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Earthquake and landslide hazards in the Carmel Valley area, Monterey County, California

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**Earthquake and landslide hazards in the Carmel Valley area
Monterey County, California**

Rosenberg, Lewis I., M.S.

San Jose State University, 1993

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**EARTHQUAKE AND LANDSLIDE HAZARDS
IN THE
CARMEL VALLEY AREA
MONTEREY COUNTY, CALIFORNIA**

A Thesis
Presented to
The Faculty of the Department of Geology
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By
Lewis I. Rosenberg
May, 1993

APPROVED FOR THE DEPARTMENT OF GEOLOGY

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ABSTRACT

The goal of this study was to evaluate seismic and landslide hazards of the Carmel Valley area. Updated geologic maps were compiled for use in the Monterey County Seismic Safety Element. Earthquake and landslide hazards were ranked using a three-value scale.

Offset late Quaternary deposits and clustered microseismicity suggests the Tularcitos, Navy, Hatton Canyon, Berwick Canyon, and Laureles faults may be “active” by State of California criteria.

Large landslides are abundant in the Monterey shale. Landslides are also common in the Tertiary sandstones, and basement rocks. Debris flows occur in colluvial deposits. Radiocarbon dating indicates deep-seated landslides in the region formed during the late Pleistocene to early Holocene.

Risks associated with most of the geologic and seismic hazards can be reduced by the Monterey County Planning Department adopting revised geologic report requirements, updating geologic maps and hazard maps, using geologic review services, and enforcing the County grading ordinance.

INTRODUCTION

Purpose

The Carmel Valley area has experienced rapid development as the population of the San Francisco Bay region has spread southward. Earthquakes and landslides are significant hazards for the growing population. Because no large earthquake has seriously affected this area since the Monterey Bay doublet ($M = 6.1$) of 1926, little attention has been focused upon seismic or geologic hazards in the area.

The main resource for planners to evaluate geologic hazards is the Seismic Safety Element of the Monterey County General Plan. The basis for the Seismic Safety Element is a report on earthquake and landslide hazards in Monterey County by Burkland and Associates (1975). However, the Seismic Safety Element needs updating to include more recent information.

The main goal of this study was to identify the most significant geologic and seismic hazards affecting the Carmel Valley area. A second goal was to create a model for revising the Seismic Safety Element using updated geologic data combined with current interpretation methods. A third goal was to develop a preliminary set of guidelines for engineering geology and geotechnical reports in the study area. This report and the accompanying maps indicate areas where detailed site-specific studies are necessary due to great complexity of hazard or inadequate geologic data.

Location and Access

The study area is approximately eight km east of Monterey and 16 km south of Salinas in Monterey County (figure 1). It lies within the central Coast Ranges and encompasses 132 km² covering the Seaside, Spreckels, Carmel Valley, and Mount Carmel

Figure 1. Index map of the Carmel Valley study area.

USGS 7.5-minute topographic quadrangles. The northern and southern boundaries of the study area are the crests of the Sierra de Salinas and the Santa Lucia Range, respectively. The eastern and western boundaries enclose the most densely populated portions of the study area. Current land uses include cattle grazing, park land, and low-density housing.

Access to the study area is from Carmel Valley Road and Laureles Grade. Numerous residential streets and hiking trails provide access to the foothills. The outlying parts of the area are difficult to reach due to steep terrain, dense vegetation, and few roads or trails.

Previous Studies

The geology of Carmel Valley was first described by A.C. Lawson in 1893. Lawson mapped the geologic units near the mouth of the valley and demonstrated the influence of faulting on the topography. Beal (1915), Galliher (1930, 1932), Trask (1926), Herold (1935), and Fiedler (1944) described the regional stratigraphy and geologic structure in the Carmel Valley area. Because the focus of these early efforts was on bedrock mapping, the Quaternary geology of the region was largely uninterpreted.

Brown (1962), Neel (1963), and Younse (1980) mapped the Rancho San Carlos, Tularcitos Creek/Cachagua Grade, and Laureles Grade/Robinson Canyon areas, respectively. Their work resulted in the refinement of the stratigraphy and structure of the Tertiary age sedimentary rocks in Carmel Valley.

Bowen (1965, 1969a, 1969b) mapped the Seaside and Spreckels 7.5-minute quadrangles with emphasis on the Tertiary stratigraphy. Dibblee revised the Jamesburg (1972), Point Sur (1973a), and Salinas (1973b) 15-minute quadrangles by compiling and modifying previous mapping. These maps are useful because they present a regional

synthesis of mapping by many workers. The main weakness of these maps is that they omit many of the Quaternary deposits and minor faults.

Preliminary geologic mapping by Clark and others (1974) suggested that several faults in the study area were potentially active. An important contribution of their mapping was to identify the connection between the active offshore faults and the potentially active onshore faults. A shortcoming of their mapping is that much of the area shown as Miocene Los Laureles sandstone actually consists of Quaternary coastal terrace deposits (Dupré, 1990). This implies that the faulting is more recent than previously recognized.

Bryant (1985) concluded that previously mapped faults were “not sufficiently active” to require zonation by the State Geologist as “active” faults, based on a 2¹/₂-day reconnaissance and review of aerial photographs and geologic maps. A study associated with the proposed New San Clemente Dam in upper Carmel Valley (Geomatrix Consultants, 1985) considered the Tularcitos fault “probably active” and tentatively assigned a M 6.75 maximum credible earthquake to this fault. Subsequent field work by Clark and McKittrick (1985) and McKittrick (1987) revealed that Tularcitos fault zone was a longer and wider zone of deformation than previously realized. However, faults concealed by alluvium and landslides are under-represented because McKittrick did not completely map the Quaternary geology.

Dupré (1990) mapped the Quaternary geology and demonstrated that the thrust faults mapped by Clark and others (1974) in the Monterey foothills locally offset coastal terrace deposits by as much as 15 to 20 m. Dupré (1990) also showed the relative liquefaction susceptibility of the Quaternary deposits. Dupré’s accurate mapping of Quaternary deposits allows a more precise determination of the recency of faulting in the area. A limitation of this map is that it does not represent a comprehensive inventory of landslides (W.R. Dupré, oral commun., 1991).

Site-specific investigations for subdivisions and single-family homes by geotechnical consultants are on file at the Monterey County Planning Department (MCPD). Several of these reports include detailed mapping and subsurface exploration that indicate late Pleistocene or Holocene activity on previously unrecognized faults. However, little of the information contained in these reports is compiled onto maps used by the MCPD.

Geologic Map Development

The first task of the study consisted of reviewing pertinent literature related to the geologic, soil, and hydrologic conditions in the study area and surrounding region. Sources of data included government agencies (U.S. Geological Survey (USGS), California Division of Mines and Geology (CDMG), USDA Soil Conservation Service (SCS), Monterey Peninsula Water Management District (MPWMD), Monterey County Public Works Department, and the Monterey County Planning and Building Inspection Department); unpublished theses and dissertations; and geotechnical consultants.

Geologic maps and reports used for this study included material from 1893 to 1992. The maps ranged from regional scale (1:250,000) to site-specific (1:240), with the majority at 1:24,000 and 1:62,500. Aerial photographs from 1930 to 1990 were reviewed at U.C. Santa Cruz, the USGS, and the Salinas office of the SCS. The aerial photographs ranged in scale from 1:9,600 to 1:31,680.

The second task involved preparing bedrock and surficial geologic maps. Existing geologic mapping was compiled onto 1:24,000 scale USGS topographic maps. The resulting maps were modified by field mapping and analyzing well log data, geophysical studies, and aerial photos. The field mapping was conducted intermittently from 1988 to 1991.

The accuracy of the geologic and hazard maps varies throughout the area with the sources used in the compilation. The sources used are shown on plates 1 and 2. Other factors that influence the accuracy of the maps include limited exposures, dense vegetation, and existing development obscuring geologic features. With these limitations, absence of evidence should not be considered evidence of absence.

Relative Geologic and Seismic Hazards Map Development

One of the goals of this study was to prepare a model for updating the Seismic Safety Element maps. The purpose of the original geotechnical study for the Seismic Safety Element was to evaluate relative seismic hazards and landslide susceptibility at a regional scale. The Seismic Safety Element depicts six levels of seismic hazards ranging from very low to very high. Maps at scales of 1:12,000 (incorporated cities), 1:24,000 (northern Monterey County), and 1:125,000 (southern Monterey County and Big Sur coastal areas) show seismic hazard zones. Landslide hazards are shown on a county-wide map at a scale of 1:125,000. Figure 2 is an example of the original seismic hazard map, and figure 3 is an example of the hazard map created for the same area as part of this study.

A limitation of the Seismic Safety Element maps is that original available data used to prepare the maps were limited, and the six hazard levels imply a higher degree of precision than interpretation of the data allows. In a 1987 report to the Monterey County Board of Supervisors, the MCPD identified several other flaws with the Seismic Safety Element maps. These included: (1) numerous errors not identified during the original County review in 1975, (2) a lack of standard format and map scales between various regions, (3) lack of a detailed landslide susceptibility map, and (4) a large volume of geologic reports (approximately 300 as of 1987) which need incorporating in a revised report and maps (Monterey County Planning Department, 1987).

To create a useful product for the MCPD, examples of classification systems used in other seismic safety elements were presented to planners. The MCPD selected the system developed by Rogers and Williams (1974) for Santa Clara County, California as the most appropriate for the County's needs. Three zones are shown on plate 3: D (major geologic and seismic hazards), E (moderate geologic and seismic hazards), and F (minor geologic and seismic hazards). These zones are subdivided into areas of landslides, liquefaction, and potentially active faults.

Preparing a geologic and seismic hazard map involves interpreting data such as rock and soil type, geologic structure, ground water conditions, and topography. In interpreting the data, certain assumptions are necessary. These assumptions include: (1) the accuracy of the basic data; (2) estimating the physical properties of a given unit based on limited test data; (3) correlating the units in Carmel Valley with similar geologic units used in other areas to establish geologic and seismic hazard zones; and (4) lack of long-term historical data, especially regarding earthquakes.

Landslides were classified based on the certainty of identification, relative age, and dominant type of movement (see plate 2) using a modified version of the method described by Wieczorek (1984). Landslide susceptibility was evaluated by estimating the distribution of landslides within the different geologic units. Areas with widespread evidence of landsliding or intensely fractured rock received a higher hazard rating than areas of infrequent sliding. Many landslides were mapped by interpreting air photos; therefore, the extent of landslides and landslide susceptibility in the densely forested Santa Lucia Range is probably underestimated.

The landslide susceptibility ratings apply mainly to the more common rotational and translational landslides. Debris flow and rockfall hazards differ significantly from rotational/translational landslides and depend on certain site-specific characteristics. Debris

Figure 2. Original Monterey County Seismic Safety Element map, Carmel Valley quadrangle (from Burkland and Associates, 1975, map J).

Figure 3. Revised Monterey County Seismic Safety Element map, Carmel Valley quadrangle.

flow activity requires a combination of slope angle, topographic hollows, and source materials. The hazard from debris flows depends on the volume and velocity of the mobilized deposits. Likewise, rockfall susceptibility requires a combination of slope angle and critically oriented intersecting discontinuities. The hazard from rockfall depends on the size and volume of dislodged rock. Insufficient data were available to fully evaluate debris flow and rockfall susceptibility.

The liquefaction susceptibility in most of the study area is based on previous work by Dupré (1990). In areas not mapped by Dupré, the liquefaction susceptibility was evaluated using his methodology. The liquefaction susceptibility varies locally depending on site geology, ground water conditions, and proximity of free faces or scarps.

Fault rupture potential was evaluated using criteria contained in State of California guidelines (Hart, 1992). Offset late Quaternary terrace deposits and clusters of microearthquake epicenters suggest that some faults in Carmel Valley may be active. However, knowledge of the absolute age of the faulted materials is lacking, and is necessary to fully evaluate fault rupture hazards.

Certain limitations are implicit in using a geologic hazard map. Users should realize that the hazard map is a guide for planning purposes, and should not be used as a substitute for site-specific studies. The hazard map was prepared using available geologic data combined with modeling techniques for the various hazards. Therefore, the map is only as precise as the data sources and models used. Although hazard areas are defined by solid lines, the hazard areas are gradational. Users also should realize that the 1:24,000 scale of the maps in this report is not sufficiently precise for actual building set-back requirements.

PHYSICAL SETTING

Topography

Carmel Valley is a narrow lowland bordered by the Sierra de Salinas to the north and the Santa Lucia Range to the south. The terrain surrounding Carmel Valley consists of gently to moderately sloping hills and steep mountains dissected by deep canyons. The Santa Lucia Range is steeper and higher than the Sierra de Salinas. Altitudes range from about 20 m along the Carmel River to about 700 m at Pinyon Peak. The altitude of the valley floor increases from about 20 m to 125 m toward the southeast.

The steepness of the slopes affects soil formation and erosion, with shallow soils and high erosion rates on the steeper slopes. The direction that the slope faces also affects the soil formation and topography. North-facing slopes receive less sun than south-facing slopes, and have denser vegetation and thicker soil.

Climate and Vegetation

Carmel Valley has a Mediterranean climate with hot, dry summers; and cool, wet winters. Summer temperatures vary from 40° to 20°C; during winter, temperatures vary from 15° to -5°C (Carmel Valley Master Plan Study Committee, 1978). Precipitation is mostly rain, except for occasional snow in the Santa Lucia Range and Sierra de Salinas. Approximately 80 percent of the rainfall occurs during January through April. Yearly rainfall in the study area varies from 50 to 35 mm per year; with periods of prolonged drought and closely spaced wet years (Kapple and others, 1984).

Vegetation on the north side of Carmel Valley consists of mostly oaks and grasses, sparse pine trees, with pockets of dense chaparral and poison oak. On the south side of the valley, the vegetation is denser and consists of oak, pine, fir, laurel, and

redwood trees, with an understory of dense chaparral, poison oak, and berries. Vegetation along the Carmel River consists of mostly cottonwoods and willows (Carmel Valley Master Plan Study Committee, 1978).

REGIONAL GEOLOGIC SETTING AND HISTORY

The Carmel Valley study area is within the Coast Ranges geologic province of central California. Tectonically, Carmel Valley is part of the complexly deformed Salinian Block bounded by the active San Andreas fault and the San Gregorio fault. The Salinian Block includes numerous subsidiary faults of the San Andreas system and characterized by compressional tectonics (Greene and others, 1988).

The oldest rocks in the study area are a group of Paleozoic(?) high-grade metamorphic rocks collectively known as the Sur Series (Trask, 1926). The Sur Series consists of a thick accumulation of regionally metamorphosed sandy, clayey, and limey sediments (Reiche, 1937). During the early Cretaceous, granitic plutons intruded the Sur Series rocks (Page, 1966). Significant uplift, deformation, and erosion of the metamorphic and plutonic rocks occurred in the late Cretaceous and continued until the end of the late Cretaceous, when the region was submerged by the sea (Taliaferro, 1943, p. 134).

Paleogene rocks are absent in the Carmel Valley area, which implies that Santa Lucia Range and Sierra de Salinas were emergent during this time (Graham, 1976, p. 178). Uplift during the middle Miocene resulted in the deposition of continental and shallow-marine sandstone—the Robinson Canyon Member and the Los Tularcitos Member of the Chamisal Formation respectively. Basalt flows are also present within the Los Tularcitos Member (Bowen, 1965). During the middle to late Miocene, regional subsidence and transgressing seas resulted in deposition of the deep-water Monterey Formation (Younse, 1980, p. 41).

Intense folding and faulting marked the late Pliocene and early Pleistocene in the northern Santa Lucia Range (Compton, 1966). The San Andreas, San Gregorio, and

Tularcitos faults were active during this time, leading to regional uplift and erosion (Graham, 1976). As tectonism continued, the Carmel River began eroding a deep and narrow canyon along the trace of the Tularcitos fault.

During the middle Pleistocene, tectonic uplift and sea level changes resulted in the formation of terrace deposits along the Carmel River (Williams, 1970). As sea level became lower, downcutting resulted in the terrace remnants that cap many of the hills in the area. Faulting continued during late Pleistocene time as indicated by offset terrace deposits. By the end of the Pleistocene, many of the present geomorphic features such as the steep range fronts and hillside benches had developed.

Wetter climatic conditions prevailed in the Monterey Bay area during late Pleistocene and early Holocene time (Dupré, 1975). These climatic conditions may have contributed to the development of the large deep-seated landslides along the valley. Radiocarbon dates of organic debris in landslide deposits confirm a late Pleistocene to early Holocene age for these landslides (Rogers E. Johnson & Associates, 1986; O'Rourke, 1980). Holocene to historic time is characterized by continued geomorphic evolution of the landscape as a result of landslides, floods, erosion, tectonic activity, and human activity.

STRATIGRAPHY

The study area contains an incomplete stratigraphic column ranging from Paleozoic(?) to Quaternary. Metamorphic and granitic rocks form the basement rocks. As a result of major unconformities, the overlying units fall into two groups; Miocene sedimentary rocks, and Quaternary alluvial, terrace, and landslide deposits.

For the purposes of this study, the geologic descriptions emphasize engineering geologic characteristics of the bedrock and surficial units. Strength descriptors and other terms used to classify physical properties of rock and soil are based on standards defined in the Engineering Geology Field Manual (U.S. Bureau of Reclamation, 1988). The term “discontinuities” is used as:

“A collective term for all structural breaks in geologic materials which usually have zero to low tensile strength ... Discontinuities comprise fractures (including joints), planes of weakness, shears/faults, and shear/fault zones.” (U.S. Bureau of Reclamation, 1988).

Color descriptions are based on the Rock Color Chart (Goddard and others, 1948) and the Munsell Soil Color Charts (Munsell Color, 1990). References to geologic time are based on those used by the USGS (Ziony, 1985; Hansen, 1991).

Pre-Tertiary

Metamorphic Rock

Metamorphic rock crops out in the mountains on the south side of the valley, and along the east side of Laureles Grade. Metamorphic rock in the study area consists almost entirely of biotite quartzofeldspathic schist and quartzofeldspathic gneiss, with rare marble lenses. Most of the metamorphic rock is intruded by and tectonically mixed with granitic rock, except in the Sierra de Salinas where the rock is almost entirely schist

(Ross, 1976). These rocks are part of the "Sur Series," which is estimated to be at least 1 km thick in the study area (Trask, 1926; Herold, 1935).

Bowen and Gray (1959) reported indistinct fossils cropping out near Fremont Peak in San Benito County. They used these fossils to correlate the Sur Series rocks with similar Paleozoic metamorphic rocks in the southern Sierra Nevada and Tehachapi Mountains. Ross (1976) suggested that the schist of the Sierra de Salinas is younger than other metamorphic rocks in the Santa Lucia Range, and may be of Mesozoic age. Until fossils or other diagnostic features are found, the absolute age of the Sur Series remains questionable.

The schist and gneiss consist of very thin to thin alternating layers of dusky yellowish-brown (10YR 2/2) fine-grained biotite and light gray (N 7) to light bluish-gray (5B 7/1) medium-grained quartz with feldspar. The overall rock color on fresh surfaces is dusky blue (5PB 3/2) to dusky yellowish-brown (10YR 2/2), and dark reddish-brown (10R 3/4) on weathered surfaces. The marble is dark grayish-blue (5PB 3/2) to very light gray (N 8), slightly metamorphosed, massive, and fine to medium grained.

The schist and gneiss are moderately to intensely fractured, with moderately to closely spaced discontinuities. The marble is slightly to moderately fractured, with moderately to widely spaced discontinuities. In fault zones, the metamorphic rock is shattered and has closely to very closely spaced fractures. Foliation typically strikes northeast and dips 25° to 60° southeast. The schist and gneiss tend to break parallel to the foliation as well as to the joints.

