Figure 1.—Preliminary geologic map of study area in northern Coast Ranges, California (from Blake and others, 1971).

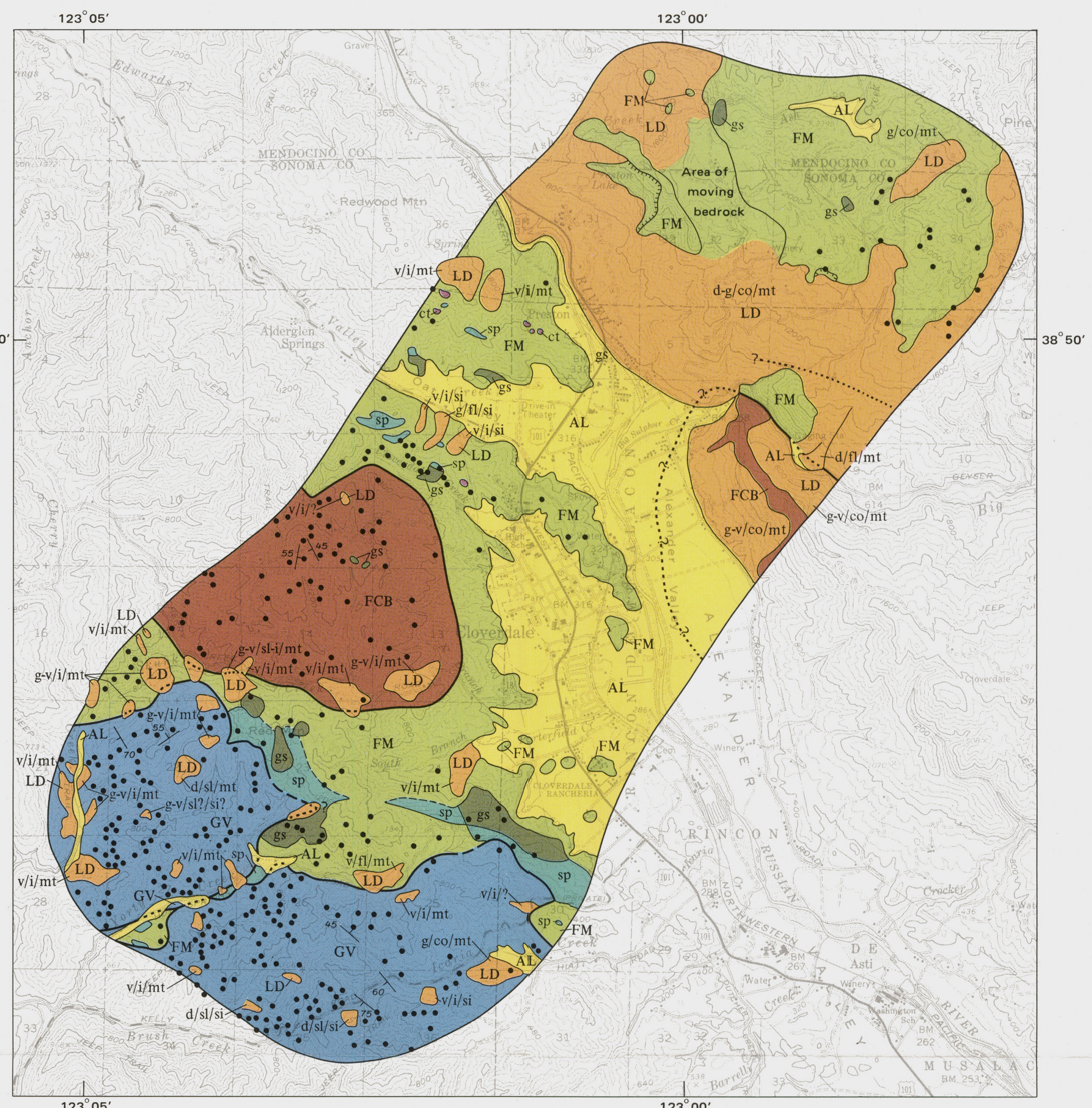


Figure 2.—Map showing landslides and alluvium superimposed on preliminary geologic map (fig. 1). Data on surficial deposits modified from Frizzell (1974).

EXPLANATION

SURFICIAL DEPOSITS

AL — Alluvium. *Includes terrace deposits and artificial fill. Shown as Qal in figure 1*

LD — Landslide deposits. *Includes scarps; landslides generally larger than 30.5 m (100 ft) but smaller than 152.5 m (500 ft) in maximum dimension shown by dots (mostly earthflows or surficial debris flows). Shown as Qls in figure 1*

BEDROCK UNITS

Franciscan assemblage

FCB — Coastal belt. *Predominantly sandstone with minor mudstone and rare greenstone. Shown as fss in figure 1*

FM, FMS, FMM, gs, ct, sp, (m) — Melange. *Predominantly mudstone and sandstone with lesser amounts of chert, greenstone, serpentinite, and high-grade metamorphic rock. Predominant rock type inferred to underlie large areas shown in parentheses; outcrops where lithology is known are labeled without parentheses (see list of abbreviations used for rock types under "Point descriptions of lithology and physical state")*

FM, *melange, undifferentiated. Shown as fs in figure 1*

FMM, *melange, undifferentiated; relatively large amounts of mudstone*

FMS, *melange, undifferentiated; relatively large amounts of sandstone, chert, and greenstone*

GV — Great Valley sequence. *Mudstone and fine sandstone, finely interbedded, and minor amounts of conglomerate. Shown as gv in figure 1*

