimate of size that is biased according to landslide type. For example, areas of debris flows incorporate source zones, travel paths (which may be primarily transport zones with very little deposition), and deposits, whereas areas of slides primarily incorporate only source and deposition zones. Additionally, slide deposits tend to be much thicker than debris-flow deposits. Area data, therefore, tend to overestimate the size of debris flows and underestimate the size of slides. Ideally, the volume of material displaced by each landslide would be used to assess the relation between landslide distribution and underlying bedrock geology. However, because of the large number of landslides and the difficulty of estimating their volumes, the cost to collect these data was prohibitive. Instead, we use landslide areas and number of landslides (count data) to calculate landslide concentrations for each geologic group (table 2), and then use these concentrations to evaluate the influence of the underlying bedrock geology on landslide distribution. Although count data do not incorporate landslide size, they do provide an accurate number of landslides initiated within each geologic group, and may therefore be the better data set (compared to area data) to assess the relation between landslide concentrations and underlying geology. Landslide concentrations calculated from count data are expressed as number/km^2, whereas concentrations from area data are expressed as a percent [area of landslides (m^2)/area of geologic group (m^2)]. Ultimately, we found that the two data types produced consistent observations and conclusions regarding the relation between landslide concentration and geology, which are described below.

Debris flows that occurred in 1998 are scattered throughout the study area across all of the geologic groups (fig. 3 and table 2). The concentration of 1998 debris flows ranges from 35.3 debris flows/km^2 and 1.0 percent for siliceous rock to 1.9 debris flows/km^2 and 0.1 percent for alluvium (table 2). The concentration for alluvium is relatively low because alluvium is in drainages that have relatively low (nearly flat) slope gradients (fig. 3). The debris-flow concentration on well-bedded, hard to firm sandstone and clayey rock is also relatively low (8.6 debris flows/km^2 and 0.4 percent, table 2), possibly because this unit also underlies an area with some relatively low slope gradients (southwest corner of map and fig. 3). Debris-flow concentrations for soft sandstone, conglomerate, and clayey rock; firm sandstone and clayey rock; and siliceous rock; all of which underlie moderate to steep hillslopes, are very similar (ranging from 23.4 debris flows/km^2 and 0.7 percent to 35.2 debris flows/km^2 and 1.0 percent, table 2). Concentrations of pre-1998 debris flows show the same general pattern with respect to geology (table 2).

Unlike debris flows, slides from 1998 are mostly concentrated in one geologic group: soft sandstone, conglomerate, and clayey rock (fig. 3b and table 2). The concentration of 1998 slides for this geologic group (12.7 landslides/km^2 and 1.0 percent) is about 4 to 19 times greater than for other groups (table 2). Concentrations of pre-1998 slides show the same general pattern with respect to geology (table 2). Recent detailed geologic mapping (Graymer and others, 1994; Ellen and Wentworth, 1995; Graymer and others, 1996) indicates that the rock units that make up this geologic group include the Mulholland Formation of the Contra Costa Group and the Contra Costa Group, undivided (referred to as unnamed sedimentary and volcanic rocks by Graymer and others, 1994, 1996). Both of these units have been ranked by Pike and others (2001) as having a relatively high susceptibility to slides. These observations suggest that bedrock geology plays an important role in determining the location of slides, but it is much less important in determining the location of debris flows. This conclusion is consistent with results from previous work (Coe and Godt, 2001) from the Walpert Ridge area in central Alameda County.

Summary

The map presented in this report documents the spatial distribution of 4,358 landslides (debris flows and slides) in a 148.6 km^2 area of Alameda and Contra Costa Counties, California. Most of the landslides (3,800) were caused by rainfall during the 1997-98 El Niño winter season. The overall concentration of landslides in the study area was 29.3 landslides/km^2. The type of underlying bedrock geology had little, if any, influence on the location of debris flows, but strongly influenced the location of slides. This conclusion is consistent with results from previous work in central Alameda County.

