

2. QUATERNARY GEOLOGY AND SEISMIC HAZARD OF THE SIERRA MADRE AND ASSOCIATED FAULTS, WESTERN SAN GABRIEL MOUNTAINS

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ABSTRACT

This detailed study of a 40-km-long section of the Sierra Madre and associated fault zones in the central Transverse Ranges, along the south side of the San Gabriel Mountains, is aimed at providing information for evaluating the seismic hazard that these faults pose to the heavily populated area immediately to the south. Evidence on the location of fault strands and the style and timing of fault movements during the Quaternary was obtained from detailed geologic mapping, aerial-photograph interpretation, alluvial stratigraphy, structural and stratigraphic relations in some 33 trench excavations at critical localities, and subsurface data.

We present a time-stratigraphic classification for the Quaternary deposits in the study area, based on soil development, geomorphology, and contact relations among the alluvial units. We distinguish four units, with approximate ages, as follows: unit 4, about 200,000 yr to middle Quaternary; unit 3: about 11,000 to 200,000 yr; unit 2: about 1,000 to 11,000 yr; and unit 1; younger than about 1,000 yr. We use this classification to evaluate on a semiquantitative basis the evidence for fault activity in the study area and to infer the relative seismicity of different segments of the Sierra Madre fault zone during the Quaternary. Alluvial-fan development (particularly fanhead incision and the ages of alluvial-fan deposits) also gives clues as to relative seismicity.

The most active segment of the Sierra Madre fault zone within the study area is the westernmost section, adjacent to the faults that broke during the 1971 San Fernando, Calif., earthquake. The age of activity, as indicated by the occurrence of Holocene faulting, decreases toward the east. Along the Sierra Madre fault, through La Cañada, Altadena, Sierra Madre, and Duarte, is abundant evidence of late Pleistocene faulting. Total vertical displacement is more than 600 m, but there is no evidence for Holocene fault movement. These observations suggest that the presently applicable recurrence interval between major earthquakes in the central and eastern sections of the Sierra Madre fault zone is longer than about 5,000 yr. The local magnitude (M_L) of the largest credible earthquake that could occur on the Sierra Madre fault zone in the study area is estimated at 7, on the grounds that the fault zone is probably limited mechanically by subdivision into separate arcuate segments about 15 km long.

The Raymond fault, which branches southwestward from the Sierra Madre fault in the eastern part of the study area, shows well-defined evidence of a late Quaternary history of repeated fault movements. Displacements of alluvial strata observed in trench excavations across the fault give evidence of five major seismic events, whose times of occurrence can be estimated from radiometric dating at approximately 36,000, 25,000, 10,000–2,200 (two events), and 2,200–1,500 yr B.P. Further evidence suggests at least three more faulting events in the past

29,000 yr, for which specific dates cannot be determined. Because some additional events probably remain undetected, we infer that an average recurrence interval of about 3,000 yr, with an average vertical displacement of 0.4 m per event, is applicable to the Raymond fault in its present state, as indicated by its history of movement over the past 36,000 yr. This level of activity is distinctly higher than that found for the Sierra Madre fault zone in the central and eastern parts of the study area. If the entire 15-km length of the Raymond fault would rupture in a single event, as seems likely, a maximum credible earthquake of $M_L 6\frac{1}{4}$ can reasonably be assumed.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this study is to understand better the seismic hazard posed by the frontal-fault system of the San Gabriel Mountains of southern California along a 40-km-long segment from the mouth of Big Tujunga Canyon to the mouth of San Gabriel Canyon. This segment of the fault system, known locally as the Sierra Madre fault, lies adjacent to or within the foothill communities of Sunland, Tujunga, La Crescenta, Glendale, La Cañada-Flintridge, Altadena, Pasadena, San Marino, Sierra Madre, Arcadia, Monrovia, Bradbury, Duarte, Azusa, and Glendora; the total combined population of these communities is approximately 350,000. Although it has long been recognized that this area shares a relatively high seismic exposure with the rest of southern California, particular impetus was given to this study by the 1971 San Fernando earthquake because the fault zone whose displacement caused this earthquake lies immediately adjacent west of, and is approximately continuous with, the Sierra Madre fault zone (fig. 2.1). The major question is whether or not these two areas share a similar seismic hazard. Indeed, it has even been suggested that because strain has already been relieved in the San Fernando segment, faults of the same system to the east and west are the most likely candidates for future earthquakes.

The investigative technique used in this study was primarily a field investigation of faults to determine their precise locations, subsurface configurations, seismic histories, and present activity. There is abundant evidence

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from worldwide experience that those faults that have had displacements most often in the recent geologic past—particularly the past 11,000 yr—are most likely to slip during significant earthquakes in the near future. Thus, in this study, we placed special emphasis on the determination of recent fault movement. To determine this movement required detailed and systematic mapping of the fault zones, mapping and interpretation of Quaternary alluvial and physiographic features, compilation of various kinds of information on subsurface fault configuration and displacements, and excavation of numerous trenches across faults suspected of being active. Most of our conclusions are based on the dating of faulted and unfaulted strata exposed in 33 trenches that were excavated as part of this study. This dating involved the use of standard radiometric techniques as well as the development of a time-stratigraphic classification for the Quaternary alluvial units exposed in the study area.

Historical seismicity is also an important clue to under-

standing seismic hazard; however, both the historical and instrumental records of earthquakes in southern California are so brief that extreme caution must be used in interpreting these statistically inhomogeneous data (Allen and others, 1965). The primary contribution of the present study is in looking farther back into the recent geologic history than is possible with the historical and instrumental data, so as to obtain a more meaningful statistical data base from which to extrapolate into the future. The current seismicity of the San Gabriel Mountains, particularly in terms of the focal mechanisms and tectonic implications of contemporary earthquakes, is discussed by Pechmann (this volume).

METHODS OF STUDY AND SOURCES OF INFORMATION

The basic method of study involved three principal elements: (1) delineation of fault traces by geologic mapping based on surface inspection, trenching, and inter-

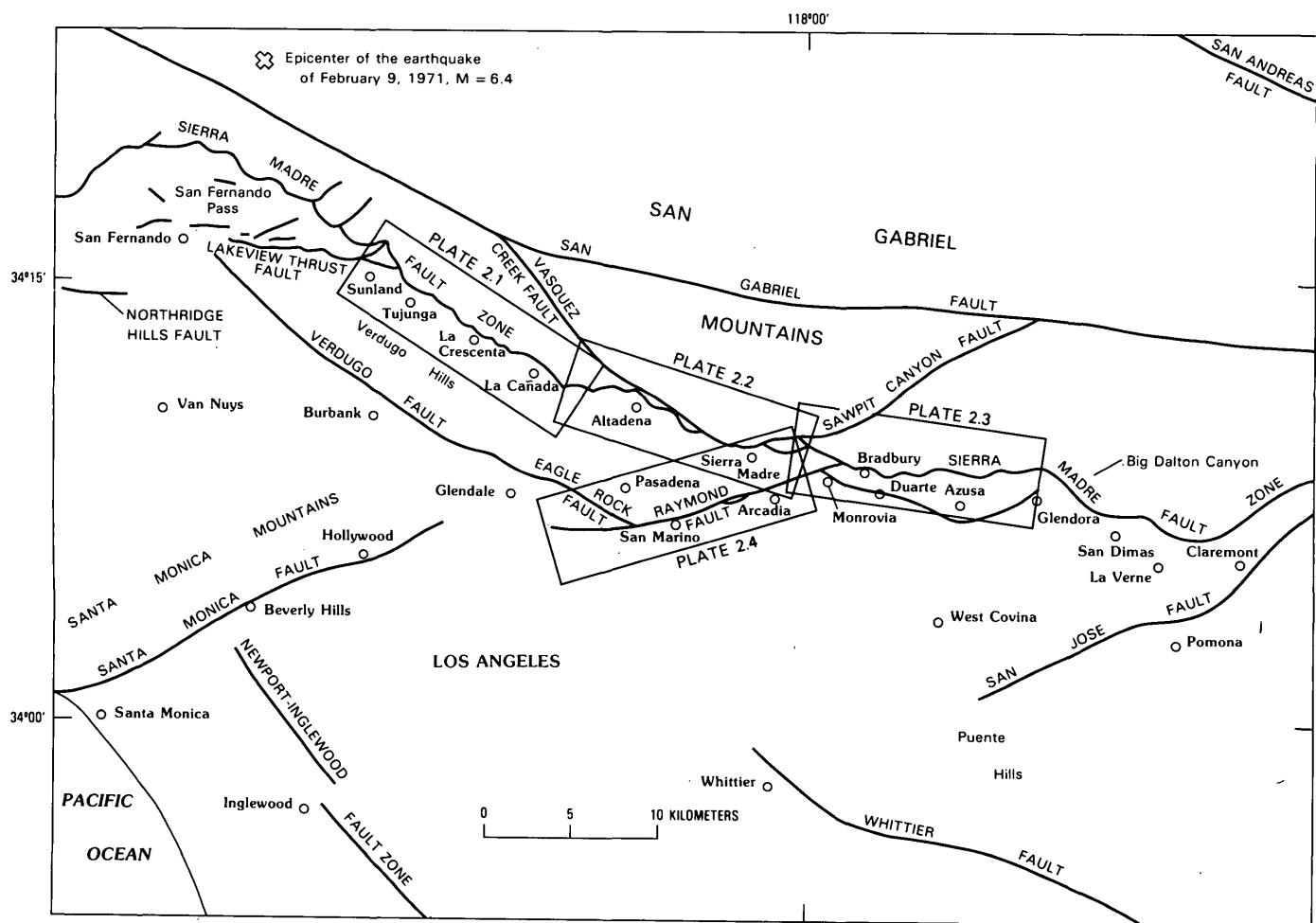


FIGURE 2.1.—Index map of study area in southern California, showing faults studied in this investigation (pls. 2.1-2.4) and their relation to other major fault systems in the Los Angeles area.

interpretation of aerial photographs; (2) determination of subsurface fault locations, configurations, and displacements from exploratory-borehole and water-well logs, from water levels, and from various geophysical data; and (3) deduction of the local history of fault movement by the use of chronologic information on the Quaternary deposits associated with fault traces.

GEOLOGIC MAPPING

Geologic mapping of the fault zones was done in the field at a scale of 1:12,000 on topographic base maps prepared from U.S. Geological Survey 7½-minute quadrangle sheets. The results, edited for presentation at a scale of 1:24,000, are presented in plates 2.1 though 2.4. Plates 2.1 through 2.3 cover the Sierra Madre fault zone in three segments from Big Tujunga Canyon on the west to the San Gabriel River on the east. The Raymond fault zone is shown in plate 2.4; its limits were chosen so as to include only those sections of the Raymond fault showing evidence for, or suspected of, Quaternary faulting.

Mapping was carried out during 1976 and 1977 with the assistance of Richard Lewis, Raymond Durkan, and Thomas Anderson. Where available, mapping by other workers was field checked and either used intact or altered where our opinions differed or where new exposures exist. Use was made of maps prepared by the following authors and agencies: Eaton (1957) and Beattie (1958), at the southwest and extreme west ends of plate 2.1; the Metropolitan Water District of Southern California (unpub. data, 1964–74), on plates 2.2 and 2.3; Morton (1973), in the east half of plate 2.2 and on plate 2.3; Saul (1976), central portion of plate 2.2; California Division of Mines and Geology (1964), at the extreme east end of plate 2.3; Buwalda (1940) on plate 2.4; and Lamar (1970) at the extreme west end of plate 2.4. Stratigraphic nomenclature and age assignments of stratigraphic units may not necessarily be those adopted by the U.S. Geological Survey.

AERIAL PHOTOGRAPHS

Extensive use was made of the oldest available aerial photographs. These are the Spence oblique aerial photograph collection (1922–52) at the University of California, Los Angeles (UCLA), Geography Department, and the Fairchild aerial photograph collection (1928–60) at the Whittier College Geology Department, Whittier, Calif. More recent aerial photographs were also examined. Special photographs for this study were taken on January 8, 1976, by I. K. Curtis, who provided a set of 48 vertical photographs at a scale of 1:12,000. Ground-view photographs dating back to the 1880's were also examined at the Henry E. Huntington Library in San Marino.

TRENCHING

A total of 33 trenches were excavated and logged during this project (table 2.1). The important features observed and conclusions reached are summarized below in the supplementary section entitled "Trenching." In addition, trenching by other workers helped to define the Raymond fault at localities 64, 67, and 68 (pl. 2.4).

DRILLING

A series of 14 exploratory boreholes were drilled at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology (CIT) in 1977; the drilling and logging were done by Le Roy Crandall & Associates under contract to JPL. We selected 11 of the borehole sites in an effort to delineate the number and location of the branches of the Sierra Madre fault zone beneath JPL; The results of this study are described below (see pls. 2.2 and 2.6).

RADIOCARBON DATING

All materials penetrated in trenches or exposed in outcrops and suspected of containing carbonaceous remains were sampled for radiocarbon dating. A total of 13 samples were deemed significant enough in placement and rich enough in carbon to be dated (see table 2.2).

SEISMIC-REFRACTION AND MAGNETOMETER SURVEYS

Unpublished information obtained from surveys by the Envicom Corp. and by Le Roy Crandall & Associates was utilized in the Duarte-Azusa area to help locate buried fault traces at localities 30 and 32 through 34 (pl. 2.13).

CLAST SOUND-VELOCITY MEASUREMENTS

We developed and tested a new method for ascertaining on a quantitative basis the relative ages of alluvial units. The extent of weathering of clasts of a definite, recognizable lithology was determined by measuring the seismic-wave velocity of the clasts, which decreases with increasing weathering. Seismic velocity was measured with a portable instrument used commercially for measuring the speed of sound in concrete (see appendix entitled "Measurement of Progressive Clast Weathering").

BOREHOLE-LOG AND WATER-LEVEL DATA

We searched the water-well files of the Los Angeles County Flood Control District for pertinent information contained in driller's logs and for water levels as they per-

RECENT REVERSE FAULTING IN THE TRANSVERSE RANGES, CALIFORNIA

TABLE 2.1.—Summary of data from trenches excavated across the Sierra Madre and Raymond faults

[CDMG, California Division of Mines and Geology; CIT, California Institute of Technology; LA, Leighton & Associates, Inc.; LRCA, Le Roy Crandall & Associates; USGS, U.S. Geological Survey]

| Trench | Fault | Location of excavation* | Property owner | Excavation method | Fault exposed | Mapped by | Map scale | Photographs taken | No. of samples taken for ^{14}C dating | Date excavated |
|--------|--------------|--|--|------------------------------|---------------|-----------------|-------------------------|-------------------|--|--------------------|
| 1 | Raymond | Foothills Junior High School athletic field, Arcadia | City of Arcadia | Backhoe | No | CIT | 1:60 | Yes | 3 | 12/22/76 |
| 2 | Sierra Madre | Arroyo Seco channel, N. of JPL bridge, Pasadena | City of Pasadena Water Department | --do-- | Yes | --do-- | 1:24, 1:60 | Yes | 0 | 12/29/76 |
| 3 | --do-- | Eaton Canyon toll road, west of bridge | City of Pasadena | --do-- | Yes | --do-- | 1:60, 1:300 | Yes | 0 | 1/5/77 |
| 3A | --do-- | --do-- | --do-- | --do-- | No | --do-- | Not mapped | No | 0 | 2/1/78 |
| 4 | --do-- | East of Pasadena Glen, west of Hastings Canyon Pasadena | City of Pasadena and Natural U.S. Forest Service | Backhoe | Yes | --do-- | not mapped | Yes | 0 | 1/5/77 |
| 5 | Raymond | Clairbourn School, south of athletic field, San Marino | Clairbourn School, San Marino | Backhoe | No | CIT, LA | 1:60 | No | 0 | 2/4/77 |
| 6, 6A | Raymond | Toe of slope on north side of ridge, Los Angeles County Arboretum, Arcadia | Los Angeles County | --do-- | No (?) | CIT | 1:48 (6A not mapped) | Yes | 0 | 2/2/77 |
| 7 | --do-- | Sunnyslope Reservoir, near southeast corner of reservoir | Sunny Slope Water Co., | --do-- | Yes | --do-- | 1:24 | Yes | 7 (15 paleo-magnetic) | 2/16- 2/18/77 |
| 8 | --do-- | Lacy Park, northwest corner near tennis courts | City of San Marino | --do-- | No | --do-- | 1:24, 1:48 | Yes | 2 | 3/2/77 |
| 9 | Sierra Madre | JPL northwest of Building 32 | JPL, Pasadena | Backhoe and natural exposure | Yes | CIT, LRCA | 1:24 | Yes | Calcite crust on cobble in gouge, 1,000-2,000 yr (USC) | 2/23/77 |
| 10 | --do-- | Behind JPL Building 150 | --do-- | Hand | Yes | CIT | Sketch | Yes | 0 | 2/77 |
| 11 | --do-- | Monastery north of Sunnyside, Sierra Madre | U.S. Forest Service | --do-- | Yes | --do-- | 1:24 | Yes | 2 | 3/77 |
| 12 | --do-- | Gould Canyon | --do-- | --do-- | Yes | --do-- | Sketch | No | 1 | 4/13/77 |
| 13 | --do-- | Duarte, west of Van Tassel Canyon | Emblem Homes | Backhoe | No | --do-- | 1:24 | No | 1 | 6/20/77 |
| 13A | --do-- | --do-- | --do-- | --do-- | No | --do-- | 1:24 | No | 1 | 7/20/77 |
| 14 | Raymond | San Marino High School | San Marino City Schools | --do-- | Yes | CDMG, CIT, LRCA | 1:24 | Yes | 6 | 8/19- 8/22/77 |
| 14A | --do-- | --do-- | --do-- | --do-- | Yes | --do-- | 1:24 | No | 2 | 8/29- 8/30/77 |
| 15 | --do-- | Edison right-of-way, Chapman Woods | Southern California Edison Co. | --do-- | Yes | CIT, USGS | 1:24 | Yes | 3 | 10/19- 10/21/77 |
| 16, | Sierra Madre | Debris basin behind Rubio Dam, east side | Los Angeles County Flood Control District | Tracked front-end loader | No | Sketched by CIT | -- | Yes | 0 | 11/22/77 |
| 16A | --do-- | East of spreading grounds, Santa Anita Wash | Metropolitan Water District | --do-- | No | Not mapped | -- | No | 0 | 11/30/77 |

