PRELIMINARY MAP SHOWING RECENCY OF FAULTING IN COASTAL SOUTH-CENTRAL CALIFORNIA*

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INTRODUCTION

Seismic shaking and surface faulting can severely damage engineered structures unless adequate precautions are taken in siting and design. The information on which such precautions must be based includes identification and delineation of those faults that are capable of generating earthquakes and rupturing the ground. This report is directed toward the identification of such faults in coastal south-central California by summarizing what presently is known about the location of faults and the recency of displacement along them.

The age of most recent movement along a fault can be approximated from the youngest stratigraphic unit displaced by it or from the relative freshness of certain geomorphic features found along its trace. The relative ages of most recent movement along different faults can then be compared. From this comparison a determination can be made of which faults should tentatively be considered active for particular land uses (Ziony, Wentworth, and Buchanan, 1974). Although the capability of movement along individual faults also can be evaluated from historic surface faulting or creep movement, historic seismicity, instrumentally determined strain accumulation, or geologically young displacement inferred from geomorphic features (Louderback, 1950; Bonilla, 1970; Allen and others, 1965; California Department of Water Resources, 1964), few of these indicators are applicable to regional studies of fault activity.

NATURE AND PURPOSE OF MAP

This preliminary map depicts (1) the locations of presently known or inferred faults in coastal south-central California between Pigeon Point and Point Arguello, including the adjacent Continental Borderland (map sheets 1 and 2), and (2) what currently is known about the recency of displacement along each fault.

The onshore part of the map represents an analysis of geologic information obtained from published or publicly available unpublished material, supplemented by limited field investigations of selected faults; the location of offshore faults and their recency of movement are based on interpretations of acoustic profiles. Limitations of these procedures are discussed in a following section. It is important to realize that because of insufficient investigation of the geology, future geologic and geophysical studies undoubtedly will identify many more faults and may also disclose evidence requiring changes in classification of the recency of movement along some faults now shown on the map.

Preparation of the map was guided by the philosophy that portrayal of questionable evidence of faulting should lead to proper investigation, whereas omission of such evidence would lead to the inference that no problems exist. Thus, some questionable data have been included on the map so long as they had some basis and were reasonable. Individual faults and inferred connections between faults have been shown where reasonable, even though conclusive evidence for their existence may be lacking. Similarly, the ages assigned to stratigraphic units used to determine the age of latest fault movement are as young as is consistent with presently available data.

A source diagram (map sheet 3) indicates the various sources used in compiling each part of the map, and the list of sources at the end of the text contains the complete bibliographic citation for each reference. Published reports are available in or through most geologic libraries. Unpublished theses can be consulted at the respective schools. Other generally unavailable data are on file at the California Division of Mines and Geology, Ferry Building, San Francisco, California, or in the library of the U.S. Geological Survey, Menlo Park, California.

This map was prepared on behalf of the U.S. Nuclear Regulatory Commission as one of a series of small-scale maps of coastal California showing geologic factors of concern to the siting and design of nuclear power reactors. Earlier products of this project (Wentworth and others, 1970; Ziony and Buchanan, 1972; and Ziony, 1973) summarize information on the Los Angeles and San Diego areas, respectively; these data, somewhat modified, were subsequently incorporated into a study of coastal southern California (Ziony, Wentworth, Buchanan-Banks, and Wagner, 1974). The present map extends these studies northward using the same philosophy and graphic techniques. Although prepared primarily to facilitate the identification and investigation of faults that may be of significance to engineering development because of their potential for movement, the map should neither be used directly as a hazards map, nor in place of detailed site studies.

Most of the text accompanying the present map is taken from U.S. Geological Survey Miscellaneous Field Studies Map MF-585, by Ziony, Wentworth, Buchanan-Banks, and Wagner (1974). It is recommended that the user refer to the previous text for elaboration of the criteria used in preparing the map.

