TABLE 1

CHARACTERISTICS OF THE MAJOR FAULTS IN SANTA CRUZ COUNTY

	San Andreas fault	San Gregorio fault	Zayante fault	Corralitos fault complex
FAULT CHARACTERISTICS:				
1. Maximum length	434-km (270 mi)-long segment from San Juan Bautista in the south to Cape Mendocino in the north ruptured in 1906. Entire fault system is more than 1000 km (600 mi) long.	205 km (127 mi) long which includes the Palo Colorado fault in Monterey County, the Seal Cove fault in San Mateo County and a probable northern extension to the San Andreas fault at Bolinas in Marin County (Greene and others, 1973).	82 km (51 mi) long which includes the Vergeles fault and the western segment of the Ben Lomond fault (Clark and Reitman, 1973).	9 km (5.5 mi) long. Could be considered either a branch of the Zayante fault or the San Andreas fault since it appears to connect the Zayante with the San Andreas fault.
2. Width of zone through which fault movement has been distributed	.6-1.8-km (2000-6000 ft)-wide zone measured in Santa Cruz County but may be as wide as 3 km farther north in Santa Clara County.	.3 m to 2 km (1000-6000 ft) wide in San Mateo County (Brown, 1972), but recent findings of Weber and Lajoie (1974) suggest a 3-km (2 mi)-wide zone of deformation at Año Nuevo.	1-km (3300 ft)-wide band of lineaments near College Lake. Zone could be as wide as 2 km (6600 ft) if all the lineaments north of Lompico are part of the Zayante.	Diffuse zone 3 km (2 mi) wide defined largely by possible faults and photolineaments, the longest of which is 5 km (3 mi).
3. History and nature of recent fault activity The time intervals used in this report are: historic: from the present to 200 years ago Holocene: from the present to 10,000 years ago late Pleistocene: from 10,000 years ago to 100,000 years ago Quaternary: from the present to 2,000,000 years ago late Cenozoic: from the present to 5,000,000 years ago post-Mesozoic: from the present to 65,000,000 years ago	No instrumentally determined fault creep has been measured north of San Juan Bautista, even though right lateral motion between the American and Pacific plates across the San Andreas fault system in central California is estimated to be 32 ± 5 mm per year (Savage and Burford, 1973). Creep on the San Andreas in Santa Cruz County may be absent, very slow, or so widely diffused that paved highways crossing the fault traces are not systematically cracked. Even though creep on the Hayward, Calaveras, and related faults in the San Francisco Bay area can account for more than half of the relative plate motion, lack of detectable creep along the San Andreas may indicate strain accumulation in Santa Cruz County on the order of 7 to 10 mm per year (R. Burford, 1974, written commun.). At present there are not sufficient survey lines in Santa Cruz County to determine accurately where and how fast, if at all, elastic strain energy is being stored. Predominantly horizontal (right-lateral) ground shifts of 1 to 2 metres occurred in Santa Cruz County on April 18, 1906 (Lawson, 1908).	No historic creep reported. Holocene activity established by sea floor scarps on Palo Colorado segment in southern Monterey Bay (Greene and others, 1973) and by deformed alluvial deposits of Año Nuevo Creek that gave a radiocarbon (^{14}C) age of 9510 ± 140 B.P. (Weber and Lajoie, 1974).	No current creep observed; very questionable historic activity in 1906.[4] A northeast-facing scarp perhaps as much as 1 metre high along southwest side of College Lake best seen in 1939 U.S.D.A. aerial photographs indicates probable Holocene activity. Late Pleistocene fluvial surface between Pinto Lake and Kelly Lake deformed by probable faulting at several locations with total vertical displacements of 10-17 m (30-50 ft).	No current creep observed. Late Pleistocene fluvial surface deformed by probable faulting at several localities. Possible sag pond and scarp near Hecker Pass Road suggest, but do not establish, Holocene activity.
4. Historic seismicity (small earthquakes with no accompanying ground rupture)[1]	Definite current activity, particularly from the Pajaro Gap southeastward, where numerous small earthquake epicenters define a linear zone southwest of and parallel to the mapped fault zone. Relatively little seismic activity is recorded from along the San Andreas in Santa Cruz County and northward (Brown and Lee, 1971).	Definite current activity; epicenters are clustered on the fault offshore at northern edge of Monterey Canyon and in a linear pattern along the fault north westward into San Mateo County (Greene and others, 1973).	There is current seismic activity in two regions near the Zayante fault. The diffuse pattern of epicenters between Corralitos and the Pajaro Gap may have occurred on the San Andreas, Corralitos, or Zayante faults (Griggs, 1973). Numerous epicenters are also concentrated in the area between the northwest segment of the Zayante fault and the Butano fault in northern Santa Cruz County (Griggs, 1973). It is not clear whether these epicenters were produced by either or both of these faults or by unrecognized faulting between the two.	The diffuse pattern of epicenters between Corralitos and the Pajaro Gap may have occurred on the San Andreas, Corralitos, or Zayante faults (Griggs, 1973).