TABLE 2.1.—Summary of data from trenches excavated across the Sierra Madre and Raymond faults—Continued

| Trench | Fault | Location of excavation* | Property owner | Excavation method | Fault exposed | Mapped by | Map scale | Photographs taken | No. of samples taken for ^{14}C dating | Date excavated |
|--------|---------|---|--|-------------------|---------------|------------|-----------|-------------------|---|----------------|
| 18A | --do-- | Spoil area west of Dunsmore Dam | Los Angeles County Flood Control District | --do-- | Yes | CIT | 1:24 | Yes | 1 | 1/18-1/20/78 |
| 18B | --do-- | --do-- | --do-- | --do-- | Yes | --do-- | 1:24 | Yes | 0 | 1/18-1/20/78 |
| 18C | --do-- | --do-- | --do-- | --do-- | Yes | --do-- | 1:24 | Yes | 0 | 1-18-1/20/78 |
| 19 | --do-- | Bradbury-Duarte boundary, south of mesa | Allen E. Bostwick | Backhoe | No | --do-- | 1:120 | Yes | 0 | 12/20/77 |
| 20A | --do-- | North of Sierra Madre Villa Dam | Coast Federal Savings and Loan Association | --do-- | Yes | --do-- | 1:24 | Yes | 0 | 1/25/78 |
| 20B | --do-- | --do-- | --do-- | --do-- | Yes | --do-- | 1:24 | Yes | 0 | 1/25/78 |
| 20C | --do-- | --do-- | --do-- | --do-- | Yes | --do-- | 1:24 | Yes | 1 | 1/26/78 |
| 21A | --do-- | JPL, Northwest of Building 32 | JPL, Pasadena | --do-- | No | --do-- | 1:60 | No | 0 | 7/10-7/11/78 |
| 21B | --do-- | --do-- | --do-- | --do-- | No | --do-- | 1:60 | No | 0 | 7/11-7/12/78 |
| 21C | --do-- | --do-- | --do-- | --do-- | No | Not mapped | -- | No | 0 | 7/13/78 |
| 22 | Raymond | Sunny Slope Reservoir, Pasadena | Sunny Slope Water Co. | Poplain excavator | Yes | CDMG, CIT | 1:24 | Yes | 3 | 9/78 |

*See Appendix 1 for more precise locations.

tain to ground-water barriers or buried faults. Additional borehole-log information was supplied by the Metropolitan Water District of Southern California. Information gathered from this search that proved to be important is noted on the geologic maps (pls. 2.1-2.4).

CONSULTANT GEOTECHNICAL REPORTS

Locally, in La Cañada-Flintridge, Arcadia, and Duarte, we obtained information on fault locations from geotechnical reports and geologic maps prepared by private consultants.

ACKNOWLEDGMENTS

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TABLE 2.2.—Radiocarbon samples and ages

[All ages based on the Libby half-life of carbon-14 of $5,570 \pm 30$ yr. n.a., not analyzed]

| Sample (laboratory No.) | Locality | ^{14}C age (yr) | Sample type | Depth of burial | Sedimentation rate (mm/yr) |
|----------------------------|------------------------------|---------------------------------|--------------------|--------------------|-------------------------------|
| Raymond fault | | | | | |
| C-3 (WSU 1834) | Sunny Slope trench 7 | ¹ $25,400 \pm 700$ | Organic silty clay | 3.7 | 0.15 |
| C-4 (WSU 1835) | --do-- | ¹ $25,500 \pm 590$ | Peat | 3.3 | .13 |
| C-5 (WSU 1836) | --do-- | ¹ $25,500 \pm 640$ | Organic silty clay | 3.3 | .13 |
| C-6 (WSU 1837) | --do-- | ¹ $2,160 \pm 105$ | Soil | (²) | -- |
| C-9 (WSU 1838) | --do-- | ¹ $20,990 \pm 440$ | Organic silty clay | (²) | -- |
| C-16 (USGS 407) | San Marino trench 14 | ³ $35,800 \pm 1,300$ | Clayey peat | 3.8 | .11 |
| C-17 (USGS 403) | --do-- | ³ $29,100 \pm 400$ | Peat | 3.0 | ⁴ .10 |
| C-18 (WSU 1849) | --do-- | ¹ $10,600 \pm 160$ | Organic silt | 1.9 | .18 |
| C-19 (WSU 1850) | San Marino trench 14 | ¹ $6,060 \pm 110$ | Soil | .9 | .15 |
| C-20 (WSU 1851) | San Marino trench 14A | ¹ $3,575 \pm 100$ | --do-- | .8 | .22 |
| C-21 (WSU 1852) | --do-- | ¹ $1,630 \pm 100$ | --do-- | .5 | ⁵ -- |
| CDA (GX 3239) | Sunny Slope trench (1973) | ⁶ $2,920 \pm 180$ | --do-- | (²) | -- |
| Sierra Madre Fault | | | | | |
| C-23 (UCLA 2079A) | Eaton Canyon | ⁷ 200 ± 80 | Charcoal | n.a. | -- |
| C-24 (UCLA 2079B) | Pasadena Glen trench 20C | ⁷ $2,200 \pm 80$ | Wood | n.a. | -- |

¹Analyst, J. C. Sheppard, Washington State University, Pullman.²Sample out of place owing to faulting.³Analyst, Stephen Robinson, U.S. Geological Survey, Menlo Park, Calif.⁴Rate between samples C-16 and C-17 is 0.12 mm/yr.⁵Rate between samples C-20 and C-21 is 0.14 mm/yr.⁶Analyst, Geochron Laboratories, Cambridge, Mass.⁷Analyst, C. R. Berger, University of California, Los Angeles.

LITHOLOGIC UNITS

PRE-TERTIARY ROCKS

The rocks that make up the crystalline basement of the San Gabriel Mountains have been described in detail by Miller (1934), Morton (1973), Ehlig (1975), and Saul, (1976), and are described only briefly here. The rocks are a highly complex mixture of materials of metamorphic and igneous origin, ranging in age from 19 m.y.B.P to at least 1.4 b.y.B.P. (Hsu and others, 1963; Silver and others, 1963).

GNEISS

The oldest and most complex unit in the study area is the gneiss that occurs throughout the study area (pls. 2.1-2.4). This gneiss is complex in both structure and

metamorphic facies. It is generally well banded and moderately well to well foliated; both features trend northwest, transverse to the mountain front. The rock is composed predominantly of quartzofeldspathic gneiss containing local patches of amphibolite and biotite schist. Locally, metasedimentary units (for example, marble and calcsilicates) occur in the Monrovia outlier and in Fish Canyon. The gneiss is pre-Cretaceous in age.

RUBIO DIORITE OF MILLER (1934)

The Rubio Diorite of Miller (1934) intruded the gneiss and now occurs as discontinuous bodies in the gneiss and as xenoliths in the Cretaceous intrusive rocks between Millard and Santa Anita Canyons (pl. 2.2). The unit occurs in close proximity to, or is encompassed within, the Vasquez Creek fault zone between Millard and Eaton

Canyons and is associated with the Sierra Madre fault zone east of Eaton Canyon. The diorite is characteristically very dark and is rich in hornblende, biotite, and plagioclase. Locally it is very coarse grained (pegmatitic); hornblende crystals are several centimeters long. The Rubio Diorite is pre-Cretaceous in age.

LOWE GRANODIORITE OF MILLER (1934)

The Lowe Granodiorite of Miller (1934) is one of the most distinctive rock types in the San Gabriel Mountains. Characteristically it is light gray to white and contains large black phenocrysts of hornblende and biotite and, commonly, large gray phenocrysts of potassium feldspar. Silver (1971) dated the rock at 220 ± 10 m.y.B.P. (Triassic).

This unit does not crop out within the study area but occurs in the upper reaches of all the major and most of the smaller drainages between the Arroyo Seco and Santa Anita Canyon. Therefore, clasts of this unit are found in nearly all the Quaternary alluvial units. We have developed a quantitative method of measuring the degree of weathering of these clasts to determine the relative ages of the Quaternary units (see appendix entitled "Measurement of Progressive Clast Weathering").

WILSON DIORITE OF MILLER (1934)

The Wilson Diorite of Miller (1934) is the most widespread rock type in the study area and the most consistent lithologically. It is exposed nearly continuously along the mountain front from Big Tujunga Canyon to San Gabriel Canyon. The Wilson Diorite is a gray medium- to coarse-grained biotite-hornblende quartz diorite, generally massive but locally foliated. It intrudes all of the previously described units. The Wilson Diorite was dated by Larson and others (1958) at 122 m.y.B.P. (Cretaceous).

QUARTZ MONZONITE AND GRANODIORITE

Another widespread plutonic unit is a gray to tan fine- to medium-grained quartz monzonite and granodiorite that occurs as small lenticular bodies and dikes. This unit intrudes all the previously described units.

TERTIARY ROCKS

INTRUSIVE ROCKS

Unmetamorphosed hypabyssal intrusive dikes of various compositions are common in several areas along the mountain front. Only the larger dikes are shown on the maps (pls. 2.1-2.3); they are presumably Miocene in age.

VOLCANIC AND SEDIMENTARY ROCKS

Volcanic and sedimentary rocks of Tertiary and inferred Tertiary age are exposed at the west and east ends of the study area. All these rocks are moderately to highly deformed and faulted, and all are unconformably overlain by deposits of Quaternary age.

In the Sunland-Tujunga area (pl. 2.1), these deposits consist of volcanic flows and sandstone—the middle Miocene Topanga Formation; shale and siltstone—the upper Miocene Modelo Formation; sandstone and conglomerate—commonly called the Pliocene Pico Formation by some workers; and upper Pliocene(?) conglomerate composed mainly of volcanic clasts. All these units are highly deformed and dip steeply, and all are faulted. All contacts with the pre-Tertiary basement are faulted.

In the Bradbury area (pl. 2.3), the Tertiary deposits consist of middle Miocene conglomerate and sandstone, as well as small amounts of shale and volcanic flows—the Topanga Formation (Shelton, 1955); the Pliocene(?) Duarte Conglomerate (Shelton, 1946); and Pliocene and Pleistocene sandstone, siltstone, and conglomerate—the Saugus Formation.

The Duarte Conglomerate is a relatively massive moderately well consolidated conglomerate containing well-rounded clasts as large as 1 m in diameter. The presence of clasts of the Pelona Schist, mylonitic augen gneiss, and the Lowe Granodiorite, indicates that the source of the clasts was the San Gabriel River drainage. The Duarte Conglomerate unconformably overlies or is faulted against the older Topanga Formation (pl. 2.3; fig. 2.13) and is unconformably overlain by and faulted against the younger unit 4 alluvium.

A distinctive sedimentary unit consisting of alternating beds of relatively clean sandstone, pebble- to cobble-size conglomerate, and red siltstone occurs in the Ruby Canyon-Monrovia Canyon area (pl. 2.8; fig. 2.12). This unit is very similar in appearance to the Pliocene and Pleistocene Saugus Formation in the Sunland area of northern San Fernando Valley.

QUATERNARY DEPOSITS

Among the most striking features in the study area are the large, sweeping alluvial-fan surfaces at the foot of the steep mountain front in the La Cañada-La Crescenta and San Gabriel Valleys (fig. 2.2). These large fans consist of hundreds of meters of sand and gravel deposits derived from the San Gabriel Mountains since middle Pleistocene time. These deposits are important to this study because they reflect the tectonic history of the San Gabriel Mountains.

We recognized at the outset of this study that a means of classifying the Quaternary deposits according to age

is necessary to determine the faulting history and to evaluate the seismicity of the Sierra Madre and Raymond fault zones. We here propose an informal four-part classification that can be applied to all the Quaternary deposits studied. The four units are classified on the basis of geomorphic relations, topographic position, stratigraphic position, and degree of soil development, as shown diagrammatically in figure 2.3. Other, less tangible but equally important criteria are color, grain size, clay content, degree of consolidation, and degree of clast weathering (as determined by both visual and clast-sound-velocity methods). This classification is similar to that of Buwalda (1940), although he used only three designations.

The basic differences between the four units are best indicated by the criteria listed above. These differences result from processes that are dependent upon time, temperature, water content, parent material, and geomorphic position. A basic assumption made in this classification is that time is the most significant variable. More detailed discussions of the classification criteria are presented in the sections on the individual units below.

UNIT 4

The oldest alluvium mapped in the study area, unit 4, is age correlative with the Pleistocene San Dimas Formation of Eckis (1928), but because this name has been used by other workers to include units we consider to be much younger, we prefer our informal designation. Within the study area, this unit consists of poorly consolidated to well-consolidated fine to coarse alluvial sand, silty sand and gravel, gravelly sheetflood deposits (McGee, 1897), and minor amounts of coarse debris-flow or mudflow deposits. These deposits are generally distinguished by

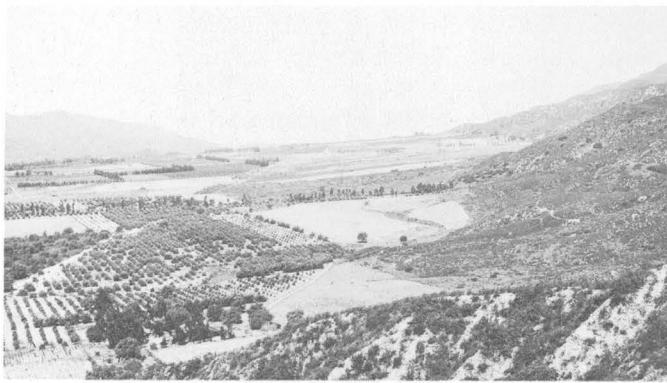


FIGURE 2.2.—Alluvial fans in La Cañada-La Crescenta area. Buried branch of Sierra Madre fault zone lies approximately at break in slope between fan surfaces and mountain front. Steeper slopes (upthrown block) consist of unit 4 alluvium (foreground) and crystalline basement (background); fans consist of unit 1 alluvium (foreground), unit 3 alluvium (center), and unit 4 alluvium (skyline). View westward from Gould Mesa above JPL. Photograph courtesy of Huntington Library collection.

having several or all of the following properties: red to reddish-yellow (2.5YR to 5YR) hues, low to high clay content, chalky-white feldspar sand grains, highly weathered clasts of all rock types, and fractures or joints with or without cementation. These properties are most obvious where a soil profile has developed but are also found throughout the deposits. Pedogenic processes apparently intensify the development of these characteristics, but they seem to continue to develop in deposits removed from the soil zone by burial.