DETERMINATION OF AGE OF LATEST FAULTING

The precise age of latest faulting is known only for those few faults that have undergone surface movement in historic time. The age of most faults must be inferred from geologic evidence that only provides limits on the span of geologic time during which the latest movement occurred and this span may be thousands or millions of years long. The length of the time span that can be defined for each fault depends on the completeness and preservation of the local geologic record. Figure 1 shows the relations between the age of the most recent faulting and the geologic evidence used to infer the time span during which faulting occurred.

Stratigraphic relations are the chief source of information for bracketing the age of latest faulting. Relations between a fault and adjacent rock or sediment units ideally can define both maximum and minimum limits within which the latest faulting occurred, as in Figure 1. How closely the time of latest movement can be assessed depends on the closeness in age of the bracketing stratigraphic units. In some areas of surficial deposits, stratigraphic and structural relations may be inferred from discontinuities in the flow or level of ground water in the deposits. For instance, the presence of ground-water barriers, impediments, or cascades within water-bearing Pleistocene valley fill may indicate faulting of at least the lower part of that material.

Displacement of the ground surface by faulting commonly produces distinctive geomorphic features. These features usually are short-lived parts of the landscape, and their presence indicates relatively recent fault movement. The age of such geomorphic features thus determines the maximum limit on the age of latest faulting, because the faulting can be no older than the age of the fault-produced feature. Criteria can be selected whereby different geomorphic features suggest different ages of the most recent ground displacement (see footnotes to age range chart in map explanation). Inference of the age of such geomorphic features is, however, particularly uncertain, because the rate at which these features are destroyed depends on such variables as material hardness, climate, and the activities of man.

The time range of latest movement can be restricted most closely for faults where the age difference between the youngest faulted rock and the oldest unfaulted rock is small. Commonly, however, the record of thousands or even millions of years of earth history may be lacking because of non-deposition, erosion, or human excavation of stratigraphic units. Thus, the time span between the maximum and minimum stratigraphic controls may be quite large, bracketing a long period of geologic time during which the most recent movement of a fault occurred. An added difficulty is that, for many faults, the preserved stratigraphic record provides no minimum limit on the time of latest faulting, except for surficial deposits that may be only a few hundred years old.

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DESIGNATION OF FAULTS AS ACTIVE

The information on recency of faulting portrayed on the map is effective in determining that some faults can be reasonably classified as active or inactive, and it may be helpful in deciding whether many other faults, whose state of activity remains uncertain, should prudently be assumed to be active for certain land uses. Whether or not a fault is active can seldom be determined with certainty, however, because the distribution and frequency of movement along active faults is not well understood and because the geologic record commonly does not provide sufficient control on the time of latest movement for many faults.

Selection of the time span since latest movement that is used to designate faults as active has been influenced by the potential consequence of seismic shaking or surface faulting on specific engineered structures. That is, the greater the risk incurred if the active nature of a fault is not recognized, the longer the time span that must be considered, in order to include more of the possibly active faults. Displacement during Holocene time (the past 10,000 years) is a generally accepted criterion of activity for many land uses; this time span is probably inadequate, however, to assume recognition of all active faults, because historic offsets have occurred along faults, such as the White Wolf fault of California, that had no previously recognized evidence of Holocene faulting.

Therefore, at least the past few hundred thousand years are important in assessing the present activity of a fault. Because the geologic record of this period of time is not available for many faults in coastal south-central California (owing to nondeposition or removal of significant stratigraphic units), evidence of movement during successively older segments of late Cenozoic time must be resorted to in evaluating fault activity.

Faults classed as historic, Holocene, or late Quaternary exhibit positive stratigraphic or geomorphic evidence of movement within the past several hundred thousand years and can reasonably be designated as active, depending on the safety factor required. On the other hand, pre-late Cenozoic faults are known or inferred to have been quiescent for at least 12 million years; most of them originated in response to stress systems that apparently have been superseded, and where the minimum control is good, these faults can be considered inactive. Similarly, faults overlain by undisturbed strata of early Pleistocene or late Pliocene age have not undergone movement for at least 700,000 years or 2,000,000 years respectively and can reasonably be considered inactive under the present state of stress. For many applications, minimum age control based on unfaulted upper Pleistocene or Holocene strata cannot, however, be considered sufficient basis for inferring that a fault is inactive. These deposits represent time spans of several thousand to several hundred thousand years, which are relatively short when compared with the length of geologic time and the probable range in duration and rates of tectonic processes. Some faults overlain only by late Pleistocene or Holocene deposits may be infrequently moving active faults that are not recognized as such because knowledge of recurrence intervals is incomplete.