Discontinuities are slightly to moderately continuous, and slightly open to moderately wide. Light-colored quartz veins ranging from hairline width to several cm wide commonly fill joints and fractures. Loose clay, sand, and silt also commonly fill fractures near the surface.

The degree of weathering is variable, and is intense to moderate in the schist and gneiss as a result of physical and chemical weathering. The marble is moderately weathered with solution pits resulting from chemical weathering. Weathering decreases with depth and increases in proportion to the amount of discontinuities. Highly weathered metamorphic rocks are moderately hard to moderately soft in strength. Less weathered metamorphic rocks are hard to extremely hard. The soils derived from metamorphic rocks in the study area include the Vista, Junipero-Sur, and Cieneba series. These consist of brown to dark grayish-brown, well-drained sandy loam with fine gravel, and are less than 1 m in thickness (Cook, 1978).

Granitic Rock

Granitic rock underlies most of the steep mountains on the south side of Carmel Valley and portions of the Sierra de Salinas. Well logs and seismic data reveal that granitic bedrock highs underlie the Carmel River alluvium (see plate 1). Compton (1966) estimated the granitic rock in northern Santa Lucia Range to be at least 3 km thick. Isotopic dating (Rb-Sr) indicates an early Cretaceous age of 109 million years for the granitic rock in the northern Santa Lucia Range (Wiebe, 1970).

Two types of granitic rock are in the study area. Ross (1976) mapped these rocks as the porphyritic granodiorite of Monterey and the granodiorite of Cachagua. The Cachagua granodiorite is a transitional unit of the Monterey granodiorite and represents a small part of the mapped area. Most workers do not separate these two units, and use the names "Santa Lucia quartz diorite" (Trask, 1926; Fiedler, 1944) or "granodiorite" (Clark and others, 1974). In this report, they are undifferentiated because they are similar from an engineering geology viewpoint. Figure 4 shows a typical outcrop of granitic rock.

The granitic rock is typically composed of approximately 70-80 percent plagioclase feldspar, 5-10 percent K-feldspar, 15-20 percent quartz, and 10-20 percent

biotite (Younse, 1980). Texture is porphyritic, with coarse to very coarse grained K-feldspar crystals in a medium-grained groundmass. Overall color on fresh surfaces is light gray (N 7); weathered surfaces are moderate pink (5R 7/4) to moderate reddish-orange (10R 6/6).

Numerous light-colored aplite dikes ranging from 2 cm to 1 m in width intrude the granitic rock. Pegmatite dikes composed of coarse-grained quartz and K-feldspar are also common. The pegmatite dikes are typically about 10 cm in width. The aplitic and pegmatic dikes are generally less weathered than the surrounding rock. Locally, pegmatic dikes are chemically altered (kaolinized) to a soft pinkish-white clayey sand. Loose clay, sand, and silt commonly fill discontinuities near the surface.

Figure 4. Photograph of granodiorite outcrop at Garland Ranch Regional Park.

The granitic rock is generally moderately to intensely fractured, with moderately to widely spaced fractures and joints. In fault zones, the granitic rock is shattered and has closely to very closely spaced fractures. Discontinuities are slightly to moderately continuous, and are slightly open to moderately wide.

The degree of physical and chemical weathering varies from intense to moderate. The granitic rock is typically intensely weathered to a saprolite in the upper few meters and along discontinuities, and become less weathered with depth. Highly weathered granitic rock is moderately hard to moderately soft in strength. Less weathered granitic rock is hard to extremely hard. The soils derived from granitic rocks in the study area include the Sheridan, Junipero-Sur, Cieneba, and Vista series. These consist of brown to dark grayish-brown, well-drained sandy loam with fine gravel, and are less than 1 m in thickness (Cook, 1978).

Tertiary System

Red Beds

This group includes the nonmarine sandstone that nonconformably overlies the basement rock. The red beds are best exposed along Robinson Canyon Road, but also crop out along Cachagua Grade. The red beds range in thickness from about 140 m in the Robinson Canyon area (Bowen, 1965) to 70 m in the Cachagua area (Neel, 1963, p. 26). Approximately 125 m of the red beds were encountered in a test well near the mouth of Robinson Canyon (Thorup, 1976). The red beds are early middle Miocene on the basis of stratigraphic position and regional correlation with similar units (Younse, 1980).

The nomenclature used by earlier workers is complex. Trask (1926) mapped the red beds as part of the Temblor Formation, whereas Fiedler (1944) mapped the red beds as part of the Vaqueros-Temblor Formation. Brown (1962) proposed the name

“Robinson Canyon Member of the Chamisal formation” for the red beds in the Robinson Canyon area. Bowen (1965) and Younse (1980) used Brown’s terminology to describe these rocks. Neel (1963) included the Cachagua area red beds in the “Cachagua Member of the Chamisal Formation.” Clark and others (1974) used the name “red beds of Robinson Canyon” in their regional mapping. Although many names are in use for these rocks, they are similar from an engineering geology viewpoint.

The “red beds” consist mostly of arkosic sandstone, with common conglomerate and siltstone beds. The sandstone is moderate red (5R 4/6) to moderate orange pink (10R 7/4) on weathered surfaces and yellowish-gray (5Y 7/2) on fresh surfaces, massively bedded, very coarse to coarse grained, angular to subangular, and poorly sorted. The conglomerate consists of very thick (1 to 10 m) beds of limited extent with well-rounded cobbles composed of granodiorite, schist, and felsite. The siltstone consists of very dark red (5R 2/6) or dusky green (5G 3/2), thin (3 to 10 cm) beds that are laterally continuous over tens to hundreds of meters.

The sandstone and siltstone are poorly indurated, moderately soft to soft, and form moderately steep slopes. Conglomerate beds are hard, well indurated, and form near-vertical cliffs. The caverns and overhanging ledges along Robinson Canyon Road are examples of this differential erosion. The sandstone is very slightly to slightly fractured, with moderately to widely spaced discontinuities. In fault zones, the sandstone is moderately to intensely fractured, with closely to very closely spaced discontinuities. Discontinuities are generally obscure in the siltstone and conglomerate beds.

Weathering ranges from moderate to intense, depending on the degree of cementation. Intense weathering of granitic clasts within the red beds makes it difficult to distinguish them from the underlying intensely weathered granodiorite, especially in drill cuttings or well logs. The soils derived from the red beds in the study area include

the San Andreas and Sheridan series. These consist of light brownish-gray to dark grayish-brown, well-drained sandy loam, and are less than 1 m in thickness (Cook, 1978).

Marine Sandstone

This group includes the shallow-water marine sandstone and areas of sediments deposited in local transitional nonmarine environments. The marine sandstone unit is stratigraphically above the continental red beds, and below the shale of the Monterey Formation. These rocks underlie the foothills in the Robinson Canyon/Pinyon Peak area, and north of Carmel Valley Village (see figure 5). The lower part (Chamisal) of the marine sandstone unit (excluding the Los Laureles Sandstone Member of the Monterey Formation of Bowen, 1965) ranges in thickness from about 120 m in the Robinson Canyon area (Bowen, 1965, p. 52) to 130 m in the Cachagua area (Neel, 1963, p. 27). The Los Laureles Sandstone Member of the Monterey Formation ranges in thickness from about 3 m (Younse, 1980, p. 27) to 200 m (Neel, 1963, p. 35). The marine sandstone is middle Miocene based on stratigraphic position and regional correlation with similar units (Younse, 1980).

The nomenclature used by earlier workers is complex. Trask (1926) mapped the sandstone as part of the Temblor Formation, whereas Fiedler (1944) mapped the sandstone as part of the Vaqueros-Temblor Formation. Bowen (1965) proposed the name "Los Tularcitos Member of the Chamisal Formation" for the marine sandstone in the Robinson Canyon area. Neel (1963) referred to similar rocks in the Cachagua area as the upper portion of the "Cachagua Member of the Chamisal formation." Dibblee (1972, 1973a, 1973b), and Clark and others (1974) used the name "marine sandstone" in their regional mapping to include the Los Tularcitos and Cachagua Members of the Chamisal Formation as well as the Los Laureles Sandstone Member of the Monterey Formation of

Bowen (1965). Although many names are in use for these rocks, they are undivided in this report because they are similar from an engineering geology viewpoint.

Figure 5. Photograph of Miocene marine sandstone outcrop along Robinson Canyon Road.

The “Chamisal” part of the marine sandstone unit consists mostly of arkosic sandstone, with common conglomerate beds, and rare siltstone beds. The sandstone is dark yellowish-orange (10YR 6/6) to dark yellowish-brown (10YR 4/2) on weathered surfaces and yellowish-gray (5Y 7/2) to very pale orange (10YR 8/2) on fresh surfaces, massively bedded, coarse to fine grained, angular to subangular, and poorly to well sorted. The conglomerate consists of very thick (1 to 10 m) beds of limited extent with well-rounded pebble to boulder-size cobbles composed of granodiorite, schist, andesite,

and felsite. Neel (1963) reported a 0.5-m-thick bentonite clay bed in the Cachagua area. Moderately thick (100 to 300 mm) shell beds are locally common. These fossils are identified as *Leptopecten andersoni* (Joseph C. Clark, written commun., 1990).

The “Los Laureles” part of the marine sandstone unit consists mostly of arkosic sandstone, with intermittent siltstone and fossil beds. The sandstone is dark yellowish-orange (10YR 6/6) to grayish-yellow (5Y 8/4) on weathered surfaces, and yellowish-gray (5Y 8/1 to 5Y 7/2) on fresh surfaces; thickly bedded; medium to fine grained; subangular to subrounded; and well sorted.

The sandstone and siltstone are poorly indurated, moderately soft to soft, and form moderately steep slopes. Conglomerate beds are hard, well indurated, and form near-vertical cliffs. The sandstone is very slightly to slightly fractured, with moderately to widely spaced discontinuities. In fault zones, the sandstone is moderately to intensely fractured, with closely to very closely spaced discontinuities. Discontinuities are generally obscure in the siltstone and conglomerate beds.

Weathering ranges from moderate to intense, depending on the degree of cementation. The soils derived from the marine sandstone in the study area include the San Andreas and Sheridan series. These consist of light brownish-gray to dark grayish-brown, well-drained sandy loam, and are less than 1 m in thickness (Cook, 1978).

Volcanic Rock

Basalt and andesite flows are exposed within the marine sandstone unit. They crop out in a 0.8-km-long patch along Schulte Road, and near Vasquez Knob. Trask (1926, p. 146) reported a maximum thickness of 20 m for the basalt near Vasquez Knob. These flows are middle Miocene based on stratigraphic position, and have not been radiometrically dated.

Bowen (1965) estimated the composition of the basalt as 30-40 percent plagioclase feldspar, 20-30 percent augite, 15-20 percent olivine and pyroxene, 5-15 percent chlorite, 5-15 percent clay minerals, and 5 percent magnetite. Texture is generally fine-grained porphyritic, but locally is vesicular due to preferential weathering of olivine phenocrysts. Color on fresh surfaces is greenish-black (5GY 2/1) to black (N 1), and on weathered surfaces is olive gray (5Y 3/2) to moderate reddish-brown (10R 4/6). Thin (1 to 5 mm) flow bands are commonly visible on fresh surfaces.

The volcanic rocks are moderately hard to hard in strength. The volcanic rocks are moderately to intensely fractured, with moderately to closely spaced fractures and joints. Discontinuities are slightly continuous and slightly open to moderately open. Loose clay, sand, and silt commonly fill fractures near the surface. The volcanic rock tends to break parallel to the flow banding as well as to the joints.

Weathering of the volcanic rocks is generally slight to moderate. The soils derived from the volcanic rock in the study area belong to the San Andreas series. These consist of light brownish-gray to grayish-brown, well-drained sandy loam, and are less than 1 m in thickness (Cook, 1978).

Monterey Shale

This group consists of the siliceous and diatomaceous shale, siltstone, and claystone that stratigraphically overlie the "Chamisal" and "Los Laureles" part of the marine sandstone unit. In places, Monterey shale rests directly on the basement rocks. Monterey shale crops out in two main areas: in the hills south of the Carmel River and west of Robinson Canyon, and in the hills north of the river. The thickness of the Monterey shale near Carmel Valley is about 900 m (Bowen, 1965). The Monterey shale is middle Miocene based on microfossil evidence (Younse, 1980).

Three stratigraphic nomenclatures are used to describe Monterey shale in the study area. Bowen (1965) divided the Monterey shale into three members: the Los Laureles Sandstone, the Aguajito Shale, and the Canyon Del Rey Diatomite. Younse (1980) also divided the Monterey shale into three members: the Laureles, the Sandholt, and the Hames. In their regional mapping, Dibblee (1972, 1973a, 1973b) and Clark and others (1974) used the name "Monterey Shale" to include the Aguajito Shale and the Canyon Del Rey Diatomite, and grouped the Laureles Sandstone with the underlying marine sandstone. The various members of the Monterey shale are undifferentiated in this report due to the level of detail and inconsistencies within the compiled sources.

The Monterey shale is very light gray (N 8) to very pale orange (10YR 8/2) on fresh surfaces, and light brown (5YR 6/4) to grayish-orange (10YR 7/4) with dark banding on weathered surfaces. Most of the Monterey shale in the study area is the siliceous variety, although diatomaceous shale is common. Bedding is well developed, with thicknesses ranging from very thin (2 cm) to thick (1 m). Thin bentonite, gypsum, and phosphorite interbeds are common within the Monterey shale (see figure 6). The bentonite and gypsum interbeds are soft, while the phosphoritic interbeds tend to be hard and resistant.

Regional folding and local faulting have resulted in fracturing across the bedding planes of the brittle shale. The Monterey shale is moderately to intensely fractured along fold axes or near faults, and moderately fractured elsewhere. Discontinuities are moderately to widely spaced; discontinuous; slightly to moderately open; and are commonly filled with loose clay, sand, and silt. Because of the thin bentonite and gypsum interbeds, bedding planes are often weak zones.

Siliceous shale is moderately to well indurated and moderately hard to hard in strength, whereas diatomaceous shale is moderately soft to soft and more extensively

weathered. However, in fault zones or along fractures, both types of shale are intensely weathered and moderately soft to soft.

Several samples of siliceous shale were tested for slaking using the “field test” method of the U.S. Bureau of Reclamation (1988, p. 64–69). Samples were submerged in fresh water for 24 hours, then air-dried for several days. No discernible slaking occurred upon drying after two test cycles.

Figure 6. Photograph of bentonite bed in Monterey shale.

The degree of weathering is variable, ranging from moderate to intense. Weathering decreases with depth and increases in proportion to the number of discontinuities. The soils derived from the Monterey shale in the study area include the Santa Lucia, Reliz, Linne, and Gazos series. These consist of light gray to dark grayish-

brown, moderately plastic, well-drained shaly to silty clay loam, and are generally 0.5 to 1.5 m in thickness (Cook, 1978).

Quaternary System

Terrace Deposits

Elevated fluvial terraces are exposed mainly on the north side of the Carmel River as discontinuous topographic benches and as patches capping hilltops. At least six sets of terraces are present in the study area and range in altitude from 30 m to 240 m. The terrace deposits in Carmel Valley are presumed to correlate with the marine terraces on the Monterey Peninsula (Williams, 1970, p. 52). However, discontinuous outcrops and faults make this connection difficult.

The terrace deposits are Pleistocene, although their absolute ages are unknown. McKittrick (1988) attempted to correlate terraces on the Monterey Peninsula with radiometrically dated marine terraces in Santa Cruz using relative altitude and soil development. Because the Navy fault offsets older terraces on the Monterey Peninsula, this correlation remains unproven.

Chualar and Lockwood series soils with well-developed B horizons cap several of the terrace deposits along the Carmel River (Cook, 1978). Tinsley (1975, p. 70) considered Chualar Series soils formed on river terraces in the Salinas Valley to be of middle Wisconsinan age (approximately 25,000 to 50,000 years). If the correlation between Chualar Series soils of the Salinas and Carmel Valleys is valid, the youngest terraces in Carmel Valley also may be middle Wisconsinan age.

Terrace deposits consist of a highly variable mixture of pale yellowish-brown (10YR 6/2) to moderate yellowish-brown (10YR 5/4), moderately to well-graded, fine to coarse-grained silty sand with fine to coarse gravel. Small discontinuous lenses of clean

sand, silty clay, clay, and organic materials are also present. The gravels are predominantly schist, gneiss, and granitic rock. Bedding is crude to well-developed and thin (3 cm) to very thick (3 m). The terrace deposits are weakly to moderately cemented, and locally are strongly cemented with carbonate in the upper few meters. The terrace deposits range in thickness from 0 to about 17 m (Williams, 1970).

Landslide Deposits

Landslides in Carmel Valley range from small, shallow soil slips to deep bedrock slides. Landslides occur in all the geologic units (see plates 1 and 2), but are most common in the Monterey shale. The relative age, relative certainty, and types of slope movement of mapped landslides are shown on plate 2.

Younger landslides have fresh scarps, disrupted drainages, closed depressions, and disturbed vegetation. Older landslides are modified by erosion, resulting in subdued scarps, reestablished vegetation, and new drainage paths. Soils have formed on some of the older landslide deposits; however, most soils are poorly developed or absent because of high erosion rates and steep slopes.

Historic landslides and landslides verified by subsurface exploration are classified as “definite.” “Probable” landslides have prominently developed geomorphic features such as closed depressions, nearly flat or reversed drainage, ponded drainage, seepage, sharp breaks in slope, and hummocky topography; but slip planes are not confirmed by subsurface data. “Questionable” landslides have very subdued, poorly developed geomorphic features; and slip planes are not confirmed by subsurface data.

Analysis of aerial photographs and geotechnical borings (where available) was used to categorize the dominant type of slope movement. Landslide types were subdivided into three categories (see figure 7) based on a simplified version of Varnes' (1978) classification system: (1) relatively deep-seated (tens of meters) rock and soil

Figure 7. Schematic illustration of types of landslides. Modified from Varnes (1978).

slides, (2) relatively shallow (less than a few meters) debris flows, and (3) areas of detached free-falling rock (rockfalls).

As landslides move, their internal structure generally becomes disrupted, thereby affecting the physical properties. Strength and stability of landslide deposits are variable and should be determined on a site-specific basis. Factors such as the type of material, slope inclination, and degree of saturation influence the strength and stability characteristics.

Colluvium

Colluvial deposits are common in the hillside areas, especially in topographic swales (hollows). These deposits are up to tens of meters wide, hundreds of meters long, and are up to about 7 meters thick. Only the largest deposits are shown on plate 2, and as a result the colluvial deposits are under-represented.

Since colluvium forms in result of active slope processes, several cycles of deposition may fill a topographic hollow. In the central Coast Ranges near San Francisco, radiocarbon dating of colluvium revealed ages ranging from 1,000 to 29,000 yr B.P. (years before present). The majority of the colluvium was 9,000 to 14,000 yr B.P., indicating a late Pleistocene to early Holocene age (Reneau and others, 1990). In Carmel Valley, radiocarbon dating of charcoal in colluvium yielded ages of $1,880 \pm 45$ (Dicarb Radioisotope Co. sample no. DIC-3115) and $2,370 \pm 60$ yr B.P. (Dicarb Radioisotope Co. sample no. DIC-3116) for samples from 1 and 1.7 m below the ground surface, respectively (Rogers E. Johnson & Associates, 1985a). However, the laboratory report states that these samples were contaminated by roots. This contamination by modern carbon suggests that the estimated age of the colluvium may be younger than indicated by the radiocarbon dating.