Acknowledgments

We thank Dick Pike, Kevin Schmidt, and Rex Baum for their critical reviews of this report. We are grateful to Margo Johnson and Craig Brunstein for editing the final map sheet and pamphlet.

References Cited

Akizuki, D., 1998, Race is on to dig out, get ready, Alameda County damage estimate now $4.1 million: San Jose Mercury News, February 5, 1998, p. 1B.

Bailey, B., Akizuki, D., Hajratwala, M., 1998, Big Storm takes aim—tense Bay Area residents brace for the arrival today of the next in a series of fronts lined up across the Pacific: San Jose Mercury News, February 6, 1998, p. 1A.

Baum, R.L., 2003, Earth flows, *in* Middleton, G.V., Church, M.J., Coniglio, M., Hardie, L.A., and Longstaffe, F.J., eds., Encyclopedia of Sediments and Sedimentary Rocks: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 247-248.

Buel, S., 1998, Say hello to El Niño—Bay Area gets floods, mud, outages; worst is over: San Jose Mercury News, February 3, 1998, p. 1A.

Campbell, R.W., 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Coe, J.A., and Godt, J.W., 2001, Debris flows triggered by the El Niño rainstorm of February 2-3, 1998, Walpert Ridge and vicinity, Alameda County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF 2384, 3 map sheets, scale 1:24,000.

Coe, J.A., Godt, J.W., Brien, D., and Houdre, N., 1999, Map showing damaging landslides in Alameda County, California, triggered by 1997-98 El Niño winter rainstorms, *in* Godt, J.W., ed., Maps showing damaging landslides caused by El Niño rainstorms, winter season 1997-98, San Francisco Bay region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2325-B, 1 map sheet, 1:125,000 scale.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K., and Schuster, R.L., Landslides—investigation and mitigation: Transportation Research Board Special Report 247, p. 36-75.

Diaz, S., 1997, East Bay tries to stem El Niño tide, crews cleaning drains, hillsides, as cities step up education efforts: San Jose Mercury News, October 27, 1997, p. 1B.

Dibblee, T.W., Jr., 1980a, Preliminary geologic map of the Dublin quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report 80-537, scale 1:24,000.

Dibblee, T.W., Jr., 1980b, Preliminary geologic map of the Hayward Quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report 80-540, scale 1:24,000.

Dibblee, T.W., Jr., 1980c, Preliminary geologic map of the Las Trampas Ridge Quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report 80-545, scale 1:24,000.

Dibblee, T.W., Jr., 1980d, Preliminary geologic map of the Diablo Quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report 80-546, scale 1:24,000.

Ellen, S.D., and Fleming, R.W., 1987, Mobilization of debris flows from soil slips, San Francisco Bay region, California, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flows/avalanches: process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 31-40.

Ellen, S.D., Mark, R.K., Wieczorek, G.F., Wentworth, C.M., Ramsey, D.W., and May, T.E., 1997, Map showing principal debris-flow source areas in the San Francisco Bay Region, California: U.S. Geological Survey Open-File Report 97-745E, 8 p., 11 maps at scales of 1:275,000 and 1:125,000.

Ellen, S.D., and Wentworth, C.M., 1995, Hillside materials and slopes of the San Francisco Bay region: U.S. Geological Survey Professional Paper 1357, 215 p., 7 plates.

Godt, J.W., ed., 1999, Maps showing damaging landslides caused by El Niño rainstorms, winter season 1997-98, San Francisco Bay region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2325.

Godt, J.W., Coe, J.A., Savage, W.Z., 2000, Relation between cost of damaging landslides and construction age, Alameda County, California, USA, El Niño winter storm season, 1997-98, *in* Bromhead, E.N., Dixon, N., and Ibsen, M-L., eds., Landslides in research, theory and practice: Proceedings of the 8th International Symposium on Landslides, Cardiff, Wales, v. 2, p. 641-646.

Godt, J.W., Highland, L.M., and Savage, W.Z., 1997, El Niño and the national landslide hazard outlook for 1997-1998: U.S. Geological Survey Fact Sheet 180-97, 4 p.