The geologic record in coastal south-central California is inadequate to classify most faults as either active or inactive on the basis of recency of faulting. Faults without minimum age control that are classed as Quaternary, late Pliocene and Quaternary, late Cenozoic, or "Unknown" lack positive evidence that either supports or refutes young displacement. Movement as recent as the present cannot be precluded along many of these faults, although the apparent absence of recognized geomorphic evidence of surface faulting, which commonly is associated with late Quaternary faulting, suggests that they may not have moved during the past several hundred thousand years. For these faults, activity cannot be further assessed unless geodetic or seismic monitoring indicates deformation currently is occurring along them.

LIMITATIONS OF MAP

Limitations of the map must be recognized so that it will be used with appropriate caution. It is important to realize that all existent faults are not portrayed on the map. Absent are many faults too short to show at the map scale and, more significantly, faults that are presently unrecognized because of a cover of surficial sediment or water. Several factors affect the reliability and completeness of the information shown: the nature of the geologic record and its availability to observation; the amount of geologic study that has been applied; the quality of the age designation of stratigraphic units that provide limits on the age of latest faulting; and the purposes for which the original data sources were prepared. Because of variations in these factors, the reliability of information on fault location and recency of displacement differs from place to place. Diagrams on map sheets 1 and 2 show the probable reliability of different parts of the map in terms of the likelihood that additions or modifications might result from further investigations.

Because direct observations are extremely limited for the offshore area, data on both location and age of faulting generally are least reliable for this part of the map. Geologic information here has been derived chiefly from interpretation of geophysical data such as subbottom acoustic-reflection profiles (for a review of the method, see Moore, 1969, p. 97-111). The presence of faults and their relations to stratigraphic units are inferred from analysis of the geometric configurations of graphically recorded reflections of sound waves (Wagner, 1974). Factors such as depth to the sea floor, the type of geophysical equipment used, and the spacing and accuracy of location of track lines determine the quality of the offshore geologic mapping. As a result, offshore data points are scarce compared with those onshore, and the positions, lengths, and trends of offshore faults are known with much less certainty than those onshore.

Finally, use of the map is limited by the small scale of 1:250,000. At this scale, a mile on the ground is represented by about a quarter of an inch on the map (1 km = 4mm), and detail, length, and spacing of fault traces must be generalized. Fault traces shorter than or closer together than about 1,500 feet (460 m) are not differentiated, except for significant young faults, which are represented by star-shaped symbols. The map scale limits accuracy of location of features to plus or minus 1,000 feet (305 m).

MAP SYMBOLS

Line symbols on the map show the location, extent, and relative certainty of existence of faults. Letters tied to these line symbols distinguish various age classes that reflect the latest known or inferred movement of each fault. The location, type, and age of stratigraphic or geomorphic control that are used to limit the age of these displacements are shown by open symbols, containing numbers, superposed on the fault traces. Faults along which historic surface displacement has occurred are emphasized by a line pattern. Patterned areas onshore represent regions in which surficial deposits generally exceed 50 feet (15 m) in thickness; unpatterned areas onshore designate bedrock units that are exposed or lie beneath a relatively thin cover of surficial deposits.

Line symbols for faults

A solid line onshore represents the trace of a fault that displaces the rock or sediment adjacent to it at the ground surface, whereas a dotted line represents the trace of a fault that is concealed by a significant thickness of rock, sediment, or water and therefore does not extend to the surface. If the existence of a fault is uncertain, a solid line with superposed queries is used. A query at the end of a fault trace indicates probable but unknown continuation of the fault for a significant distance beyond that point. Faults that are too short to show as a line at the map scale but are significant because of relatively young movement are represented by a star.