POTENTIAL FOR SURFACE RUPTURE: (see Fig. 5)	HIGH	MODERATE TO HIGH	MODERATE The entire Zayante fault is considered to have a MODERATE potential for surface rupture and, consequently, a MODERATE pattern is used to enclose the most confidently established fault traces within its fault zone. The remainder of the fault zone in which the probable locations of future surface rupture are not well established is depicted by the INSUFFICIENT DATA category.	MODERATE The entire Corralitos fault complex is considered to have a MODERATE potential for surface rupture and consequently, a MODERATE pattern is used to enclose the most confidently established fault traces within its fault zone. The remainder of the fault zone in which the probable locations of future surface rupture are not well established is assigned to the INSUFFICIENT DATA category.
CHARACTERISTICS OF MAXIMUM EARTHQUAKE:				
1. Magnitude[2]	8.5 (R. Wesson, 1974, written commun.) (8.3 in 1906)	7.2 to 7.9 (Greene and others, 1973); up to 8.5 if fault moves with a significant vertical component (R. Wesson, 1974, written commun.).	7.4	6.9 if the Corralitos fault complex is considered to be the southeast end of the segment of the Zayante fault extending northwestward from the town of Corralitos.
2. Recurrence interval[3]	100 to 1000 years (Wallace, 1970, fig. 6), although historic evidence suggests the shorter end of this interval might be a more realistic estimate for another great 1906-type earthquake on the San Andreas fault from San Juan Bautista northward. Wallace (1970, Fig. 8) also suggests a recurrence interval of 50 to 100 years for a major (magnitude 7-8) earthquake on the San Andreas.	Possibly analogous to the Hayward fault (Greene and others, 1973) which generated major earthquakes in 1836 and 1868. Wallace (1970) estimated a recurrence interval of 10-100 years for magnitude 6-7 earthquakes on faults like the Hayward.	Virtually unknown, but the probable Holocene offsets suggest a maximum interval of 10,000 years. This calculation assumes that the 1-metre scarp at College Lake was produced by a single episode of faulting and that a minimum of 10 such episodes are required to produce a 10-metre scarp over a 100,000 year period. A recurrence interval measured in hundreds to a few thousand years is perhaps more realistic for the Zayante fault.	Probably similar to the Zayante fault, that is, with a recurrence interval measured in hundreds to a few thousand years.
SUMMARY COMMENTS:	The San Andreas fault is the boundary between the American and Pacific plates in California and consequently is one of the world's major faults (Canby, 1973). In 1906 it produced a maximum right lateral slip of about 6 m (20 ft) in Marin County; in 1857 it may have moved as much as 9 m (30 ft) west of Bakersfield (Wallace, 1968). The San Andreas poses a greater potential earthquake and ground rupture hazard than any other fault in Santa Cruz County.	The San Gregorio fault should be considered a major and active branch of the San Andreas fault that is capable of generating major earthquakes and destructive tsunamis (seismic sea waves) for Santa Cruz County. (For further information on tsunamis in the San Francisco Bay region, see Ritter and Dupré, 1972). The faults at Greyhound Rock may be part of the eastern margin of the San Gregorio fault zone.	The Zayante has a long and well-documented history of vertical movement. The kinds and distribution of granitic basement rocks across the Zayante suggest that horizontal slip has also occurred (Ross and Brabb, 1973), but the amount of this movement is not known. Post-Mesozoic formations are a maximum of .9 to 3 km (3000-10,000 ft) higher on the south side of the Zayante northwest of Boulder Creek than they are on the north side (Clark and Reitman, 1973). Geomorphic and stratigraphic evidence suggests that the Zayante fault is connected to the San Andreas by a diffuse system of possible fault breaks herein defined as the Corralitos fault complex. Furthermore, the southeast end of the block bounded by the Zayante, Corralitos, and San Andreas faults has been uplifted during late Pleistocene or Holocene time.	Existence and nature of the Corralitos fault complex is not conclusively established by this study. Detailed site investigations of the dominant lineaments in this zone might further establish their origin as well as the origin of the adjacent but more subtle lineaments. Geomorphic evidence implies uplift (possible imbricate thrusting) of the block between the Zayante and the San Andreas northwest of the Corralitos fault complex and subsidence of the block between these faults southeast of the Corralitos fault complex.