PHYSICAL STATE OF BEDROCK

Massive to fractured

Fractured, contorted, or crushed. *More than 50 percent of rock in category shown. Pattern omitted from bedrock areas where data are insufficient to determine physical state. Physical state of many small areas of specific rock types has not been checked*

Sheared

LD/FMM — Lithology and physical state of bedrock underlying landslide deposits. *Inferred from composition of landslide debris. In this example, sheared rocks of unit FMM are assumed to underlie the landslide*

OTHER SYMBOLS

Area of anomalous topography. *Inferred to indicate deep-seated gravitational creep*

Contact

Fault. *Dashed where approximately located; dotted where concealed or inferred; queried where doubtful*

Topographic trenches. *Some trenches are associated with undrained depressions*

Undrained depressions

Spring or seep

Source area for landslide debris

× 90ss-m, f; mu-s   ⊗ (ss, mu)-s

Point descriptions of lithology and physical state. *Number indicates percentage of indicated lithology; letters after dash indicate physical state, according to abbreviations given below. Rock types shown in parentheses if percentages unknown. Example on left shows 90 percent sandstone—massive, fractured; remaining percentage mudstone—sheared. ⊗ indicates places where more than 50 percent of rock is sheared. Abbreviations used in point descriptions:*

Lithology	Physical state
fd—fine debris (predominantly clayey landslide debris)	s—sheared
sp—serpentinite	cr—crushed
gs—greenstone	c—contorted
ss—sandstone	m—massive
mu—mudstone, undifferentiated	f—fractured
ms—mudstone, silty	
mc—mudstone, clayey	
ct—chert	

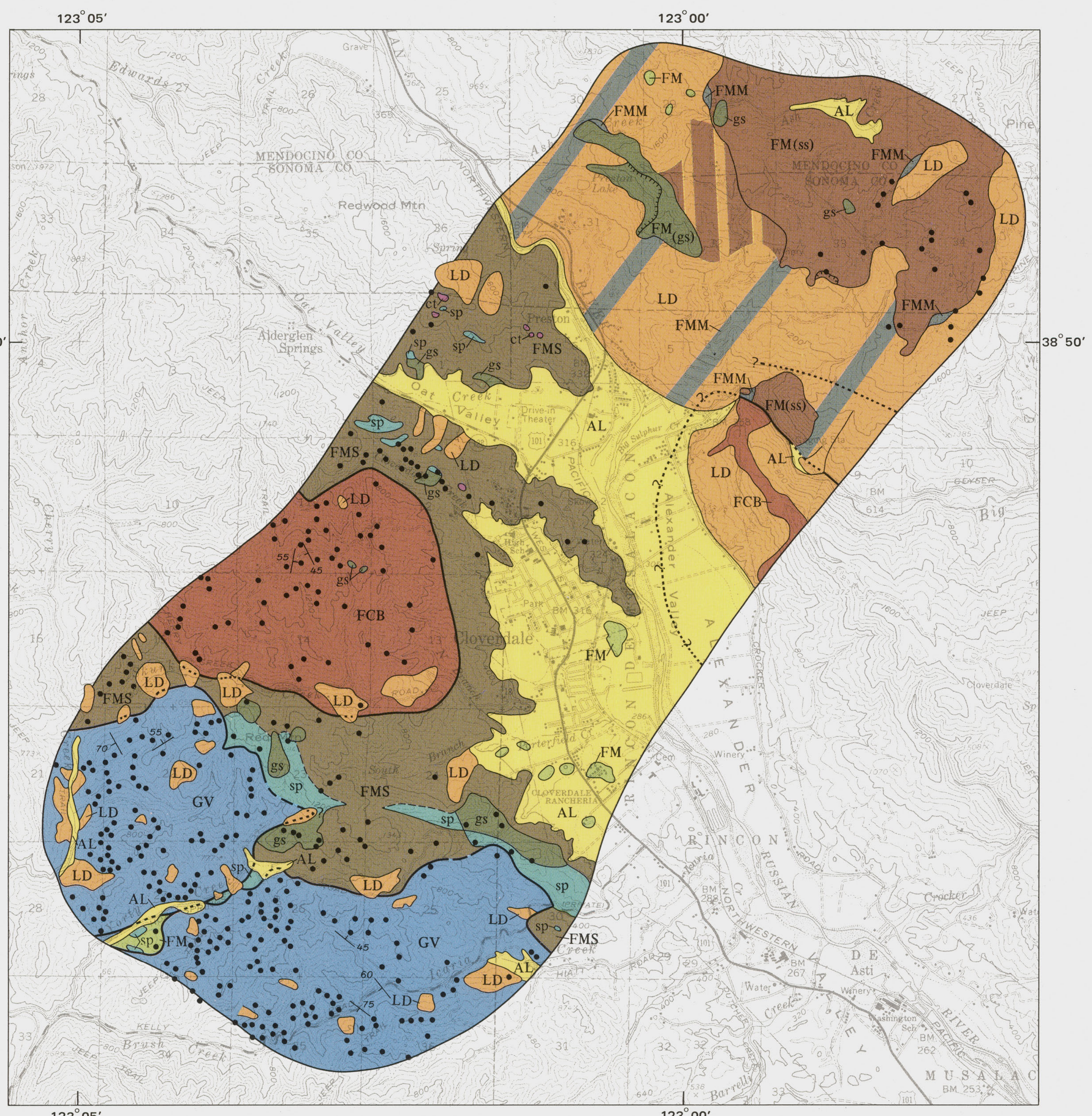
d-g/co/mt

Landslide classification symbols for larger landslides. *First letter indicates degree of clarity on aerial photographs used in this study; second indicates type of landslide; last indicates complexity. Abbreviations used in landslide classification:*