Almost the entire Sunland-Tujunga-La Crescenta area is devoid of exposures of unit 4. The unit probably exists below younger alluvial deposits, but at the surface it is restricted to one small fan at the mouth of Rowley Canyon and several small remnants between Haines and Cooks Canyons (pl. 2.1).

The west half of the city of La Cañada is built on a composite unit 4 fan surface. This surface, the ancient La Cañada fan, formed from coalescing fans from Snover, Hall Beckley, Winery, and Hay Canyons and probably was once continuous with the Gould Mesa surface but has been displaced from it along the Sierra Madre fault zone.

Unit 4 of the La Vina fan extends from Gould Mesa eastward almost to Lake Avenue in Altadena (pl. 2.2). These deposits, which have been extensively eroded by both large and small drainages, offer excellent exposures. Below Gould Mesa, on the west side of the Arroyo Seco is a continuous exposure, more than 90 m thick. Here, the deposits consist of discontinuous beds and lenses of poorly to moderately well sorted fine to coarse sand and pebble, cobble, and boulder gravel; clasts are generally subrounded to rounded. Boulders as much as half a meter in diameter are common, and some exceed a meter in diameter. Clast lithologies vary considerably but are typical of those found in recent alluvium of the Arroyo Seco. All the clasts are highly weathered; the clasts of the Lowe Granodiorite in this unit have the lowest seismic velocity of such clasts in all the alluvial units (see supplementary section below entitled "Measurement of Progressive Clast Weathering"). This exposure also contains a buried soil (B horizon), approximately 15 m above the canyon bottom; remnants of a buried B horizon are also exposed in a small canyon southeast of La Vina Sanitarium.

A nearly complete profile of the highly developed soil typical of unit 4 is exposed on a housing pad on the ridge south of the La Vina Sanitarium. This soil is also evident on the Gould Mesa surface and continues, unfaulted, down over the south face of the mesa to the base of the slope near JPL Building 251.

At Monk Hill, approximately 3.5 km south of the frontal-fault system, a small patch of unit 4, exposed at the surface, surrounds a small outcrop of quartz-rich metasedimentary rock.

Several small fault-bounded unit 4 blocks, exposed between Rubio and Eaton Canyons, have been raised above the Altadena fan surface along a branch of the Sierra Madre fault zone. The highest surfaces have a moderately well developed soil, though not so highly developed as that on the La Vina-Gould Mesa surfaces.

Unit 4 between Eaton and Santa Anita Canyons consists mainly of the coarse alluvial facies; the finer sheet-flood facies crops out between Pasadena Glen and Hastings Canyon. In this reach, most of the original unit 4 fan surface has been removed by erosion and covered by younger alluvial units or faulted basement. A few isolated original depositional surfaces are exposed in Eaton Canyon, Little Santa Anita Canyon, and high on a ridge east of Bailey Canyon.

The Eaton Canyon deposit is unusual in that unit 4 appears to be composed of two subunits separated by an erosional surface. Both subunits consist of fine- through coarse-grained sand containing a few layers and lenses of pebble-cobble gravel and a few scattered boulders. Although the lower subunit has been eroded, the remnants of the B horizon appear more highly developed than the B horizon of the upper subunit. Both subunits and the erosional contact are visible beneath the transmission towers just north of the Civil Defense Center on New York Drive.

In the Pasadena Glen-Hastings Canyon area, the unit 3 fan surface is underlain at a depth of 2 to 3 m by a unit 4 fan with a paleosol at its upper surface that appears equivalent in development to the soil on the upper unit 4 unit in Eaton Canyon. These deposits are the sheetflood facies, with thick (max 3 m) sequences of massive fine-grained silty sand containing a few boulders as much as 2 m in diameter.

Unit 4 on the ridge above Bailey Canyon consists of a 15-m-thick section of crudely bedded silty sand containing numerous angular to subrounded pebbles and cobbles. The upper surface includes a reddish-brown soil containing abundant clay. This is the highest occurrence (elev, 762 m) of alluvial deposits within the study area.

Unit 4 exposed in Little Santa Anita Canyon is the coarse alluvial facies, containing numerous rounded boulders of the Lowe Granodiorite and the Wilson Diorite, all highly weathered. Small remnants of the original fan surface remain on the east side of the canyon, but most of the surface has been stripped by erosion.

The Monrovia outlier between Santa Anita and Monrovia Canyons contains numerous small remnants of unit 4, once part of a fan surface that covered the entire low-lying block of crystalline basement (pl. 2.3). This surface, here named the "Alta Vista surface," can be traced nearly

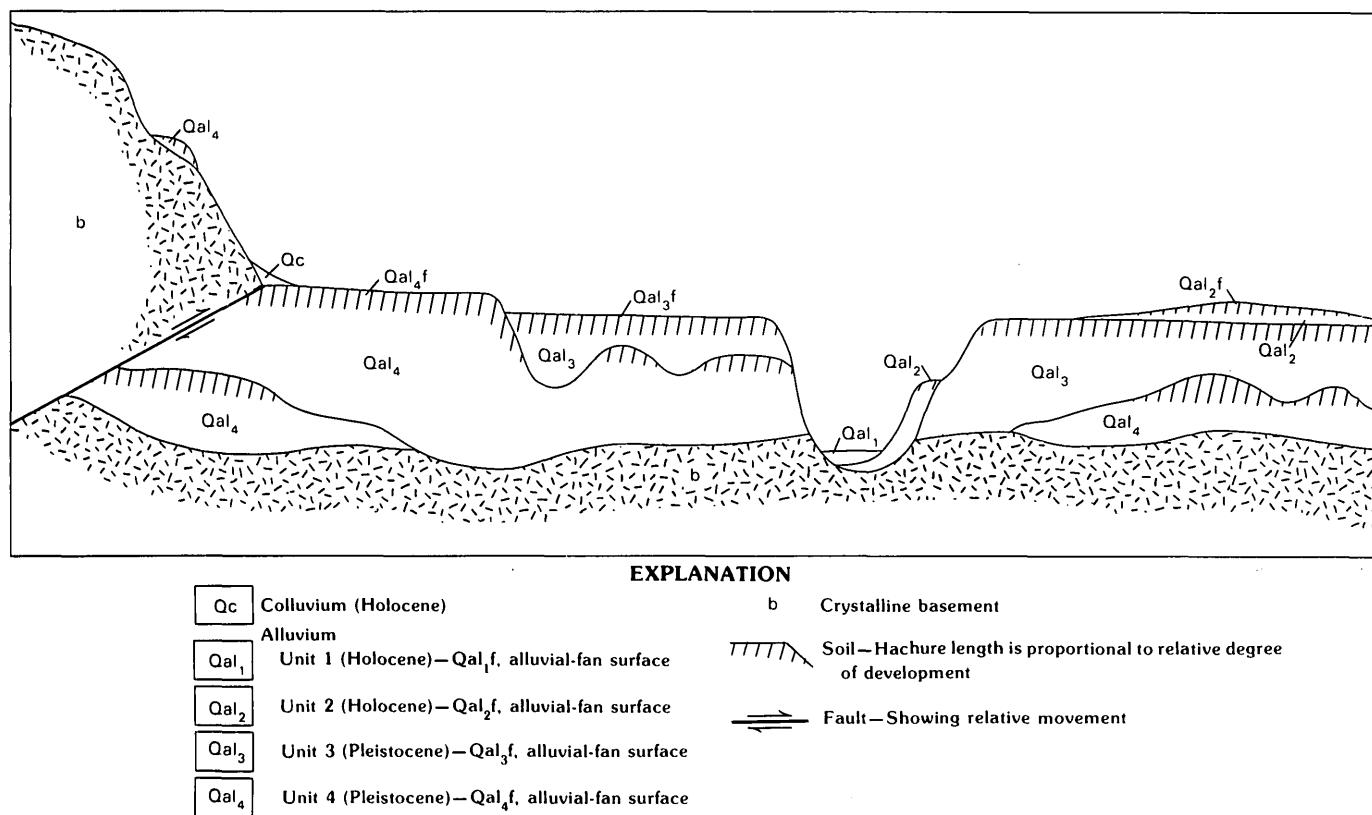


FIGURE 2.3.—Diagrammatic cross section of Quaternary alluvial units and geomorphic surfaces.

continuously for about 1.6 km up Monrovia Canyon, but nearly all of the surface along Santa Anita Canyon has been eroded away.

Most of unit 4 in this area consists of moderately well consolidated medium to coarse sand and pebble and cobble gravel, with a few boulders 1.5 m in diameter. Clasts range from subangular to rounded and all are highly weathered. All the deposits have a highly developed soil at their upper surface, although erosion has removed the upper part from most of the small remnants. The deposits underlying the surface along Alta Vista Drive are finer grained, have a sheetflood-mudflow origin, and include a more highly developed soil than elsewhere on the surface. The higher degree of soil development may be due in part to the fine-grained texture of the deposit.

The Bradbury area contains extensive deposits of unit 4, as well as remnants of the original fan surfaces. These deposits consist of both the coarse-grained alluvial sand and gravel and the finer grained sheetflood deposits. Some unusually fine-grained deposits in the Norumbega Drive area west of Bradbury are composed of silty fine-grained sand, silt, and some clay. All remnants of the original fan surfaces have a highly developed soil on them. The distribution of unit 4 east of the San Gabriel River was taken from the maps by Streitz (1964) and Morton (1973) by correlating the units that were mapped by them as the San Dimas Formation with our unit 4.

UNIT 3

By far the most abundant of the exposed Quaternary deposits mapped in the study area is unit 3. Most earlier workers lumped unit 3 with our unit 4 and called them earlier alluvium (Mendenhall, 1908) or older alluvium (Eckis, 1934). It was not until Buwalda's (1940) study of the Raymond Basin that these deposits were recognized as a separate unit, which he designated "old alluvium" as distinct from "recent alluvium" and "ancient alluvium."

The unit 3 deposits form most of the alluvial fans between the Arroyo Seco and Santa Anita Canyon, and a few of the fans between Big Tujunga Canyon and the Arroyo Seco. These deposits, in addition to the typical coarse-grained alluvial sand and gravel and sheetflood deposits, include a facies of very large boulders. This facies generally consists of 80 percent or more of cobbles and boulders, many with diameters of more than a meter; 2- to 3-m sizes are common. These deposits occur at the mouths of the present larger drainages; a good exposure is along the Mount Wilson Toll Road at the mouth of Eaton Canyon (pl. 2.2).

Distinguishing characteristics of unit 3 are: yellow through yellowish-brown to pale-brown hues (7.5YR to 10YR), unconsolidated to moderately consolidated, little to no clay, unaltered feldspar sand grains, no fractures

or joints such as are common in unit 4, moderately to highly weathered clasts with moderate to high biotite content, relatively fresh and hard clasts with little or no biotite, and moderately high seismic velocities in clasts of the Lowe Granodiorite. Where undisturbed, surfaces of unit 3 have a poorly developed soil profile. Near the fan heads this profile generally consists of an A horizon and a cambic B horizon (Soil Survey Staff, 1975). The older surfaces on distal parts of the larger fan surfaces may have a poorly to moderately developed textural B horizon, examples of which are visible in Interstate Highway 210 roadcuts in western Pasadena. This more advanced development is probably due in part to the older age and in part to the finer parent material that occurs in distal parts of the fan (Eckis, 1938).

In the area between Big Tujunga and Blanchard Canyons, unit 3 consists of isolated remnants of fan heads and stream terraces along the lower parts of the larger drainages. The original fan surfaces are still recognizable in a few localities, for example, above Sunland and in Cooks Canyon, but most of the deposits have been removed by erosion subsequent to uplift along the frontal-fault system.

Most of the fans between Blanchard and Pickens Canyons are composed of unit 3. All except the Dunsmore fan are incised at their heads and offer good exposures. Some fans, such as in Shields and Pickens Canyons, appear to be offset near their heads by the frontal faults (locs. [3] - [6], pl. 2.1).

The Altadena fan, the largest example of a unit 3 fan (pl. 2.2), is actually a composite feature formed by a series of coalescing fans. The Altadena fan is bounded on the west and east by the incised Arroyo Seco and Eaton Canyon, and on the north and south by the Sierra Madre and Raymond fault zones. Excellent exposures of the deposits are afforded in both the Arroyo Seco and Eaton drainages. Along the Arroyo Seco the deposits consist of crudely bedded moderately consolidated to loose sand and gravel containing boulders as much as half a meter in diameter; locally, some of the finer sand layers contain minor amounts of red clay. Near the mouth of Eaton Canyon the deposits are the large-boulder facies. Farther downstream, this facies gives way to the normal coarse-grained sand and gravel, which is visible unconformably overlying unit 4 about 750 m north of New York Drive.

Profiles drawn radially down the Altadena fan surface show it to be a segmented fan, typical of an area undergoing periodic uplift (Bull, 1964). A comparison of the surface soil at the fan head at Las Flores Canyon and the lower fan surface along Interstate Highway 210 indicates that the lower fan surface is distinctly older.

The Arroyo Seco and Millard Canyon contain remnants of stream-cut terraces covered with thin deposits of unit 3. Most of these deposits are on crystalline basement, but

a few are on surfaces cut in unit 4, for example, the high surface at the confluence of Millard Canyon and the Arroyo Seco. The Kinneloa and Sierra Madre fans are mapped as unit 3, although their soil development, clast weathering, and stage of dissection indicate they probably consist of older deposits of unit 3. The Hastings fan also contains unit 3 deposits, but their stratigraphic position, high seismic velocities of clasts, and the more youthful appearance of the fan suggest that these deposits represent some of the youngest unit 3.

A small remnant of the unit 3 fan that once extended southward from the mouth of Santa Anita Canyon is exposed along the access road to Arcadia Wilderness Park. This is the large-boulder facies, which has been overthrust by crystalline basement (loc. ④8, pl. 2.2).

Between Santa Anita Canyon and the San Gabriel River, unit 3 consists of three remnants of a fan surface in Monrovia Canyon. These deposits are the large-boulder facies and are exposed along both canyon walls and in the east wall of Ruby Canyon. Apparently most of this area north of the frontal-fault system never had unit 3 deposited on it.

UNIT 2

Unit 2 consists of fluvial and alluvial-fan deposits of unconsolidated gray through olive to pale brown (5YR to 10YR), fine to coarse sand and pebble, cobble, and boulder gravel. The clasts are subangular to rounded, as much as 2 m in diameter, and generally unweathered, although some of the biotite-rich rock types are moderately weathered. Soil development on this material is restricted to poorly developed A horizons. These deposits also form numerous stream terraces both within the mountain front and within incised drainages on the older fan surfaces.

In the Sunland-Tujunga area, most of unit 2 forms alluvial fans. The surface designated "Old Zachau fan" on plate 2.1 appears to be uplifted and was once continuous with the distal parts of the composite fan underlying the western part of the city of Sunland; the intervening area has been covered by younger deposits. Approximately 20 m upstream from the mouth of Haines Canyon, an uplifted unit 2 fan head is perched 50 m above the present channel.

Dunsmore Canyon has a unit 2 fan that has buried most of a larger unit 3 fan. The unit 2 fan has two prominent scarps on its surface (loc. ⑦, pl. 2.1) whose upper surfaces probably correspond to two unit 2 terraces upstream from the fan. The deposits of this fan were exposed in three bulldozer trenches across the lower, most prominent scarp (fig. 2.4). A soil with an unusually thick A horizon has developed across the fault scarp, but it is thinner above and 10 m south of the scarp (fig. 2.5).

Many of the drainages incised in the older fans in this area contain remnants of unit 2 along them. In the Cooks

and Pickens drainages they are deposited on unit 3, and in Hall Beckley Canyon they are on unit 4. There are several unit 2 terraces in the Arroyo Seco—just downstream from the JPL bridge on the east side of the wash, in Oak Grove Park (pl. 2.1), and just above the present stream channel upstream from the canyon mouth.

The Las Flores and Rubio Canyon drainages (pl. 2.2), which have incised the upper part of the Altadena fan surface, have built a moderate-size unit 2 fan on the middle part of the Altadena surface south of the Altadena Golf Club.

Unit 2 makes up most of the fans between the Santa Anita and San Gabriel Canyon drainages. The deposits are designated as unit 2 on the basis of their stratigraphic and geomorphic position, shape, and size. They were deposited after uplift of unit 3 and have subsequently been buried in part by Holocene deposits from numerous small drainages.

UNIT 1

Unit 1 underlies the channels and flood plains of all drainages, as well as several fan surfaces. These deposits consist of unconsolidated, poorly sorted, white to gray coarse sand and pebble, cobble, and boulder gravel. Typical exposures are visible in the numerous gravel-pit operations in most of the major drainages. None of these deposits has a soil developed on it.