Colluvium consists of a variable mixture of unconsolidated; poorly drained; poorly sorted clayey sand, sandy clay, and gravelly clay with significant amounts (up to 20 percent by volume as visually estimated) of organic debris. The composition and physical properties of colluvial deposits are dependent on the parent material. Soils have formed on some of the older colluvial deposits; however, most soils are poorly developed or absent because of high erosion rates and steep slopes. Colluvium has low strength, especially under saturated conditions.

Older Flood Plain Deposits

Older flood plain deposits are stratigraphically between terrace deposits and younger flood plain deposits, and are probably of Holocene age (Dupré, 1990). The older flood plain deposits are nearly flat to gently sloping and fill an irregularly shaped valley beneath the Carmel River (Logan, 1983). Interpretation of well log data suggests that the older flood plain deposits are typically less than 18 m thick in the study area, but may be up to 40 m in thickness.

Older flood plain deposits consist of a variable mixture of poorly consolidated, well drained, moderately to well-graded sand and silt with thin clay layers, and minor amounts of gravel, cobbles, and boulders (Dupré, 1990). The gravels and cobbles consist of mostly schist, gneiss, and granitic rock, with a minor amount of siliceous shale. Depth to ground water ranges from 0 to 10 m below the ground surface in years of normal rainfall.

Younger Flood Plain Deposits

Holocene age younger flood plain deposits occupy the Carmel River channel and are less than 6 m in thickness. These deposits consist of unconsolidated, well drained, heterogeneous deposits of sand and silt, including relatively thin, discontinuous layers of

clay and local gravel deposits (Dupré, 1990). The gravels consist of mostly schist, gneiss, granitic rock, and siliceous shale. Water levels fluctuate rapidly in response to recharge, and can be within a few meters of the ground surface.

Undifferentiated Alluvial Deposits

Undifferentiated alluvial deposits of variable thickness and composition fill the channels of major hillside drainages. These include unconsolidated, moderately to poorly-graded clean sands, moderately to well-graded silty sands with gravel containing discontinuous lenses of clay and silty clay, and moderately-graded gravels and cobbles. Depth to ground water is ranges from 0 to 18 m below the ground surface, but is usually less than 8 m.

Artificial Fill

Manmade (artificial) fill is common throughout Carmel Valley. Known areas of fill range from several to hundreds of meters in width and up to 15 m in thickness. Only the largest deposits are shown on plate 2, and as a result fill areas are under-represented. Fill consists of a highly variable mixture of sand, silt, clay, and gravel with varying amounts of organic material.

The physical properties of fill areas depend on the type of material and the method of placement. The main distinction for manmade fills is between “engineered” and “nonengineered fills.” Engineered fills are those placed, compacted, and tested according to grading recommendations that specify the type of material, density, and moisture content. Nonengineered fills are often loosely compacted or improperly placed, and may contain significant amounts of unsuitable material. Because of this variability in physical properties, the susceptibility to landslide and earthquake hazards vary.

STRUCTURE

Folds

At least three major periods of deformation are recorded in the rocks of the northern Santa Lucia Range. The first episode of deformation is middle Paleozoic to late Mesozoic age and is represented by northeast-trending, southeast-dipping foliations in metamorphic rocks. The second episode of folding occurred during emplacement of plutonic rocks in the middle to late Mesozoic. This resulted in northwest-trending minor fold axes in the metamorphic rocks (Wiebe, 1970). Severe deformation occurred during the late Pliocene to early Pleistocene, folding both the basement and younger rocks (Compton, 1966).

Two types of folding are common in the Tertiary rocks: (1) very tight and broken folds such as those occurring in the Monterey shale near fault zones, and (2) much broader, open folds that are mappable on a regional scale (see plate 1). The regional fold axes trend mainly N. 65° W. to N. 85° W. Dips typically are vertical or overturned within the fault zones, with common drag folds. Most of the major folds are subparallel to faults (N. 40° W. to N. 50° W. trend) and are truncated by faults, indicating that folding preceded faulting.

Several lines of geologic evidence indicate ongoing tectonic deformation. These include: bedrock highs within Carmel Valley, some of which appear to offset older flood plain deposits; faulted Pleistocene terrace and Holocene(?) landslide deposits; and clustered earthquake epicenters.

Faults

Tularcitos Fault

First mapped by Fiedler (1944), the Tularcitos fault is a northwest-striking, steeply southwest-dipping reverse fault that separates Tertiary sedimentary rocks from Cretaceous granitic basement rocks. Bowen (1965) correctly pointed out that the Tularcitos fault is not a single trace, rather a "... braided, imbricate system of many steeply-dipping faults." As shown on plate 1, the Tularcitos fault is a zone of several discontinuous segments approximately 2½ km wide exposed in the foothills along the Carmel River.

The Tularcitos fault zone extends from mid-Carmel Valley to the Jamesburg area (about 18 km east of the study area) where it branches into the Paloma fault for a total length of approximately 42 km. Vertical displacement of the Tularcitos fault is about 380 m (Fiedler, 1944, p. 237). Graham (1976, p. 151) postulated that at least 3.2 km and possibly 16 km of right-lateral displacement has occurred along the Tularcitos fault, based on the apparent offset of distinctive Monterey shale beds.

The Tularcitos fault is poorly exposed; however, several key exposures indicate the nature of the fault. At least two strands of the Tularcitos fault cut deposits of a very large landslide on the north side of Tularcitos Ridge east of the study area. About 1 km east of the study area in the southwest corner of projected sec. 21, T. 17 S., R. 3 E., a trace of the Tularcitos fault offsets late Pleistocene to early Holocene age debris flow deposits; and younger debris flow deposits are offset by the fault (Kingsley Associates, 1988, p. 9). Because the fault is within a large landslide complex, it is not clear whether the observed offset is related to active faulting or internal deformation of the landslide. Geomorphic features such as deflected drainages and linear closed depressions visible on aerial photographs of the area suggest, but do not prove active faulting along this segment

of the Tularcitos fault. Subsurface exploration and dating of Quaternary deposits are needed to evaluate if the offset debris flows are a result of recent faulting.

At the east end of the study area, the Tularcitos fault is exposed along a roadcut on Carmel Valley Road about 150 m east of Cachagua Grade. At this location, granitic rocks are thrust over Monterey shale in a zone of sheared rock dipping approximately 50° SW. Further west on Carmel Valley Road, the Tularcitos fault offsets unconsolidated gravels of the lowest and youngest river terrace against Monterey shale in a zone of intensely fractured rock several meters wide, dipping approximately 74° SW. (locality 9, plates 1 and 2). The shale beds dip steeply into the fault zone (see figure 8). Thin colluvial deposits overlying the fault are not offset at this exposure, suggesting this strand of the fault has not moved in the past few thousand years.

Quaternary deposits cover most of the Tularcitos fault between the Tularcitos Guard Station and Robles del Rio. Near the Tularcitos Guard Station, granitic rock is faulted against Monterey shale. However, Pleistocene river terraces along the Carmel River are not offset by this trace of the Tularcitos fault (Thorup, 1978). In the northwest corner of sec. 10, T. 17 S., R. 2 E. (Carmel Valley quadrangle), three subparallel near-vertical traces of the fault juxtapose granitic rock against Monterey shale and Miocene marine sandstone along Southbank Road (Kingsley Associates, 1981). Field checking during this study revealed that the faults on Southbank Road do not offset overlying thin colluvial deposits. These three faults project beneath, but do not appear to displace landslide deposits to the northwest at Robles del Rio.

Vague tonal lineaments on aerial photographs and steeply dipping Monterey shale beds define three faults near Carmel Valley Village. A branch near the landing strip (localities 7 and 8, plates 1 and 2) juxtaposes Pleistocene terrace deposits against steeply

Figure 8. Photograph of Tularcitos fault along Carmel Valley Road. Note change in dip of Monterey shale from gently dipping to near-vertical across the fault and Pleistocene river terrace deposits offset by fault.

dipping Monterey shale, but does not offset a moderately developed soil layer (McKittrick, 1987; Dupré, 1990). McKittrick (1987) showed two faults in the foothills north of Carmel Valley Village in the Monterey shale. The northernmost trace offsets terrace deposits and dies out beneath the broad fluvial terrace on the north side of the Carmel River (locality 6, plates 1 and 2). The recency of activity along these faults is probably late Pleistocene to early Holocene.

The Tularcitos fault is concealed by alluvium from Carmel Valley Village to the west end of Garzas Road. This portion of the fault was located by plotting bedrock lithology as interpreted by Logan (1983) from water well logs. Logs of wells completed

after Logan's 1983 report were also interpreted to plot bedrock lithology. Wells completed in shale or sandstone are on the north side of the fault and wells completed in granite are on the south side. Water well logs and geophysical data also suggest a buried granitic bedrock high near the mouth of Juan de Matte Canyon.

From the west end of Garzas Road to Garland Ranch Regional Park (NE¹/₄ sec. 30, T. 16 S., R. 2 E., Seaside quadrangle), the Tularcitos fault is a high-angle zone of crushed granitic rock thrust over Miocene marine sandstone along the foothills. This segment of the Tularcitos fault appears on aerial photographs as a series of topographic benches and saddles. A broad flat-lying terrace near the 500-foot contour in the NE¹/₄ sec. 30, T. 16 S., R. 2 E. (Seaside quadrangle) appear to be a result of uplift along the Tularcitos fault. However, plowing of the terrace surface obscures any possible geomorphic evidence of recent faulting. Four springs lie near the Tularcitos fault in Garland Park (Nikki Nedeff, Monterey Peninsula Regional Park District, written commun., 1991). These springs emanate from the intensely fractured rock within the fault zone. Drainages that cross this segment of the Tularcitos fault are not offset, suggesting that recent strike-slip displacement has not occurred.

Clark and others (1974) depicted the Tularcitos fault as striking westward near Snivelys Ridge where it is truncated by the northern extension of the Pinyon Peak fault (the Snivelys fault of Bowen, 1965). Exploratory trenching did not reveal the presence of this segment of the Tularcitos fault (Earth Systems Consultants, 1984). Also, magnetometer and seismic refraction studies by O'Rourke (1980) show inconclusive evidence for this segment of the fault. Field checking of new roadcuts at Carmel Valley Ranch (NW¹/₄ sec. 30, T. 16 S., R. 2 E.) during this study revealed this contact is an unconformity, rather than a fault.

The Tularcitos fault is concealed by the Carmel River near Scarlett Road in an area known locally as “the narrows.” The name “narrows” is derived from the abrupt constriction of the valley between granitic outcrops. Steeply dipping sandstone beds and “anomalously thick sandstone” found in a water well boring indicate faulting in this area (Richard R. Thorup, oral commun., 1986, cited in McKittrick, 1987, p. 10). Logs of water wells drilled in the narrows show that granitic bedrock is separated from Monterey shale along the trend of the Tularcitos fault. The Tularcitos fault emerges from the alluvium near the mouth of Meadows Canyon where it offsets Pleistocene terrace deposits (locality 3, plates 1 and 2) and appears to join the Berwick Canyon fault. If the Tularcitos fault is continuous with the on-land extensions of the Monterey Bay fault zone, its total length would be as much as 74 km.

Sieck (1964) used geophysical data to infer the Tularcitos fault as striking westward beneath the Carmel River toward the coast. Sieck stated, “The fault on the south side of the valley is questionable, but the gravity curves fit very well with such an interpretation.” No other features indicate the continuation of the Tularcitos fault into this part of the valley. Interpretation of water well logs and Sieck’s gravity data suggest that a mass of granitic rock is concealed by alluvium between Cañada de la Ordena and Cañada de la Segunda. The limited extent of this body, nearby gently dipping Monterey shale beds, and lack of geomorphic evidence suggests that this granitic rock mass is a bedrock high resulting from erosion rather than faulting.

Navy Fault

The Navy fault is a northwest-striking, steeply southwest-dipping reverse fault that places Monterey shale over Pleistocene terrace deposits. Zones of intensely fractured and contorted Monterey shale usually less than 45 m wide are characteristic of the Navy fault. The total amount of vertical displacement along the Navy fault is unknown;

however, Pleistocene terrace deposits are offset about 10 m near Jacks Peak. The linear trace of the Navy fault and alignment with the Tularcitos fault and the Monterey Bay fault zone suggest strike-slip movement along the Navy fault, although this remains unproven.

Clark and others (1974) originally mapped the Navy fault extending approximately two km from the mouth of Cañada de la Ordena northwest to the U.S. Naval Postgraduate School in Monterey. Near the southern end of Cañada de la Ordena, intensely fractured and steeply dipping Monterey shale beds delineate the Navy fault, although the trace is locally concealed by alluvium and landslide deposits.

The Navy fault splits into two subparallel branches near Cañada de la Ordena. This segment of the fault appears on aerial photographs as well-defined linear drainages, aligned benches, and saddles. Clark and others (1974) cited "prominent southwest-facing scarps" as evidence for this part of the Navy fault. Bryant (1985) suggested out that southwest-facing scarps are incompatible with a southwest-dipping reverse fault, and were the result of stream erosion. Alternatively, these scarps could be anti-dip slopes developed along joint sets in the Monterey shale.

The two traces rejoin for a short distance near the head of Cañada de la Segunda, and then diverge again northwestward toward Monterey. Clark and others (1974) observed a spring draining from a northeast-facing scarp at this location. As part of a feasibility study for a new dam, Wahler Associates (1990) excavated three exploratory trenches and one large-diameter boring in a valley along the mapped trace of the Navy fault (sec. 10, T. 16 S., R. 1 E., Seaside quadrangle). The trenches exposed sandy clay colluvium containing angular fragments of Monterey shale to the explored depth of 4 m. The trench logs show no offset of the colluvium. The large-diameter boring encountered 4.5 m of colluvium underlain by "crushed and sheared shale" to the explored depth of 18

m. Although the subsurface data suggest that the Navy fault is present, the trenches are not sufficiently deep to determine the nature of the colluvium/bedrock contact and the recency of movement along the fault at this location.

A splay of the Navy fault was found in an exploratory trench next to the water tank along the west boundary of sec. 10, T. 16 S., R. 1 E. (Wahler Associates, 1990). In this trench, a thin horizontal clay seam was vertically offset 30 cm by a normal fault oriented N. 47° W., 65° SW. The fault plane consists of a 30-cm-wide zone of crushed shale. Field checking of the trench during this study revealed that neither the bedrock nor the overlying soil are offset; therefore, this splay is probably inactive.

An unresolved question is whether the Navy fault continues offshore into the Monterey Bay fault zone (Greene and others, 1973; Clark and others, 1974) or terminates as a series of thrust faults near the city of Monterey as suggested by Dupré (1986). Two main lines of evidence support a connection with the Monterey Bay fault zone. The first is that unpublished geotechnical studies and water well data indicate that faulting is present along the inferred trace of the Navy fault in Monterey mapped by Clark and others (1974). The second is that the thrust faults may be related to strike-slip movement along the Navy fault. The presence of northwest-trending thrust faults and en echelon fold axes is consistent with transpression developed along a right-lateral strike-slip fault. First motion studies and fault plane solutions show right lateral strike-slip motion along vertical fault planes for the Monterey Bay fault zone (Cockerham and others, 1990).

In addition to these previously mapped thrust faults, J.C. Clark recently mapped an east-striking, low-angle thrust fault that joins a similar trending lineament across a coastal terrace mapped by Dupré to the east (J.C. Clark, written commun., 1992). These thrust faults cut across the main trace of the Navy fault. Further work is necessary to determine the relationship of the Navy fault with these newly mapped thrust faults.

Berwick Canyon Fault

Beal (1915) originally mapped, but did not name two short, en echelon, northwest-striking faults near Berwick Canyon. Clark and others (1974) mapped these faults and a short fault at the mouth of Tomasini Canyon as the Berwick Canyon fault. Many of the exposures used to map the Berwick Canyon fault in the early 1970's are now obscured by development (J.C. Clark, oral commun., 1990).

The Berwick Canyon fault extends about 5 km from the Carmel River to the crest of the Sierra de Salinas and offsets Monterey Shale against Pleistocene terrace deposits. McKittrick (1987) mapped a 35-m-wide zone of near-vertical dipping Monterey shale extending for 2 km along the Berwick Canyon fault. The dip of the fault is probably near-vertical to steeply dipping with a reverse sense of displacement, based on the geometry and relation to nearby faults. The total displacement is not known, although Younse (1980) shows approximately 90 m of vertical offset along the Berwick Canyon fault.

The eastern branch of the Berwick Canyon fault begins near Carmel Valley Road (N¹/₂ sec. 29, T. 16 S., R. 2 E.) and continues northwest to Meadows Canyon. This branch juxtaposes granitic rock against Monterey shale in Coyote Gulch, and offsets Pleistocene terrace deposits near the Carmel River (locality 4, plates 1 and 2). The eastern branch of the Berwick Canyon fault is defined in the field by steeply dipping Monterey shale; and on aerial photographs by poorly developed topographic benches and saddles.

The main (western) branch of the Berwick Canyon fault is defined by intensely fractured, steeply dipping Monterey shale in an area of otherwise gently dipping beds (see figure 9). On aerial photographs, this segment of the fault appears as a series of aligned linear drainages. The western branch of the Berwick Canyon fault offsets Pleistocene

terrace deposits and may be continuous with the Tularcitos fault (localities 2 and 3, plates 1 and 2).

The western branch of the Berwick Canyon fault appears to end near the crest of the Sierra de Salinas. Clark and McKittrick (1985) inferred a west-striking extension of the Berwick Canyon fault that connects with the Navy fault along a well-developed linear drainage parallel to the crest. However, no fault-related features such as steeply dipping beds are present to support the presence of this inferred trace. Clark and McKittrick (1985) suggested that the Berwick Canyon fault continues beneath a large landslide on

Figure 9. Photograph of Berwick Canyon fault. Note change in dip of Monterey shale from gently dipping to near-vertical across the fault, and intense fracturing in the fault zone. Scale bar is 16.5 cm long.

the north side of the Sierra de Salinas and merges with the Chupines fault near Highway 68. Vaughan and others (1991) logged an exploratory trench across the projected fault trace and found offset soil horizons. Radiocarbon dating of these offset soils indicates several episodes of movement during Holocene time. The trench exposure was examined during this study; however, the cause of the offset soils is equivocal and could be landslide-related. Additional subsurface exploration would help clarify the origin of these fault-like features.

Hatton Canyon Fault

A group of northwest-striking, near-vertical dipping reverse faults that offset Monterey shale against Pleistocene terrace deposits is exposed in Hatton Canyon approximately 3 km west of the study area. The Hatton Canyon fault is a 3-km-long, 30-m-wide zone of steeply dipping and intensely fractured Monterey shale. Minor cross-faults with less than 30 cm of vertical displacement are common within the Hatton Canyon fault zone. The total displacement along the Hatton Canyon fault is unknown, but similar terrace deposits are located about 120 m south of the fault and are approximately 30 m lower in elevation. This suggests at least 30 m of vertical offset during Quaternary time.

Beal (1915) and Galliher (1930, 1932) showed, but did not name this fault. Recent unpublished mapping in the Monterey quadrangle by J.C. Clark has confirmed this earlier work (J.C. Clark, written commun., 1991). The fault extends northwest from Hatton Canyon, where it aligns with an anomaly in the coastal terrace deposits. Another northwest-trending strand of this zone offsets Quaternary terrace deposits north of Carmel High School (Dupré, 1990).