Clarity on aerial photographs	Type
d—distinct (definite scarps and toes)	sl—slide
g—good (topography definite or shape fairly clear but no good scarps and toes)	fl—flow
v—vague or questionable	co—complex (includes several types of movement)
	i—indeterminate

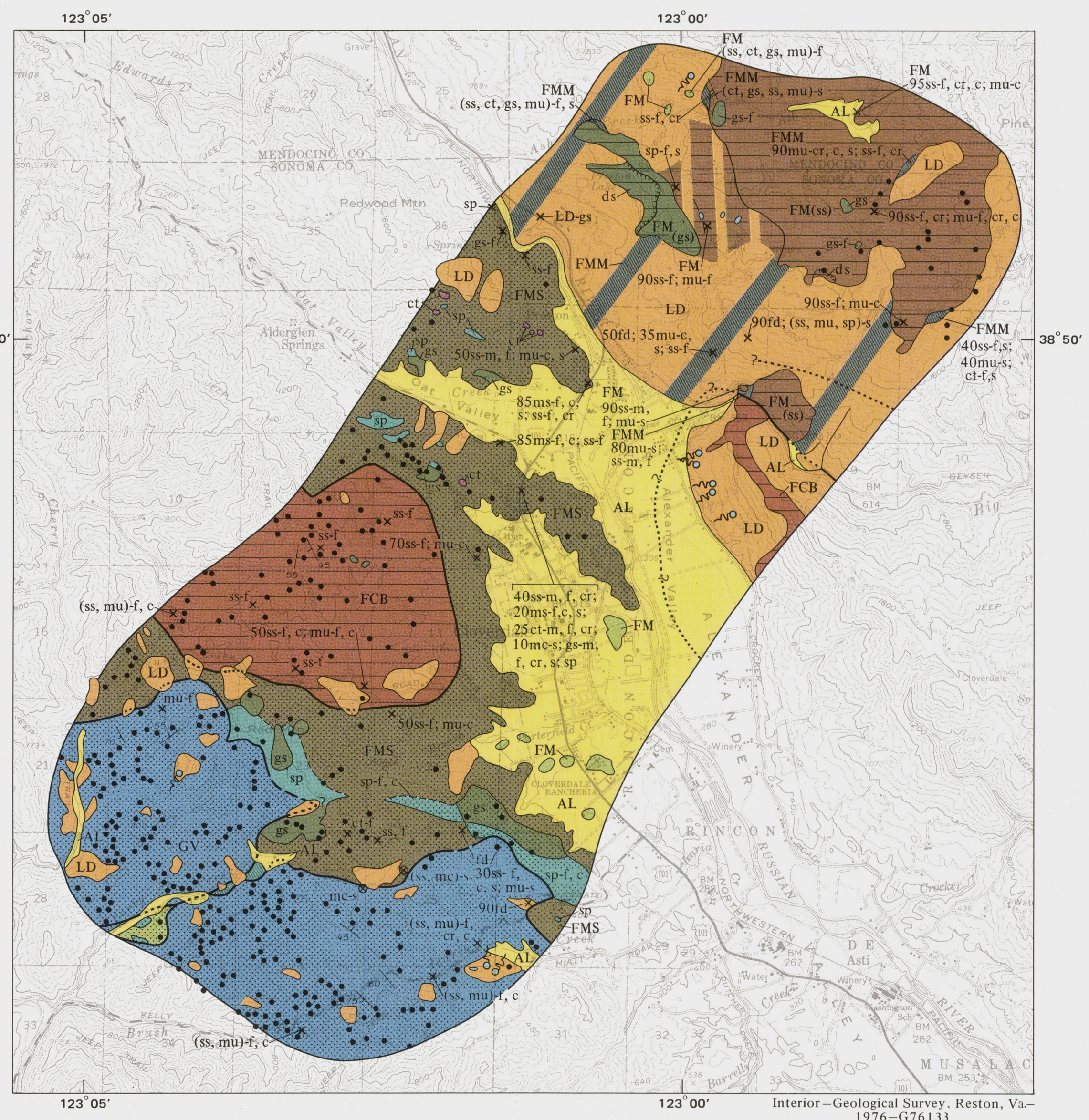
Complexity

si—single
mt—multiple (includes several landslides of one or more types)



Base from U.S. Geological Survey, 1:62,500, Kelseyville, 1959; Hopland, 1960, California.

Figure 3.—Map showing lithology superimposed on preliminary geologic map (fig. 1) and landslide map (fig. 2).



Interior—Geological Survey, Reston, Va.—1976—G76133

Fieldwork by D. H. Radbruch-Hall, 1972–74; assisted by C. Kaehler and J. Wallace

Figure 4.—Map showing physical state (shearing and fracturing) of bedrock added to preliminary geologic map, landslide map, and lithologic map.

INTRODUCTION

This study was made to determine, if possible, the geologic factors influencing slope stability in a part of the northern Coast Ranges of California and to illustrate a method of showing these factors on a map. An area between Cloverdale and Squaw Rock (index map) that seemed to be geologically and topographically similar to other parts of the northern Coast Ranges underlain primarily by rocks of the Franciscan assemblage was selected for investigation, with the hope that the results of the work could reasonably be extrapolated to other areas in the northern Coast Ranges.