Graymer, R.W., and Godt, J.W., 1999, Map showing damaging landslides in Contra Costa County, California, triggered by 1997-98 El Niño winter rainstorms, *in* Godt, J.W., ed., Maps showing damaging landslides caused by El Niño rainstorms, winter season 1997-98, San Francisco Bay region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2325E, 1 map sheet, 1:125,000 scale.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1994, Preliminary geologic map emphasizing bedrock formation in Contra Costa County, California: U.S. Geological Survey Open-File Report 94-622, scale 1:75,000.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1996, Preliminary geologic map emphasizing bedrock formations in Alameda County, California—A digital database: U.S. Geological Survey Open-File Report 96-252, map scale 1:75,000, 14 p. database pamphlet and 33 p. geologic explanation pamphlet.

Helley, E.J., and Graymer, R.W., 1997, Quaternary geology of Alameda County, and parts of Contra Costa, Santa Clara, San Mateo, San Francisco, Stanislaus, and San Joaquin Counties, California—a digital database: U.S. Geological Survey Open-File Report 97-097, 8 p.

Highland, L., Godt, J.W., Howell, D., Savage, W.Z., 1998, El Niño 1997-98: Damaging landslides in the San Francisco Bay Area: U.S. Geological Survey Fact Sheet 089-98.

Keefer, D.K., and Johnson, A.M., 1983, Earth flows: morphology, mobilization, and movement: U.S. Geological Survey Professional Paper 1264, 56 p.

Leetmaa, A., and Higgins, W.R., 1998, El Niño 1997/98, forecasting California rainfall: Eos, Transactions of the American Geophysical Union, v. 79, no. 45, p. 265.

Majmundar, H.H., 1996a, Landslides and related features, *in* Landslide hazards in the Hayward quadrangle and parts of the Dublin quadrangle, Alameda and Contra Costa Counties, California: California Division of Mines and Geology Open-File Report 95-14, plate B, scale 1:24,000.

Majmundar, H.H., 1996b, Landslides and related features, *in* Landslide hazards in the Las Trampas Ridge quadrangle and parts of the Diablo quadrangle, Alameda and Contra Costa Counties, California: California Division of Mines and Geology Open-File Report 95-15, scale 1:24,000.

Monteverdi, J., and Null, J., 1997, El Niño and California precipitation: National Oceanic and Atmospheric Administration, Western Region Technical Attachment No. 97-37, 23 p. Data accessed month/day/year at URL http://tornado.sfsu.edu/geosciences/elnino/elnino.html#Final

National Climatic Data Center, 1998, Storm data, February 1998: National Climatic Data Center, Storm Data Report, v. 40, no. 2, 183 p.

Nilsen, T.H., 1971, Preliminary photointerpretation map of landslide and other surficial deposits of the Mount Diablo area, Contra Costa and Alameda Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-310, scale 1:62,500.

Nilsen, T.H., 1973a, Preliminary photointerpretation map of landslide and other surficial deposits of the Concord 15-minute quadrangle and the Oakland West, Richmond, and part of the San Quentin 7.5-minute quadrangles, Contra Costa and Alameda Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-493, scale 1:62,500.

Nilsen, T.H., 1973b, Preliminary photointerpretation map of landslide and other surficial deposits of the Livermore and parts of the Hayward 15-minute quadrangles, Alameda and Contra Costa Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-519, scale 1:62,500.

Nilsen, T.H., Bartow, J.A., Frizzell, V.A., and Sims, J.D., 1975, Preliminary photo-interpretation maps of landslide and other surficial deposits of 56 7.5-minute quadrangles in the southeastern San Francisco Bay region, Alameda, Contra Costa, and Santa Clara Counties, California: U.S. Geological Survey Open-File Report 75-277, scale 1:24,000.

Perkins, B., 1997, Don't let El Niño give you a nasty insurance shock: San Jose Mercury News, September 20, 1997, p. 1F.