The eastern extension of the Hatton Canyon fault appears to join an unnamed fault in Martin Canyon mapped by Galliher (1930, 1932). This fault was exposed in an

excavation for a water tank (see figure 10). At this location, the fault clearly offsets Monterey shale against an upper level fluvial terrace deposit (locality 1, plates 1 and 2). Several strands of this zone also offset landslide and colluvial deposits by 15 to 30 cm. Dating of the colluvium is necessary to constrain the time of the latest movement, which may be as recent as Holocene.

Figure 10. Photograph of Hatton Canyon fault in Martin Canyon looking east. Main trace of fault offsets steeply dipping Monterey shale on the south from Pleistocene river terrace deposits on the north. At left side of photo, a splay of the fault juxtaposes Pleistocene river terrace and Holocene(?) landslide deposits. Note offset colluvium above both fault traces. For scale, foundation is approximately 30 cm high.

As a result of this discovery, an exploratory trench was excavated across the Hatton Canyon fault 20 m east of the water tank exposure (Upp Geotechnology, 1991).

This trench exposure was examined during this study. Terrace deposits were faulted against steeply dipping Monterey shale beds in a 3.6-m-wide zone of faulting. A bedding plane fault filled with topsoil was observed in the trench, suggesting that recent minor displacement had occurred on the fault.

Between Roach Canyon and Cañada de la Segunda, the fault trace is discontinuous and offsets lower fluvial terrace deposits. Two anomalous landslide deposits crop out on the south side of the fault. A recent study by the Monterey Peninsula Water Management District (Oliver, 1991) suggests a hydrogeologic barrier along the projected trend of this faulting east of Roach Canyon. Offset of the water-bearing alluvium which Dupré (1990) considers to be Holocene, would confirm recent activity along this zone.

Laureles Fault

This fault was first mapped by Herold (1935) in the southwest corner of the Spreckels quadrangle. Fiedler (1944) extended the Laureles fault southeast into the Carmel Valley quadrangle, and renamed it the Del Monte fault for an exposure near Rancho Del Monte (now the Los Laureles Lodge). In this report, the original name "Laureles" is retained to avoid confusion with faults near the Del Monte district of Monterey.

Herold (1935) described the Laureles fault as a northwest-striking, vertical fault separating Cretaceous granitic rock and Miocene marine sandstone. Fiedler (1944) showed the Laureles fault as a southwest-dipping normal fault, whereas Dibblee (1972) mapped the Laureles fault as high-angle reverse fault dipping 75° NE. The length of the Laureles fault is about 6.5 km. McKittrick (1987) mapped a 15-m-wide zone of near-vertical dipping Monterey shale extending for 3.5 km along the Laureles fault. Estimates

of vertical displacement on the Laureles fault range from about 180 m (Fiedler, 1944) to 300 m (Herold, 1935).

Steep to near-vertical dipping Monterey shale thrust against Pleistocene terrace deposits (locality 5, plates 1 and 2) characterizes the northwest portion of the Laureles fault from Tomasini Canyon to Laureles Grade. An anomalously thick section of Miocene marine sandstone was encountered in a water well boring adjacent to the south side of the Laureles fault about 150 m west of Laureles Grade. Granite was not found in the drilled depth of 176 m although it crops out nearby on the north side of the fault (R.R. Thorup, oral commun., 1992).

From Laureles Grade to Carmel Valley Village, the fault separates granitic rock from steeply dipping Miocene sedimentary rock. Northeast of Carmel Valley Village, the Laureles fault trends eastward into a large landslide deposit and dies out. Fiedler (1944) showed the Laureles fault terminated by a cross-fault; however, field evidence and analysis of aerial photographs do not support his interpretation.

Stephani Fault

Fiedler (1944) mapped a northwest-striking fault dipping 60° NE. juxtaposing granitic basement rock against Miocene sandstone and shale near Camp Stephani. He described the Stephani fault as a narrow zone of faulting extending for 4 km and estimated about 230 m of vertical displacement. Neel (1963) interpreted the Stephani fault as an unconformity.

On plate 1, the contact between the granitic rock and Monterey shale west of the Carmel River is depicted as a questionable fault. The main evidence for faulting is intensely fractured Monterey shale along the contact. East of the Carmel River, no evidence of faulting was observed between the granitic rock and Miocene marine sandstone; therefore, the contact is shown as an unconformity.

Cachagua Fault

The Cachagua fault was first mapped by Fiedler (1944), as a northwest-striking, near-vertical dipping reverse fault separating Miocene sandstones from pre-Cenozoic metamorphic basement rocks. Dibblee (1972) measured the fault dipping from 70° to 75° SW.

Fiedler (1944) showed the Cachagua fault as approximately 12 km long, but speculated that if the Cachagua fault is continuous with nearby faults in the adjoining Point Sur and Soledad 15-minute quadrangles, then the overall length is at least 40 km. The fault plane is a shear zone of broken and contorted schist ranging from about 15 m (Fiedler, 1944) to 60 m wide (Neel, 1963). Vertical displacement is about 530 m (Fiedler, 1944).

The northeastern part of the Cachagua fault from Las Garzas Creek to the east side of the San Clemente Dam is poorly exposed in the field due to similar crystalline basement rocks on both sides of the fault. This segment of the Cachagua fault appears on air photos as a prominent linear feature flanked by numerous landslides. From the San Clemente Dam to the east edge of the study area, the Cachagua fault places schist against Miocene marine sandstone.

Quaternary stream terraces along this segment of the fault are not offset by the Cachagua fault (Rogers E. Johnson & Associates, 1985b). Quaternary landslide deposits are common along the fault trace, but are not offset by the Cachagua fault.

Pinyon Peak Fault

Two parallel northwest-striking, normal faults dipping 85° SW. on the northeast side of Pinyon Peak were originally mapped by Trask (1926) as the Piñon Peak fault. Current USGS topographic maps refer to Piñon Peak as Pinyon Peak, and that spelling is used in this report. The Pinyon Peak fault shows 210 m of throw, and separates Miocene

sedimentary rock from granitic basement rock (Trask, 1926). Brown (1962) and Dibblee (1973a) did not show the Pinyon Peak fault on their maps.

Brown (1962) mapped a northwest-striking fault on the southwest side of Snivelys Ridge separating granite and sandstone. This fault appears to be the northern extension of the Pinyon Peak fault. Bowen (1965) named it the Snively fault and showed the dip as vertical. O'Rourke (1980) described the fault as a 30-m-wide, nearly vertical zone of sheared granodiorite, with a vertical offset of 95 m. A 550-m-long high-angle fault juxtaposing Monterey shale and Miocene marine sandstone located in the center of sec. 25, T. 16 S., R. 1 E. (Seaside quadrangle) is also included as part of the Pinyon Peak fault zone in this study. The combined length of the Pinyon Peak and Snively faults is approximately 4 km.

The southern end of the Pinyon Peak fault dies out in granodiorite approximately 1.5 km southeast of Pinyon Peak. O'Rourke (1980) used exploratory borings and magnetometer data to extend the Snively fault north beneath the large landslide in the NE¹/₄ sec. 25, T. 16 S., R. 1 E. During this study, 10-m-deep construction excavations for a new road within the landslide area were field checked. No evidence for the concealed portion of the Snively fault as mapped by Clark and others (1974) and O'Rourke (1980) was observed in the landslide area.

The Pinyon Peak fault zone is poorly exposed in the field, but is distinguished by the contact between Miocene marine sandstone and granitic rock. On air photos, the Pinyon Peak fault appears as a prominent linear feature flanked by several landslides. Quaternary landslide deposits along the fault zone within the study area are not offset by the Pinyon Peak or Snively faults.

Robinson Fault

Trask (1926) mapped a northwest-striking, normal fault dipping 75° NE. near Rancho San Francisquito as the Robison fault. Current USGS topographic maps refer to Robison Canyon as Robinson Canyon, and that spelling is used in this report. The Robinson fault separates Miocene sedimentary rocks from granitic basement rocks, and is approximately 3 km long and less than 30 m wide. Estimates of vertical displacement on the Robinson fault range from about 90 m (Brown, 1962) to 300 m (Trask, 1926). The northern end of the fault dies out in Miocene marine sandstone, while the southern end is cut off by the San José thrust immediately south of the study area (Dibblee, 1973a).

Because of access restrictions, only part of the Robinson fault was field checked. The Robinson fault is poorly exposed in the field, and is distinguished by the contact between Miocene sandstones and granitic rock. On air photos, the Robinson fault is delineated by a prominent topographic lineation and faceted spurs along the contact between the high relief granitic rocks and the low relief sandstones. Because of the large amount of rainfall and high erosion rates in the area, these geomorphic features may represent erosion along a fault line, rather than active faulting. Quaternary landslide deposits along the fault trace within the study area are not offset by the Robinson fault. Further field work is necessary to evaluate the Robinson fault.

Garzas Fault

South of Pinyon Peak, Trask (1926) mapped a northeast-striking, reverse fault dipping 80° SE. that juxtaposes Miocene marine sandstone and granitic basement rock as the Garces fault. Current USGS topographic maps refer to Garces Creek as Garzas Creek, and that spelling is used in this report. The Garzas fault is approximately 4 km long and less than 30 m wide. Trask (1926) estimated the total vertical displacement at 180 m.

The eastern end of the fault is cut off by the Pinyon Peak fault, while the western end dies out in the Miocene marine sandstone. Trask (1926) depicted the west portion of Garzas fault as bending sharply south and then west along the sandstone/granite contact and ending at the Robinson fault. Because high-angle reverse faults typically form linear traces, this suggests the contact may be in part nonconformable. Brown (1962) felt that the contact between the sandstone and granite was nonconformable, rather than faulted. Dibblee (1973a) did not show the Garzas fault.

Because of access restrictions, the Garzas fault was not field checked, but was examined using aerial photographs. On air photos, the Garzas fault appears as a faint topographic lineation along the contact between the Miocene marine sandstone and granitic rock. Quaternary landslide deposits along the fault trace within the study area are not offset by the Garzas fault. Field work is necessary to fully evaluate the Garzas fault.

Vasquez Fault

Trask (1926) depicted the Tertiary sedimentary and volcanic rock in secs. 17 and 18, T. 17 S., R. 2 E. (Mount Carmel quadrangle) as separated from granitic rock by an unnamed circular group of high-angle (80°) normal faults. Because the closest geographic feature is Vasquez Knob, these faults are herein referred to as the Vasquez fault. According to Trask (1926), the main criterion for faulting is a 3-m-wide brecciation zone along the contact with volcanic rock. Trask (1926) did not estimate the amount of displacement. Dibblee (1973a) showed the contact between the Tertiary rocks and granitic rocks as unfaulted.

On plate 1, the Vasquez fault is on the north side of the Tertiary rocks, because of the linear truncation of the beds against the granitic rock. The circular fault trace shown by Trask (1926) would be expected with low-angle thrust faulting. As the measured dip of the fault is steep, the circular trace likely represents an unfaulted contact.

Because of access restrictions, the Vasquez fault was not field checked, but was examined using aerial photographs. On air photos, the Vasquez fault (as shown on plate 1) appears as a distinct topographic lineation with contrasting vegetation. This is not conclusive evidence for faulting, and is probably due to differential weathering of the rock units. No geomorphic features suggestive of recent faulting were observed on the air photos. Field work is necessary to fully evaluate the Vasquez fault.

EARTHQUAKE HAZARDS

Regional Seismicity

An important part of evaluating the seismic hazard potential for an area involves analyzing the distribution of regional earthquakes in time and space. One limitation is that the historic record of large earthquakes is short in comparison to their recurrence intervals. From the nineteenth century to 1934, the earthquake history is based on descriptions from mission records, newspapers, and personal accounts (Griggs, 1973). The pre-instrumental earthquake record is lacking events with magnitudes of 4 or less because only the largest earthquakes are reported.

Since 1934, seismometers have been used to record earthquakes in central California (Griggs, 1973). The accuracy of an earthquake location is influenced by the number and location of the seismometers detecting that event. Before the installation of the USGS seismometer network (CALNET) in 1969, the seismometer coverage was sparse. In 1979, CALNET coverage improved since additional instruments were added to the network (J.C. Tinsley, USGS, oral commun., 1992).

Because the study area is near the coast, coverage to the west is absent. The lack of closure in this part of the seismometer network limits the accuracy of the relative epicenter locations near the study area. A source of uncertainty in the absolute location is crustal velocity model used to locate earthquakes. The USGS uses a modified version of the Coast Range velocity model to locate earthquakes recorded by CALNET in the Carmel Valley area. However, this model needs to be revised using seismic refraction studies and inversion of earthquake travel time data (Fred Klein, USGS, oral commun., 1992). Because of the differences in earthquake location methods during the past 250 years, the relative accuracy of earthquake locations varies and is listed in Table 1.

Table 1. Estimated uncertainty in earthquake locations in the Monterey Bay area.

Year	Estimated horizontal uncertainty in km	Source of estimate
pre-1934	15–60	Kilbourne and Mualchin (1980)
1934-1968	± 10	Greene and others (1973)
1969-1978	± 5	Greene and others (1973)
1979-1992	± 3	F.W. Lester, USGS, written commun. (1992)

Plots of earthquakes of magnitude 4 or greater within a 100 km radius of the center of the study area are shown on figures 11 through 14. The 100 km radius is suggested by the California Division of Mines and Geology (1975) to include significant regional faults. Epicenter locations and magnitudes are compiled mainly from CDMG and CALNET data (see appendix A). Fault locations are from Buchanan-Banks and others (1978). Although the locations of pre-instrumental and early instrumental earthquakes are questionable, they show the general pattern of seismicity in the region.

The three largest recorded earthquakes (as of 1990) were approximately 60 km north (M 7.1; October 17, 1989), 83 km north (M 6.6; July 1, 1911), and 90 km north (M 6.3, October 8, 1865) of the center of the study area. The 1865 and 1989 earthquakes were probably on the San Andreas fault (Ellsworth, 1990; Plafker and Galloway, 1989). The 1911 earthquake was probably on the Calaveras fault (Ellsworth, 1990).

In addition, on October 22, 1926 two M 6.1 earthquakes occurred within one hour of each other in Monterey Bay (Mitchell, 1928). The epicenters were approximately 53 and 37 km from the center of the study area. Because these are pre-instrumental events, it is unknown whether the earthquakes occurred on the Monterey Bay fault zone or the San Gregorio fault.

Figure 11. Earthquake epicenters greater than M 4 for the period 1841-1933, and faults within 100 km of the center of the study area (36.5°N., 121.75° W.).

Figure 12. Earthquake epicenters greater than M 4 for the period 1934-1968, and faults within 100 km of the center of the study area (36.5°N., 121.75° W.).

Figure 13. Earthquake epicenters greater than M 4 for the period 1969–1978, and faults within 100 km of the center of the study area (36.5°N., 121.75° W.).

Figure 14. Earthquake epicenters greater than M 4 for the period 1979–1990, and faults within 100 km of the center of the study area (36.5°N. , 121.75°W.).

Local Seismicity

Numerous examples of faulted late Quaternary deposits (see plates 1 and 2) suggest that some of the faults in the Carmel Valley are more recently active than previously thought. CALNET seismograph records for the Carmel Valley area were examined to determine the relationship between seismicity and faults in the area. Figure 15 shows the locations of earthquake epicenters that occurred near Carmel Valley between January 1, 1969, and December 31, 1991. These epicenters range in magnitude from M 0.7 to M 2.8, and have an estimated horizontal uncertainty of 0.2 to 3.0 km (F.W. Lester, USGS, written commun., 1992). The epicenter data are included as appendix B.

Three patterns of seismicity are apparent on figure 15. The first is a prominent cluster of epicenters near the cities of Monterey and Carmel. These earthquakes occurred between December 1975 and January 1976, and ranged in magnitude from M 1.7 to M 2.7. Previous workers speculated these earthquakes were associated with the Cypress Point fault (Coppersmith and Griggs, 1978, p. 35; Bryant, 1985, p. 8).

It seems more likely that these earthquakes are associated with recently mapped thrust faults in the area because their epicenters coincide with the surface traces of these thrust faults. The horizontal uncertainty in location for earthquakes in this cluster ranges from 0.4 to 1.1 km, and the average uncertainty is 0.6 km. The depths of the epicenters are relatively shallow and consistent with low-angle faulting. First motion studies and fault plane solutions indicate a combination of thrust and strike-slip motion for several of these earthquakes (Cockerham and others, 1990). Recent surface movement on these thrust faults is unlikely given the small magnitude of the events, and no indication of historic movement was observed in the field during this study.

A second pattern of seismicity is the alignment of epicenters with the surface traces of the Tularcitos, Navy, Chupines, Berwick Canyon, Hatton Canyon, and Pinyon

Figure 15. Faults and earthquake epicenters in the vicinity of Carmel Valley.

Peak faults. First motion studies and fault plane solutions indicate strike-slip motion for several of these earthquakes (Cockerham and others, 1990). This pattern indicates that at least some of these faults are active at depth. These earthquakes are most likely associated with movement along the Navy and Tularcitos faults for the following reasons: (1) their apparent continuity with the seismically active Monterey Bay fault zone, and (2) several documented examples of late Quaternary movement along these faults.

A third pattern of seismicity is the alignment of several earthquakes in the Rancho San Carlos area with the surface traces of the Robinson fault and the San Clemente thrust. Definite correlation of earthquakes with faults in this area is speculative because of the lack of information on the nature of these faults. Several deep water well test holes were recently drilled at Rancho San Carlos and may yield information on the subsurface structure in the area. However, the well logs were unavailable at the time of this study.

Although many earthquakes in the Carmel Valley area align with mapped fault traces, they can not be positively correlated at this time for the following reasons: (1) the uncertainty in relative epicenter location resulting from the lack of closure in the seismometer network, (2) the uncertainty in absolute epicenter location resulting from lack of a revised crustal velocity model for the northern Santa Lucia Range, and (3) the lack of knowledge regarding the subsurface characteristics of the faults.

Maximum Credible Earthquake

One of the basic tasks in evaluating seismic hazards is determining the earthquake used in the analysis of related hazards such as liquefaction and landsliding. One approach is to calculate the maximum credible earthquake (MCE). The MCE is defined by the CDMG (1975) as:

“... the maximum earthquake that appears capable of occurring under the presently known tectonic framework. It is a rational and believable event

that is in accord with all known geologic and seismic facts. In determining the maximum credible earthquake, little regard is given to its probability of occurrence, except that its likelihood of occurring is great enough to be of concern.”

The seismic characteristics of active regional faults such as the San Andreas and potentially active local faults such as the Tularcitos are considered in determining the MCE. Three methods were used to calculate the maximum credible earthquake for each fault. Slemmons (1977) and Bonilla and others (1984) related fault magnitude to rupture length, whereas Wyss (1979) related magnitude to fault rupture area. These methods are based on empirical relationships that relate fault parameters to maximum magnitude. The data used to calculate the MCE are included in table 2. From table 2, the MCE is a M 7.4 earthquake on the San Gregorio fault.

Maximum Probable Earthquake

A second approach is to consider the most likely earthquake to affect the area during a given period. This event is the maximum probable earthquake (MPE) and is defined by the CDMG (1975) as:

“... the maximum earthquake that is likely to occur during a 100-year interval. ... the postulated magnitude shall not be lower than the maximum within historic time.”

The 100-year interval (return period) was calculated using the relationship suggested by Richter (1958, p. 359) and the earthquake data compiled for this study. The equation for this relationship is:

$$\log_{10}N = a - bM$$

where N is the number of earthquakes of magnitude of M or greater per unit time for the area considered, and a and b are constants derived from the plot of $\log_{10}N$ versus M . The relationship for the earthquake data in appendix A is $\log_{10}N = 3.66 - 0.83M$ (see figure 16).

Table 2. Faults and maximum credible earthquakes for the Carmel Valley area.