	Monterey Bay fault complex	Butano fault	Ben Lomond fault
FAULT CHARACTERISTICS:			
1. Maximum length	40-km (25 mi)-long zone of faults in Monterey Bay that may connect southeastward with faults in the Salinas Valley and the Sierra de Salinas (Greene and others, 1973).	37 km (23 mi) long (Brabb, 1970; Brabb and Pampeyan, 1972)	18 km (11 mi) long. As originally defined, the Ben Lomond fault extended west of Boulder Creek (Branner and others, 1909) but in this study is restricted to the segment between Boulder Creek and the city of Santa Cruz (Clark and Reitman, 1973).
2. Width of zone through which fault movement has been distributed	Diffuse zone 10-15 km (6-9 mi) wide of short en echelon faults, the longest of which is 10 km (6 mi).	Largely unknown. Multiple subparallel lineaments near Redwood Estates that might be related to the Butano fault outline a zone 400 to 1200 m wide.	Unknown
3. History and nature of recent fault activity	Holocene activity suggested by at least four strands in the fault complex that are topographically expressed as sea-floor scarps. The faults lying closest to the Santa Cruz County shoreline all have cut deposits interpreted to be at least as young as late Pleistocene (Greene and others, 1973).	No current creep reported. The Butano fault appears to be the boundary for some of the Quaternary stream terrace deposits along Pescadero Creek in San Mateo County (Brabb and Pampeyan, 1972) which may indicate Quaternary activity. Elsewhere Quaternary deposits are not reported from along or across the fault and its recent history of movement, if any, is therefore difficult to ascertain.	No current creep observed. There is no conclusive evidence for Quaternary movements because San Lorenzo River terrace deposits of Quaternary age, which overlie the trace of the Ben Lomond fault, appear to be undeformed (Clark, 1966). Anomalous convexities in stream profiles that cross the extension of this fault northwest of Boulder Creek, herein considered part of the Zayante fault, are believed by Spencer (1974) to indicate Quaternary activity. Youngest rock layers unequivocally displaced by the Ben Lomond fault are of the Santa Margarita Formation formed approximately 12 million years ago.
4. Historic seismicity (small earthquakes with no accompanying ground rupture)[1]	The diffuse pattern of epicenters in Monterey Bay (Griggs, 1973) and the cluster of epicenters on the western boundary of this fault complex at its apparent junction with the San Gregorio fault (Greene and others, 1973) indicate that some strands in the Monterey Bay fault complex are probably active.	Numerous epicenters are concentrated in the area between the northwest segment of the Zayante fault and the Butano fault in northern Santa Cruz County (Griggs, 1973). It is not clear whether these epicenters were produced by either or both of these faults or by unrecognized faulting between the two.	The insignificant number of epicenters along the trace of the Ben Lomond fault from Boulder Creek southeastward (Griggs, 1973) suggest it is inactive.
POTENTIAL FOR SURFACE RUPTURE: (see Fig. 5)	MODERATE	MODERATE	INSUFFICIENT DATA
CHARACTERISTICS OF MAXIMUM EARTHQUAKE:			
1. Magnitude[2]	>6.5? It is difficult to estimate the overall length of the zone until possible landward extensions are better established.	6.4	5.5
2. Recurrence interval[3]	Virtually unknown, but probably less than 10,000 years and possibly less than 1000 years.	Unknown, but possibly similar to the Corralitos-Zayante faults in view of the analogous geometric relation of the Butano to the San Andreas fault.	Unknown
SUMMARY COMMENTS:	Some of the faults in the Monterey Bay fault complex might be the northwestern extensions of the Tularcitos, Chupines, and King City fault zones (Greene and others, 1973; Ross and Brabb, 1973). Possibly northerly extensions of faults within this complex pose a potential but as yet undefined hazard for Santa Cruz County. In view of the recency of movements within this complex and the large number of people who might be adversely affected by the onshore activity, we recommend that a detailed onshore study be undertaken. Fault activity in this complex could also generate destructive tsunamis for the Santa Cruz coastline.	The San Andreas fault zone becomes very wide north of Skyland Ridge where the Butano fault merges with it from the northwest and the Sargent fault merges with it from the southeast. The Butano and Sargent faults appear to have a symmetrical relation to the San Andreas and consequently might have similar histories and seismic potential. The Sargent fault is associated with one of the highest concentrations of small-earthquake activity in the San Francisco Bay region (Brown and Lee, 1971) and it offsets Holocene deposits (McLaughlin, 1973).	The Ben Lomond fault has a long history of vertical movement. Uplift of the southwestern block, which began about 40 million years ago, caused a vertical separation of approximately 180 m (600 ft) within the past 12 million years. Deformed rocks of late Cenozoic age indicate a continuation of faulting (Spencer, 1974), but as yet continued activity into Quaternary time has not been conclusively documented. Because the Ben Lomond fault is connected to the potentially active Zayante fault, and because the Ben Lomond strikes directly towards the city of Santa Cruz, further study to determine its recent geologic history is strongly recommended.