Perkins, B., and Whetzel, O., 1997, With severe winter weather predicted, it's time to repair, caulk, and weather-strip: San Jose Mercury News, September 19, 1997, p. 1E.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flows/avalances: process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology, v. 7, p. 1-12.

Pike, R.J., Graymer, R.W., Roberts, S., Kalman, N.B., Sobieszczyk, S., 2001, Map and map database of susceptibility to slope failure by sliding and earthflow in the Oakland Area, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2385, scale 1:50,000.

Pillmore, C.L., 1989, Geologic photogrammetry in the U.S. Geological Survey: Photogrammetric Engineering and Remote Sensing, v. 55, p. 1,185-1,189.

Rantz, S.E., 1971a, Precipitation depth-duration-frequency relations for the San Francisco Bay region, California: U.S. Geological Survey, San Francisco Bay Region Environment and Resources Planning Study Basic Data Contribution 25, 1:500,000-scale map and 5 p. text.

Rantz, S.E., 1971b, Mean annual precipitation and precipitation depth-duration-frequency data for the San Francisco Bay region, California: U.S. Geological Survey, San Francisco Bay Region Environment and Resources Planning Study Basic Data Contribution 32, 1:500,000-scale map and 23 p. text.

Reid, M.E., Brien, D.L., LaHusen, R.G., Roering, J.J., de la Fuente, J., and Ellen, S.D., 2003, Debris-flow initiation from large, slow-moving landslides, *in* Rickenmann, D., and Chen, C., eds., Debris flow hazards mitigation: mechanics, prediction, and assessment: Millpress, Rotterdam, v. 1, p. 155-166.

Richards, G., 1997, El Niño gives commuters on Highway 17 reason to fret, for now, state plans to 'winterize' summit: San Jose Mercury News, October 6, 1997, p. 1B.

Rogers, P., 1997, Predictions bring memories of 1982-83 flooding back: San Jose Mercury News, August 20, 1997, p. 16A.

San Francisco Bay Landslide Mapping Team, 1997, The San Francisco Bay region, California, Landslide Folio: U.S. Geological Survey Open-File Report 97-745, 82 p., plus multiple maps. Report available at URL http://wrgis.wr.usgs.gov/open-file/of97-745/

Taylor, F.A., and Brabb, E.E., 1972, Maps showing distribution and cost by counties of structurally damaging landslides in the San Francisco Bay Region, California, Winter of 1968-69: U.S. Geological Survey Miscellaneous Field Studies Map 327, scale 1:1,000,000.

Taylor, F.A., Nilsen, T.H., and Dean, R.M., 1975, Distribution and cost of landslides that have damaged manmade structures during the rainy season of 1972-1973 in the San Francisco Bay Region, California: U.S. Geological Survey Miscellaneous Field Studies Map MF 679, scale 1:1,000,000.

Tucker, J., 1998, Storms battering Bay area--more rain expected to douse region today: The Oakland Tribune, February 3, 1998.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides, analysis and control: Transportation Research Board Special Report 176, p. 11-33.

Waltz, J.P., 1971, An analysis of selected landslides in Alameda and Contra Costa Counties, California: Bulletin of the Association of Engineering Geologists, v. VIII, no. 2, p. 153-163.

Wentworth, C.M., 1997, General distribution of geologic materials in the San Francisco Bay region, California: A digital map database: U.S. Geological Survey Open-File Report 97-744.

Wentworth, C.M., Graham, S.E., Pike, R.J., Beukelman, G.S., Ramsey, D.W., Barron, A.D., 1997, Summary distribution of slides and earth flows in the San Francisco Bay Region, California: U.S. Geological Survey Open-File Report 97-745C, 10 p., 11 maps at scales of 1:275,000 and 1:125,000.

Wieczorek, G.F., Harp, E.L., Mark, R.K., and Bhattacharyya, A.K., 1988, Debris flows and other landslides in San Mateo, Santa Cruz, Contra Costa, Alameda, Napa, Solano, Sonoma, Lake, and Yolo Counties, and factors influencing debris-flow distribution, *in* Ellen, S.D., and 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, p. 133-162.