Fault and main type of movement	Direction and distance to nearest point from center of study area (km)	Total length (km)	Rupture length (km)	Magnitude vs. rupture length (Bonilla and others, 1984) ⁷	Magnitude vs. rupture length (Slemmons, 1977) ⁸	Magnitude vs area (Wyss, 1979) ⁹
San Andreas, S. Santa Cruz Mts. segment (strike-slip) ¹	45 NW	61	30.5	7.1	6.9	6.9
San Andreas, S.F. Peninsula segment (strike-slip) ¹	78 NW	40	20	7.0	6.8	6.8
Calaveras (strike-slip) ¹	50 NIE	50	25	7.0	6.9	6.9
San Gregorio (strike-slip) ²	18 SW	189	94.5	7.4	7.2	7.4
Zayante-Vergeles (strike-slip) ³	25 NIE	80	40	7.2	7.0	7.1
King City-Reliz (strike-slip) ⁴	21 SE	51	25.5	7.0	6.9	6.9
Tularcitos-Navy-Monterey Bay (strike-slip) ⁵	0.2 NE	74	37	7.1	7.0	7.0
Sur, northern segment (reverse) ⁶	19 SW	69	34.5	7.1	7.0	7.0

¹ Working Group on California Earthquake Probabilities (1990)

² Wesnousky (1986)

³ Coppersmith (1979)

⁴ Dibblee (1976)

⁵ Fiedler (1944); Clark and others (1974)

⁶ Gilbert (1971)

⁷ $M_s = 6.04 + 0.704(\log L)$; where M is magnitude, L is rupture length in kilometers

⁸ $M = 4.398 + 0.568(\log L)$; where M is magnitude, L is rupture length in meters (equation for reverse-oblique-slip faults)

⁹ $M = \log A + 4.15$; where M is magnitude, A is area in kilometers, with assumed focal depth of 10 km and dip of 75°

The return period is the reciprocal of N . From this relationship and the graph in figure 16; the 50-, 100-, and 250-year earthquakes are M 6.5, M 6.9, and M 7.3, respectively for the Carmel Valley area. Because the historical record is short relative to the 100-year return period, the calculated MPE is lower than the 1989 M 7.1 earthquake that has occurred in historic time. Therefore, according to State of California criteria, the MPE is M 7.1.

Figure 16. Cumulative frequency distribution of earthquakes for the Carmel Valley area, 1841–1990. Curve is based on earthquake catalog compiled for this study (see appendix A).

In 1990, the Working Group on California Earthquake Probabilities estimated a 23 percent probability for a M 7 earthquake occurring on the San Francisco Peninsula segment of the San Andreas fault between 1990 and 2020. Earthquake probabilities have

not been calculated for other regional faults near Carmel Valley. However, estimates of recurrence intervals for large earthquakes on some of these faults are available.

Weber (1980, p. 165) estimated a recurrence interval of 225 to 400 years for a M 7.5 earthquake along the San Gregorio fault using long-term slip rates calculated from offset marine terrace shoreline angles, and analysis of cyclical sag pond deposits and faulted colluvium. Tuttle (1985) studied the pattern of seismicity along the San Gregorio fault, and concluded that the segments from Santa Cruz to San Francisco and from Monterey to Ragged Point had fewer earthquakes than other segments and represent seismic gaps. Tuttle also postulated these relatively quiet segments are capable of producing M 7.2 to 7.4 earthquakes, and observed that amount of M 4 to M 6 earthquakes increased in the twenty years preceding large events such as the 1926 M 6.1 Monterey Bay doublet and the 1952 M 6.0 Bryson earthquake.

Recent earthquakes (M 5.2, 01/23/84; M 4.6, 01/23/84; M 4.7, 02/04/91; M 5.1, 09/17/91) are associated with the southern end of the Ragged Point segment. If Tuttle's hypothesis is correct, then a M 6 or larger earthquake on the Ragged Point segment of the San Gregorio fault is likely in the next decade. A similar pattern of seismicity occurred on the San Andreas fault before the 1989 Loma Prieta earthquake, with the mainshock and aftershocks filling in the seismic gap (Plafker and Galloway, 1989). Oppenheimer and others (1990) identified a seismic gap immediately south of Calaveras Reservoir in Santa Clara County, and speculated that it was capable of a M 5.5 earthquake. When this major earthquake will occur was not specified.

Fault Rupture

One of the characteristics of earthquakes with magnitudes of M 5.5 or greater and hypocenters shallower than 15 km is the cracking and displacement of the ground surface

along the causative fault trace (Ziony and Yerkes, 1985, p. 43). Fault rupture is a hazard along “active” faults. As defined by the State of California (Hart, 1992), an active fault has:

“... had surface displacement within Holocene (about the last 11,000 years).” A potentially active fault has, “... evidence of displacement during Quaternary time (last 1.6 million years).”

Inactive faults are those which do not show indications of movement in the past 1.6 million years.

Many of the faults in the study area are poorly exposed because of rugged terrain and dense vegetation. The lack of clear exposures and detailed maps have caused some geologists to regard the faults in the study area as inactive or potentially active. However, converging lines of evidence suggest recent faulting, the extent and nature of which have not been previously recognized.

These indications of recent fault activity include: (1) in the foothills of Monterey, thrust faults locally offset coastal terrace deposits by 15 to 20 m (Dupré, 1990); (2) a fault near Carmel Woods School (Monterey quadrangle, not mapped in this study) offsets lower Quaternary coastal terrace deposits as mapped by Dupré (1990) rather than middle Miocene Los Laureles Sandstone as mapped by Clark and others (1974), indicating a younger age of faulting; (3) excavations along the Hatton Canyon fault revealed faulted Quaternary landslide deposits and colluvium; (4) offset soil horizons possibly related to faulting exposed in an exploratory trench across a projected trace of Berwick Canyon (Vaughan and others, 1991); (5) on the north side of Tularcitos Ridge, a very large landslide deposit is cut by at least two strands of the Tularcitos fault, apparently offsetting late Pleistocene to early Holocene debris flow deposits (Kingsley Associates, 1988); (6) a hydrogeologic barrier within Holocene alluvial deposits along the projected trend of the Hatton Canyon fault (Oliver, 1991); (7) buried bedrock highs appear to align with

projected surface traces of mapped Quaternary faults; and (8) a plot of 1969–1991 earthquake epicenters indicates activity on several of the area's faults (see figure 15).

The Tularcitos, Navy, Hatton Canyon, Berwick Canyon, and Laureles faults are potentially active; but may be active because of displaced late Quaternary strata and alignment of earthquake epicenters. Additional work is needed to determine the age of the late Quaternary deposits in Carmel Valley, and the recency of faulting.

Because no instances of offset Quaternary deposits are documented along the Cachagua, Garzas, Vasquez, and Stephani faults, they are probably inactive. However, clusters of earthquakes near the Pinyon Peak fault, the Robinson fault and the San Clemente thrust suggest that these faults may not be “inactive,” and detailed studies are necessary to determine the recency of activity on these faults. Therefore, the risk of fault rupture is highest along the Tularcitos, Navy, Hatton Canyon, Berwick Canyon, and Laureles faults; and lowest along the other faults.

Strong Ground Shaking

Strong ground shaking is the seismic hazard most likely to affect the area. Strong shaking could result from either a regional fault such as the San Andreas, or from a local fault. Ground shaking intensity depends on several variables such as earthquake magnitude, epicenter distance, local geology, thickness and seismic wave-propagation properties of unconsolidated materials, ground water conditions, and topographic setting. Because of the complexity in predicting ground response, site-specific studies are necessary to fully quantify the characteristics and magnitude of strong shaking.

Of the deposits in Carmel Valley and vicinity, younger Holocene flood plain deposits have the highest potential for amplified ground shaking, especially soft fine-grained silty units (Rogers and others, 1985). Older Holocene flood plain deposits have a

lower, but still high potential for amplified ground shaking as compared to younger flood plain deposits. Semiconsolidated Pleistocene terrace deposits have a moderate potential for amplified ground shaking. Exposed or very shallow bedrock areas have a low potential for amplified ground shaking. Figure 17 shows depth to bedrock beneath the flood plain and terrace deposits of the Carmel River.

Because all the buildings in Carmel Valley are less than five stories high, short-period (high frequency) ground motion is most significant for these structures. Rogers and others (1985, p. 241) observed that in the Los Angeles basin, unconsolidated materials between 11 to 20 m in thickness produced the greatest resonant effect for short-period ground motion. In the study area, there are two main areas of sediments in this thickness range. The first area is along the margins of the Carmel Valley where the alluvium is as much as 15 m in thickness (see figure 17).

A second area of sediments in this thickness range is in alluvium-filled canyons. Exploratory borings show that the alluvium in the lower reach of Cañada de la Segunda is approximately 12 to 16 m in thickness (Wahler Associates, 1990). As the geometry of other canyons such as Potrero and Robinson Canyons are similar, the alluvial thicknesses are also comparable, and the potential for amplified short-period ground shaking is high on the floors within the lower reaches of the canyons.

Amplified ground shaking along ridgetops is possible during earthquakes with magnitudes of about M 6 or greater. The causes of ridgetop shaking are complex and poorly understood. Amplified ground shaking occurs along narrow ridgetops as seismic waves reflect upward along the rock/air interface of a steep hillside and energy is concentrated at the ridgetop (Davis and West, 1973). Topographic effects were partly responsible for intense shaking and damage that occurred locally along ridges in the

Figure 17. Depth to bedrock beneath Carmel Valley flood plain deposits. (Modified from Logan, 1983).

EXPLANATION:

*Thickness of flood plain,
alluvial, and terrace
deposits, in meters*

16	15	Projected section boundaries and numbers
21	22	

1 km

1 mile

Santa Cruz Mountains during the 1989 Loma Prieta earthquake (Plafker and Galloway, 1989).

Ground cracking also occurred along ridgetops during the Loma Prieta earthquake. The mechanism of the cracking is poorly understood and has been attributed to a variety of causes. These include strong ground shaking (Hart and others, 1990), although landsliding (Spittler and others, 1990), and coseismic movements along bedding plane faults (Cotton and others, 1990) are possible causes. Another explanation is that slip on thrust faults bounding the Santa Cruz Mountains during the Loma Prieta earthquake concentrated seismic energy, resulting in local areas of high intensity shaking and ground deformation (Plafker and Galloway, 1989, p. 17).

No evidence of ridgetop cracking from the Loma Prieta earthquake was observed in Carmel Valley. However, ridgetop cracking could occur in the Carmel Valley area during a M 6 earthquake on the Ragged Point segment of the San Gregorio fault, or on a fault within Carmel Valley. Ridgetop amplification is most likely along the steep ridges bordering the north and south sides of Carmel Valley, and along narrow spur ridges on both sides of the valley. Sites near faults may experience strong shaking if coseismic slip occurs during a M 6 earthquake on the Ragged Point segment of the San Gregorio fault, or on a fault within Carmel Valley.

Recurrence Interval of Strong Shaking

Historical accounts of earthquake intensities are useful for predicting the recurrence of severe shaking in an area. While magnitude is a measure of energy released in an earthquake, intensity is a subjective measure of ground shaking. The Modified Mercalli scale is one method of describing earthquake intensity.

At least ten earthquakes with Modified Mercalli (MM) intensities of V to VI affected the Carmel Valley area between 1906 and 1991. Wood and Neumann (1931) define these intensities as:

MM V: "Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop."

MM VI: "Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight."

These events include the 1906 M 8.3 San Francisco (Lawson, 1908), 1926 M 6.1 Monterey Bay (Mitchell, 1928), 1952 M 7.7 White Wolf (Richter, 1958), 1952 M 6.0 Bryson (Monterey Herald, 1952), 1969 Pine Canyon (2 events, magnitude not listed; Burkland and Associates, 1975), 1970 Carmel Valley (magnitude not listed; Burkland and Associates, 1975), 1984 M 5.2 Big Sur (Monterey Herald, 1984), 1984 M 6.2 Morgan Hill (Stover, 1984), and the 1989 M 7.1 Loma Prieta earthquakes (this report). This indicates that MM V to VI shaking intensities occur about every 8½ years.

Ground Shaking Effects of the 1989 Loma Prieta Earthquake

The October 17, 1989, M 7.1 Loma Prieta earthquake is the largest magnitude earthquake to occur within the 100 km radius during the historic record. The earthquake epicenter was about 60 km north of Carmel Valley in the Santa Cruz Mountains (Plafker and Galloway, 1989).

Ground shaking intensity was strongest on the valley floor. At the grocery store in the Mid Valley Shopping Center (Carmel Valley Road), the store manager reported that light fixtures fell and the shelves emptied (Ray Ward, oral commun., 1990). Mr. Ward said that standing was difficult and the ground seemed to roll from east to west. At a pharmacy in the Mid Valley Center, north-south oriented shelves emptied, while east-

west oriented shelves did not, indicating an east-west motion (Tony Ricigliano, oral commun., 1990).

Employees at the Carmel Valley Ranch development near Robinson Canyon stated that shaking was severe and that the ground seemed to roll. A guard in a truck during the earthquake stated, "It felt like someone was jumping up and down on the truck's bumper" (Harry Klema, oral commun., 1990). Chimneys separated from a few of the homes in the development. Interviews with merchants in Carmel Valley Village revealed that the amount of damage there was less severe, with only some items falling from shelves.

Water well logs indicate that Mid Valley Shopping Center and Carmel Valley Ranch are underlain respectively by approximately 14 to 32 m of alluvium, and terrace deposits near Carmel Valley Village are typically less than 3 m thick (see figure 17). This suggests that Rogers and others (1985) explanation of amplification due to resonance may apply in Carmel Valley. The water level in a MPWMD monitoring well at Carmel Valley Ranch was 11.5 m below the ground surface on the day of the Loma Prieta earthquake (J.W. Oliver, MPWMD, written commun., 1989).

Interviews with residents indicate that the ground shaking was less severe than on the valley floor. The grocery store manager, Mr. Ward, was home during many of the strong aftershocks and was able to compare the effects of shaking between the hillside and valley areas. Mr. Ward's home is on shallow shale bedrock in the Laureles Grade area. He stated that the shocks were strong jolts rather than rolling sensations. Damage at his home was minimal with cabinet doors opening, but not spilling their contents. Cabinets and a grandfather clock toppled at a home on El Caminito Road near Carmel Valley Village (Carmel Valley Sun, 1989). Residents of Hitchcock Canyon situated on exposed granitic rock reported strong shaking with little damage. These reports suggest

that ground shaking intensity reached MM VI in the valley, and MM V in the hillsides during the 1989 Loma Prieta earthquake.

Liquefaction

A common type of ground failure associated with moderate and larger earthquakes is liquefaction. Liquefaction occurs when water-saturated fine-grained cohesionless sediments are strongly shaken, and lose strength. This results in rearrangement of the soil particles into a denser condition, causing localized areas of ground failure. Common types of liquefaction-related ground failure include differential settlement and lateral spreading. Secondary ground cracks frequently occur as a result of liquefaction-related ground failure and should not be confused with ground deformation resulting from fault rupture.

In determining the liquefaction potential, two factors need to be considered. The first is the liquefaction susceptibility, and the second is the liquefaction opportunity. The liquefaction susceptibility depends on the age and type of material, relative density of the material, and the depth to first (shallowest) water (see figure 18). Younger sediments (especially latest Holocene that are less than 1,000 years old), such as loose fill, river channel, and flood plain deposits are more likely to liquefy than older Pleistocene terrace deposits. Sands and silty sands are more likely to liquefy than gravelly and clayey sands (Tinsley and others, 1985).

The type and distribution of geologic materials are determined from a variety of sources, including geologic maps, soil maps, engineering borings, and water well logs. The relative densities are estimated from data contained in engineering borings and correlation with similar sediments in other areas. Depth to first water is extrapolated from data contained in water wells and engineering borings. Dupré (1990) used these

methods to produce a liquefaction susceptibility map for part of Carmel Valley. This methodology was used to evaluate the liquefaction susceptibility in the areas not mapped by Dupré (1990).

Dupré (1990) correctly considered the area along the channel of the Carmel River as having the highest liquefaction susceptibility (see plate 3). Because the Carmel River aquifer consists of coarse-grained alluvium, water levels change rapidly in response to stream flow or pumping. Significant ground water extraction or periods of extended

Figure 18. Probable liquefaction susceptibility of cohesionless, granular, non-gravelly sediments. Modified from Tinsley and others (1985, table 43).

drought tend to lower the liquefaction susceptibility by increasing the depth to ground water. Areas of older flood plains and terraces have a moderate to low liquefaction susceptibility. Expected liquefaction effects would include lateral spreading near river and creek channels, differential settlement in granular younger flood plain deposits and loose fill, and shallow landsliding along clay layers in flood plain deposits.

The opportunity for liquefaction depends on the potential for moderate to large earthquakes. The earthquake history clearly shows that magnitude 6 and larger earthquakes will occur during the design life of most structures in the study area. However, historical records do not include accounts of liquefaction in Carmel Valley. This is probably due to lack of reporting, rather than lack of damage.

Dupré (1990) used a M 8.3 earthquake on the San Andreas fault (equivalent to the 1906 San Francisco event) as the basis for evaluating the liquefaction opportunity. In this report, a M 7.4 MCE on the nearest point of the San Gregorio fault and a MPE of 7.1 on the nearest point of the San Andreas fault were used to evaluate liquefaction opportunity. As the 1906 event and the 1989 Loma Prieta earthquake produced MM V-VI shaking in the area, the opportunity is similar for both events.

Tinsley and others (1985, figure 155) developed a chart correlating between historic liquefaction, epicenter distance, and earthquake magnitude. From this chart, liquefaction would be likely at highly susceptible sites in Carmel Valley during the M 7.4 MCE on the San Gregorio fault and the M 7.1 MPE on the San Andreas fault. As part of this study, a damage survey was carried out the day after the Loma Prieta earthquake, and no evidence of liquefaction-related ground failure was observed. This discrepancy is probably a result of prolonged drought conditions and lowered ground water levels at the time of the Loma Prieta earthquake.

Earthquake-Induced Landsliding

Earthquakes are one of several mechanisms that can trigger slope failures. Because steep slopes and weak geologic materials are common in Carmel Valley, landsliding is the most likely seismic hazard next to strong shaking. Earthquakes can trigger widespread landsliding, and susceptible areas need to be mapped and evaluated.

Two main factors need to be considered in evaluating the potential for earthquake-induced landsliding. The first is the susceptibility, and the second is the opportunity. The landslide susceptibility depends on the type and age of material, the steepness of the slope, the amount and orientations of discontinuities, and the degree of saturation. Areas underlain by intensely fractured or weakly cemented rocks, thick accumulations of colluvium, or improperly placed fill are susceptible to landsliding. The susceptibility of the geologic units, and the effects of other contributing factors are discussed in the following chapter entitled, "LANDSLIDE HAZARDS."

The opportunity for earthquake-induced landslides depends on the potential for moderate to large earthquakes (greater than M 4). Keefer (1984) studied earthquake-induced landslides and concluded that rockfalls are very abundant, deep-seated soil slides and slumps are abundant, shallow soil flows are moderately common, and deep-seated rock block slides are uncommon during earthquakes greater than magnitude M 6.

Wilson and Keefer (1985) grouped earthquake-induced landslides into three categories. The first group consists of disrupted shallow landslides such as rockfalls and soil slides. The second group consists of coherent deep landslides such as rock block slides, and rock and soil slumps. The third group consists of lateral spreads and flows. Rapidly moving shallow soil flows (debris flows) are the main hazard in this group. Lateral spreading is not discussed in this section as it is a liquefaction-related failure.