Zachau, Haines, and Blanchard Canyons in Tujunga (pl. 2.1) all have well-developed unit 1 alluvial fans at their mouths. Early aerial photographs indicate that these fans were actively building before flood control channels were built and the area developed. Also, in Gould Canyon, a unit 1 fan was actively building on the eastern part of the ancient La Cañada fan.

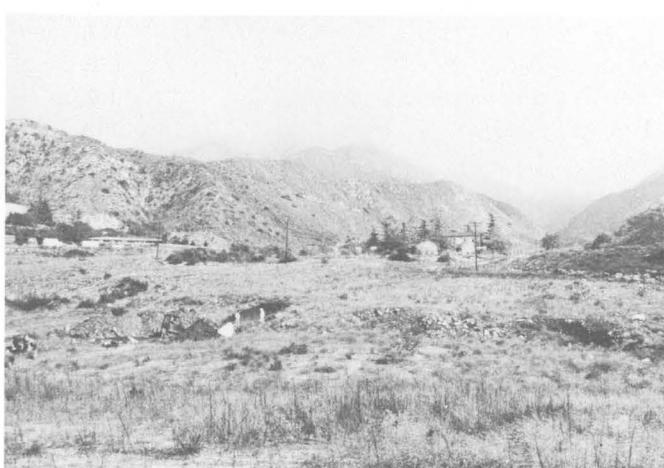


FIGURE 2.4.—South scarp on unit 2 Dunsmore fan. Scarp trace is indicated by line of boulders to right of excavation in center of photograph. Three trenches were excavated across the scarp, all of which exposed the fault.

In the Bradbury-Duarte area (pl. 2.3) several small unit 1 fans have formed at the mouths of intermediate-size drainages, where they cross a buried trace of the Sierra Madre fault zone. A very large composite fan of unit 1 has formed where the Eaton, Little Santa Anita, and Santa Anita Washes cross the Raymond fault (pls. 2.2, 2.4). A small unit 1 fan has been deposited in Eaton Wash by the Hastings Canyon drainage.

AGES OF QUATERNARY UNITS

Although no radiometric dates are available for most of the units classified as Quaternary (except for a single ¹⁴C date on unit 2 alluvium in the Pasadena Glen-Hastings Canyon area), their Quaternary age can be established with confidence. These units are identical in appearance and similar in origin to the Pacoima Formation in the San Fernando Valley (Oakeshott, 1958), where

they overlie the Pliocene and Pleistocene Saugus Formation. A similar relation is visible in the Monrovia Canyon area. Additionally, Eckis (1928) reported that parts of a skeleton of *Elephas imperator*(?) of Pleistocene age were found approximately 20 m below a fan surface in the San Dimas Formation, which is equivalent to our unit 4.

With no absolute dates for unit 4 available, other methods must be used to estimate its upper time boundary. Because this unit everywhere appears to show effects of fan-surface stabilization and concurrent soil development, we attempt to use rates of soil development to estimate its age.

All unit 4 alluvium that was not immediately buried by younger deposits has a moderately well developed to well-developed soil at its surface. This soil was mapped by the Soil Conservation Service (Eckman and Zinn, 1917) as either the Placentia or Ramona series; the Placentia is the more highly developed. The Placentia and Ramona

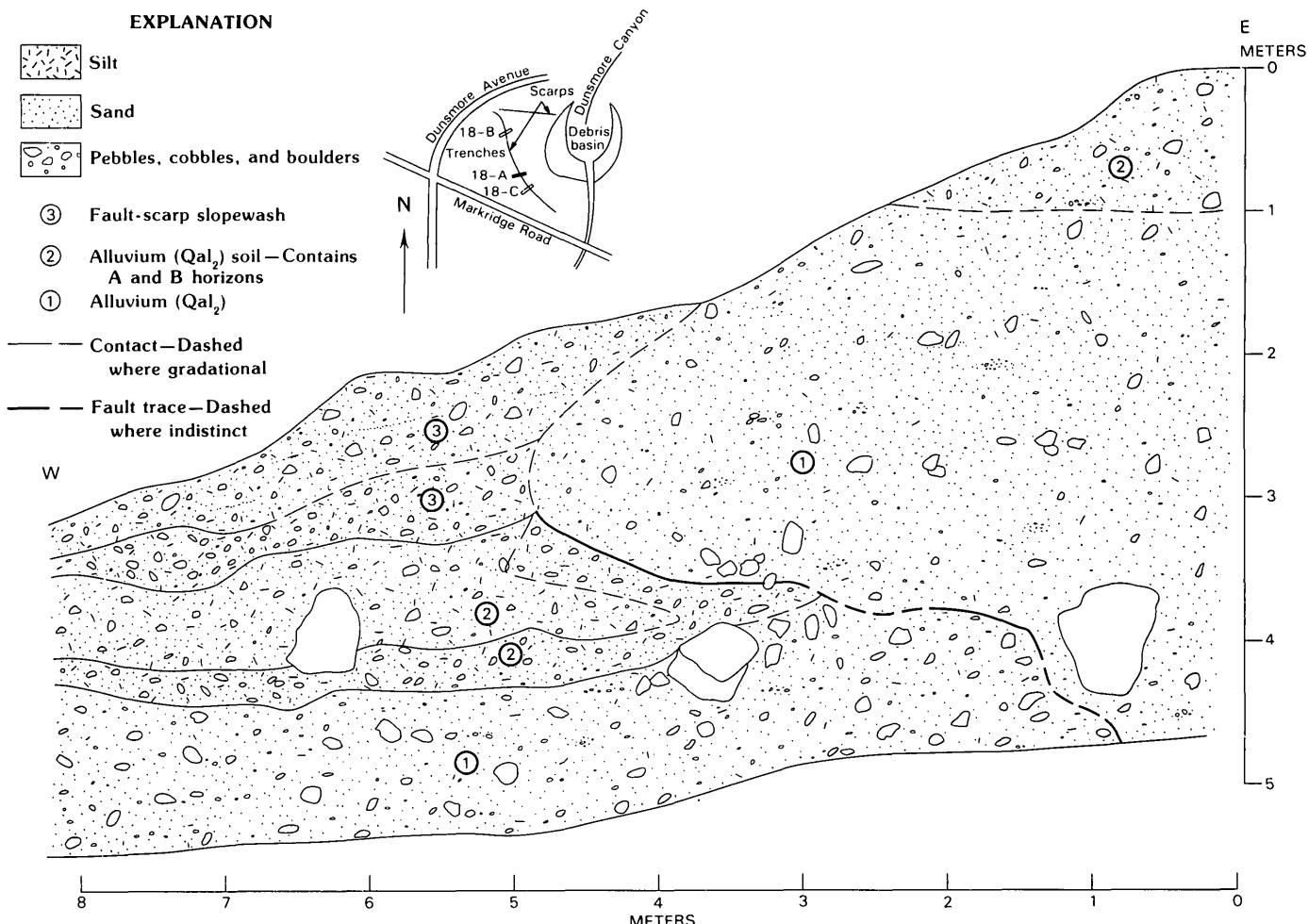


FIGURE 2.5.—Log of trench 18-A (bearing, N. 75° E.) on unit 2 Dunsmore fan, in Dunsmore Canyon, Glendale. Fault surface is indicated by differences in color of deposits or, locally, by sheared highly weathered biotite-rich clasts; fault trends N. 20° W. Thick soil here is due to local accumulation of debris washed from upper fan surface; soil was much thinner at other two excavation sites.

soils appear similar in parent material and degree of development to the Montpellier and Snelling soils mapped by Marchand (1977) in the northeastern San Joaquin Valley. Marchand tentatively assigned ages of 300,000 to 500,000 yr to the Montpellier soil developed on the upper surface of the Turlock Lake Formation, and of 100,000 years to the Snelling soils on the Riverbank Formation. Roy Shlemon (oral commun., 1978) indicated that 100,000 yr is the minimum time required in southern California to develop a strong argillic B horizon with 2.5YR to 5YR hues.

The most highly developed unit 4 soils (Placentia) occur on the La Vina, Gould Mesa, Alta Vista, and Older Spinks fan surfaces. These soils have been at the surface since their formation; they are probably at least 200,000 yr old, but more likely are closer to the 300,000-year age assigned by Marchand to the Montpellier soil. The unit 4 surfaces that were buried by unit 3 deposits some time after their formation exhibit less well developed (Ramona) soils, probably 100,000 yr old or younger. This age suggests that the oldest unit 4 soils have been exposed approximately 200,000 years longer than the buried unit 4 soils and would put the upper age boundary of unit 4 at about 200,000 yr.

Unit 3 appears to range in age from 11,000 to 200,000 yr, on the basis of several lines of evidence. The 200,000-yr lower age boundary discussed above is substantiated by the Ramona-type soils (Eckman and Zinn, 1917) found on the lower parts of the Altadena fan (~100,000 yr old) that overlie an unknown thickness of unit 3. An upper age boundary of about 11,000 yr is suggested by the Hanford series soils that occur on the heads of the Altadena fan, which resemble the Hanford series soils in the San Joaquin Valley considered to be Holocene by Marchand (1977). W.B. Bull (oral commun., 1978) also considered one of the soils mapped as Hanford in the Altadena area—believed by us to be the youngest unit 3—to be Holocene.

The following reasoning indicates to us that the upper boundary of unit 3 coincides with the Pleistocene-Holocene boundary. Bull and others (1979) proposed that a 50-m-thick terrace in San Gabriel Canyon represents a rapid aggradation cycle caused by climatic change; they suggested that the cycle occurred during the Holocene, on the basis of ^{14}C dating of two samples collected near the base of the terrace (W. B. Bull, oral commun., 1980). Deposits of Holocene age suggesting similar aggradational cycles are found in the Arroyo Seco and Eaton Canyon (pls. 2.1, 2.2; see also subsection above entitled "Unit 2"), and in Cajon Pass (45 km northeast of Glendora) (R.J. Weldon, oral commun., 1981), all of which might be correlative with the San Gabriel Canyon terrace. The Arroyo Seco, Eaton Canyon, and Cajon Pass aggradation cycles, however, were preceded by a major

erosional cycle that, at least in Cajon Pass, occurred approximately 11,000 to 10,000 yr B.P. (R.J. Weldon, oral commun., 1981). We propose that this cycle caused the major incision of the large unit 3 fans (for example, the Altadena fan). Additionally, a statistically significant clustering of ^{14}C dates around 10,000 yr B.P. in the southern California area (J.C. Tinsley, oral commun., 1981) suggests a major change in the depositional-erosional process that may also be attributable to the climatic change at the Pleistocene-Holocene boundary (Ericson and others, 1961).

Unit 2 is considered to be Holocene. This unit has a single ^{14}C age of $2,200 \pm 80$ yr in the Pasadena Glen-Hastings Canyon area (fig. 2.10; table 2.2). The boundary between units 2 and 1 is placed at 1,000 years B.P.

GEOMORPHOLOGY

Only those aspects of geomorphology are discussed here that pertain directly to fault activity: (1) Alluvial-fan development, particularly fan-head incision, may reflect differences in the degree of fault activity along the range front; and (2) landslides may represent prehistoric earthquakes, especially those that originate as thrust faults ("thrust-rooted slides"). The continuity from thrust fault to landslide indicates continuing tectonic deformation.

ALLUVIAL FANS

The most obvious geologic evidence of activity along faults, such as the Sierra Madre zone, comes from fault scarps and related features that are directly caused by surficial displacements. Alluvial-fan development, however, can also give significant clues to the rate and periodicity of movements along faults whose displacements have caused the uplift that, in turn, has caused deposition of the alluvial fans. In particular, Bull (1964) suggested that segmented fans generally reflect episodic uplift and that when uplift ceases for a sufficiently long period, fan heads tend to become incised and active deposition occurs farther down the fan surface. Thus, varying degrees of fan-head incision along a given mountain front may indicate different degrees of activity along the bounding fault system, as appears to be the case along the front of the San Gabriel Mountains.

Generally speaking, fan heads in the area of the San Fernando earthquake, west of the study area, are incised to a lesser degree than those in the La Cañada-Pasadena area—for example, the relatively untrenched fans of Pacoima and Little Tujunga Canyons, in the San Fernando area, in comparison with the deeply incised fan heads of the Arroyo Seco and Eaton Canyon in Pasadena. Similarly, fans at the east end of the San Gabriel Mountains, such as at Day and Deer Canyons (Eckis, 1928), are

far less incised than those near Pasadena. Thus, on the basis of this evidence alone, we might conclude that the present rate of uplift along the Sierra Madre fault is less in the study area than to the east and west. Other geologic factors, however, also influence the relative degree of fan-head incision. For example, the incision in the Arroyo Seco, was, at least in part, caused by drainage piracy near the foot of the fan. Nevertheless, one conclusion of this study, based primarily on other, nongeomorphic lines of evidence, is that the degree of activity along the Sierra Madre fault zone is less in this area than to the east and west; the geomorphic evidence supports this conclusion.

Within the study area, detailed examination of fan geomorphology reveals possible differences in present uplift rates. Starting at the west end in the Tujunga area (pl. 2.1), Fairchild aerial photographs taken in 1928 show that the fans at the mouths of Zachau, Haines, and Blanchard Canyons were actively building before human intervention. The fact that the more distal parts of these fans are composed of older unit 2 deposits suggests continuing uplift, at rates exceeding the rates of incision by the streams—a reasonable relation, as evidenced by the nearby 1971 San Fernando earthquake. It is unlikely that such fault features as scarps, lineaments, or depressions would last long in such depositionally active areas. Indeed, careful study of the 1928 aerial photographs fails to reveal any such features on the Zachau, Haines, or Blanchard fans except for a single lineament near the west edge of the Haines fan (loc. [2], pl. 2.1). Fans in this area are being built with geologic rapidity. Not only have some of the world's highest short-period rainfalls been recorded in the San Gabriel Mountains (for example, 66.34 cm in 24 hours in 1943, at Santa Anita Canyon), but also major floods occur here at far higher recurrence rates than do major earthquakes, as was locally demonstrated by the 1934 La Crescenta-Montrose flood (Chawner, 1934) and similar episodes in 1916 (McGlashan and Ebert, 1918), 1926 (Jahns, 1971), and 1938 (Troxell, 1942).

Eastward for the next 5 km, most fan surfaces are composed of unit 3 deposits except at Dunsmore and Shields Canyons; these two drainages have unit 2 deposits on the fan heads that are only slightly incised. These features suggest a lower degree of fault activity than in the Haines Canyon area, although the unit 2 deposits have been faulted, as shown in the trenches across the more prominent of the two scarps preserved on the Dunsmore fan (see fig. 2.6). This faulting is the youngest that has been documented along the Sierra Madre fault zone (in the study area) east of the 1971 breaks (pl. 2.1).

The Cooks, Shields, and Pickens unit 3 fan heads are deeply incised, and the area of active deposition here is on the lower parts of the fans, as demonstrated by the 1934 New Year's Day flood (Chawner, 1934). The presence on these fans of what appear to be scarps (locs.

[3—6], pl. 2.1) in varying states of degradation indicates displacement of unit 3. These facts suggest that in this area little, if any, faulting (uplift) has occurred since the beginning of Holocene time.

Still farther east, between Snover and Hay Canyons, the fan surface is underlain by unit 4. This surface is deeply incised by all but the smallest drainage, and, in addition, several drainages have eroded headward from the toe of the fan. Recent deposition mainly on the lower parts of the fan suggests local, relatively minor uplift associated with seismic activity since the deposition of unit 4.

The conclusion from the foregoing evidence is that the most recently active section of the Sierra Madre fault zone within the study area is in the Sunland-Tujunga segment, adjacent to the 1971 San Fernando earthquake zone. The interval since the last period of fault activity (uplift) appears to increase progressively eastward and is greatest in the La Cañada Section.

In the Pasadena-Altadena-Sierra Madre area, these criteria indicate relatively little seismic activity since the deposition of unit 3. In fact, there is little evidence that any but the older unit 3 has been faulted, as discussed below. East of the juncture of the Sierra Madre and Raymond fault zones, in the Monrovia Canyon-Bradbury area, the criteria indicate that faulting has taken place more recently here than west of the juncture, and the existence of the large unit 1 fan south of the Raymond fault in Arcadia strongly suggests recent and continued activity for this fault.