This report is a summary of the work to date. It has been prepared to make the existing information available for current planning and construction in this and similar areas of the Coast Ranges. Only a small part of the total study area is discussed here (index map). Geologic fieldwork is partly finished for the remainder of the study area, so that some information from the rest of the area is drawn upon for this progress report.

Work so far completed indicates that lithology and physical state (amount of shearing and fracturing) of the rocks are the primary geologic factors influencing slope stability in this area. The accompanying maps (figs. 1–4) illustrate the relation between these factors and the amount and kind of landsliding and demonstrate a method of showing the geologic factors which differs from the system normally used on conventional geologic maps.

An additional aim of this study was to suggest a general procedure for identifying the basic geologic factors causing conditions that are hazardous or costly to development in any given area, using the slope stability problems of the northern California Coast Ranges as an example. Identification of these basic factors is necessary if these potentially hazardous or costly geologic conditions are to be avoided, corrected, or otherwise ameliorated.

METHOD OF INVESTIGATION

The part of the study area considered in this report is covered by a geologic map (Blake and others, 1971) that was prepared largely by compilation and reconnaissance. Three bedrock units, Franciscan melange, Franciscan coastal belt, and Great Valley sequence, were shown on the map by Blake and others along with alluvium, some landslides, and some small areas of specific lithologic types within the melange (fig. 1).

A preliminary map of landslides and alluvium was prepared using aerial photographs so that the relation between landslides and bedrock units shown on the map by Blake and others could be determined. This step was necessary because the now-published map of surficial deposits by Frizzell (1974), part of which was used for the maps in this report, was not yet available. A somewhat modified part of Frizzell's map was superimposed on the original geologic map for figure 2. Some small areas of specific lithology on the original geologic map were deleted to reduce clutter on the combined maps.

This overlay showed that the Great Valley sequence contains numerous small surficial landslides and some larger landslides; the Franciscan coastal belt also contains some surficial landslides and a few larger landslides in one area, and a large number of massive landslides in another; the Franciscan melange in places contains a large number of massive landslides, some mantling entire hillsides, and in other places has only a few surficial landslides or none at all.

Obviously the Great Valley sequence has uniform slope stability throughout the study area, but the Franciscan coastal belt and the Franciscan melange do not. Parts of the Franciscan melange, in particular, had very different types and amounts of landslides than other parts. The published geologic map showed no differences in the various parts of the Franciscan melange that could account for the difference in slope stability. It was therefore necessary to determine by field examination the factors that influence slope stability in this area.

Before the geologic conditions were studied in the field, other factors that might influence slope stability were investigated, including climate, slope, exposure, and vegetation. None of these factors seemed to be critical determinants of slope stability. Climate is relatively uniform over the entire small study area. The relation of exposure to landsliding did not appear to be pronounced; for example, massive landsliding and slopes with no landsliding, both in the Franciscan melange, can be seen on slopes of quite different orientation (fig. 2). Angle of slope with and without landslides in Franciscan melange varies greatly; this is particularly evident in the undifferentiated melange shown on the eastern part of figure 2. Slope appears to be closely related to rock type, with the steeper slopes generally in more resistant rock. A study of vegetation visible on aerial photographs showed that vegetation type and distribution reflect both rock type and current landslide activity; different types and amounts of vegetation grow on various geologic units and on stable and unstable terrain. Landslides that do not appear to be currently moving support more trees than those that are, although vegetation, particularly oak trees, may be abundant on those that are moving. Most landslide areas are very wet, but it is difficult to tell whether this is cause, effect, or a combination of both. Mudstone beds and shear zones may act as barriers to the flow of ground water, so that it comes to the surface along such beds and zones, thus contributing to landslides in sheared rocks and mudstone. Water also occupies depressions in relatively impervious clayey landslide debris.

The rocks in the area were examined in the field to see if any geologic factors could be isolated that would account for the variations in landslide type and abundance, particularly for the uniformity of the type and amount of landsliding in the Great Valley sequence and the extreme variation in type and amount of landsliding among parts of the Franciscan melange. This examination showed that a combination of variations in lithology and physical state (amount of shearing and fracturing) apparently accounts for the variation in slope stability in this area. The Great Valley sequence is relatively uniform in lithology and physical state; it consists predominantly of finely interbedded mudstone and sandstone, somewhat fractured and contorted, but not sheared. The Franciscan melange, on the other hand, contains not only interbedded mudstone and sandstone that are fractured and contorted but also interbedded mudstone and sandstone that are extensively sheared, masses of hard greenstone and sandstone that are only slightly fractured, greenstone and sandstone that are crushed and sheared, serpentinite, both fractured and sheared, and other types of rocks in various physical states. The amount and type of landsliding could be correlated with these variations in lithology and physical state throughout the area.

Bedding does not appear to be a major factor influencing landsliding in this area, particularly in the Franciscan melange where most bedding has been destroyed by tectonic disturbance. A few individual landslides may have moved on bedding planes.

It was apparent that a geologic map intended to relate landsliding and geologic factors in this area should show lithology and physical state. Accordingly, bedrock lithology and physical state were studied in the field, and additional data on lithology were then superimposed on the previous geologic map and the landslide map (fig. 3), and data on physical state were added (fig. 4).