Wilson and Keefer (1985, figures 164 and 174) correlated seismically-induced landslides with epicenter distance and earthquake magnitude based on a data set of mainly historic California earthquakes. From this empirical correlation, they developed a series of charts depicting the relative probability of different types of earthquake-induced landslides. Their analysis assumes critical displacements (the distance a slope could move before losing a significant amount of strength) of 2 cm for disrupted slides and 10 cm for coherent landslides and flows. Because these probabilities are derived from many different earthquakes, they are general in nature. Saturated or intensely fractured slopes would be at higher risk. The probabilities estimated from these charts are shown below on table 3.

Table 3. Estimated probabilities of seismically-induced landslides for the Carmel Valley area.

Type of landslide	Percentage probability of occurring during M 7.4 MCE (San Gregorio fault)	Percentage probability of occurring during M 7.1 MPE (San Andreas fault)
Coherent (soil slumps)	98	0-50
Disrupted (rockfalls)	> 98	50-98
Debris flows	> 98	0-50

As part of this study, a damage survey was carried out the day after the 1989 Loma Prieta earthquake, and numerous small landslides were observed in all the bedrock units. These landslides were mainly rockfalls and rock slides ranging from about 10 to 40 cubic meters in volume. No debris flows or large deep-seated landslides are known to have formed in Carmel Valley during the earthquake. Although deep-seated landslides in the nearby Santa Cruz Mountains were reactivated during the Loma Prieta earthquake (William Cotton & Associates and Leighton & Associates, 1991), there is no indication

that the deep-seated landslides in Carmel Valley were reactivated. These observations are in agreement with the predicted values in table 3. The number and severity of landslides would have been greater if the Loma Prieta earthquake had occurred during the a relatively wet period instead of a four year drought.

LANDSLIDE HAZARDS

Landslides are very common in the study area. Prior studies identified many of the larger landslides, but few of the smaller and less obvious ones. In this study, geologic units with similar landslide hazards are grouped together. The factors used to establish these groups are based on the geotechnical characteristics, geologic structure, relative frequency of landsliding, and steepness of the slopes.

Igneous and Metamorphic Rock

This group includes granite, schist, basalt, and marble. These rocks are generally stable when dry. When saturated, they are subject to slope failure. Most of the landslides in this group are structurally controlled by the orientation and spacing of joints and foliations. The high density of fractures reduces the overall strength of the rock and provides a path through which ground water can flow. In intensely weathered rocks, the physical properties of the rock mass have a greater influence than the discontinuities on the slope stability.

Landslides are common in granite and schist, and infrequent in the basalt and marble. Small to moderate size rock slumps and slides are widespread on steep slopes and near fault zones. Many of these slides are highly dissected and are probably hundreds to thousands of years old, although more recent occurrences are common. An example is located between the traces of the Tularcitos and Berwick Canyon faults (see figure 19). The landslide occurred in intensely fractured granodiorite during the intense storms of March 1983. High pore pressures in the fractures resulting from abnormally high rainfall caused the slope to fail (William Cotton and Associates, 1983). Cotton's explanation is probably correct because small rockfalls continue to occur at this location after storms producing several days of 4 cm per day rainfall.

Figure 19. Photograph of recent rock slides and rockfalls on Carmel Valley Road. Slide on right occurred in 1983 and was repaired by remedial grading.

Rockfalls along road cuts and steep slopes are widespread in the igneous, metamorphic, and volcanic rocks. However, most of these are too small to depict on plate 2. Rockfalls usually occur shortly after periods of intense rainfall and during earthquakes. Many rockfalls are a result of failure along closely spaced intersecting discontinuities, especially where undercut by roads or streams.

Large block slides in the igneous, metamorphic, and volcanic rocks are rare. Curry (1984) mapped a large deep-seated block slide in the Tularcitos fault zone at the eastern end of the study area. The toe of the landslide diverted Tularcitos Creek northward, creating a wide alluvial fill deposit. Numerous small debris flows (less than 30 m maximum dimension) overlie the block slide (Kingsley Associates, 1988). Geomorphic features such as a prominent headscarp, disrupted drainages, and jumbled topography imply a Holocene age for this landslide. Insufficient data are available to determine the cause of sliding, but the size of the slide suggests that it may be earthquake-induced. Future occurrences of very large block slides in igneous and metamorphic rock could create landslide dams on the Carmel River. Although the hazard of flooding associated with landslide dams is extreme, the likelihood of a landslide dam forming is low because very large block slides rarely occur in igneous and metamorphic rocks in Carmel Valley.

Debris flows involving colluvium derived from highly weathered granite and schist are widespread. The weathered rocks decompose to sands, silts, and clays. When saturated, they become mobilized and incorporate brush and trees into debris flows. Debris flows are most common on 25 to 45 degree slopes (Campbell, 1975). Landslide hazards for colluvium are discussed in greater detail in the section of this chapter entitled "Colluvium."

Miocene Sandstone

This group includes the Miocene red beds and the marine sandstone stratigraphically below the Monterey shale. These rocks are generally moderately stable when dry. When saturated they are moderately unstable, and subject to shallow rotational slumps, deep-seated slides, earthflows, and rockfalls. Landslides in this group are largely controlled by a combination of lithology and structure.

Slides and slumps are common on all dip slopes (slopes inclined in the direction of bedding), but are most prevalent in members with claystone interbeds. Other areas of common landslides are near lithologic contacts and within fault zones. Along Robinson Canyon Road, thin laterally continuous very dark red and dusky green clay beds crop out in landslide areas (see figure 5). The claystone layers create a potential failure plane by forming a less permeable surface, resulting in perched ground water and increased pore pressures.

Many of these slides are probably early Holocene age as indicated by poorly to moderately defined scarps, hummocky topography, and well-developed drainages. O'Rourke (1980) found a soft and wet slickensided clay slide plane at a depth of 17 m in sec. 25, T. 16 S., R. 1 E. Radiocarbon dating of a peat sample found on top of this slide indicates a minimum age of $9,600 \pm 160$ yr B.P. for the landslide. This radiocarbon date supports the relative age suggested by the geomorphic features.

Rockfalls mainly occur in thick resistant sandstone beds. The sandstone beds are commonly jointed and prone to rockfall along anti-dip slopes (slopes inclined in a direction opposite to the dip of bedding), and along drainages or roadcuts where oversteepened. Rockfalls in indurated conglomerate beds are less common. Rockfalls usually occur shortly after periods of intense rainfall and during earthquakes.

Numerous small, shallow earthflows occur on steeper slopes, especially after periods of intense rainfall. The flows are spoon-shaped and typically tens of meters long and wide, and several meters deep. Figure 20 shows a cluster of these small earthflows along Robinson Canyon Road. However, most of these are too small to depict on plate 2. They occur in residual soils developed over bedrock, or within highly weathered zones of bedrock over less weathered rock. Mobilization of these flows is probably a result of increased pore water pressure along the bedrock/regolith contact.

Debris flows involving colluvium derived from weathered sandstone are common. Landslide hazards for colluvium are discussed in greater detail in the section of this chapter entitled "Colluvium."

Figure 20. Photograph of earthflows along Robinson Canyon Road.

Monterey Shale

This group includes the siliceous and diatomaceous shale, siltstone, and claystone of the Monterey shale. These rocks are generally moderately stable when dry. When saturated, they are moderately unstable and subject to large deep-seated slides, shallow slides and slumps, rockfalls, and earthflows. The main factors affecting landslide susceptibility in this group are dip slope conditions, clay beds, and intense fracturing. Landslides are more common in siliceous and clay shale than in diatomaceous shale.

Dip slope locations are particularly hazardous. The likelihood of dip slope failure conditions increases where stream erosion or improper grading removes material, allowing beds to dip out of cut slopes. Areas of dip slope conditions are not shown on plate 1, because slope angle and bedrock attitudes vary and should be measured on a site-specific basis.

Deep-seated rotational/translational slides are the most common type of landslide in area, but are the least common in number. Near the west end of the study area, there are several large landslide complexes in the foothills near the Carmel River. The deep-seated slides are probably late Pleistocene to early Holocene age as indicated by eroded headscarps, stream drainages developed along the margins, and smaller slumps and flows within the landslide.

Radiocarbon dating of landslide material confirms that many of the deep-seated landslides occurred during the late Pleistocene-early Holocene. Samples of decayed plant matter from a slide plane in a large slide immediately north of the study area have radiocarbon ages of $12,780 \pm 90$ and $13,000 \pm 110$ yr B.P. (Rogers E. Johnson & Associates, 1986, p. 31). Charcoal fragments obtained from an 18-m-deep slide plane in Cañada de la Segunda have a radiocarbon age of 31,000 yr B.P., however, the accuracy of this date is unknown (A.S. Buangan, Wahler Associates, oral commun., 1991).

Since the deep-seated slides are late Pleistocene, they probably formed under conditions different than the present. A combination of lowering sea levels and subsidence would cause the Carmel River to entrench its channel. As the channel deepened, the bordering slopes became oversteepened, and exposed dip slope beds. This series of events, combined with a wetter climate provide an explanation for the formation of the deep-seated slides. Future occurrences of very large block slides in the Monterey shale could create landslide dams on the Carmel River. However, the likelihood of this occurring under present conditions is low because the alluvial fill probably acts as a buttress against the deep-seated block slides. Improper grading or stream undercutting in dip slope areas of the Monterey shale could expose beds and cause deep-seated sliding.

The smaller, shallow slumps and slides occur in the same areas as the deep-seated slides. Because many of the shallow slides occur within older large landslide complexes, they are probably Holocene. Many of these landslides are due to a combination of weak, pervasively fractured shale and dip slope oriented clay beds. The fractures decrease the strength of the rock mass and allow water to percolate downward. The water weakens the rock by increasing pore pressure inside the fractures and decreasing the cohesion along bedding planes. This type of failure would be likely during periods of intense precipitation.

Similar failures occurred within Monterey shale bedrock during the severe 1982 storms in Santa Cruz County. One example of this type of failure is the Love Creek landslide in the Santa Cruz Mountains. The Love Creek landslide involved intensely fractured rock and colluvium sliding on a thin layer of clay and sand. This layer was approximately 9 m deep and inclined parallel to the slope (Cotton and Cochrane, 1982). Similar conditions probably exist in the Carmel Valley area, and could result in failure during periods of sustained high intensity rainfall.

Small rockfalls mainly occur in closely jointed beds along anti-dip slopes, and along drainages or roadcuts where oversteepened. Rockfalls usually occur shortly after periods of intense rainfall and during earthquakes. However, most of these are too small to depict on plate 2.

Small earthflows occur on moderate to steep slopes, especially after periods of intense rainfall. The flows are spoon-shaped and typically tens of meters long and wide, and several meters deep. They occur in residual soils developed over bedrock, or within highly weathered zones of bedrock over less weathered rock. Mobilization of these flows is probably a result of increased pore water pressure along the bedrock/regolith contact.

Debris flows involving colluvium derived from weathered shale are uncommon, but locally occur on steep slopes during heavy rains. Landslide hazards for colluvium are discussed in greater detail in the section of this chapter entitled "Colluvium."

Terrace Deposits

The stability of terrace deposits is controlled by their lithology and topographic expression. Terrace deposits are moderately stable when dry. When saturated, they are moderately unstable and subject to earth slumps and topples, and lateral spreading. Landslides in terrace deposits are most common along steep roadcuts and steep margins of stream channels.

Terraces that consist of cemented coarse gravel and sand can stand at near-vertical orientation, as visible along the north side of Carmel Valley Road. These deposits are fairly resistant to landsliding. Failure usually occurs when erosion or grading undercuts less resistant beds. These failures can occur as slumps or as topples. Lateral spreading can also occur, especially where close to an unsupported free face.

In some areas, the terraces are composed of fine sands, silts, and clays. Landsliding is more common in these deposits, occurring mainly as slumps. Several mechanisms can cause landslides in the fine-grained terrace deposits. These include loss of cohesion along clay layers, buildup of pore pressures along less permeable surfaces, and undercutting. Small slope failures occur where ground water percolates to the edge of the terrace deposits. These deposits are more susceptible to lateral spreading than their coarse-grained counterparts.

Landslide Deposits

Landslide deposits range from small, shallow soil slips to deep bedrock slides. These landslides range from modern day to late Pleistocene. An area may be susceptible to more than one type of landsliding. Younger, shallow rotational slides and debris flows are commonly found on older, deeper landslides.

Because of their disrupted nature and accompanying cracks, fractures, and voids, landslide deposits are generally less stable than surrounding materials of similar composition. Existing landslides should be considered to have a high risk of further movement, unless detailed slope stability analyses prove otherwise.

Older (so-called ancient) landslides that appear stable, may be reactivated by the same forces that caused the original failure. Reactivation is more likely to occur along preexisting discontinuities such as faults, fracture zones, adversely inclined bedding, and plastic clay layers. Trapped ground water weakens landslides by decreasing the shear strength of clay layers, and increasing the pore pressure in discontinuities. Trapped ground water is usually the result of percolating intense rainfall, but can also result from leaking water pipes, or septic system effluent. Improper grading can result in reactivation by removing support from the toe of the slide, or by increasing the driving forces near the top

of the slide. The lack of slides during the 1989 Loma Prieta earthquake suggests that seismic activity is subordinate to other mechanisms in reactivating landslides in Carmel Valley.

Colluvium

Colluvial deposits are common on all the bedrock units, and are scarce on the terrace and landslide deposits. Colluvium is relatively unstable, and fails mainly as debris flows. The hazards posed by debris flows differ substantially from those posed by rotational and translational landslides, especially in the surface area affected and speed of movement.

Debris flows in this group are controlled by a combination of source area, topography, water saturation, and vegetation. The most important debris flow source areas are colluvium-filled topographic depressions (Reneau and Dietrich, 1987). Topographic depressions in bedrock (swales or hollows) tend to concentrate water by collecting sheet flow from surrounding areas. Debris flows are common on 25 to 40 degree slopes in the San Francisco Bay area, but occur on 27 to 56 degree slopes in southern California (Campbell, 1975; Ellen and Fleming, 1987). Widespread areas of bedrock hollows are in the steep foothills south of Carmel Valley Village, and northeast of Laureles Grade.

Analysis of air photos and anecdotal accounts indicate that most of the debris flows in Carmel Valley occur during periods of relatively long-duration high intensity rainfall, such as the storms of 1958, 1969, and 1982. Failure occurs when infiltration takes place at a greater rate than deep percolation into bedrock (Campbell, 1975). The intense rainfall saturates the colluvium, and forms a perched water table that flows parallel to the slope. Ground water seeping from highly fractured bedrock can also contribute to subsurface

flow, and sustain high pore pressure (Hayes, 1985). Therefore, debris flow susceptibility is greater in intensely fractured rocks such as granite, schist, and Monterey shale.

Debris flows occur more frequently on grass-covered slopes as compared to brush-covered or forested area (Wieczorek and Sarmiento, 1988). Vegetation reduces the amount of runoff by dissipating rainfall, and the roots bind the colluvium and soil. Burning of chaparral increases the debris flow susceptibility by creating a water-repellent layer near the surface (Wells, 1987). This results in increased surface runoff during storms which is then concentrated in the topographic hollows. The severity of debris flows in the nearby Big Sur area increased dramatically during the winter after the 1972 Molera fire (Cleveland, 1973). This suggests that areas of Carmel Valley that are burned in future fires may have a higher debris flow susceptibility until vegetation is reestablished.

Alluvial Deposits

This group includes younger and older flood plain deposits, and undivided alluvium. Alluvial deposits are moderately stable when dry. When saturated, they are moderately unstable and subject to earth slumps and topples, and lateral spreading. The stability of alluvial deposits is controlled by their composition and topographic expression. Younger granular flood plain deposits have a moderately low potential for lateral spreading near river and creek channels, and for shallow landsliding along clay layers. During earthquakes, the potential for failure increases, especially in the younger deposits.

Coarse-grained older alluvium can stand near vertical as seen along the Carmel River. Bank caving usually occurs when undercut by erosion or grading. Small slope failures occur where ground water percolates to the edge of the alluvial deposits. Lateral spreading can also occur, especially where close to an unsupported free face.

Artificial Fill

Shallow rotational slumps and debris flows are the most common type of landslides in artificial fills. The susceptibility to landsliding is largely dependent on the engineering and construction practices used during construction. Fill placed according to modern grading codes has a relatively low susceptibility of landsliding. The risk of landsliding is significantly higher with increased water content. This could result from severe storms, heavy yard watering, or poorly maintained drainage and septic systems. Altering the fill configuration by undercutting the toe of a slope, or by placing additional fill also increases the hazard of landsliding.

Older fills placed before the County Grading Ordinance was established in 1979 and recent non-engineered fills generally have a moderate to high susceptibility to landsliding because of poor quality control. Many of these failures are due to poor earthwork construction practices such as lack of drainage provisions, inadequate ground preparation (clearing and grubbing), and excessively steep slopes. Numerous examples of small failures of older fill are found in the foothills. Enforcement of the County Grading Ordinance is the simplest way to reduce landslide hazards from artificial fill.

RECOMMENDATIONS

Landslide and earthquake hazards affect most of the Carmel Valley area. By implementing prudent planning and enforcement standards, the risks and losses from these hazards can be reduced. The recommendations in this report are intended to make the planning community and general public aware of some of the methods available to reduce the local geologic and seismic hazards.

Engineering Geology and Geotechnical Site Investigations

Studies show that losses from geological hazards can be reduced by at least 90 percent by requiring thorough engineering geology and geotechnical studies before site development, and enforcing grading codes (Slosson and Krohn, 1977). To reduce the risk from potential geologic hazards in the study area, detailed engineering geology and geotechnical investigations are needed (see plate 3). Ideally, the engineering geology study should characterize geologic and seismic conditions, and the geotechnical study should use modeling techniques such as computer-aided slope stability analysis to evaluate potential hazards.

Policy 15.5.3 of the Monterey County General Plan (1982) requires “preliminary geologic reports, detailed geologic reports, and engineering geologic reports” in hazardous areas depending on the type of project and seismic zonation shown by Burkland and Associates (1975). In practice, the preliminary and detailed geologic reports are often engineering geology reports, the main difference being that subsurface exploration is part of a detailed geologic report. These requirements are confusing to both planners and applicants. Because these standards are not clear, geologic reports are sometimes required in low hazard areas where they are not necessarily needed. This creates the perception that most of the geologic reports are unnecessary because they state that hazards do not exist.

Most geologic reports associated with land development are concerned with applying geologic data to civil engineering problems. Therefore, the MCPD should require “engineering geology” reports instead of “preliminary” or “detailed geologic” reports. Engineering geology reports should be prepared by California registered geologists certified in the specialty of engineering geology. The Seismic Safety Element recommends CDMG Note 37 (1973) “Guidelines to Geologic/Seismic Reports” as the format for geologic reports. However, CDMG Note 44 (1986) “Guidelines for Preparing Engineering Geology Reports” is a more pertinent set of guidelines for most of the reports required by the MCPD.

Another problem is the question of when are geologic versus geotechnical (soil) reports required. In high hazard areas (Seismic Safety Element zones IV-VI) or Alquist-Priolo Special Studies Zones, geologic reports usually determine the feasibility for development. If the proposed project is geologically feasible, then a geotechnical (soil) report should be required. However, the MCPD does not have any written standards for geotechnical reports. Report standards are necessary for geotechnical reports as well as for geologic reports.

One of the goals of this study was to develop a set of guidelines specifying when engineering geology and geotechnical reports are necessary, and the appropriate level of detail. The intent of the system shown on plate 3 is to require in-depth reports in troublesome geological formations, areas of known or suspected landslides, areas of liquefiable ground, along potentially active faults, and on hillsides.