Offshore faults inferred from apparent stratigraphic discontinuities in acoustic profiles are indicated by dashed lines. Some of these faults may be overlain by significant amounts of young sediment on the sea floor, but the available acoustical data commonly do not permit resolution of relations at or near the sea floor. Fault trends shown on the map are approximate and are based on inferred connections between relatively widely spaced ship-track crossings of interpreted faults. Because of probable undocumented extensions, the ends of all submarine fault traces are queried.

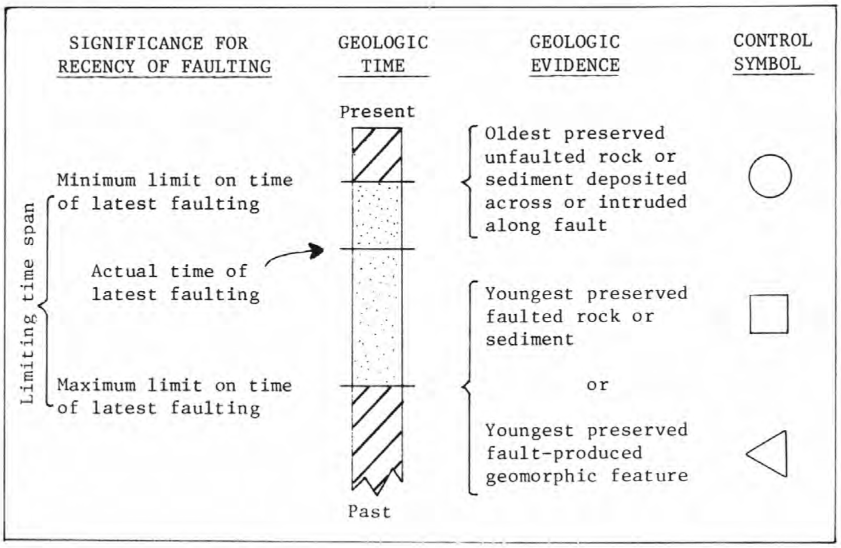

Figure 1.--Basis for determining recency of faulting: available geologic limits on time of latest faulting and symbols used to show that control on map.