FIGURE 2.6.—Dunsmore Canyon and head of unit 2 Dunsmore fan, showing two distinct fault scarps (arrows). Several unit 2 terrace surfaces, visible on right (east) side of canyon above building probably correspond to segments of the fan surface separated by the fault scarps. Oblique aerial photograph courtesy of UCLA Spence collection.

LANDSLIDES

Landslides are common throughout the San Gabriel Mountains, particularly close to the range front, where the shattered and highly weathered rock is especially susceptible to mass movement. Most of the slides observed in the study area, however, appear to be shallow "skin" failures of only local extent, rather than large rotational blocks such as are present elsewhere in the range. No direct evidence of massive earthquake-triggered slides was observed, although numerous rock falls were seen to take place at the time of the 1971 San Fernando earthquake. A possible exception is the Henninger Flats landslide (Eaton Canyon area), which Saul (1976) suggested may have been triggered by a prehistoric earthquake. This particular slide is a highly complex feature of undetermined size and extent; one frontal fault cuts the base of the slide in Moist Canyon (loc. ④1, pl. 2.2). We do not anticipate that massive landsliding will be a major problem in the area of this study during future local earthquakes; instead, we expect that numerous shallow failures and rock slides will occur, somewhat analogous to those reported in the San Fernando area in 1971 (Morton, 1975).

An unusual but important form of landsliding along the mountain front occurs downhill from various segments of the Sierra Madre fault zone. These features, here termed "thrust-rooted slides," consist of highly fractured masses of crystalline basement rock that have moved downhill on slide planes effectively continuous with the thrust planes above and behind them, so that the slide-thrust surface takes on an antiform configuration. The slide mass is derived directly from the upthrown block of the thrust, so that there is no clear dividing line between the part of the mass that should be termed a slide and the part that represents the upthrown block. A somewhat similar phenomenon, on a much larger scale, was described along the Alpine fault of New Zealand by Wellman (1955). He mapped shallow nappe-like structures of Alpine schist overlying glacial moraines in front of the locally thrusted Alpine fault in the South Island. We suspect that there may be many more of these thrust-rooted slides along the front of the San Gabriel Mountains than have generally been recognized. Probably the best exposure of these slides in the study area is in Gould Canyon (see section below entitled "Sierra Madre Fault Zone").

SIERRA MADRE FAULT ZONE

REGIONAL STRUCTURAL PATTERN

The southern boundary of the Transverse Ranges tectonic province is characterized by east-west-trending structural elements that are strikingly anomalous within the otherwise northwest-trending structural grain of coastal California. The tectonic environment of the

province has been discussed by numerous workers (for example, Bailey and Jahns, 1954; Morton and Baird, 1975) and is not described further here except to emphasize that the reason for the anomalous trend is not well understood. This trend is probably related to the mechanics of the "great bend" of the San Andreas fault in southern California, although the Transverse Ranges extend considerably farther to the east and west than does the bent segment of the fault. The present regional stress system is, however, presumably dominated by the plate boundary represented in California by the northwest-trending San Andreas fault.

The San Gabriel Mountains constitute one of the principal tectonic blocks within the Transverse Ranges, bounded on the north by the San Andreas fault and on the south by the Sierra Madre fault zone. The steep south face of the range was recognized as a fault scarp early in the 20th century (Arnold and Strong, 1905; Mendenhall, 1908), but the delineation and naming of the bounding structure as the Sierra Madre fault was by Kew (1924). Kew and subsequent workers, including Davis (1927), interpreted the mountain front as due to normal faulting; however, Hill (1930) effectively demonstrated the dominant reverse or thrust nature of the faulting, at least in the western section near San Fernando. The most striking evidence for low-angle thrusting has come from major tunneling operations in the foothill area, as described by Proctor and others (1970), who also pointed out 11 specific exposures between Altadena and Glendora where crystalline rocks of the range front are thrust southward over Quaternary gravel lying at the base of the escarpment. The same relations were confirmed by the 1971 San Fernando earthquake, which was associated with a maximum of about 2.5 m of combined thrust and left-lateral surface displacements on faults having an average dip of about 40° N. (Kamb and others, 1971; Sharp, 1975).

Although rocks within the San Gabriel Mountains are as old as Precambrian and have a complex history (Ehligh, 1975), the present range is the result of tectonism that has occurred in coastal California throughout much of late Mesozoic and Cenozoic time. Some parts of the range were sufficiently elevated to have shed coarse detritus into adjacent basins during Oligocene time, although the principal uplift of the mountain block in its present configuration appears to have been an abrupt middle Pleistocene event (Oakeshott, 1958). On the basis of evidence from a deep well near San Fernando, the total post-Pliocene uplift on bounding members of the Sierra Madre fault zone may be about 4 km. Continuation of this uplift is indicated by numerous earthquakes in the area, including the 1971 event, as well as by geodetic observations (Castle and others, 1976).

Recognition many years ago that the Sierra Madre fault is by no means a single break (Miller, 1928; Eckis, 1934)

has led to some confusion in its nomenclature. Today, however, the term "Sierra Madre fault zone" is generally applied to the entire 100-km-long complex zone of mechanically related faults that grossly demarcate the base of the San Gabriel Mountains from San Fernando Pass on the west to Cajon Pass on the east; some workers (Proctor and Payne, 1972; Wesson and others, 1974) extend the zone of thrust faults farther west to include members of the Santa Susana fault system.

In contrast to the reconnaissance mapping carried out by earlier workers, detailed geologic mapping within the study area was recently carried out by Morton (1973) and Saul (1976) in the Mount Wilson and Azusa quadrangles. Although we have independently restudied the fault zone in these same areas, we have been greatly influenced by these earlier investigations.

In addition to pointing out the complexity of faulting at individual localities along the mountain front, several investigators have noted that the Sierra Madre fault zone appears to be segmented into a series of arcuate salients, convex toward the valley (for example, Proctor and others, 1972, fig. 1). Ehlig (1975) argued that each of these 15- to 25-km-long segments may have behaved as a structural unit, and he pointed to the association of the 1971 San Fernando earthquake with a single salient; he postulated that the maximum sizes of earthquakes elsewhere along the mountain front may be controlled by the dimensions of individual salients. We discuss the evidence for this view in the subsection below entitled "Fault Activity and Recurrence Interval Between Major Earthquakes."

DETAILED DESCRIPTION OF THE FAULT ZONE

Many places where direct evidence of faulted Quaternary alluvium can be demonstrated are shown on the geologic maps (pls. 2.1-2.4). In addition, 60 localities with indirect evidence of faulted alluvium are listed. The following sections describe the most noteworthy evidence and the localities where these features are most easily visible, from west to east.

BIG TUJUNGA TO GOULD CANYONS

Immediately east of the 1971 fault trace in Big Tujunga Canyon (Proctor and others, 1972; Barrows and others, 1975), the Sierra Madre fault zone begins one of its characteristic arcuate salients, convex toward the valley. The fault zone in this area is composed of at least two separate traces, which converge eastward in the vicinity of Haines Canyon. The northern trace skirts the east side of Big Tujunga Canyon, where it has displaced the surface of a unit 3 fan but has not cut the unit 2 fan to the north. The southern trace has cut the unit 2 Old Zachau fan (map and cross section A-A', pl. 2.1) and joins an east-

west-trending segment which moved during the 1971 earthquake, a relation implying that the southern trace is the presently active one.

The fault trace for the next 2 km eastward is inferred to be at the base of the break in slope. The geomorphic evidence for this inference—the truncated ridges and hanging drainages shown on the 1933 Fairchild aerial photographs (flight 2878)—is convincing, even though no actual fault traces are presently visible.

The fault is well exposed in the west wall of Cooks Canyon, where it dips 40° N. and thrusts diorite over alluvium (unit 3). A high scarp is visible just west of this exposure at the mouth of the canyon, and a lower scarp existed on the east side of the canyon before grading for homes obscured it.

Two distinct fault scarps, one 4 and the other 2 m high, were visible on the unit 2 Dunsmore fan before spring 1978 (fig. 2.6). The more southerly, more prominent of the two was trenched and logged (fig. 2.5) in January 1978; the scarps were subsequently buried by debris hauled from local debris basins. This locality is the east limit for confirmed Holocene faulting on the Sierra Madre fault zone within the study area.

Between Dunsmore and Pickens Canyons, a distance of 2.7 km, the fault trace is inferred both from the present geomorphology and from its appearance before development. Both Shields and Pickens fans appear to have scarps in unit 3 alluvium. A second trace to the south is postulated across Shields fan on the basis of an exposure of crystalline basement; however, this outcrop may be part of the shallow rock ridge shown by the California Water Rights Board (1961) south of the fault.

Unit 3 alluvium was seen to be faulted in three places in Pickens Canyon. The northernmost locality (loc. ⑧, pl. 2.1) has a 4-m vertical offset of the basement-alluvium contact; the other two traces have displacements exceeding the 7-m height of the exposures. The total displacement of unit 3 is unknown but must exceed 18 m of vertical slip.

At least 10 additional exposures of the Sierra Madre fault zone between Snover Canyon and the Arroyo Seco involve thrusting of crystalline basement over the oldest alluvium (unit 4). Multiple traces are inferred near Snover and Winery Canyons and just east of Hay Canyon on the basis of scarp-like features, in addition to the exposed traces.

On the west side of Hall Beckley Canyon the upper plate of the thrust fault is seen as a lobe draped over the nose of a ridge. Gravitational forces have caused the distal edge of the lobe to dip downhill to the southeast. Two features similar to this thrust-rooted slide (see subsection entitled "Landslides" in preceding section) are found in Gould Canyon and are described below.

At Winery Dam, basement rocks are clearly thrust over unit 4; however, just 250 m west the contact is deposi-

tional. This is one of the few places in La Cañada where the observed unit 4-basement contact is not a fault.

In the unnamed canyon between Hay and Gould Canyons, just east of Haskell Street (loc. ⑯, pl. 2.1), diorite is thrust over unit 4, as was noted during grading operations in 1964. To the west, the same fault can be seen in the Haskell Street cut, totally within basement rocks.

Just west of Gould Canyon, the Sierra Madre fault zone splits into two separate traces. The northern trace swings northeastward into the mountains and forms the east end of the Tujunga-La Cañada salient; the southern trace swings southeastward and forms the beginning of the Arroyo Seco-to-Santa Anita Canyon salient.

The Gould Canyon thrust fault, here named, is the best exposed and best studied example of a thrust-rooted slide. Immediately north and west of Lone Grove Way in Gould Canyon, diorite can be seen overlying unit 4 and unit 3 alluvium. Here, the contact dips 15°–25° S. toward the valley. Traced northward, the fault surface can be seen to level off; 400 m farther upcanyon, it dips sharply 20°–30° N., still with diorite over unit 4 (cross section *B-B'*, pl. 2.1).

In 1969, heavy rains caused reactivation of part of the south-dipping gravity part of the thrust plate. A bucket-auger borehole was drilled by private consultants through the projected slide plane between the Southern California Edison Co. transmission towers. The borehole log revealed 16 m of diorite overlying old alluvium, separated by 3 cm of gouge. Mapping during the present study revealed that the "slide" is part of the upper plate of a major thrust, of which two distinct lobes form the ridges on either side of Gould Canyon. The feature is well exposed along the Southern California Edison Co.'s access road on the west side of the canyon.

The main thrust can be traced northward to Aqua Canyon, where the fault is exposed in a roadcut on the Angeles Crest Highway. Here, basement overlies unit 3 alluvium along a 35°-N. dipping plane. The fault was traced eastward into the Arroyo Seco, where it cuts only basement rocks.

GOULD CANYON TO ARROYO SECO

The Gould Canyon-Arroyo Seco area is cut by several east-west-trending north-dipping faults between the frontal fault at the mouth of the Arroyo Seco and the Gould Canyon thrust fault, 2 km north. Considerable attention has been given to the area of JPL in northwesternmost Pasadena, west of the Arroyo Seco (fig. 2.7, pls. 2.1, 2.6) because the present study coincided with an independent review of local seismic hazards by JPL itself, so that parts of these two studies were meshed. In particular, we had access to information derived from boreholes drilled

to determine the local subsurface fault geometry, and we assisted in locating additional boreholes. In addition, we excavated four trenches in the area and participated in examining other excavations. As a result, more is known about the subsurface geometry of the Sierra Madre fault zone in the vicinity of JPL than at any other locality along the mountain front.

During excavation in 1971 for a bridge across the Arroyo Seco adjacent to JPL, a fault was revealed that appeared to thrust crystalline basement southward over Holocene stream alluvium, with a postalluvium throw of at least 10 m (Converse Consultants, written commun., 1971). This fault, here termed the "Bridge fault" of the Sierra Madre fault zone, projected along the base of the steep escarpment through JPL and appeared to be one member, if not the major member, of the Sierra Madre fault zone in this area.

As part of the present study, the Bridge fault was again trenched in about the same place (loc. ⑭, pls. 2.2, 2.6). Although the search for datable materials in the trench walls was unsuccessful, the fault geometry was apparent, and it became clear that the gravel beneath the thrust is not Holocene alluvium but the older more consolidated unit 3 alluvium. Natural but poor exposures of the same fault are visible on the terrace riser to the east (loc. ⑮, pls. 2.2, 2.6), and trench 9, excavated by Le Roy Crandall & Associates 200 m southwest (loc. ⑯, pls. 2.1, 2.7; fig. 2.8) revealed a similar thrust relation. An additional 150 m of trench was excavated in unit 2 deposits of the small fan underlying the facility between trench 9 and borehole 4 in an attempt to ascertain whether or not faulting has occurred on the Bridge fault since the beginning of Holocene time. The trenches (21A, 21B, 21C) were located on the projected strike of the fault (pl. 2.6), but no evidence was found to indicate that the unit 2 deposits had been faulted. One other exposure within the JPL property, showing basement rocks thrust over Quaternary gravel, is visible north of Building 150 (loc. ⑰, pls. 2.1, 2.6), but it was uncertain whether this fault represented the main break, inasmuch as it strikes into the mountain front rather than along its base. As a result of these and other concerns about the precise positions of fault traces throughout the JPL property, 14 boreholes were drilled, 5 of which penetrated the fault plane. The fault traces shown on the geologic map of the area (pl. 2.6) are based on the resulting borehole data, together with information on surface exposures.

The cross sections based on the surface and borehole data (pl. 2.6) are generally self-explanatory in demonstrating the fault geometry. Of particular interest is cross section *C-C'* because not only is the attitude of the fault well documented by the two boreholes that penetrate it (and one that must barely "miss"), but also a throw of at least 244 m is indicated by borehole 4, which penetrated

244 m of gravel without reaching basement. Clearly the fault is not minor.

From the many exposures and boreholes within the JPL area, it appears that the fault zone consistently dips about 45° N. and crops out near the base of the escarpment. No conclusions can be drawn concerning possible changes of dip with depth. In the western part of the property, the Bridge fault splits into at least three branches, although the southernmost trace shown on the geologic map (pl. 2.6) is inferred entirely from the topography. In interpreting this map, it should be borne in mind that the

dotted lines represent extrapolated traces at the ground surface, but in some areas the control is so poor that the actual trace could be as much as 100 m from the dotted trace shown. The three branches probably reconverge to the northwest and form a single trace that bounds the west side of Gould Mesa.

Gould Mesa is the most conspicuous remnant of the once-extensive unit 4 fan formed by the Arroyo Seco. It is now bounded on the north, west, and south by branches of the Sierra Madre fault zone. The southern or Bridge fault branch has displaced the fan surface approximately



FIGURE 2.7.—Arroyo Seco and site of JPL in 1934. Bridge fault (BF) is exposed in bluff just east of bridge at mouth of canyon; borehole data indicate that fault trace is north of road west of trench 9 (pl. 2.6), near second bush along road west of bridge, which also exposed fault. Unit 2 fan deposits (Qal₂f) have not been faulted. Geologic and geomorphic evidence suggests that main branch of fault crosses west end of road and bends sharply northwestward. Two unit 4 fan surfaces (Qal₄f) were once con-

tinuous; unit 3 and unit 4 fan surfaces (Qal₃f and Qal₄f, respectively) at lower right are separated by a fault scarp (loc. 20, pl. 2.2). Qal₁, unit 1 alluvium. Note thrust-rooted slides (arrows) of Gould Canyon thrust fault (GCT) in upper left corner. Fault lines solid where location certain; dashed where approximately located; dotted where concealed. Oblique aerial photograph courtesy of UCLA Spence collection.

220 m vertically, on the basis of "red clay" encountered at depth in water wells south of the fault. The discrepancy between this displacement and the minimum of 244 m given previously can be explained by faulting contemporaneous with deposition.