Plate 3 shows three zones, each with different report requirements. In zone D, engineering geology studies involving subsurface exploration, combined with geotechnical studies involving subsurface exploration and laboratory testing are mandatory. In zone E, engineering geology studies are required (subsurface exploration recommended), and

geotechnical studies involving subsurface exploration and laboratory testing are required. In zone F, engineering geology studies are required in hillside areas, and recommended in low-land areas. Geotechnical studies in zone F may be waived for single-family residences that infill existing non-hillside subdivisions, if sufficient data show stratigraphic continuity across the site. In areas of potentially active faults, engineering geology studies are required and subsurface exploration (trenching) is recommended.

These suggested report requirements will help target the type and depth of investigation needed for future development. These requirements will be most useful if comments from planners, geologists, engineers, and the public are incorporated into a revised set of MCPD standards for engineering geology and geotechnical reports.

Updating of Geologic and Seismic Hazard Maps

At present, the updating of geologic and seismic hazard maps is a low priority item at the County level. Recent state regulations set forth in the Seismic Hazards Mapping Act of 1990 mandate that “lead agencies” (the County) identify and map seismic hazard zones to protect public safety. In addition, the Monterey County General Plan (1982) states that:

“The County shall continually update seismic and other geologic information to reflect the most current and accurate information available.”
(Policy 15.4.5).

To date, there has been almost no updating of county geologic or hazard maps. The County seismic hazard maps are derived mostly from 1:62,500 scale geologic maps, and the resulting seismic zonation is inexact.

Other deficiencies identified by the MCPD include: (1) numerous errors not identified during the original County review in 1975, (2) a lack of standard format and map scales between various regions, (3) lack of a detailed landslide susceptibility map, and (4) a

large volume of geologic reports (approximately 300 as of 1987) which need incorporating into a revised report and maps (Monterey County Planning Department, 1987).

Since the publication of the Seismic Safety Element in 1975, the USGS and CDMG have released updated geologic maps of Monterey County at 1:24,000 and 1:62,500 scale. Studies by consultants and researchers have identified new fault traces and landslides in the county. Many of these studies will be useful in updating geologic and seismic hazard maps. If updated maps were available, then required reports could focus on the areas with high geologic hazards. In addition, a set of up-to-date geologic maps and hazard maps could allow for some studies to be waived, provided that sufficiently detailed data were available near a project.

The County is transferring some of its planning documents onto a computer-based geographic information system (GIS). To develop improved geologic and seismic hazard maps, GIS layers showing geology, ground water, and soils are needed. The computer-based system will make updating maps a relatively simple task. The County should obtain and use local geologic expertise in preparing these maps.

Geologic Review

Geologic review is an important part of the evaluation process of a proposed development (Hart and Williams, 1978). Recognizing this, the County General Plan (Monterey County Planning Department, 1982) mandates that:

“The County should have geologic expertise available to the staff because of the numerous seismic and other geologic hazards in the County.” (Policy 15.4.4).

Because of the pressure to develop marginal land, and the potential bias of geologists hired by developers, independent geologic review is necessary.

The Planning Department relies on staff planners rather than a registered geologist to review reports. This lack of formal review contributes to poor quality reports, and increases the risk to the public and county government. The County needs a qualified engineering geologist to review reports because of the complex geology and the specialized nature of geologic hazard assessment. In addition, the Seismic Hazards Mapping Act of 1990 requires that "lead agencies" use certified engineering geologists to conduct reviews of seismic hazard reports.

An on-staff geologist is preferable to using third-party reviewers because of the consistency of the review process. Also, when a third-party reviewer that practices in the county performs geologic reviews, a conflict of interest arises because it is difficult for a consultant to objectively review a competitor's report. Besides reviewing reports, the geologist would perform field review during the exploration phase of geological investigations, as is customary in many California cities and counties. A County Geologist could also provide expertise to other county offices such as the Public Works Department, the Water Resources Agency, and the Environmental Health Department.

The primary objection to hiring an on-staff geologist is the cost of salary and benefits. By instituting a geologic report review fee, this position could be self-funded. The results of a survey by the Santa Clara County Geologist, Jim Berkland, show that comparable size agencies (City of San Jose, County of Santa Clara, County of Contra Costa) in the San Francisco Bay area each review approximately 300 geologic reports per year. As of 1987, the cost of geologic review by these jurisdictions ranged from \$3,000 in the city of Cupertino to "zero" where costs were completely absorbed by Contra Costa County, with the average being about \$500 (J.O. Berkland, unpublished data, 1987).

The Monterey County Planning Department issued 2,949 building permits in 1989 (Carmel Valley Sun, 1990). Assuming that 300 of the permits required geologic reports, a

fee of \$500 would generate \$150,000 that would cover the costs of salary and benefits. For comparison, the annual salary range for the Santa Cruz County Geologist was \$42,804–\$57,360 in 1991 (Santa Cruz County Personnel Department, written commun., 1991).

Enforcement of Grading Ordinance

Modern grading codes such as Chapter 70 of the Uniform Building Code (UBC) have significantly reduced loss of property and life where implemented and enforced. In 1979, Monterey County adopted a slightly modified version of the 1972 edition of the UBC Chapter 70 as the county grading ordinance (Monterey County Board of Supervisors, 1979).

Enforcement of the grading ordinance can reduce geologic hazards associated with hillside grading. However, provisions of the grading ordinance that require geotechnical and engineering geology reports in preparing grading plans (Section 110), and “as-built” geotechnical and geologic grading reports (Section 123a) are usually waived. As a result, some projects are improperly designed or constructed. The county grading ordinance can be improved by requiring involvement of the geologist and engineer during all phases of the project, from pre-construction to post-construction. Geotechnical and engineering geology reports should be part of grading plans, and the engineers and geologists should review the grading plan to verify that it complies with their recommendations.

An excellent discussion of modern grading code standards and enforcement is contained in the book by Scullin (1983). As suggested by Scullin, public safety can be improved by effective grading enforcement. During construction, the geologist and engineer should be given the opportunity to reveal subsurface conditions exposed by grading. Unmapped faults and landslides have been discovered as a result of grading, and corrective

measures were made. Grading reports should include the following items: (1) an in-construction report at the rough grade stage that covers all rough grading of streets and building pads, buttress fills, keyways, subdrains, retaining walls, and surface drainage provisions; and (2) final grading reports should cover foundations, fine grading of pads and roadways, utility trench backfill, landscaping, and drainage.

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APPENDIX A

**LIST OF EARTHQUAKES GREATER THAN MAGNITUDE M 4.0
WITHIN 100 KM RADIUS OF CARMEL VALLEY
(LATITUDE 36°30'N AND LONGITUDE 121°46'W)
OCCURRING BETWEEN JULY 3, 1841 AND AUGUST 31, 1990**

DATE	HR:MN	LAT	LONG	MAG	SOURCE
<i>1841-1899:</i>					
07/03/41	22:07	36.60	122.00	4.0	K-M
04/01/57	11:35	36.67	121.25	5.0	T-A
09/03/58	08:40	37.00	122.00	4.3	T-A
03/25/90	00:00	37.00	121.57	5.0	T-A
04/04/59	21:00	37.33	121.92	4.3	T-A
08/11/59	05:30	37.33	121.92	4.3	T-A
04/03/60	04:00	37.00	122.00	4.3	T-A
02/26/64	13:47	37.10	121.70	5.9	CDMG
03/05/64	16:49	37.20	121.50	5.9	K-M
04/18/65	21:31	36.83	121.50	5.5	T-A
05/24/65	11:21	37.10	121.80	5.5	CDMG
10/08/65	20:46	37.30	121.90	6.3	CDMG
03/26/66	20:12	37.10	121.60	5.4	CDMG
08/31/68	00:00	37.00	122.00	4.3	T-A
11/17/68	21:30	37.00	122.00	4.3	T-A
02/17/70	20:12	37.20	122.10	5.8	CDMG
08/30/73	00:00	37.33	121.92	4.3	T-A
03/06/82	21:45	36.90	121.20	5.7	CDMG
03/30/83	15:45	36.90	121.60	5.6	CDMG
03/26/84	00:40	37.10	122.20	5.9	CDMG
03/31/85	07:56	36.70	121.30	5.5	CDMG
04/02/85	15:25	36.80	121.40	5.4	CDMG
04/12/85	04:05	36.40	121.00	6.2	CDMG
07/23/85	20:25	37.33	121.92	4.3	T-A
12/28/85	11:30	37.00	122.00	4.3	T-A
08/13/87	11:17	36.58	121.92	4.3	T-A
10/12/87	08:55	37.33	121.67	4.3	T-A
09/17/88	11:51	37.10	121.80	4.5	CDMG
11/04/89	11:36	37.33	121.67	4.3	T-A
04/15/89	03:28	37.10	121.90	4.8	CDMG
01/15/90	13:05	37.33	121.67	4.3	T-A
04/24/90	11:36	36.90	121.60	6.0	CDMG
06/30/90	20:30	37.00	122.00	5.0	T-A
01/02/91	20:00	37.30	121.80	5.5	CDMG
06/14/91	00:27	36.58	121.92	4.3	T-A
06/28/91	11:03	37.33	121.67	4.3	T-A
02/05/92	14:28	37.33	121.67	4.3	T-A
11/13/92	12:45	36.80	121.50	5.6	CDMG
09/02/93	07:16	37.00	122.00	4.3	T-A
06/20/97	20:14	37.00	121.50	6.2	CDMG

04/30/99	22:41	36.90	121.70	5.6	CDMG
07/06/99	20:10	37.20	121.50	5.8	CDMG
<i>1900-1990:</i>					
04/30/00	22:41	36.90	121.60	4.5	CDMG
09/28/00	12:17	37.00	121.60	4.0	MGI
12/11/01	21:58	37.30	121.60	4.0	MGI
08/03/03	06:49	37.30	121.80	5.5	CDMG
04/21/04	11:50	37.30	121.90	4.0	CDMG
08/27/04	20:59	37.30	121.60	4.6	MGI
04/04/05	10:23	37.30	121.90	4.0	MGI
01/08/07	23:45	37.00	122.10	4.5	TOP
04/25/08	11:33	36.60	121.80	4.5	CDMG
10/18/08	08:21	36.80	121.40	4.6	MGI
11/22/09	15:21	36.70	121.40	4.5	CDMG
03/11/10	06:52	36.90	121.80	5.5	CDMG
12/31/10	12:11	36.83	121.42	5.0	CDMG
03/11/11	21:30	36.83	121.42	4.5	CDMG
07/01/11	22:00	37.25	121.75	6.6	CDMG
03/08/12	09:48	37.33	121.67	4.3	T-A
09/12/12	17:27	37.33	122.17	4.5	CDMG
10/25/12	03:16	36.83	121.42	4.0	MGI
11/09/14	02:31	37.17	122.00	5.5	CDMG
12/28/14	10:42	37.17	122.17	4.5	CDMG
04/06/15	16:28	36.92	121.75	4.0	MGI
12/27/15	07:23	36.83	121.42	4.0	CDMG
06/27/16	13:43	36.67	121.25	4.0	CDMG
08/06/16	19:38	36.67	121.25	5.5	CDMG
08/08/16	16:50	37.10	121.90	4.0	CDMG
10/24/16	13:30	36.00	121.17	4.0	CDMG
06/09/17	03:34	36.58	121.33	4.0	CDMG
09/24/17	21:21	36.83	121.42	4.0	CDMG
10/26/17	09:20	37.33	121.75	4.0	CDMG
11/25/19	11:03	37.08	121.83	4.5	CDMG
09/09/20	16:47	37.33	121.92	4.0	MGI
10/15/20	19:04	36.58	121.67	4.0	MGI
06/12/21	03:42	36.75	122.00	4.0	CDMG
07/25/21	05:05	36.92	121.67	4.0	CDMG
10/17/22	05:30	36.83	121.42	4.0	MGI
09/19/23	22:54	37.00	121.83	4.0	CDMG
04/03/24	23:54	37.30	121.67	4.5	CDMG
12/28/24	04:21	36.67	121.67	4.0	CDMG
07/19/25	19:24	37.25	122.00	4.0	CDMG
07/25/26	17:58	36.60	120.80	5.0	CDMG

10/22/26	12:35	36.61	122.35	6.1	CDMG
10/22/26	13:35	36.57	122.17	6.1	CDMG
10/22/26	16:04	36.65	122.10	4.5	CDMG
10/24/26	22:52	37.02	122.20	5.5	CDMG
02/15/27	23:54	36.95	122.26	5.0	CDMG
05/28/27	17:39	37.30	121.90	5.0	MGI
09/02/27	00:00	37.33	121.82	4.6	MGI
01/09/28	02:50	37.00	121.57	5.3	MGI
11/26/29	08:05	36.42	121.00	4.5	CDMG
01/09/30	08:06	36.80	121.50	4.5	CDMG
01/09/30	08:16	36.80	121.50	4.5	CDMG
01/09/30	09:56	36.80	121.50	4.0	CDMG
01/06/31	23:29	36.50	121.40	4.0	CDMG
02/07/31	07:40	36.92	121.57	4.3	MGI
06/10/31	12:20	37.33	121.92	4.0	CDMG
10/09/31	19:50	36.67	121.67	4.0	CDMG
10/18/31	19:58	36.33	121.67	4.0	CDMG
12/04/31	00:53	36.50	121.67	4.0	CDMG
01/08/32	18:17	36.67	121.33	4.0	CDMG
02/26/32	16:58	36.00	121.00	5.0	CDMG
04/16/32	18:48	36.67	121.22	4.5	CDMG
04/22/32	00:08	36.78	120.75	4.0	CDMG
06/14/32	09:44	37.25	122.08	4.5	CDMG
06/27/32	05:17	36.00	122.00	4.0	CDMG
07/17/33	00:32	37.00	122.00	4.3	MGI
04/23/34	16:08	37.00	122.00	4.0	CDMG
06/16/34	23:03	36.50	121.00	4.0	CDMG
12/03/34	01:54	35.95	121.50	4.5	CDMG
12/30/34	13:55	37.20	122.00	4.3	MGI
01/03/35	17:36	37.20	122.00	4.3	MGI
06/18/35	04:15	37.00	121.40	4.0	CDMG
06/30/35	23:28	36.00	121.00	4.0	CDMG
10/25/35	20:56	36.90	121.75	4.0	CDMG
03/11/36	13:56	37.30	121.75	4.3	MGI
03/17/36	01:55	36.60	121.20	4.0	CDMG
05/23/36	04:41	36.17	120.92	4.0	CDMG
05/27/36	19:55	36.50	121.17	4.5	CDMG
09/24/36	14:12	37.00	122.00	4.0	GRN
01/09/37	00:47	37.00	121.80	4.3	MGI
02/17/37	03:33	36.70	121.20	4.5	CDMG
02/22/37	18:10	36.17	121.53	4.0	CDMG
03/05/37	12:47	36.70	121.70	4.5	CDMG
05/26/37	02:11	36.95	121.60	4.3	MGI

09/18/37	13:29	36.50	121.20	4.0	CDMG
10/27/37	15:53	36.60	121.50	4.5	CDMG
11/03/37	10:00	36.15	121.00	4.3	MGI
11/12/37	02:50	37.00	122.00	4.0	CDMG
02/12/38	20:00	36.00	122.00	4.5	CDMG
05/10/38	10:32	36.20	121.30	4.5	CDMG
05/10/38	10:41	36.20	121.30	4.0	CDMG
05/13/38	19:34	36.20	121.30	4.0	CDMG
09/16/38	06:11	36.40	121.20	4.0	CDMG
09/27/38	12:23	36.45	121.25	5.0	CDMG
10/14/38	15:31	36.58	121.40	4.0	CDMG
06/24/39	13:02	36.80	121.45	5.5	CDMG
07/04/39	10:49	36.85	121.40	4.0	CDMG
07/17/39	09:25	36.85	121.68	4.5	CDMG
09/20/39	02:45	36.68	121.56	4.0	CDMG
03/02/40	13:27	36.80	121.45	4.0	CDMG
09/07/40	13:02	36.50	121.50	4.5	CDMG
04/14/41	16:17	37.03	121.97	4.0	CDMG
05/28/41	06:23	37.08	121.75	4.5	CDMG
09/18/41	07:33	37.38	121.68	4.0	CDMG
01/14/42	09:45	36.65	121.22	4.2	CDMG
02/04/42	09:08	37.00	121.30	4.0	CDMG
04/08/42	14:20	36.60	121.30	4.0	CDMG
04/11/42	08:41	36.75	121.32	4.0	CDMG
06/05/42	12:33	36.98	121.67	4.2	CDMG
10/15/42	13:54	36.48	121.40	4.3	CDMG
10/18/42	12:02	36.00	121.00	4.3	MGI
10/20/42	10:25	36.00	121.00	4.3	MGI
06/07/44	12:36	36.58	121.28	4.0	CDMG
01/07/45	22:26	36.73	121.20	4.7	CDMG
05/17/45	15:07	36.82	121.37	4.6	CDMG
08/27/45	09:13	37.27	121.80	4.5	CDMG
11/03/45	15:50	36.63	121.25	4.2	CDMG
11/08/45	20:09	37.17	121.52	4.2	CDMG
02/10/46	11:01	36.50	121.00	4.2	CDMG
05/29/46	17:51	36.77	121.42	4.5	CDMG
08/05/46	04:09	36.85	121.78	4.1	CDMG
06/22/47	23:30	37.00	121.77	4.7	CDMG
07/07/47	04:40	36.77	121.42	4.3	CDMG
08/10/47	21:58	36.88	121.42	4.4	CDMG
11/15/47	22:30	36.78	122.12	4.1	CDMG
01/11/48	05:37	36.43	121.48	4.3	CDMG
03/28/48	22:36	36.85	121.57	4.0	CDMG

03/28/48	22:38	36.85	121.57	4.6	CDMG
03/28/48	22:45	36.85	121.57	4.5	CDMG
04/27/48	16:41	36.77	121.27	4.0	CDMG
04/27/48	20:22	36.77	121.27	4.4	CDMG
04/28/48	07:30	36.75	121.40	4.3	MGI
05/11/48	10:45	36.78	121.40	4.3	MGI
06/11/48	08:28	36.60	121.20	4.0	CDMG
12/20/48	04:43	35.80	121.50	4.5	CDMG
12/31/48	14:36	35.67	121.40	4.6	CDMG
01/01/49	01:18	36.90	121.62	4.5	CDMG
03/09/49	12:29	37.02	121.48	5.2	CDMG
03/14/49	06:10	37.02	121.48	4.4	CDMG
06/10/49	03:07	37.30	121.67	4.6	CDMG
06/22/49	18:09	37.33	121.68	4.1	CDMG
06/27/49	10:36	35.80	121.10	4.5	CDMG
10/22/49	21:45	36.58	121.17	4.7	CDMG
09/30/50	21:27	36.90	121.38	4.1	CDMG
11/23/50	13:58	36.82	121.52	4.1	CDMG
07/29/51	10:54	36.58	121.18	5.0	CDMG
08/06/51	09:05	36.62	121.22	4.9	CDMG
10/30/51	19:55	36.90	121.42	4.0	CDMG
10/30/51	19:59	36.90	121.42	4.2	CDMG
10/31/51	20:58	36.90	121.42	4.8	CDMG
11/22/52	07:47	35.73	121.20	6.0	CDMG
11/22/52	13:38	35.73	121.20	4.0	CDMG
11/25/52	21:59	35.73	121.20	4.4	CDMG
03/01/53	18:53	35.90	121.00	4.3	MGI
03/16/53	08:52	36.95	121.67	4.0	CDMG
05/25/53	00:24	36.82	121.47	4.0	CDMG
12/17/53	05:13	36.92	121.67	4.2	CDMG
03/27/54	15:44	36.52	121.17	4.4	CDMG
04/10/54	22:17	37.18	121.80	4.1	CDMG
04/22/54	18:50	36.90	121.68	4.3	CDMG
04/25/54	20:33	36.93	121.68	5.3	CDMG
06/22/54	11:49	36.57	121.42	4.4	CDMG
06/22/54	12:50	36.57	121.42	4.3	CDMG
03/02/55	15:59	36.00	120.93	4.8	CDMG
09/05/55	02:01	37.37	121.78	5.5	CDMG
11/02/55	19:40	36.00	120.92	5.2	CDMG
02/18/56	23:59	36.67	121.32	4.2	CDMG
07/23/56	08:04	36.30	121.30	4.7	CDMG
10/19/56	12:32	36.65	121.23	4.1	CDMG
11/22/56	16:44	36.60	121.30	4.2	CDMG