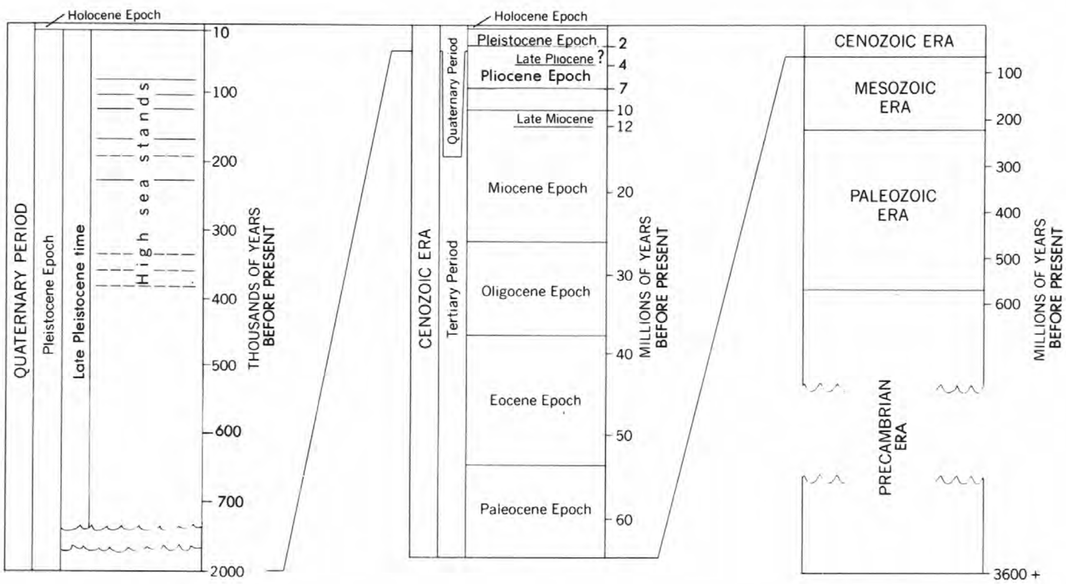

Figure 2. Approximate provincial geologic time scale for coastal south-central California. The tentative eustatic high stands of sea level (solid line, control from radiometric dates; dashed line, inferred from Barbados terraces and solar radiation curve) represent the most likely times of sediment accumulation during late Pleistocene time. Time scale chiefly after Geologic Names Committee of U.S. Geological Survey (written commun., 1972) except as follows: high sea stands are from Mesolella, Matthews, Broecker, and Thurber (1969); Holocene-Pleistocene boundary is from Hopkins (1975); beginning of late Pleistocene time from Butzer (1974); and beginning of late Miocene time is from Turner (1968). The boundaries of late Miocene time shown are those most consistent with current California usage. The beginning of late Pliocene time is uncertain and is arbitrarily placed at 4 million years.

Symbols for geologic control

The geologic control on which the age of latest faulting is based is shown by symbols placed on the fault trace at or near the point where the controlling geologic relations occur. The youngest displaced rock or sediment unit along a fault is indicated by an open square, and the age of that unit is represented by the number within the square keyed to the age range chart in the explanation (sheet 1). Similarly, the oldest geologic unit that overlies or intrudes a fault without displacement is shown by an open circle containing a number keyed to the same chart. Geomorphic features indicative of geologically recent faulting are shown by an open triangle; the inferred age of the geomorphic features is shown by the number inside the symbol.

AGE CLASSIFICATION OF FAULTS

The faults are assigned to eight classes by age of latest displacement. A fault is classified chiefly on the basis of the youngest known stratigraphic or geomorphic evidence of faulting preserved along it, which is indicated on the map by the control symbols. This classification emphasizes the possible youthfulness of a fault. Faults lacking positive evidence for or against late Cenozoic movement are assigned to the "Unknown" class unless they can be related to other faults whose history is better understood. The age range of a particular fault in a class may be restricted by the presence of unfaulted deposits that provide a minimum limit on the age of the most recent faulting. The entire length of a fault is assigned to a single age class consistent with the evidence of youngest movement along its length, unless minimum control indicates that one part of a fault cannot have moved as recently as another part.

The age categories are based on time-stratigraphic boundaries within late Cenozoic time (approximately the last 12 million years of earth history) because older history probably has little bearing on current fault activity in coastal south-central California. Classes selected are derived from the available stratigraphic record as indicated by regionally significant unconformities and by widespread correlative deposits. An approximate geologic time scale (Fig. 2), presents age designations and their approximate limits in years as commonly used by geologists for strata in coastal south-central California and as referred to in the text and map explanation. Figure 3 summarizes the assignment of stratigraphic units to selected time intervals of the late Cenozoic for purposes of the map; each stratigraphic unit (with the exception of the Paso Robles and Pismo Formations) is placed in a single time interval that contains the youngest known age compatible with available geologic evidence.

The classes used to represent recency of faulting are:

- Historic - latest movement within period of reliable observations of surface faulting (since 1890).
- Holocene - latest movement within past 10,000 years.
- Late Quaternary - latest movement within past 700,000 years.
- Quaternary - latest movement within past 2 million years.
- Late Pliocene and Quaternary - latest movement within past 4 million years.
- Late Cenozoic - latest movement within past 12 million years.
- Pre-late Cenozoic - latest movement before about 12 million years ago.
- Unknown - history of movement in past 12 million years indeterminate.

Historic

In this region, faults classified as historic have had documented displacements since 1890. Townley and Allen (1939) describe the 1890 earthquake as producing "...fissures in the San Andreas fault zone near Chittenden, east of Watsonville. The railroad track was moved, and the railroad bridge over the Pajaro River was displaced." This event produced a segment of surface faulting approximately 7 mi (11 km) long extending from Pajaro Gap southeasterly to near San Juan Bautista.