A second fault (loc. ②1, pl. 2.1) approximately 760 m north of the Bridge fault has offset the Gould mesa surface approximately 30 m vertically, north side up. This fault can be traced through the unit 4 alluvial deposits and exhibits associated sedimentary features which suggest that faulting was contemporaneous with deposition.

The fault mapped on the north side of Paradise Canyon appears to have displaced the mesa surface vertically an additional 30 m. The total offset is difficult to estimate here, because the unit 4 alluvium north of the fault has been removed by erosion.

The northernmost branch of the Sierra Madre fault zone in this area is the eastward extension of the Gould Canyon thrust fault. The probable minimum throw of this fault, 300 m, suggests a total of more than 660 m for this series of faults (cross section *B-B'*, pl. 2.1).

ARROYO SECO TO CHIQUITA CANYON

None of the faults just described can be traced more than a few hundred meters east of the Arroyo Seco. The Bridge fault appears to have formed a small scarp (loc. ⑯3, pl. 2.2) on the Altadena fan surface northwest of Audubon School. It then is inferred to trend along, and possibly be the contact between, the Altadena fan unit 3 and the older La Vina surface unit 4 north of Loma Alta Drive. Two more scarps are visible just west of Lincoln Avenue and north of Loma Alta Drive (loc. ⑯29, pl. 2.2).

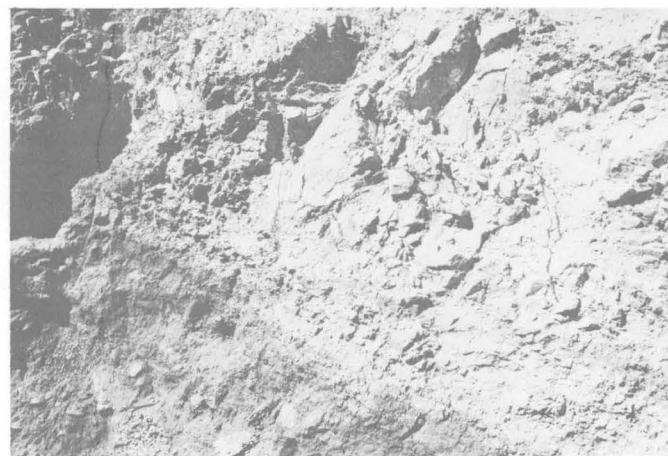


FIGURE 2.8.—Exposure of a thrust fault in trench 9 at JPL, showing light-colored granitic rocks thrust over unit 3 alluvium. Note weathering of several clasts in unit 3 that were broken off by the backhoe. Fault is overlain by unfaultered colluvial deposits, visible in upper left corner. Field of view, approximately 2 m square. Photograph courtesy of JPL.

The northernmost scarp appears to be the contact between units 3 and 4 and probably marks the trace of a significant fault, but it cannot be traced westward into the Arroyo Seco. Eastward, it probably converges with the Bridge fault.

Near the north boundary of the La Vina Sanitarium, another east-west-trending branch of the Sierra Madre fault zone appears near, or becomes the contact between, basement rocks and the unit 4 La Vina surface (loc. ⑯30, pl. 2.2). Here, diorite is thrust over unit 4 alluvium; the fault dips 23°–30° N. Displacement on this branch is probably small, because the depositional contact between unit 4 and basement rocks is seen in close proximity on both the hanging wall and the footwall. Furthermore, the fault cannot be traced for a distance of more than 1 km, even though excellent exposures occur in Millard Canyon to the west and along the Chaney Trail to the east.

CHIQUITA CANYON TO EATON CANYON

In the vicinity of Camp Chiquita in Altadena (northwest corner, pl. 2.2), the Vasquez Creek fault zone (Miller, 1928; Jahns and Proctor, 1975), which is a branch of the San Gabriel fault, and the Sierra Madre fault zone merge in a complex zone of anastomosing faults, 0.6 to 1.2 km wide. Traces of this combined zone can be followed to the Rubio-Eaton Canyons area and, possibly, for another 4.8 km still farther east. This merging of zones is indicated by the presence of the Rubio Diorite, which occurs as long dikelike features, xenoliths, and fault slivers in and along the Vasquez Creek fault zone. Most of these bodies have a northwestward strike and a steep northerly to vertical dip. In the complexly faulted Eaton Canyon area (center, pl. 2.2), the Vasquez Creek fault zone appears to die out, and the Rubio Diorite becomes associated with the frontal-fault system. The outcrop pattern indicates a change in attitude to a shallow northward dip subparallel to the thrust faults of the Sierra Madre fault zone. This change in attitude, also suggested by the gneiss-diorite contact northeast of the Kinneloa fan, may indicate that stresses in the crystalline basement have been relieved in part by folding. Such folding must have occurred early in the fault history of the Sierra Madre fault zone because unit 4 deposits in the area are not similarly folded.

Near the mouth of Chiquita Canyon (north of Altadena), the frontal fault swings abruptly from a northeastward to a southeastward trend and parallels the Vasquez Creek fault zone to the north. The frontal fault is well exposed for about 460 m from near the top of Cañon Boulevard northward to where it appears to merge with one of the traces of the Vasquez Creek fault zone. The trace is highly sinuous as it winds in and out of several local drainages; the fault dips 13°–15° N. Basement rock is thrust over unit 4 alluvium and is highly crushed and weathered as

far as 10 m above the fault plane. Here, a small spur fault from this trace thrusts alluvium over basement—the only place where this condition was observed in the entire study area.

From the Arp property southeastward to Rubio Canyon, the frontal fault is nowhere exposed and, therefore, has been projected along the toe of the slope as a buried trace; a considerable amount of grading and natural alluviation have obliterated the surface trace in this area. A seismic-refraction survey was carried out near the top of Lake Avenue in an attempt to locate the projected main frontal fault. Seismic lines totaling 180 m were run transverse to the projected fault trace on the fan surface on the west side of Las Flores Canyon (Cobb estate). The absence, to a depth of 30 m, of anomalous conditions suggestive of faulting indicates either that the fault is deeply buried or that there is little or no velocity contrast between the rock and (or) soil materials presumably displaced by the fault. Another possibility is that the fault trace is more than 90 m north or south of the projected trace.

Near the Las Flores debris basin, the frontal fault bifurcates. One trace continues southeastward along the main break in slope of the mountain front, where basement has been thrust over unit 4 alluvium along a plane dipping 18° – 40° N.; the other trace is inferred to bound the low basement outlier between Rubio and Gooseberry Dams, and then swing southeastward to Eaton Canyon. A bore-hole near the intersection of Allen Avenue and Altadena Drive penetrated basement rocks at a depth of 42 m; this observation suggests that, owing to the shallow depth of bedrock, the fault trace lies south of this site. Outcrops of gneiss exposed on either side of Eaton Canyon (pl. 2.2) suggest that the fault probably lies to the south. Additional evidence for this fault is provided by the log of a recently drilled Pasadena Water Department well (C-115; see pl. 2.2) in Eaton Canyon, which indicates basement rock between depths of 10 and 24 m, in turn underlain by alluvial sand and gravel.

EATON CANYON TO PASADENA GLEN

In the Eaton Canyon area, the high-angle nearly linear faults of the Vasquez Creek fault zone give way to the low-angle sinuous thrust faults of the Sierra Madre fault zone. Here, a series of five thrust faults are exposed that provide evidence suggesting a trend of progressively younger faulting from south to north. The three southernmost faults have thrust diorite and gneiss over unit 4 alluvium, units 4 and 3, and unit 3, respectively, from south to north (map and cross section $C-C'$, pl. 2.2). This series of faults cannot be traced laterally owing to the presence of artificial fill and younger alluviation, but they

may be manifested eastward by two low scarps on the Kinneloa fan. The fourth fault can be traced nearly continuously from Eaton Canyon, where unit 3 alluvium is faulted, eastward to Hastings Canyon, where unit 4 alluvium is faulted. The fifth trace is entirely within crystalline basement except that it has faulted the basal part of a large landslide that overlies unit 3 deposits 150 m to the south (cross section $C-C'$, pl. 2.2). To the west this fault can be traced to the mouth of Eaton Canyon, where it has thrust quartz monzonite over unit 3 alluvium, as exposed in trench 3, but appears not to have faulted unit 2 alluvium, as exposed in trench 3A. This fault can be traced only a short distance to the east, where it appears to die out in a splay of several faults in Pasadena Glen.

Minimum vertical displacement on the low-angle faults is approximately 152 m, as estimated from the displacement of the base of unit 4. Minimum displacement on the basement trace is unknown but may be 30 m, on the basis of the offset of the nearly horizontal diorite-gneiss contact north of the Kinneloa West Debris Dam.

Most of the movement on these faults probably occurred before deposition of the upper part of unit 3 alluvium because the Altadena fan surface adjacent to Eaton Canyon does not appear deformed or disrupted, and the correlative fan surface across Eaton Canyon has the same elevation. In addition, the fault exposed in trench 3 cannot be traced upward through unit 3 alluvium, and there is no offset of the fan surface to correspond to a projected trace.

Saul (1976) showed most of this area (south of Henninger Flats landslide, pl. 2.2) as the "Henninger Flats landslide complex," with its head in upper Eaton Canyon and its toe buried by unit 1 alluvium in Eaton Canyon. In our opinion, it is unlikely that this slide either is so extensive or is rotational, as shown in his cross section $B-B'$. The Rubio Diorite associated with the low-angle faults retains its structural continuity through this area, and the units 3 and 4 alluviums contained within this supposed complex have not been rotated but, instead, retain the original shallow southward dip.

PASADENA GLEN TO BAILEY CANYON

In this segment, the Sierra Madre fault zone consists of several separate traces—two low-angle thrusts involving alluvial units that lie at the base of the mountain front, and two high-angle faults to the north within the basement complex. The two low-angle thrusts are nearly parallel and less than 100 m apart (fig. 2.9). The upper fault thrusts gneiss over unit 4 alluvium and can be traced nearly continuously from the Eaton Canyon area to the Sunnyside debris basin, where it becomes much steeper

and more complex. The lower trace is not nearly so well defined. It is exposed at the surface in two localities separating diorite from unit 4 alluvium and was exposed

at two localities in CIT trenches 20A, 20B, and 20C, where it was seen to have disrupted colluvium overlying unit 4. The fault could not be traced into the valley fill, which

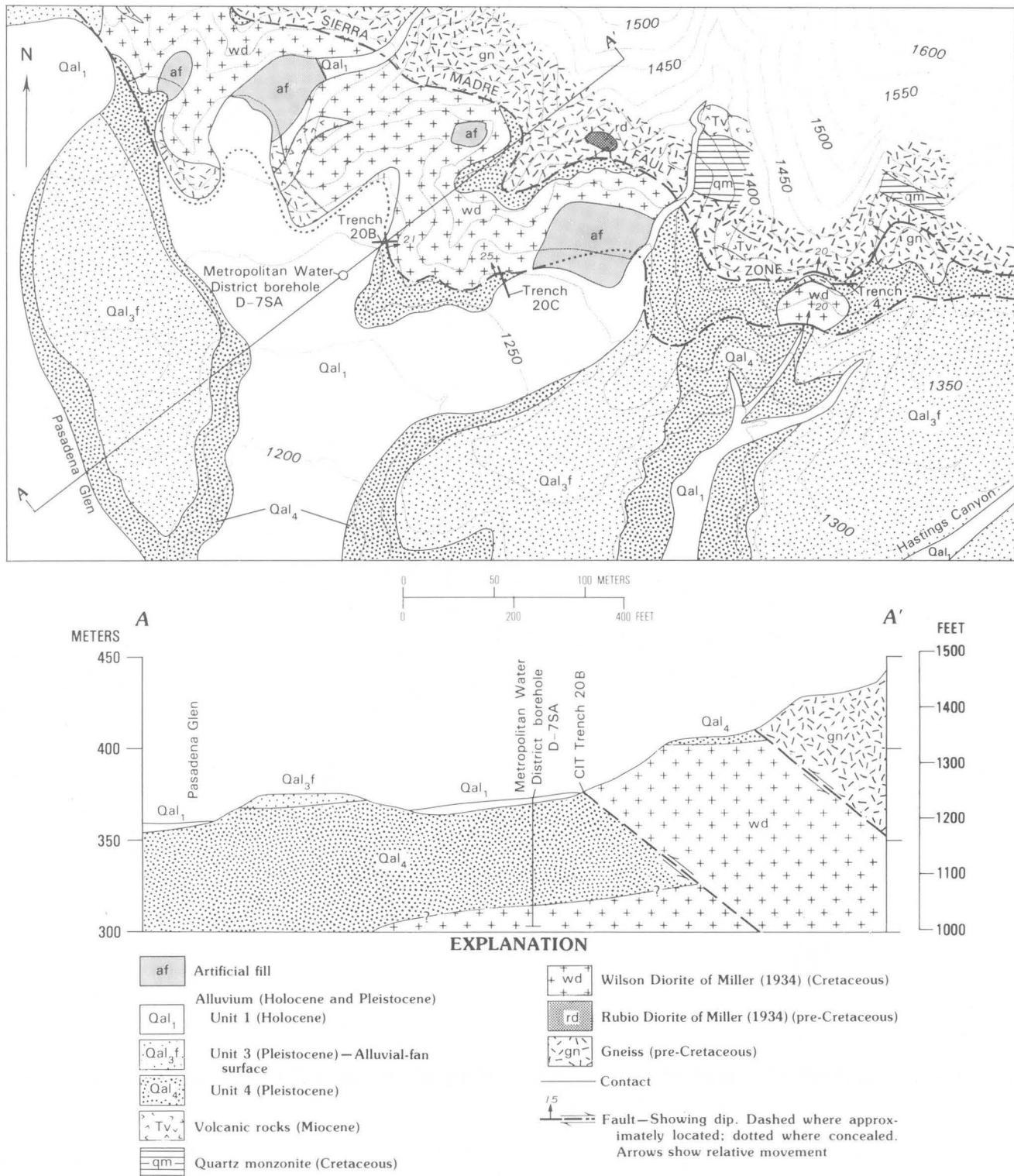


FIGURE 2.9.—Detailed geologic map and cross section of Pasadena Glen-Hastings Canyon area, showing traces of two thrust faults and locations of CIT trenches 20B and 20C (see fig. 2.10 for cross section of trench 20C and pl. 2.2 for locations).

is probably unit 2 alluvium. In trench 20C, the fault is overlain by 0.6 m of unfaulted bedded silty sand with a Holocene soil (fig. 2.10). This unit contained an in-place root that yielded a ^{14}C age of $2,200 \pm 80$ yr B.P.

The lower fault could not be traced into Pasadena Glen or Hastings Canyon, although it must have moved recently enough to have cut the Kinneloa fan surface (loc. 19, pl. 2.2), as indicated by the fact that the faulted colluvium is younger than the incision of unit 3 surfaces. The sides of the incised channel are mantled by the faulted colluvium.

The positions of the two high-angle faults in most of this reach are inferred from two series of aligned canyons and notches in ridges. The lower fault is exposed in Bailey

Canyon, and further evidence is provided by the patches of unit 4 alluvium high on a ridge on the east side of the canyon.

In this area, a minimum total vertical displacement of approximately 330 m has occurred since deposition of unit 4—210 m along the high-angle fault in the basement and 120 m along the thrust faults. This conclusion is based on displacement of the unit 4 alluvium-basement depositional contact.