1/ The faults along which small earthquakes recur are considered active and therefore potentially capable of generating much larger and more damaging earthquakes some of which may be accompanied by sudden and extensive surface faulting (Brown and Lee, 1971). A good example in the San Francisco Bay area is the Hayward fault, which is currently generating many small earthquakes, but which generated a major earthquake in 1868 accompanied by ground rupture of up to 3 feet (Tocher, 1959). On the other hand, seismically quiet fault segments such as the San Andreas from Santa Cruz County northward may pose an equal or greater risk. Allen (1968) noted that the segments of the San Andreas that are quietest now have been the sites of one or more great earthquakes in the past and suggested that during periods of seismic quiesence large amounts of strain may accumulate.

2/ The largest magnitude earthquake a fault is likely to generate has been estimated using the empirical curves for North American faults of Bonilla and Buchanan (1970), which correlate length of historic surface rupture on faults with the magnitudes of the associated earthquakes. Since rupture is not likely to occur along the entire length of a fault in a single event, the half-length of a fault has been used in the estimation of magnitude following the suggestion of Wentworth, Bonilla, and Buchanan (1972). The magnitudes thus estimated are somewhat conservative and might be exceeded since (1) the curves used are based on least-squares approximations (that is, some earthquakes have had much larger and much smaller magnitudes for a given rupture length), (2) more than half the length of a fault might rupture, and (3) the actual total length of a fault might not be recognized at present.

3/ In order to calculate the recurrence interval of a particular magnitude earthquake at a given location on a fault zone, the long-term strain rate across the fault is needed. This can be determined either from geodetic data (measured and remeasured survey lines) or from measurements of accurately dated offset geologic strata. A lengthy historic record of fault activity in a region can also be used as a basis for predicting future earthquakes and surface rupture. Unfortunately, since this kind of data is largely unavailable at present for Santa Cruz County, recurrence intervals can be estimated only in very general terms. The fact that the San Andreas is the only fault in the county with a documented history of large magnitude earthquakes and accompanying surface rupture in no way indicates that other faults pose no hazard. On the contrary, the absence of historic activity including creep could indicate significant accumulations of strain energy (Lamar and others, 1973) and the likelihood of future destructive events on such faults as the Zayante, Corralitos, Butano, and San Gregorio.

Several assumptions are incorporated in the recurrence interval tabulation:

1. The intervals shown are for the maximum magnitude earthquakes anticipated on the various faults. Depending upon the strain-releasing mechanism in a particular region, lower magnitude earthquakes can be expected to occur more frequently than the maximum anticipated earthquake (Wallace, 1970).
2. Estimates of recurrence intervals refer to a fault zone and not to a particular lineament within a zone, although it is likely that future surface rupture will occur on those lineaments within a zone most confidently established as being faults.
3. Unless specific information on the strain rate of a fault is available, it is estimated that faults in the HIGH potential rupture category have recurrence intervals for their maximum magnitude earthquakes on the order of tens to hundred of years (Wallace, 1970); faults in the MODERATE category may have recurrence intervals an order of magnitude less frequent, that is, hundreds to thousands of years.

4/ During the field investigations after the 1906 earthquake, G. A. Waring followed the San Andreas fault from Los Gatos to San Juan Bautista and described the features of ground rupture, but he apparently wandered off the fault at Skyland Ridge and followed a swath of felled trees southeastward towards Corralitos. Although Waring stated (in Lawson, 1908, p. 110), "The road at Corralitos is said to have been slightly cracked and in the low hills between Valencia and Corralitos a few cracks were found; but the fault evidently runs fully 0.5 mile east of Corralitos," the San Andreas fault, as mapped in the present study, lies no closer than 3 miles from Corralitos. Even though it is probable that the cracks, fissures, and felled trees Waring observed were caused by seismically induced ground failures such as lurching, sliding, or settling, Waring's observations suggest the possibility that sympathetic fault movement on the Zayante or Corralitos fault zones accompanied the 1906 rupture of the San Andreas.

FAULTS AND THEIR POTENTIAL HAZARDS IN SANTA CRUZ COUNTY, CALIFORNIA

by

N. Timothy Hall, Andrei M. Sarna-Wojcicki, and William R. Dupré

1974