Another episode of historic surface faulting occurred along the San Andreas fault in 1906 (Lawson and others, 1908). The surface ruptures from this earthquake extended northwestward from San Juan Bautista for approximately 270 mi (434 km), 38 mi (61 km) of which was within the present map area. One surface rupture east of San Juan Bautista may have had an origin other than faulting and is shown with a query following the date.

The most recent fault movements in the map area are occurring as fault creep (that is, small apparently continuous movements along a fault, usually of an aseismic nature) (Steinbrugge and Zacher, 1960; Tocher, 1960; and Radbruch and Bonilla, 1966). Where this phenomenon has been observed along faults, it is indicated on the map by the word "creep". Fault movements that are questionably the result of creep are shown with a query following the notation.

On map sheet 1, the San Andreas fault shows evidence of creep movement from the vicinity of San Juan Bautista southeasterly to beyond the map boundary. Fault slip of about 0.12 inches/year (3 mm/yr) has been observed on the Sargent fault approximately 12 miles (20 km) northwest of its junction with the Calaveras fault (Prescott and Burford, 1976). Creep events on the Calaveras fault within the map boundary extend from the south end of Anderson reservoir to about 5 miles (8 km) south of Hollister, a distance of about 27 miles (45 km).

On map sheet 2, geodetic measurements along the More Ranch fault near Goleta Point record movement that is tentatively considered to be the result of tectonic creep (Sylvester, 1977, oral commun.).

Holocene

The Holocene age class represents faults that are known or inferred to have moved within the past 10,000 years. Historic displacement may have occurred along such faults, but none has been recognized. Faults assigned to this class displace stream and flood-plain sediments deposited since the rise in sea level at the close of the Pleistocene Epoch approached present sea level. The base of these Holocene deposits, which have been dated precisely in only a few places, is the only widespread common datum for evaluating fault movements within the past 50,000 years. It may range in age from about 10,000 years to several hundred years or less for modern alluvium.

Fault-produced geomorphic features provide the other main source of age information for the Holocene class. In the present study, the following features in association with a fault trace are considered criteria for inferring displacements during the past 10,000 years: sag ponds or other closed depressions, offset stream courses in Holocene deposits, linear scarps in Holocene deposits, and linear submarine scarps in sea-floor sediments above wave base. These features are rapidly degraded, and their presence thus strongly suggests very young fault movements.

Late Quaternary

Faults that are known or inferred to have moved in the past 700,000 years are included in the late Quaternary category. Holocene or even historic displacements may have occurred on faults so classed unless contrary minimum stratigraphic control, such as unfaulted basal Holocene sediments, exists.

Displaced marine terrace and nonmarine alluvial deposits of late Pleistocene age constitute the main basis for defining faults of this class. Good control on the age of most of these deposits is not yet available. In only a few places can their age be determined from diagnostic fossils or from volcanic horizons dated radiometrically by the potassium-argon method. Most of the deposits are too old for radiometric dating using carbon-14. With few exceptions, the older alluvium that flanks the mountains and underlies many of the basins and plains of coastal south-central California is not accurately or even approximately dated, but it is presumed to be largely of late Pleistocene age on the basis of its stratigraphic relations.

Fault-produced geomorphic features are another source of age information for determining late Quaternary faulting. The following are considered criteria for inferring faulting during late Quaternary time; offset stream courses in Pleistocene or older deposits, linear scarps in Pleistocene deposits, markedly linear steep mountain fronts associated with adjacent concealed fault traces, and linear submarine scarps in sea-floor sediments below wave base.

Quaternary

The Quaternary class consists of faults that have offset rocks or sediments as young as early Pleistocene