Both Pasadena Glen and Hastings Canyon contain mutually exclusive, distinctive rock types in outcrop—the Lowe Granodiorite in Pasadena Glen and porphyritic andesite in Hastings Canyon. This unique feature allows a distinction between alluvial deposits from each of the

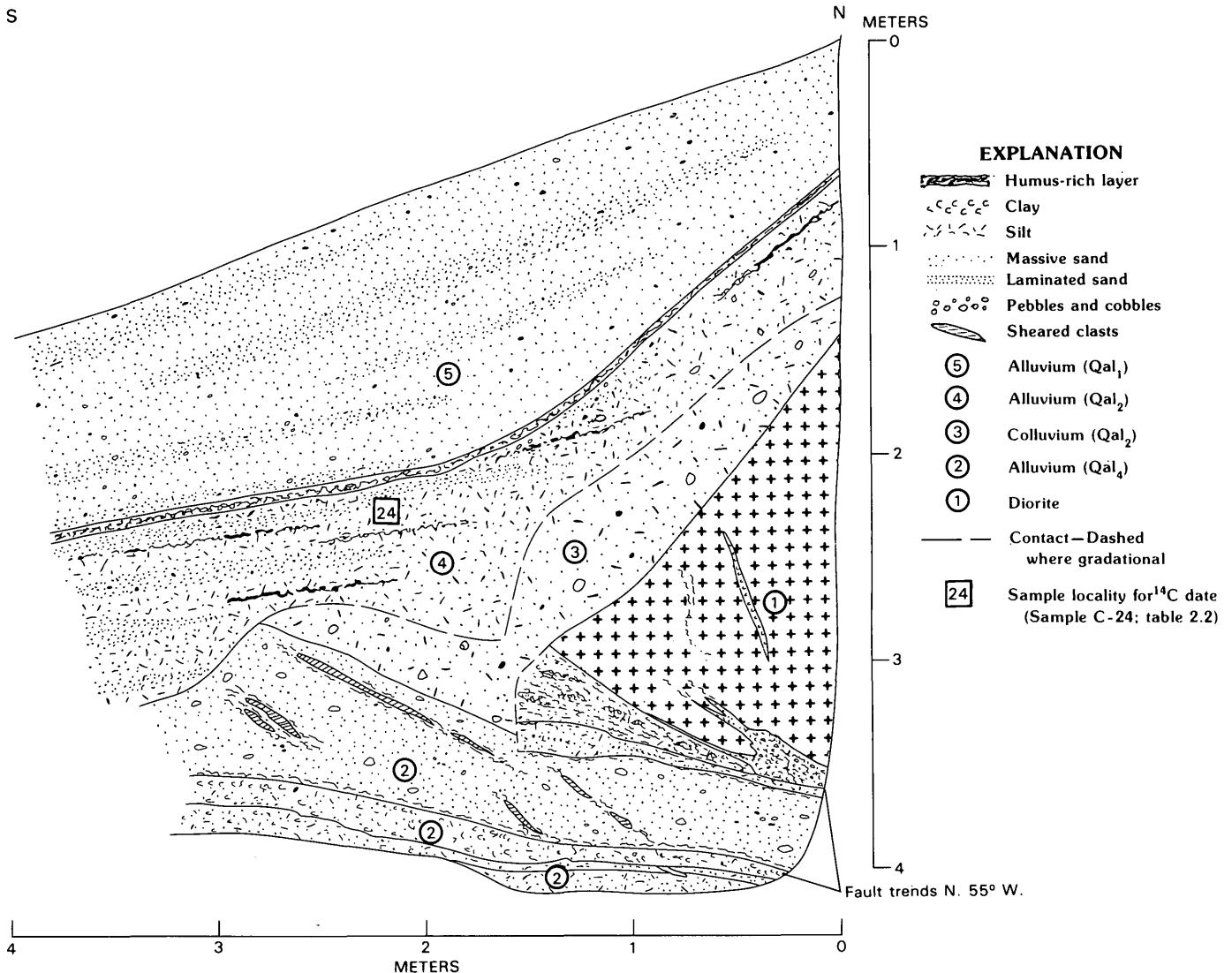


FIGURE 2.10.—Log of west wall of CIT trench 20C (bearing, N. 23° E.) in Pasadena Glen, Pasadena, showing a branch of Sierra Madre fault (see fig. 2.9 for location).

two adjacent drainages. Thus, left-lateral offset of these distinctive unit 4 deposits cannot be more than 1.2 km from their source drainage.

BAILEY CANYON TO SANTA ANITA CANYON

Between Bailey Canyon and Santa Anita Canyon, evidence for faulting along the mountain front is only suggestive. Aligned notches in ridges indicate two high-angle faults in the basement, one of which is exposed behind the Carter Dam; Buwalda (1940, p. 35) mentioned a steep fault with "ancient alluvium" (unit 4) against diorite in the vicinity of the high-angle fault north of the Sturtevant Dam. A thrust fault is postulated at the base of the scarplike feature between the Sierra Madre and Lannan fans. The upthrown block consists of units 3 and 4 deposits resting on crystalline basement; minimum vertical displacement of the unit 3 deposits across this trace is 20 m.

SANTA ANITA CANYON TO MONROVIA CANYON

At Santa Anita Canyon, the Sierra Madre fault zone enters what is here called the Monrovia outlier, where it becomes the most complex system of frontal faults in the study area (map and cross section *D-D'*, pl. 2.3). Part of the system branches off to the northeast as the Clamshell-Sawpit fault zone (Morton, 1973), whereas the rest of the system continues easterly across the outlier to emerge at the mouth of Monrovia Canyon. To further complicate the

picture, the Raymond fault joins the Sierra Madre fault zone at the southeast corner of the outlier.

At the west side of Arcadia Wilderness Park (loc. 48, pl. 2.2) is one of the most impressive exposures of a thrust fault in the Sierra Madre fault zone (fig. 2.11). Banded gneiss is thrust over the large-boulder facies of unit 3 alluvium. This fault consists of several feet of gouge and crushed rock generated from the gneiss. The fault cannot be traced into the upper part of the unit 3 alluvium and probably has been inactive since the faulted part was deposited. The fault continues to the northeast and becomes part of the Clamshell-Sawpit fault zone.

Numerous east-west-trending north-dipping thrust faults cross the central part of the Monrovia outlier. Many of these faults were seen in the Metropolitan Water District's water tunnel, but because of the heavy cover of chapparal and poison oak in this area, surface continuity of these traces was not proved. They clearly do not cut the unit 4 remnants, nor do they appear to have displaced them vertically relative to each other. One of the thrust faults, exposed in Ruby Canyon (loc. 51, pl. 2.3; fig. 2.12), is visibly overlain by unfaulted unit 4 alluvium. In Monrovia Canyon (loc. 52, pl. 2.3), faulting has displaced Quaternary deposits; here, quartz monzonite has been thrust over the large-boulder facies of unit 3 alluvium. Morton (1973) showed the San Dimas Formation (equivalent to our unit 4) as faulted against basement 0.8 km northwest of Ruby Dam. Closer examination indicates, however, that the faulted material is the Saugus Formation, which has steep dips, and that the fault appears to be overlain by nearly flat-lying unit 4 deposits that make up the Alta Vista fan.

Whereas faulting within the outlier appears to have preceded the deposition of alluvial unit 4, the elevations of the unit 4 remnants suggest a subsequent uplift of the entire block and northward tilting by as much as 2°. This tilting is also indicated by gentle northward dips in some of the deposits.

MONROVIA CANYON TO SAN GABRIEL CANYON

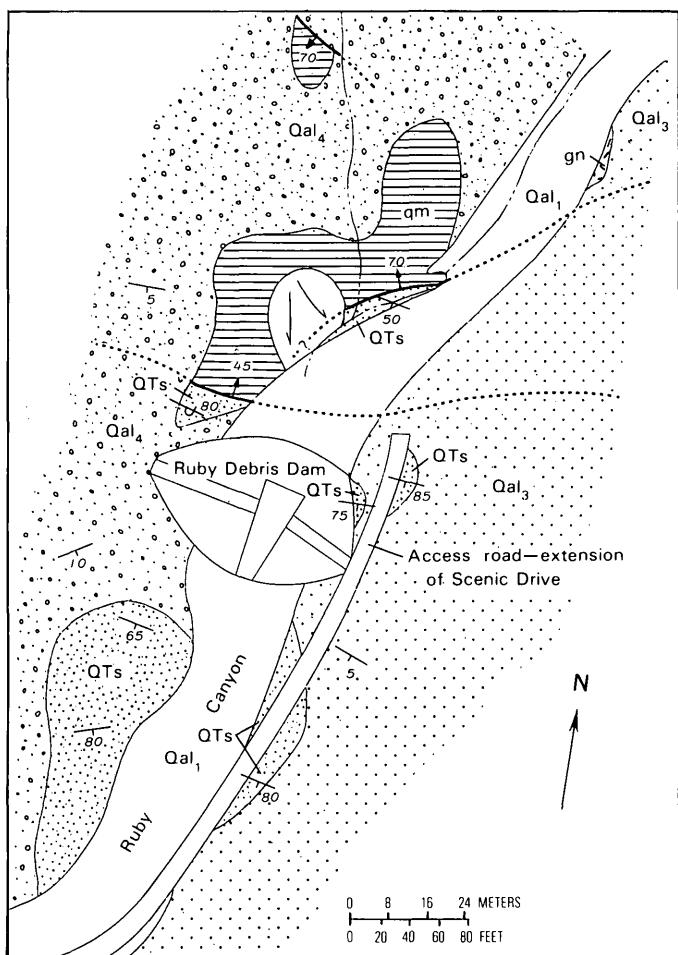
East of Monrovia Canyon and throughout the Bradbury area, the Sierra Madre fault zone appears simpler than to the west in terms of the number of fault traces, but more complex in terms of the number and age of sedimentary units involved. Exposures are insufficient to allow a completely satisfactory explanation for the complex relations between the folded and faulted units, and we can make only broad generalizations concerning the history of faulting in this area.

Evidence for the earliest faulting and deformation along the Sierra Madre fault zone within the study area is found here. Exposures of the Miocene Topanga Formation southeast of the Spinks Dam (pl. 2.3) show that the



FIGURE 2.11.—Thrust fault exposed in Arcadia Wilderness Park. Fault surface is just below man's arms. Photograph courtesy of Metropolitan Water District of Southern California.

Topanga Formation was already highly deformed before deposition of the Pliocene(?) Duarte Conglomerate. An



EXPLANATION

| | |
|--|--|
| | Unit 1 alluvium (Holocene) |
| | Unit 3 alluvium (Pleistocene) |
| | Unit 4 alluvium (Pleistocene) |
| | Saugus (?) Formation (Pleistocene and Pliocene) |
| | Quartz monzonite (Cretaceous) |
| | Gneiss (pre-Cretaceous) |
| | Contact—Approximately located |
| | Fault—Showing direction of dip. Dotted where concealed; queried where doubtful |
| | Strike and dip of beds |
| | Strike and dip of overturned beds |
| | Landslide—Showing direction of movement |

FIGURE 2.12.—Geologic map of Ruby Debris Dam area, Monrovia, showing an old branch of Sierra Madre fault. Unfaulted unit 4 alluvium of Alta Vista surface overlies faulted crystalline basement and the Saugus (?) Formation (see pl. 2.3 for location).

angular discordance of 110° can be seen here between the south-dipping Duarte Conglomerate and the overturned north-dipping Topanga Formation. Just west of the Bradbury Dam (fig. 2.13), two exposures of the contact between the Duarte and the Topanga can be seen—one is a fault contact, and the other a conformable depositional contact. These relations, in addition to the fact that the two units are everywhere dipping at moderate to high angles, indicate continued faulting and folding along this zone up to the time of deposition of unit 4 alluvium, as substantiated by the tilting of the Pliocene and Pleistocene Saugus (?) Formation in Monrovia Canyon and the steep dips on the Saugus Formation beneath nearly flat-lying unit 4 deposits in Ruby Canyon.

The great discordance between the Topanga Formation and the Duarte Conglomerate raises an interesting question concerning the Sierra Madre fault zone in this area. Jahns (1973) suggested that the ancestral right-lateral San Gabriel fault was active in this area, as the deformed Tertiary sediment may indicate. The common occurrence of calc-silicate units and marble beds in gneiss in the Monrovia outlier and in the Fish Canyon area may also indicate right-lateral displacement, as do the fault-bounded slivers of the Duarte Conglomerate near Monrovia Canyon that were derived from the San Gabriel River drainage. The Sierra Madre fault zone has subsequently become active in this zone of weakness.

There is little evidence for faulting on the northernmost fault trace in the Bradbury area since the deposition of unit 4 alluvium. The surface of the Older Spinks fan has not been faulted, although it does appear to have been warped slightly upward in the vicinity of the buried fault. To the northwest, deformation of unit 4 alluvium becomes progressively greater, as evidenced by the steepening dips, but the age of these deposits is believed to increase in this direction, and they probably grade into the Saugus(?) Formation that underlies unit 4 alluvium in Ruby Canyon.

Two fault exposures near the mouth of Monrovia Canyon (loc. 52, 54, pl. 2.3) appear to contradict the idea of minor post-unit-4-alluvium movement on the northern fault trace. Movement here may occur sympathetically with that on the Duarte and Raymond faults in a manner similar to that of the Veterans fault and the main fault zone in the 1971 San Fernando earthquake (Kamb and others, 1971).

The most recent faulting in this area has occurred along the Duarte fault, since deposition of unit 3 alluvium (California Department of Water Resources, 1966), perhaps as recently as the youngest unit 2 alluvium. A scarplike feature on the older Monrovia fan and a lineament seen on aerial photographs south of Bradbury (locs. 24, 25, pl. 2.3) indicate that the unit 2 fan surfaces may be faulted. Also, two small unit 1 alluvial fans at the mouths of Bradbury and Spinks Canyon suggest relatively recent uplift.

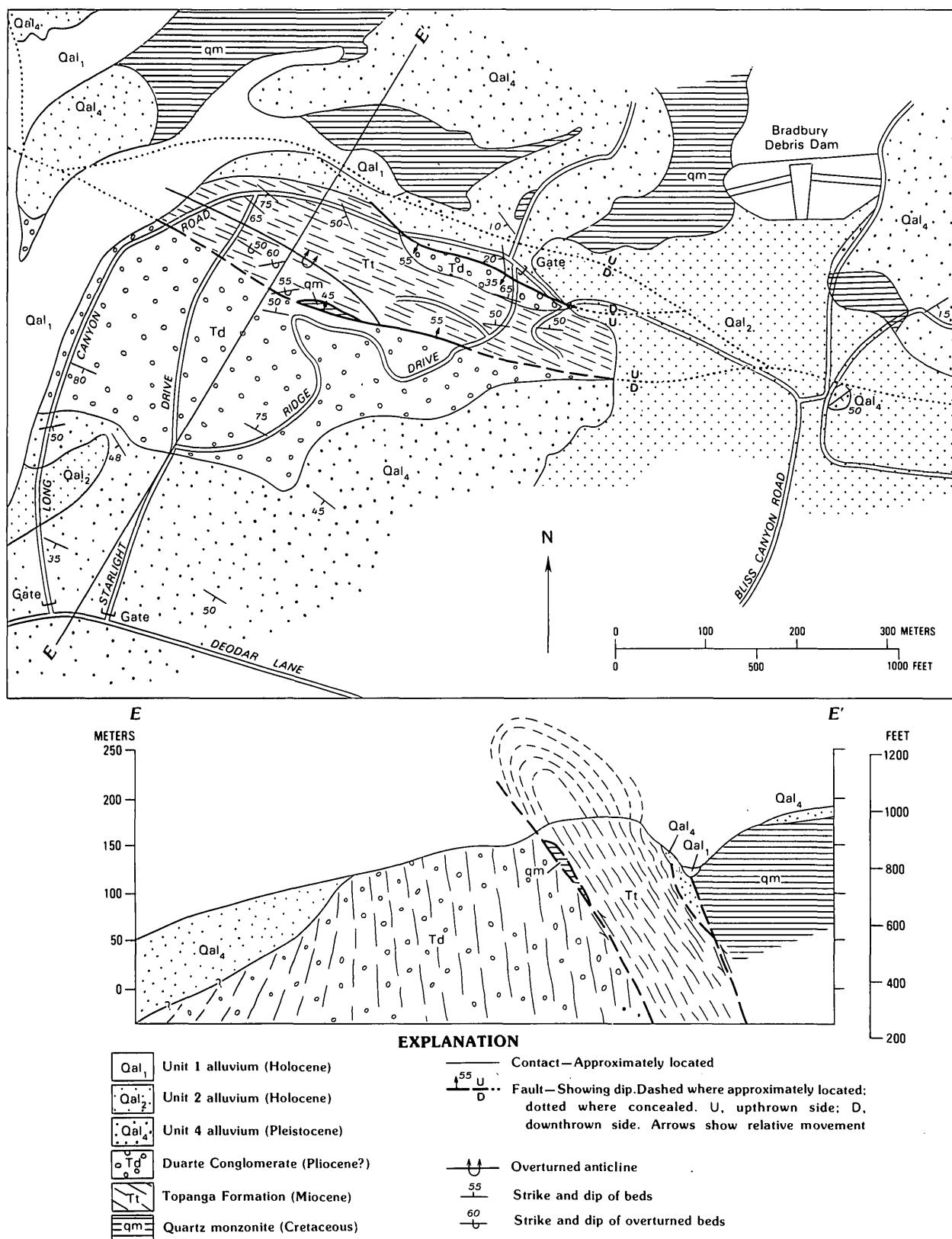


FIGURE 2.13.—Geologic map and cross section of Bradbury Dam area, Bradbury, showing complexity of faulting in upper branch of Sierra Madre fault zone. The highly deformed Topanga Formation is overlain by and faulted against the Duarte

Conglomerate, which, in turn, is somewhat less deformed and is overlain by still less deformed unit 4 alluvium, which is also faulted. These relations suggest that faulting here was nearly continuous from at least Pliocene through late Quaternary time.