On the final map (fig. 4) bedrock geologic units from Blake and others (1971), including Great Valley sequence, Franciscan melange, and Franciscan coastal belt, are shown by symbol. Lithology is shown by color, and physical state by pattern. Bedrock under large landslide areas is shown by alternate wide stripes of the color representing landslide debris and narrower stripes of the appropriate color and pattern for the underlying bedrock. The lithology and physical state of the bedrock underlying landslide deposits were largely assumed from the composition of the overlying landslide debris. Most landslide debris in the Franciscan melange consists of a high percentage—in many places more than 50 percent—of very fine debris, much of it clay, which has been derived from the source material by disintegration and weathering, so that the original lithology is not easily identifiable. However, almost all debris contains enough rock fragments, including shale, to indicate what the original material was. The assumption that landslide debris resembles the source material was reinforced by the results of drilling in landslide debris and underlying bedrock reported by geologists of the California Division of Water Resources who investigated the Dos Rios reservoir site in similar terrane of the Franciscan melange. These investigations showed that it was sometimes difficult to identify the contact between landslide debris and underlying bedrock because of their close similarity (M. E. Huffman, oral commun., 1973).

Point data, indicating the type of information that was collected in the field, as well as the location of undrained depressions, springs, and trenches are shown on the final map (fig. 4).

Physical state is shown in three categories: massive to fractured (includes no contorted or crushed rock); fractured, crushed, contorted (includes no massive rock); and sheared. This classification was adopted after field observation showed that type and abundance of landslides differed for the three categories. Pattern indicates the predominant category, although small amounts of other categories may exist within the predominant one.

Rocks were considered massive if fractures were 2 m or more apart. Fractured rocks are those with fractures from 2 m to 0.5 cm apart. Rocks having all fractures less than 0.5 cm apart but without shear planes were considered "crushed." The designations "crushed" and "contorted" are primarily applicable to relatively hard and relatively soft rocks, respectively, and describe rocks that have been intensely deformed but not sheared (slickensides none or very few). The "sheared" category includes gouge and rocks pervasively sheared. No attempt was made to subdivide the "fractured" category on the basis of fracture spacing, as there appeared to be no significant differences in overall stability related to fracture spacing where fractures are more than 0.5 cm apart. Some differences in stability related to fracture spacing might be detected if fracture spacing were studied in detail on a larger scale.

Areas of alluvium and landslide debris on the accompanying maps are taken primarily from a published map by Frizzell (1974) with some modifications for the purposes of this map. In particular, most landslides shown as queried on Frizzell's map are omitted, partly to reduce clutter on the map on which so many other data were to be shown, and partly because most seemed questionable enough that it was appropriate to omit them. The arrows used for small slides were changed to dots to make them more readily visible and further to reduce clutter. A few other changes represent differences of opinion. The landslides are classified according to a classification developed for use in this study (see map explanation).

The point data, indicated by × on the map, illustrate the type of data on lithology and physical state of bedrock or composition of landslide debris that were collected in the field. Not all points of field observation could be shown on the map.

DISCUSSION

Once it has been determined that lithology and physical state influence slope stability in the map area, the concept seems simple and obvious. However, the variations in slope stability behavior due to these two factors are far from simple.

The two variables, lithology and physical state, combine in roughly the following categories: (1) relatively dense, resistant rocks (sandstone, greenstone, chert, high-grade metamorphic rocks) that are massive, fractured, or crushed but not sheared; (2) relatively dense rocks that are sheared; (3) relatively soft rocks (mudstone with minor sandstone) that are fractured and contorted, but not sheared; (4) relatively soft rocks that are sheared. In terms of their behavior, the rocks most prone to massive landsliding are, as might be expected, sheared soft rocks; those least prone to any kind of landsliding are massive dense rocks. Sheared dense rocks are prone to landsliding, unsheared soft rocks less so.

Inasmuch as the physical state of the rocks is due in large part to tectonic deformation, consideration of the tectonic history of the area is helpful in understanding the reasons for their behavior and physical properties, which are so closely related to physical state.

A recent publication by Blake and Jones (1974) suggests a tectonic model for the northern Coast Ranges. The map units of Blake, Smith, Wentworth, and Wright (1971) shown on the accompanying maps (figs. 1–4) are roughly those used in defining this model. Blake and Jones suggest that the Franciscan melange consisting of chert, greenstone, and serpentinite with included blueschist and eclogite, all derived from the oceanic crust and upper mantle and set in a matrix of sheared mudstone and sandstone (graywacke), is a tectonic mixture formed by subduction during Early Cretaceous to early Tertiary time. The mudstone and sandstone matrix of the melange possibly represents a seaward part of the Great Valley sequence; the high-grade blueschist and eclogite are thought to have formed during an earlier period of subduction, then been embedded in the serpentinite, which was again subducted with the Great Valley sequence rocks. In the northern Coast Ranges, bands of melange separate several northwest-trending bands of sedimentary Franciscan rocks; the westernmost of these bands is the coastal belt, which is exposed in the present study area. After the period of subduction, rocks of the Great Valley sequence were thrust over the melange and the bands of rock bounded by the melange.

In general, the rocks of the melange matrix are more sheared and therefore more subject to landsliding than other bedrock units of the area.[1] The mudstone (mixtures of clay, silt, and fine sand of varying proportions) of the melange matrix is commonly pervasively sheared (each fragment of rock is bounded by slickensides, and if broken down, each smaller fragment is also bounded by slickensides, down to fragments less than 0.5 cm across) or sheared to gouge, whereas the sandstone of the matrix is fractured or crushed, but rarely sheared. Where the matrix consists predominantly of mudstone (roughly more than 50 percent), intensive sliding and development of thick blankets of moving debris are almost inevitable. Landsliding and debris accumulation also depend to some extent on distribution of the sandstone and mudstone. Landsliding is more intense if the mudstone occurs in wide bands than if sandstone and mudstone alternate in relatively thin beds. For this reason, the exact percentage of mudstone and sandstone that will slide cannot be specified. In some places a relatively thin layer of sheared mudstone acts as a surface along which large masses of sandstone move; in other places blocks of interbedded sandstone and sheared mudstone are relatively stable, although few blocks remain intact that contain more than 50 percent mudstone.