Wilson, R.W., 1998, 1997/98 El Niño rainfall in northern California and its adverse effects on slope stability: Eos, Transactions of the American Geophysical Union, v. 79, no. 45, p. 265.

Table 1. Area data for mapped landslides. All area numbers rounded to the nearest 10 m^2. Study area is 148.6 km^2.

Type of landslide	Area of smallest mapped landslide (m^2)	Area of largest mapped landslide (m^2)	Mean area of all mapped landslides (m^2)	Total area of all mapped landslides (m^2)	Percent of study area
1998 debris flows	10	13,120	360	917,350	0.6
Pre-1998 debris flows	10	5,490	640	154,790	0.1
1998 slides	20	27,210	670	645,700	0.4
Pre-1998 slides	70	788,720	2,670	824,490	0.6
All Types	10	788,720	580	2,542,330	1.7

Table 2. Geologic and concentration data for mapped landslides. Geologic group names are from Ellen and Wentworth (1995). Table 2a has landslide concentrations calculated from number of landslides. Table 2b has landslide concentrations calculated from area of landslides.

Table 2a.

Geologic Group	Area (km^2)	Number of 1998 debris flows	Concentration of 1998 debris flows (number/ km^2)	Number of pre-1998 debris flows	Concentration of pre-1998 debris flows (number/ km^2)	Number of 1998 slides	Concentration of 1998 slides (number/ km^2)	Number of pre-1998 slides	Concentration of pre-1998 slides (number/ km^2)	Number of all landslides	Concentration of all landslides (number/ km^2)
Alluvium	13.9	27	1.9	4	0.3	42	3.0	10	0.7	83	6.0
Soft sandstone, conglomerate, and clayey rock	53.9	1261	23.4	105	1.9	683	12.7	230	4.3	2279	42.3
Firm sandstone and clayey rock	35.4	861	24.3	95	2.7	119	3.4	38	1.1	1113	31.4
Siliceous rock	11.4	400	35.2	22	1.9	23	2.0	17	1.5	462	40.5
Well-bedded, hard to firm sandstone and clayey rock	34.1	292	8.6	24	0.7	92	2.7	13	0.4	421	12.3
All	148.6	2841	19.1	250	1.7	959	6.5	308	2.1	4358	29.3

Table 2b.

Geologic Group	Area (m^2)	Area of 1998 debris flows (m^2)	Concentration of 1998 debris flows expressed as percent (area of 1998 debris flows/area of geologic group)	Area of pre-1998 debris flows (m^2)	Concentration of pre-1998 debris flows expressed as percent (area of pre-1998 debris flows/area of geologic group)	Area of 1998 slides (m^2)	Concentration of 1998 slides expressed as percent (area of 1998 slides /area of geologic group)	Area of pre-1998 slides (m^2)	Concentration of pre-1998 slides expressed as percent (area of pre-1998 slides/area of geologic group)	Total area of all landslides (m^2)	Concentration of all landslides expressed as percent (area of all landslides/area of geologic group)
Alluvium	13,857,100	19,140	0.1	4,020	<0.1	21,970	0.2	36,580	0.3	81,710	0.6
Soft sandstone, conglomerate, and clayey rock	53,913,900	418,420	0.8	74,120	0.1	523,980	1.0	642,230	1.2	1,658,750	3.1
Firm sandstone and clayey rock	35,373,500	243,610	0.7	53,400	0.2	73,140	0.2	129,360	0.4	499,510	1.4
Siliceous rock	11,350,800	114,600	1.0	11,120	0.1	9,680	0.1	11,180	0.1	146,580	1.3
Well-bedded, hard to firm sandstone and clayey rock	34,139,800	121,580	0.4	12,130	<0.1	16,930	<0.1	5,140	<0.1	155,780	0.5
All	148,635,100	917,350	0.6	154,790	0.1	645,700	0.4	824,490	0.6	2,542,330	1.7