<table>
<tr><th>TIME INTERVAL
YEARS BEFORE PRESENT</th><th colspan="3">MAJOR STRATIGRAPHIC UNITS</th></tr>
<tr><td>0 to 10,000 years</td><td colspan="3">Soil, younger alluvium, and beach deposits</td></tr>
<tr><td>10,000 to 700,000 years</td><td colspan="3">Older alluvium, marine terrace deposits
Orcutt Sand, Aromas Sand</td></tr>
<tr><td>700,000 to 2 million years</td><td>Santa Barbara Formation, and "Paso Robles" Formation of Hall (1973)</td><td rowspan="2">700,000 to 4 million years</td><td rowspan="2">Santa Clara Formation, San Benito Gravels of Wilson (1943), Morales Formation and Paso Robles Formation</td></tr>
<tr><td>2 million to 4 million years</td><td>Careaga Sand, Purisima Formation, Etchegoin Formation, upper part of Pismo Formation</td></tr>
<tr><td>4 million to 12 million years</td><td colspan="3">Lower part of Pismo Formation, Santa Cruz Mudstone of Clark (1966), Pancho Rico Formation, Sisquoc Formation, Santa Margarita Formation, Monterey Formation</td></tr>
</table>

Figure 3.--Time-stratigraphic chart for late Cenozoic deposits of coastal south-central California. The late Cenozoic time span is divided into intervals and each stratigraphic unit is assigned to a single interval that contains youngest known age compatible with existing evidence. Time intervals correspond to those in map explanation of sheet 1. The time span of a particular stratigraphic unit does not necessarily coincide with the entire time interval.

in age. Those faults of this class that are not covered by unfaulted late Quaternary sediments could have been active in late Quaternary, Holocene, or historic time, but no evidence of such displacement is known, and geomorphic evidence of younger surface faulting is lacking.

Stratigraphic control is provided by faulted marine strata of early Pleistocene age preserved near Goleta Point and the adjacent offshore area. Faults classed as Quaternary in the Pismo syncline and Santa Maria Valley displace the nonmarine "Paso Robles" Formation of probable early Pleistocene age (Hall, 1973).

Late Pliocene and Quaternary

Faults that offset deposits of late Pliocene age or of late Pliocene and early Pleistocene age make up this age class. Upper Pliocene marine strata are exposed extensively along coastal south-central California and intertongue inland with nonmarine sediments whose age is less well documented; the nonmarine deposits represent a time range that may extend into early Pleistocene time.

Unless younger unfaulted deposits are present to restrict the range of latest displacement, faults designated late Pliocene and Quaternary could have moved more recently than early Pleistocene time, although no stratigraphic or geomorphic evidence of such younger faulting has been found.

Late Cenozoic

Late Cenozoic faults displace deposits of late Miocene and early Pliocene age. Those faults that lack minimum age control may have moved in late Pliocene, Quaternary, late Quaternary, Holocene, or even historic time; however, no stratigraphic evidence of such displacement is preserved nor are fault-produced geomorphic features evident.

The wide distribution and locally distinctive lithology make the basal upper Miocene deposits most useful for assessing the movement history of faults in coastal south-central California.

Pre-late Cenozoic

A small number of faults are categorized as pre-late Cenozoic because available evidence suggests that they probably have undergone no displacement since middle Miocene time or earlier. Minimum control for the age of displacement is provided by the unfaulted base of the upper Miocene and locally older strata and by intrusion of the faults by middle Miocene and older volcanic rocks. Because the generally poor exposures of middle Miocene and older rocks in coastal California may obscure field evidence of possible faulting of intrusive rock, absence of late Cenozoic fault movement is commonly assured only where control from unfaulted overlying upper Miocene strata is available.

Unknown

Faults whose late Cenozoic histories are poorly known are placed in the "Unknown" class. Such faults occur chiefly in terranes where late Cenozoic rocks were either eroded or never formed and the youngest preserved rocks are middle Miocene or older.

The latest movement on faults in this class could have occurred at any time after deposition of the youngest pre-upper Miocene faulted rocks. It may conceivably be as young as historic time, but no geomorphic evidence of surface faulting has been recognized.

There are, however, places along the coast where faults of the "Unknown" class are overlain by unfaulted late Pleistocene marine terrace deposits that establish a minimum age of most recent movement. These faults are classified as of unknown age but having minimum age control.

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LIST OF MAP SOURCES

References followed by single asterisk (*) are on file with the California Division of Mines and Geology, Ferry Building, San Francisco. Those followed by double asterisk (**) are on file in the U.S. Geological Survey Library, Menlo Park, California. Numbers refer to sheet 3.

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