Another factor influencing the stability of the mudstone and sandstone matrix is the composition of the mudstone. Highly clayey rock is generally sheared pervasively or sheared to gouge, but in either case it is a very soft, plastic material susceptible to landsliding and to rapid breakdown to an incoherent mass. Silty to sandy mudstone may be intensively crushed so that it consists of small grains rather than gouge, but even where it is pervasively sheared, it may not break down as extensively as the clayey material. This relation between grain size and tendency to shear has also been noted by Skempton (1966).

Thick beds or large blocks of sandstone, greenstone, or chert of the melange are commonly fractured or crushed, but rarely sheared. Landslides form where these rocks are sheared, but inasmuch as the shearing is generally in bands no more than a few metres wide, landslides due to shearing of sandstone, greenstone, or chert are relatively small. These rocks are commonly fractured, and for this reason most blocks protruding from landslide debris gradually disintegrate. Landslide debris commonly piles up behind such masses of sandstone or other resistant rocks on hillsides and creeps away from the downhill side. Rock fragments from the resistant blocks fall to the downhill side and may be carried downhill by the moving debris to form a train of rock blocks or fragments extending downslope from the mass, eventually forming an extensive deposit of rocky colluvium. In some places these deposits have been exploited for road surfacing or other construction purposes. Sandstone and greenstone may also form larger masses as much as several kilometres long, in many places capping hills. Many of these masses of fractured and crushed rock at the heads of landslides are major sources of material for debris flows on the lower slopes. As they disintegrate, they constantly add material to the heads of the flows; this addition of material, combined with heavy seasonal rainfall, poor drainage, and removal of material from the toe by erosion, is a factor in the ever-renewed movement of the landslides. The debris source area in greenstone above Preston Lake (fig. 2) is a good example of a disintegrating mass in this type of setting.

Serpentinite characteristically consists of rounded boulders of hard, unsheared rock set in a very soft, pervasively sheared matrix. Serpentinite has often been described as having poor slope stability, but this characteristic of serpentinite is due in part to its sheared condition, not to lithology alone.

High-grade metamorphic rock may be fractured, but most is extremely resistant. It crops out as masses or boulders on the surface and protrudes from the sheared serpentinite in which it is included or from landslide debris.

The response of rock units within the melange to tectonic forces has been influenced by the amount of contrast between adjacent rock masses, whether these are stratigraphically or tectonically juxtaposed. Where beds of sandstone and mudstone are interlayered, the sandstone will fracture, whereas the mudstone will flow and shear as it is forced against the more resistant sandstone layers or blocks. However, where layers of mudstone and sandstone are gradational or finely interbedded, so that the contrast between various parts of the sequence is not great, the rock may fracture, contort, or shear as a unit rather than as individual beds responding in different ways.

Sequences within the melange that consist primarily of resistant rocks, such as massive sandstone, chert, and greenstone or combinations of these rocks, show very little shearing, generally only narrow bands several centimetres or at most a few metres wide, commonly where rocks of different types are in contact. Not only are all these rocks hard and resistant, but also the contrast in physical properties between the several types is not great enough to allow one to be sheared against the other on a large scale.

Rocks of the coastal belt of the Franciscan assemblage in this area consist predominantly of sandstone with minor mudstone. They tectonically underlie the melange, which indicates that at least part of the coastal belt rocks were subducted (Blake and Jones, 1974). In general, however, rocks of the Franciscan coastal belt are not extensively sheared, possibly because of their composition or because subduction had slowed or nearly ceased by the time these rocks were involved.

The Great Valley sequence in the study area consists predominantly of finely interbedded mudstone and fine sandstone. These relatively soft rocks have been deformed and contorted but rarely sheared. They overlie the Franciscan melange (Blake and others, 1971; Blake and Jones, 1974) and therefore were less subject to tectonic deformation than the melange. Moreover, because they are relatively uniform throughout, they have tended to respond to tectonic forces as a continuum.

TYPES OF LANDSLIDES

In this report, the term "landslide" is used as a general term for all types of slope movement. Landslides shown on the maps are classified according to three basic types of movement, as defined by Varnes (1958): slide, flow, and fall. Type of movement is based largely on what could be determined from aerial photographs. Individual landslides that display more than one type of movement are designated complex, and those whose type of movement could not be established are called indeterminate.

Landslides in the melange of the Franciscan assemblage consist predominantly of extensive masses of slow-moving debris derived from the underlying bedrock, although in some places the landslide may also involve movement of the bedrock underlying the debris. Studies made of similar landslides by the California Division of Water Resources show that the landslides may be nearly 200 feet (61 m) thick, indicating that the moving material is thin relative to the slide area, which may be several square miles in extent (Huffman and others, 1969). In the present larger study area, the ridge north of Cloverdale that extends along the east side of the Russian River from Big Sulphur Creek northward to Pieta Creek (index map) is nearly covered with landslide deposits. Small flows are superimposed on the larger masses of moving debris when the surface material flows during rainy seasons. In some places at the top of the ridge, anomalous trenches and closed depressions in apparently otherwise undisturbed bedrock (labeled "area of moving bedrock" on map) indicate large-scale, deep-seated gravitational movement of the bedrock.