12/01/56	14:11	36.87	121.60	4.4	CDMG
01/29/57	21:20	35.87	122.12	4.9	CDMG
08/16/57	18:02	36.85	121.50	4.3	MGI
09/28/57	21:05	36.60	121.23	4.5	CDMG
07/09/58	05:24	37.25	121.67	4.1	CDMG
09/21/58	07:25	36.35	121.12	4.6	CDMG
11/07/58	21:33	36.87	121.88	4.3	CDMG
01/29/59	16:41	37.13	121.57	4.3	CDMG
03/02/59	23:27	36.98	121.60	5.3	CDMG
03/03/59	07:24	37.00	121.60	4.4	CDMG
03/03/59	18:32	36.98	121.60	4.0	CDMG
03/24/59	02:21	37.27	121.72	4.1	CDMG
05/26/59	15:58	36.72	121.62	4.6	CDMG
09/11/59	18:05	36.70	121.30	4.0	CDMG
10/11/59	02:03	36.45	121.12	4.1	CDMG
12/29/59	02:33	36.90	121.48	4.7	CDMG
01/20/60	03:26	36.78	121.43	5.0	CDMG
11/03/60	06:50	36.53	121.13	4.1	CDMG
01/04/61	00:30	36.87	121.67	4.1	CDMG
04/09/61	07:23	36.68	121.30	5.6	CDMG
04/09/61	07:26	36.70	121.30	5.5	CDMG
04/28/61	01:03	36.60	121.37	4.2	CDMG
07/22/61	18:02	36.40	121.20	4.0	CDMG
05/07/63	07:08	36.86	121.65	4.4	CDMG
05/22/63	22:41	37.27	122.31	4.6	CDMG
08/31/63	16:31	36.76	121.58	4.2	CDMG
09/14/63	19:46	36.87	121.63	5.4	CDMG
09/14/63	20:28	36.92	121.65	4.6	CDMG
05/13/64	12:19	36.55	121.16	4.0	CDMG
11/16/64	02:47	37.06	121.69	5.0	CDMG
09/14/65	09:09	36.63	121.36	4.0	CDMG
01/17/66	02:03	36.98	121.49	4.1	CDMG
05/13/66	17:26	36.92	121.57	4.5	CDMG
10/10/66	06:54	36.58	121.22	4.1	CDMG
10/14/66	20:34	36.98	121.75	4.2	CDMG
09/07/67	12:39	37.04	121.78	4.7	CDMG
09/28/67	15:39	37.23	121.61	4.9	CDMG
12/18/67	17:25	37.00	121.78	5.3	CDMG
03/21/68	21:55	37.02	121.75	4.3	CDMG
10/27/69	11:00	36.79	121.39	4.6	CDMG
11/15/69	20:58	36.75	121.41	4.2	CDMG
11/17/69	20:49	36.43	121.05	4.4	CDMG
11/19/69	06:29	36.45	121.52	4.2	CDMG

01/06/70	02:29	36.542	121.105	4.0	USGS
03/31/70	07:02	36.868	121.408	4.5	CDMG
08/04/70	04:14	36.650	122.190	4.7	CDMG
03/08/71	18:32	36.790	122.140	4.1	CDMG
03/09/71	15:35	36.800	122.150	4.6	CDMG
04/16/71	12:59	36.800	122.180	4.5	CDMG
02/24/72	15:57	36.578	121.209	5.1	CDMG
02/27/72	22:13	36.529	121.103	4.6	CDMG
09/04/72	18:05	36.625	121.274	4.6	CDMG
09/23/72	10:56	36.793	121.526	4.1	CDMG
09/23/72	15:08	36.793	121.526	4.1	USGS
10/03/72	06:30	36.802	121.529	4.8	CDMG
10/03/72	11:10	36.814	121.545	4.1	CDMG
01/15/73	09:43	36.672	121.334	4.1	CDMG
06/22/73	01:29	36.563	121.205	4.2	CDMG
10/03/73	10:07	37.204	121.585	4.6	USGS
11/12/73	18:17	37.226	121.975	4.0	CDMG
01/10/74	11:22	36.950	121.590	4.4	CDMG
08/19/74	12:47	36.530	120.680	4.4	CDMG
11/28/74	23:01	36.910	121.480	5.2	CDMG
11/29/74	01:04	36.920	121.480	4.0	CDMG
12/31/74	20:22	36.920	121.470	4.3	CDMG
03/03/75	11:35	36.934	121.471	4.3	USGS
03/17/76	04:01	36.819	121.133	4.3	USGS
12/15/77	11:15	36.577	121.228	4.2	USGS
07/02/78	11:58	36.892	122.182	4.3	USGS
08/29/78	00:15	37.365	121.709	4.2	USGS
05/08/79	05:11	37.301	121.661	4.5	USGS
08/02/79	21:43	36.806	121.544	4.0	USGS
08/06/79	17:05	37.110	121.511	5.9	USGS
08/06/79	22:34	37.005	121.471	4.3	USGS
08/09/79	07:03	37.025	121.456	4.2	USGS
03/06/80	11:05	36.679	121.356	4.0	USGS
04/13/80	06:16	36.780	121.516	4.0	USGS
06/18/80	04:52	36.898	121.637	4.1	USGS
10/13/80	02:47	36.573	121.083	4.0	USGS
01/07/81	11:43	36.854	121.632	4.5	USGS
01/15/81	12:48	37.377	121.727	4.9	USGS
01/27/81	22:11	36.845	121.617	4.1	USGS
04/25/81	19:42	37.094	121.893	4.0	USGS
06/08/81	03:09	36.748	121.357	4.1	USGS
08/14/81	12:50	36.780	121.286	4.0	USGS
09/28/81	07:35	36.792	121.560	4.1	USGS

06/19/82	10:18	36.510	121.060	4.1	BRK
08/10/82	02:11	36.583	121.230	4.5	USGS
08/11/82	07:47	36.628	121.299	4.6	USGS
08/18/82	08:44	37.017	121.745	4.5	USGS
08/31/82	03:11	36.639	121.314	4.0	USGS
09/24/82	08:06	36.659	121.328	4.0	USGS
02/05/83	12:01	36.680	121.850	4.2	BRK
08/08/83	13:13	36.576	121.070	4.2	USGS
08/29/83	10:11	35.836	121.346	5.4	USGS
01/23/84	05:40	36.353	121.908	5.2	USGS
01/23/84	07:00	36.363	121.900	4.6	USGS
02/10/84	07:23	36.377	121.897	4.2	USGS
03/26/84	07:59	36.739	121.483	4.0	USGS
04/24/84	21:15	37.313	121.656	6.2	USGS
06/05/84	16:56	37.259	121.583	4.0	USGS
09/26/84	20:46	37.338	121.697	4.5	USGS
10/05/84	16:16	36.549	121.212	4.1	USGS
11/24/85	19:22	36.018	120.889	4.1	USGS
11/28/85	15:14	36.555	121.082	4.2	USGS
01/14/86	03:10	36.563	121.213	4.5	USGS
01/26/86	19:21	36.809	121.288	5.7	USGS
01/26/86	23:47	36.823	121.290	4.2	USGS
05/31/86	08:48	36.613	121.281	4.3	USGS
01/06/88	22:50	36.777	120.887	4.3	USGS
02/20/88	08:40	36.800	121.307	5.0	USGS
06/13/88	01:46	37.391	121.747	5.3	USGS
06/27/88	18:43	37.127	121.903	5.0	USGS
07/26/88	03:27	36.554	121.182	4.5	USGS
11/10/88	05:08	37.375	121.732	4.7	USGS
12/30/88	23:54	37.289	121.652	4.3	USGS
08/08/89	08:13	37.134	121.943	5.2	USGS
08/08/89	08:44	37.130	121.940	4.2	USGS
08/08/89	15:53	37.141	121.971	4.5	USGS
10/18/89	00:04	37.036	121.883	7.1	USGS
10/18/89	00:07	37.218	121.955	4.6	USGS
10/18/89	00:08	36.955	121.792	4.9	USGS
10/18/89	00:09	36.953	121.769	4.1	USGS
10/18/89	00:10	37.016	121.765	4.0	USGS
10/18/89	00:12	37.148	122.011	4.0	USGS
10/18/89	00:13	37.123	122.023	4.5	USGS
10/18/89	00:13	37.164	122.052	4.1	USGS
10/18/89	00:17	37.078	121.940	4.1	USGS
10/18/89	00:19	37.142	122.000	4.0	USGS

10/18/89	00:24	37.023	121.784	4.0	USGS
10/18/89	00:25	37.029	121.803	4.8	USGS
10/18/89	00:31	37.082	122.000	4.2	USGS
10/18/89	00:38	37.162	122.010	4.3	USGS
10/18/89	00:41	37.169	122.047	5.2	USGS
10/18/89	00:46	36.914	121.714	4.0	USGS
10/18/89	02:16	37.060	121.729	4.5	USGS
10/18/89	02:26	37.018	121.766	4.2	USGS
10/18/89	04:17	37.052	121.896	4.1	USGS
10/18/89	04:50	37.139	122.050	4.3	USGS
10/18/89	05:19	37.022	121.854	4.2	USGS
10/18/89	10:22	36.984	121.853	4.5	USGS
10/19/89	08:46	36.958	121.842	4.3	USGS
10/19/89	09:54	36.924	121.687	4.5	USGS
10/19/89	10:15	36.953	121.838	5.0	USGS
10/19/89	12:26	36.915	121.687	4.0	USGS
10/21/89	00:50	37.019	121.883	4.3	USGS
10/21/89	22:15	37.052	121.887	4.6	USGS
10/25/89	01:27	37.077	121.827	4.5	USGS
11/02/89	05:50	37.053	121.808	4.3	USGS
11/05/89	13:38	37.043	121.883	4.0	USGS
11/07/89	23:43	37.213	122.036	4.2	USGS
12/01/89	12:38	36.666	121.357	4.3	USGS
12/18/89	17:08	36.675	121.368	4.1	USGS
01/12/90	09:10	36.405	120.816	4.3	USGS
02/07/90	14:12	36.938	121.698	4.2	USGS
04/18/90	13:38	36.907	121.663	4.7	USGS
04/18/90	13:42	36.916	121.670	4.4	USGS
04/18/90	13:54	36.918	121.670	5.4	USGS
04/18/90	14:52	36.904	121.660	4.0	USGS
04/18/90	15:28	36.928	121.681	4.0	USGS
04/18/90	15:46	36.946	121.695	5.0	USGS
08/05/90	06:52	36.889	121.608	4.3	USGS

NOTES:

As this list represents a compilation from various sources, the accuracy and precision may vary within the list (F.W. Lester, written comm., 1990). The data should be

used accordingly with discretion. Time is in coordinated universal time (UTC): DATE, hour (HR), minute (MN). To convert to local Pacific Standard Time (PST), subtract eight hours. To convert to Pacific Daylight Time (PDT), subtract seven hours. Depending on the time, one day may have to be subtracted from the UTC date to get the local date. Epicenters are in decimal degrees of north latitude (LAT) and west longitude (LONG). Magnitude is (MAG).

Sources of data:

BRK	University of California at Berkeley, cited by Blake (1989)
CDMG	California Division of Mines and Geology earthquake catalog, compiled by Real and others (1978)
GRN	Greene and others (1973)
K-M	Kilbourne and Mualchin (1980)
MGI	CDMG catalog for which only intensity data are available, magnitudes estimated by Blake (1989)
USGS	U.S. Geological Survey, preliminary determination of epicenters (F.W. Lester, written commun., 1990)
T-A	Townley and Allen (1939)

APPENDIX B

**LIST OF EARTHQUAKES IN THE
VICINITY OF CARMEL VALLEY OCCURRING
BETWEEN JANUARY 1, 1969 AND DECEMBER 31, 1991**

DATE	HR:MN	LAT	LONG	DEPTH (km)	ERH (km)	ERZ (km)	MAG
06/19/69	06:46	36.567	121.792	13.46	2.1	2.0	1.7
06/12/72	10:13	36.466	121.628	7.63	0.6	1.2	1.8
06/29/72	15:09	36.551	121.835	6.14	1.0	1.8	2.2
07/05/72	18:55	36.555	121.886	0.27	2.4	2.1	1.3
08/20/72	04:23	36.473	121.857	2.62	0.9	1.3	1.4
01/14/73	17:19	36.467	121.628	7.78	0.6	1.1	1.6
01/21/73	20:05	36.635	121.875	3.61	1.0	2.0	2.1
01/29/74	14:19	36.507	121.797	7.66	1.2	2.6	1.2
06/13/74	18:28	36.485	121.810	9.38	0.5	2.3	2.0
10/20/74	07:49	36.487	121.797	6.70	0.5	1.4	2.1
12/30/74	18:28	36.571	121.888	5.64	0.5	0.6	2.8
08/07/75	04:53	36.614	121.886	6.60	1.4	1.7	2.1
10/13/75	13:12	36.516	121.804	4.79	0.7	1.2	1.8
10/21/75	16:58	36.514	121.808	3.68	0.8	1.3	1.9
12/19/75	19:25	36.578	121.885	1.66	0.9	3.4	2.1
12/20/75	01:02	36.575	121.928	0.50	1.0	7.0	2.1
12/20/75	05:10	36.573	121.915	0.32	0.8	4.3	1.9
01/04/76	19:17	36.580	121.888	2.66	0.8	1.3	2.2
01/07/76	06:58	36.578	121.882	0.33	0.5	2.3	2.1
01/10/76	21:55	36.573	121.908	4.46	0.4	0.6	2.3
01/10/76	21:59	36.571	121.911	0.34	0.8	4.5	1.8
01/11/76	08:22	36.580	121.892	0.15	0.5	2.1	2.0
01/11/76	18:37	36.570	121.908	3.69	0.5	0.8	2.7
01/12/76	16:09	36.583	121.884	2.50	0.4	1.0	2.6
01/12/76	18:57	36.575	121.928	6.05	0.5	0.6	1.8
01/13/76	03:12	36.573	121.916	4.98	0.6	0.6	1.8
10/13/76	21:30	36.569	121.904	3.80	0.5	0.8	2.3
01/13/76	21:41	36.570	121.909	4.24	0.6	0.7	1.7
01/14/76	00:17	36.570	121.899	3.56	0.4	0.7	2.5
01/14/76	00:18	36.570	121.898	0.42	0.8	4.8	2.1
01/14/76	23:23	36.576	121.900	0.42	1.1	4.5	1.9
01/16/76	00:28	36.569	121.912	4.59	0.6	0.6	1.9
01/16/76	00:31	36.578	121.920	5.44	0.6	0.5	1.8
01/19/76	13:54	36.571	121.910	4.48	0.5	0.5	1.8
01/29/76	02:41	36.576	121.935	6.66	0.4	0.6	1.9
04/05/76	18:07	36.622	121.936	5.81	0.5	0.4	2.0
08/07/76	20:36	36.595	121.936	12.04	0.8	0.8	1.9
01/17/79	23:32	36.644	121.858	8.21	0.8	2.2	1.6
04/30/79	05:24	36.399	121.681	7.30	0.6	1.4	1.6
06/19/79	04:04	36.504	121.754	10.57	0.4	1.2	1.5

04/12/80	19:42	36.519	121.776	10.51	0.4	1.1	1.8
07/10/80	22:22	36.557	121.776	7.63	0.3	1.1	2.1
01/09/81	10:00	36.521	121.779	9.41	0.5	1.2	1.4
11/06/81	04:18	36.515	121.786	5.84	0.3	0.9	1.8
05/22/82	01:14	36.427	121.732	8.99	0.4	2.5	1.6
04/25/83	22:31	36.597	121.897	1.45	1.1	1.2	1.8
03/02/84	14:03	36.525	121.882	10.24	0.4	1.1	1.3
03/12/84	03:49	36.429	121.711	3.01	1.4	2.3	1.4
05/05/84	23:44	36.571	121.908	3.64	0.5	0.3	1.8
05/15/84	15:50	36.562	121.853	8.80	0.5	0.9	1.8
08/05/84	20:52	36.588	121.905	3.58	0.8	0.3	1.3
09/25/84	02:30	36.587	121.909	1.19	0.5	0.4	2.5
09/25/84	02:47	36.589	121.920	1.16	0.5	0.5	2.4
10/07/85	02:42	36.494	121.748	10.18	0.4	1.1	1.4
02/23/86	21:30	36.524	121.862	14.95	0.8	1.6	1.6
04/28/86	23:50	36.579	121.943	4.84	0.4	0.3	1.7
04/27/87	18:23	36.622	121.936	13.64	0.5	0.7	1.4
05/24/87	20:27	36.616	121.965	5.88	1.6	0.4	1.3
08/13/87	15:14	36.603	121.859	3.01	0.2	0.8	2.5
03/17/88	06:35	36.572	121.810	8.44	0.6	2.0	0.8
07/12/88	17:56	36.545	121.863	9.83	1.7	3.5	1.3
08/07/88	16:21	36.488	121.681	0.17	0.7	5.7	1.2
10/05/88	03:39	36.435	121.949	8.63	0.7	1.8	1.4
01/30/89	09:16	36.535	121.883	10.87	0.4	0.9	1.4
06/09/89	07:44	36.546	121.845	4.71	3.0	6.0	2.8
07/08/89	05:18	36.448	121.781	10.80	0.4	0.8	0.7
02/10/90	07:04	36.456	121.778	20.06	0.6	0.9	1.3
07/31/90	18:52	36.401	121.740	6.07	0.6	0.3	1.5
10/04/91	02:56	36.556	121.866	12.63	0.4	1.1	0.9
12/27/91	11:17	36.583	121.771	9.23	0.6	2.5	1.2

Source of data: USGS (F.W Lester, written commun., 1992).

NOTES:

Every attempt has been made to provide the most accurate and complete information possible in this listing. However this listing is not necessarily complete or correct since some of the data are preliminary and subject to revision. Therefore, any use or interpretation of these data should be made with discretion (F.W Lester, written commun., 1992).

An attempt has been made to discriminate between earthquakes and man-made explosions and eliminate the explosions from the data base. However, due to limitations in the ability of the USGS to make this distinction, some locations of explosions may have been included in this listing.

Time is in coordinated universal time (UTC): DATE, hour (HR), minute (MN). To convert to local Pacific Standard Time (PST), subtract eight hours. To convert to Pacific Daylight Time (PDT), subtract seven hours. Depending on the time, one day may have to be subtracted from the UTC date to get the local date. Epicenters are in decimal degrees of north latitude (LAT) and west longitude (LONG). Depth of hypocenter focus (DEPTH) is in kilometers. Horizontal error (ERH) in the hypocenter in kilometers. Vertical error (ERZ) in the hypocenter in kilometers. Magnitudes are computed from the signal duration.