No detailed measurements were made of dimensions or rate of movement of individual landslides or landslide areas. However, it is apparent that rate of movement varies. Some landslide deposits appear nearly stable, others move very slowly over tens of years, whereas others move rapidly with every rainy season. Measurements made of similar landslides by geologists of the California Division of Water Resources recorded rates of movement ranging from 0.7 inch (1.8 cm) to 20 feet (6 m) per year (Huffman and others, 1969).

Large masses of greenstone and sandstone (part of the Franciscan melange) lie at the tops of some of the hills on the east side of the river, where softer sheared rocks of the melange are exposed on the slopes, topographically and possibly structurally below the greenstone and sandstone. In some places large blocks of the more resistant rocks have broken away and slid down the hillslide as massive landslides. The steep, southwest-facing scarp of greenstone above Preston Lake appears to be the scarp of a massive landslide of this type. Abundant greenstone can be seen in the debris between the scarp and the Russian River. Smaller rock masses are constantly breaking from the face, and there is continued movement of the debris below it, particularly during wet years when cutting of the toe by the Russian River is accelerated. The area east of the greenstone consists of sandstone and mudstone that are cut by anomalous trenches and closed depressions, indicating that deep-seated movement involving the entire slope, probably including the greenstone mass, is now taking place or has taken place recently enough that topographic evidence of the movement is still visible. No linearity of trenches, gouge, or other evidence implies that the trenches could be caused by active faulting, although recently active faults are known southeast of this area and trend toward it. Very few large landslides form within the masses of resistant chert, greenstone, or massive sandstone, although small surficial flows are common in debris that accumulates in ravines and depressions in these rocks.

Sheared serpentinite and its overlying soil tend to creep, flow, and slide, although fractured and crushed serpentinite may be relatively stable. Where large blocks are not sheared, they may form resistant bands or knobs. The erosional topography characteristic of massive to fractured stable blocks of serpentinite or high-grade metamorphic rock surrounded by sheared rock is sometimes difficult to distinguish from the hummocks and swales of landslide topography.

Landslides in the predominantly sandy rocks of the Franciscan coastal belt are both massive slump-type slides and debris flows. Most of the slumps appear to be old, possibly Pleistocene. A few large currently active debris flows form in sheared bands within the unit, particularly where the proportion of mudstone to sandstone is high. Most of the sandstone has weathered in place; the weathered material and overlying soil may slide during the rainy season to form relatively small surficial debris flows.

Landslides in the Great Valley sequence of the study area are predominantly small flows involving soil and weathered bedrock, although there are also larger slumps involving primarily bedrock. The small surficial flows are particularly abundant during a wet year, when the soil and colluvium become saturated with water that percolates downward and accumulates at the surface of the less permeable unweathered bedrock. This type of landslide most commonly forms in shallow swales or linear depressions extending down the slopes, or at the head and along the sides of ravines.

Pronounced differences can be seen in landslide behavior within the map units of Blake, Smith, Wentworth, and Wright (1971), owing to internal variations in lithology and physical state (fig. 4); massive, large-scale debris flows are active in the area of Franciscan melange on the east side of the Russian River, but relatively few occur in the same unit on the west side. The Franciscan melange contains a large amount of sheared mudstone with lesser amounts of other rocks on the east side of the river and predominantly more resistant rocks with lesser amounts of sheared mudstone on the west side. Where sheared mudstone surrounds blocks of more resistant rocks on the west side, large flows have developed, some of which have caused continual problems for the railroad along the west side of the river, north of the map area of figures 1–4.

Massive old slump-type landslides also exist in sandstone of the Franciscan coastal belt on the east side of the river east and southeast of Cloverdale, and not on the west side. A mixture of rocks of the Franciscan melange lies at the base of the slope southeast of Cloverdale (Blake and others, 1971; south of map area of figs. 1–4) and may possibly underlie the Franciscan coastal belt there; this situation might facilitate landsliding in the coastal belt sandstone. It also appears that landslides form in both the sandstone of the Franciscan coastal belt and in predominantly sandstone parts of the Franciscan melange, wherever bands of mudstone occur. Large landslides in the southern part of the westernmost mass of the coastal belt are in areas where the percentage of mudstone is higher than elsewhere in the coastal belt (see point data on fig. 4). The composition of landslide debris indicates that the percentage of mudstone may be higher where sandstone of the Franciscan coastal belt has slid east of Cloverdale, but no exposures of mudstone were visible to confirm this possibility.

ENGINEERING PROBLEMS

The many landslides in the northern Coast Ranges cause nearly insurmountable construction difficulties in some areas. Extensive landslide problems occurred during construction of the present U.S. Highway 101 between Cloverdale and Hopland (Forster, 1933), and maintenance of the highway has been a problem ever since. The Squaw Rock landslide, 11 km north of Cloverdale, has been known to be active since the settlement of the region; local residents say that constant repair of the old stage road across the landslide was necessary. At the present time a highway bridge spans the toe of the landslide, but constant removal of debris still is required to prevent damage to the bridge.

The Preston landslide, 5 km north of Cloverdale, has been almost equally troublesome, and there have been continual other slope stability problems between these two major landslide areas. Maintenance records of the California Department of Highways show that removal of landslide debris and repair of landslide damage have cost $55,000 for the Squaw Rock landslide and $70,000 for the Preston slide area for the period 1964 to 1974. These are minimum figures, as much of the minor routine maintenance is not recorded for individual landslide areas.

Widening and possible relocation of the highway between Hopland and Cloverdale are now being considered, but no completely satisfactory solution to the slope stability problems has yet been found.

FUTURE MAPPING OF SLOPE STABILITY FACTORS

The method used in this study to determine the essential geologic factors related to slope stability can be used in the following way, both in the Coast Ranges and elsewhere, in preparing maps for evaluation of slope stability and for other engineering geologic uses:

1. The slope stability behavior of the rocks in any area, as well as other behavior relevant to engineering construction, can be determined and compared with existing geologic maps, to learn whether the behavior is covariant with established map units. (See Varnes, 1974, for a discussion of covariance in geologic maps.)

2. If it is not, a field reconnaissance can be made to discover the reason for the lack of covariance, and the factors that do correlate with the behavior can be determined.

3. These factors, whether they be stratigraphic, tectonic, physiographic, climatic, or some combination of these and other factors, can then be mapped. Their characteristics and distribution, as well as their relation to existing geologic units and engineering geologic behavior, can also be shown on maps.

4. Behavior can then be predicted from maps showing these factors in other areas where the geologic and other natural conditions are similar.

This technique can be applied to maps of various scales and in various geologic terranes. Factors that are critical in one area may not be critical in another, however, so that factors established as determinants for engineering geologic behavior in one region may not be applicable in another, particularly where either tectonic or stratigraphic conditions are vastly different. The criteria used in the Sierra Nevada granitic terrane would not, for example, be applicable to glaciated areas of the Midwest.

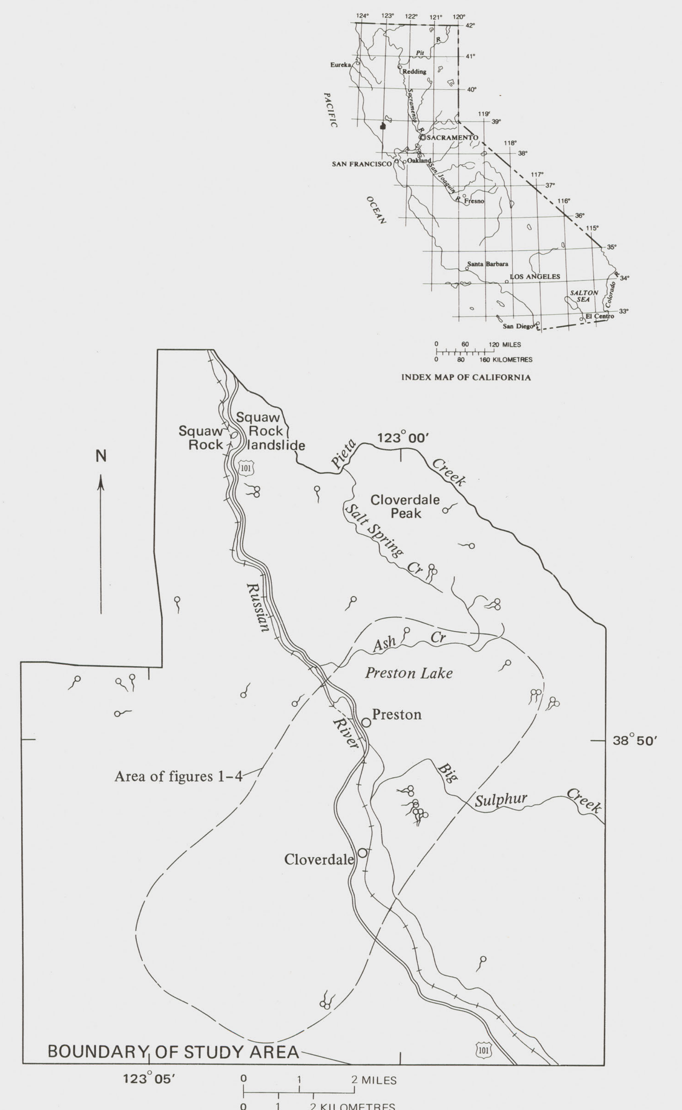
SUMMARY

Using the technique outlined in the previous section, certain geologic factors critical for slope stability in the northern Coast Ranges have been determined and shown on the illustrative map.

The basic geologic conditions that cause massive slope movement in the northern Coast Ranges are lithology and physical state (amount of fracturing and shearing) of the bedrock. These conditions are the result of the original circumstances of formation of the rocks and their subsequent history, particularly tectonic history. Maps showing lithologic units and their physical state can be used to predict slope stability for engineering purposes. Establishing broader geologic units that reflect age, genesis, tectonic history, and structure of the lithologic units may provide clues to their behavior.

A similar technique can be used anywhere to prepare geologic maps showing map units based on the appropriate geologic factors that influence engineering geologic conditions.

[1] Landslide debris is itself prone to further landsliding but is not considered a bedrock unit.



Index map showing location of study area in northern Coast Ranges, California, and area of figures 1–4.

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SCALE 1:62,500

1 ½ 0 1 2 3 4 5 MILES

1 .5 0 1 2 3 4 5 6 7 KILOMETRES

CONTOUR INTERVAL 80 FEET
DATUM IS MEAN SEA LEVEL

MAPS SHOWING AREAL SLOPE STABILITY IN PART OF THE NORTHERN COAST RANGES, CALIFORNIA

By
Dorothy H. Radbruch-Hall

1976

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