Although the Duarte fault trace is not exposed, its topographic expression is evident in the Bradbury area as a mesalike feature north of Foothill Boulevard, where a minimum vertical displacement of 60 m is indicated, assuming that the analog of the unit 4 surface on the mesa top lies just below the surface south of the fault.

AZUSA AREA

East of Bradbury, the Sierra Madre fault zone is inferred to split into at least three separate traces, mainly on the basis of geophysical surveys and water-level data. Seismic-refraction and magnetometer surveys carried out by several private consulting firms (Envicom Corp., Evans-Goffman and McCormick, Leighton & Associates, Inc., and Le Roy Crandall & Associates) indicate anomalies in several localities that are interpreted as faults (locs. [30], [32]-[34], pl. 2.3).

A small scarp on the lower part of the Maddock fan and a lineament formed by vegetation observed on a 1928 aerial photograph in the Holocene San Gabriel River gravels (locs. [27], [31], pl. 2.3) seem to substantiate one of these traces. Anomalous ground-water levels in numerous water wells in the Azusa fan indicate ground-water barriers that coincide with the faults inferred from the geophysical data. Although the age of faulting cannot be determined from these data, the scarp, vegetation lineament, and ground-water levels only 2 to 3 m below the surface (loc. [36], pl. 2.3) in the eastern part of the city of Azusa suggest that Holocene sediment has been faulted.

Trenches 13 and 13A (table 2; see supplementary section below entitled "Trenching") along the upper trace of the Sierra Madre fault zone between Maddock and Van Tassel Canyons (loc. [32], pl. 2.3) indicate that movement along this trace has not occurred since the upper 4 m of alluvium was deposited.

FAULT ACTIVITY AND RECURRENCE INTERVAL BETWEEN MAJOR EARTHQUAKES.

The 1971 San Fernando earthquake dramatically illustrated that for at least a part of the Sierra Madre fault zone, the seismic hazard is far from negligible. However, the extent to which the same degree of activity extends eastward into the area of this study is subject to debate because, although the fault system as a whole extends along the entire 100-km-long mountain front, it is not clear that all parts of the frontal fault necessarily have the same extent of late Quaternary displacement. Many workers have pointed out that abrupt fault scarps in alluvium are not obvious along the mountain front in the Pasadena-Azusa area except along the Raymond fault (discussed in the next section below), although most of the foothill area has been urbanized to such an extent that diagnostic

physiographic features might well have been removed or concealed. Thus, the primary focus of this study is to determine the recency of faulting in this area and its implication for seismic-hazard evaluation.

Although old aerial photographs have been extensively studied and the Sierra Madre fault zone has been systematically trenched, we are unable to positively identify either fault scarps or displaced strata in units younger than late Pleistocene anywhere east of Dunsmore Canyon (between Tujunga and La Crescenta). Some subdued scarplike features and ground-water barriers in the Duarte-Azusa area could represent breaks in Holocene deposits, but the evidence is marginal. This situation contrasts sharply with that in the area of the 1971 San Fernando earthquake, where units correlative with our unit 2 alluvium were clearly broken even before 1971. Thus, although the escarpment represented by the mountain front is continuous across the entire area, the recency of displacement along the bounding fault zone apparently decreases toward the east. To our knowledge, it is only as far away as Cucamonga Canyon, 30 km east of the study area, that abrupt scarps again occur in units as young as unit 2 alluvium (Eckis, 1928; Morton, 1976). It is particularly anomalous that the part of the range front opposite the very highest peaks of the range should be the segment where the evidence for recent displacements is least persuasive. This relation is the exact opposite of that seen along the east face of the Sierra Nevada.

In view of the absence of significant displacement in unit 2 alluvium throughout most of the study area, again except for the Raymond fault, we conclude that major earthquakes have not occurred in this segment of the Sierra Madre fault zone for several thousand years, perhaps as long as 11,000 years (the oldest age tentatively assigned to unit 2). This conclusion is unexpected, inasmuch as our initial working hypothesis was that the seismic hazard should be considered relatively uniform along the entire mountain front, including the San Fernando area.

In addition to the recurrence interval between major shocks, another important problem in the evaluation of seismic hazard is specification of the maximum earthquake that is realistically possible here under present tectonic conditions—what we term the "maximum credible earthquake." Certainly it must be as large as the $M=6.4$ event in 1971. Wesson and others (1974) postulated a "maximum expectable earthquake" of magnitude $7\frac{1}{2}$ to $7\frac{3}{4}$ for the same general area. Their estimate was based on an assumed rupture of half the total length of the fault zone, which they put at 130 km, as well as on comparisons with the 1952 Kern County $M=7.7$ earthquake, which occurred on a somewhat similar thrust-fault system 100 km to the north.

In contrast, Ehlig (1975) pointed out that the Sierra Madre fault zone comprises several distinct arcuate salients, each 15 to 20 km long and convex toward the

valley. He proposed that these individual salients are mechanically coherent and that a single earthquake might be expected to involve no more than a single salient, as was in fact observed during the 1971 San Fernando earthquake, particularly in Big Tujunga Canyon, where the breaks terminated in a major cusp between adjacent arcuate salients. No such individual salients or sectors are present along the White Wolf fault, where movement over the entire 50-km length caused the 1952 Kern County earthquake.

Within and adjacent to the study area, four individual salients can be identified, separated by cusps pointing toward the mountains; these salients extend: (1) from San Fernando Pass to Big Tujunga Canyon (20 km), (2) from Big Tujunga Canyon to the Arroyo Seco (15 km), (3) from the Arroyo Seco to Monrovia Canyon (18 km), and (4) from Monrovia Canyon to Big Dalton Canyon (16 km). We agree with Ehlig (1975) that these sectors are so distinct in their structural patterns that a single earthquake involving more than one of them would come as a surprise, although we hesitate to label such an event as "incredible." Examples can be found elsewhere in the world of several distinct segments of a fault zone breaking at the same time, such as in Japan (Allen, 1975). Assuming that two salients broke at once, the total length of 32 km would suggest an average causative earthquake of $M = 6.9$ (Slemmons, 1977), although errors in such extrapolations can be great (Bolt, 1978).

On the basis of the faulting that occurred during the 1952 Kern County earthquake, generally assumed to have been of $M = 7.7$, some investigators have proposed that an event at least as large should be expected on the Sierra Madre fault zone because it has an even greater total length than the White Wolf fault, whose rupture caused the 1952 event. We disagree with such a direct comparison for three reasons: (1) As argued above, the segmentation of the Sierra Madre fault is quite unlike the relatively continuous geometry of the White Wolf fault; (2) field studies by Cotton and others (1977) along the White Wolf fault showed evidence of pre-1952 faulting of probable Holocene age, in contrast to the absence of such evidence along much of the Sierra Madre fault; (3) recent work by Kanamori and Jennings (1978) showed that the $M = 7.7$ assigned to the 1952 event by Gutenberg (1955) is approximately comparable to the surface-wave magnitude (M_S) rather than to the local magnitude (M_L) which is commonly assigned to local southern California earthquakes and is measured at a frequency that is most appropriate to the evaluation of engineering damage. Using strong-motion accelerograms from the 1952 earthquake, Kanamori and Jennings (1978) proposed that the equivalent M_L for this earthquake should be about 7.2.

In our opinion, the maximum credible earthquake for the segment of the Sierra Madre fault that we have studied should be about magnitude (M_L) 7, and the

average recurrence interval between major shocks longer than 5,000 yr. Although such a recurrence interval is long relative to those of such very active faults as the San Andreas, it is certainly not too long to be of concern in the siting and planning of critical structures. Furthermore, the recent study by Sieh (1978) of prehistoric large earthquakes on the San Andreas fault demonstrated the large variations in the intervals between individual events. Although the average recurrence interval over the past 1,500 yr is 160 yr, the intervals between major events on this section of the San Andreas fault during the same period have ranged in length from about 50 to 300 yr.

RAYMOND FAULT ZONE

REGIONAL STRUCTURAL PATTERN

Just as several branches of the Sierra Madre fault system diverge into the range, several other branches diverge out into the valley floor in front of the range. Probably the most important of these branches is the Raymond fault, which diverges southwestward from the range front near Monrovia and represents the southernmost element of the Transverse Ranges in the study area. Still farther west, other faults on the continuation of the Raymond trend mark the boundary between the Santa Monica Mountains on the north and the Los Angeles basin on the south. There is some doubt, however, that the Raymond fault itself is continuous with individual breaks in this western area (Lamar, 1970).

The Raymond fault has long been recognized as a significant ground-water barrier in the Pasadena-San Marino area and was first described as a dike or buried ridge of impervious rock (Mendenhall, 1908; Conkling, 1927). The first recognition that the alluvial gravel is truly offset was apparently by Miller (1928), who considered the feature to be a basinward extension of the Sawpit fault, which trends northeast into the range north of Monrovia. It was subsequently termed the "Raymond fault" by Eckis (1934) and was the subject of an extensive investigation by Buwalda (1940) in connection with litigation over water rights (California Division of Water Resources, 1941). In recent years, it has been termed both the "Raymond fault" and the "Raymond Hill fault" on State geologic maps (Jennings and Strand, 1969; Jennings, 1977). We prefer the simpler terminology in recognition of Eckis' (1934) first usage of the name as applied to a demonstrated fault.

FAULT CHARACTERISTICS

The Raymond fault is a high-angle reverse fault that also shows significant left-lateral displacement. Its recent activity is attested to by numerous geomorphic features along its entire length. The fault trace is defined by a

scarp that is continuous between Monrovia Canyon and the Arroyo Seco, except where it passes through Holocene alluvium in Santa Anita and Eaton Canyons.

Between Monrovia Canyon and Santa Anita Canyon, the Raymond fault is the frontal fault, and, although it cannot be seen, it is presumed to thrust basement rocks over alluvium. Westward from Santa Anita Canyon to Raymond Hill, alluvium is faulted against alluvium. From Raymond Hill to the Arroyo Seco and beyond, the Miocene Topanga Formation is thrust over alluvium.

EVIDENCE FOR FAULTING

Much clear evidence for recent movement on the Raymond fault was documented by Buwalda (1940), including: (1) a nearly continuous fault scarp, (2) closed depressions, (3) springs and a high ground-water table, (4) backtilted fan surfaces, (5) displaced drainages, (6) pressure ridges, (7) recent surface cracking, and (8) surface exposures.

SCARPS

The most prominent feature of the fault is the continuous scarp from the Arroyo Seco eastward to San Marino High School in San Marino. East of the school to the Los Angeles County Arboretum (Arcadia), the scarp has been nearly obliterated by erosion from Eaton Wash and subsequent fan development along the Raymond trace (map and cross section $G-G'$, pl. 2.4). Two elongate pressure ridges, trending parallel to the fault trace at the Arboretum and immediately north of the Santa Anita Race Track, are separated by a prominent fault scarp. Between the Santa Anita Race Track and the Monrovia outlier, the fault scarp has been obliterated by the active Santa Anita Canyon. The south boundary of the Monrovia outlier is believed to be the fault scarp, although the fault itself is not seen along this segment.

The scarp is most prominent through the San Marino-South Pasadena area and attains a maximum height of more than 30 m north of Lacy Park. It is a linear feature except for the sharp S-curve northwest of Lacy Park at the inferred juncture with the Eagle Rock fault (Buwalda, 1940, p. 64). The scarp does not appear to indicate a highly active fault, such as the San Andreas, because the average slope of the scarp face is less than 20° and the numerous small canyons eroded across it and into the upthrown block have maintained relatively low gradients (Wallace, 1977). Additionally, Buwalda, (1940, p. 48, 49) says the movement causing "a 4-foot scarplet crossing the floor of the mouth of the Kewen Canyon***must therefore have transpired many centuries ago." This observation could not be substantiated because the site is now covered with houses.

In western Arcadia, a low scarp and two lineaments show clearly on 1929 Fairchild airphoto K-363. These

features are significant because they are in the unit 1 alluvium of Eaton Wash.

CLOSED DEPRESSIONS

Buwalda (1940) recognized six closed depressions along the Raymond fault (pl. 2.4), of which at least Lacy Park and Baldwin Lake (Los Angeles County Arboretum) are sag ponds fed by springs north of the fault. An excavation dug into Lacy Park (Wilson Lake) "revealed at least 20 feet of interbedded clay, peat, [and] tule stems" (Buwalda, 1940, p. 47). It is not known whether the other depressions have similar sediments rich in organic material.

SPRINGS AND HIGH GROUND-WATER TABLE

The Raymond fault is an effective ground-water barrier and was first recognized as such (Mendenhall, 1908) because of the numerous springs, marsh deposits, high ground-water table, and artesian pressure in wells north of the barrier. All these springs have since stopped flowing because of lowering of the ground-water table except for those at Baldwin Lake and two perennial springs along the east bank of the Arroyo Seco. The latter two springs may each define a separate trace of the Raymond fault (loc. [3], pl. 2.4).

Additional evidence of a high ground-water table is provided by the black poorly drained soils, rich in organic materials, mapped as the Chino loam on the 1917 Pasadena area soil survey (Eckman and Zinn, 1917). These soils, which occur between trench 7 and Baldwin Lake north of the Raymond fault trace (east center, pl. 2.4), apparently are the result of abundant decayed vegetation in perennial marshes.

BACKTILTED FAN SURFACES

Buwalda (1940, pl. 1) showed many areas along the Raymond fault zone "that originally sloped south, now slope north or are horizontal." Most of these surfaces are north of the fault and are the lower parts of the Altadena and Sierra Madre fans; several surfaces are south of the fault, the largest of which contains the Lacy Park sag pond. Most of the backtilting is attributed to the vertical component of movement on the Raymond fault.

DISPLACED DRAINAGES

Abundant evidence for the position of the Raymond fault is provided solely by its effect on the numerous drainage systems that cross it. Many small drainage channels either terminate or begin at the fault; many others cross the fault with a jog that generally suggests left-

lateral movement, although in most places it is impossible to prove offset of the channel as opposed to diversion parallel to the fault trace. One example of an offset channel is visible adjacent to trench 7 (pl. 2.4), and Alhambra Wash is an example of a diverted drainage (Buwalda, 1940, p. 46).

PRESSURE RIDGES

Two 18-m-high hills, elongate parallel to the Raymond fault, are visible at the Arboretum and Santa Anita Park. These hills are considered to be pressure ridges squeezed up between several branches of the fault.

Two trenches (6, 6A) were excavated at the base of the north slope of the Arboretum ridge (table 2.1; see supplementary section below entitled "Trenching"). Although the fault was not seen, a south-dipping lithologic contact of undetermined origin was exposed downslope from north-dipping alluvial deposits that may be of unit 4. The fault probably is north of the end of the trenches and inaccessible. Another trace presumably bounds the south side of the hill.

RECENT SURFACE CRACKING

Several localities were noted where pavement or structures showed cracking along the trace of the Raymond fault. Although these cracks were first thought to suggest fault creep (Payne and Wilson, 1974; Proctor, 1974), they are now considered to be largely the result of subsidence due to ground-water withdrawal. Tension cracks commonly form along basin boundaries as fluid is removed from unconsolidated alluvium within it. One unusual feature here, however, is that the cracks at the Sunny Slope Reservoir in Pasadena suggest a horizontal component of movement.

SURFACE EXPOSURES

The only known surface exposure of the Raymond fault is on the east side of Alhambra Wash in a manmade cut (loc. 59, pl. 2.4). Buwalda (1940, p. 44) also described what appear to be other breaks north of this site. The existing outcrop exposes the north-dipping main break(?) at the toe of the scarp. The fault plane juxtaposes unit 3 alluvium to the north against unit 2 or, possibly, unit 1 alluvium to the south. The fault is 5 to 10 cm wide and is iron stained. No gouge or other fault-generated debris is apparent.

LITHOLOGIC UNITS

Surficially, the Raymond fault displaces only alluvial deposits except in the Monrovia outlier, where crystalline

basement is presumed to be the upthrown block, at Raymond Hill, and at Grace Hill, where the Topanga Formation forms the upthrown block (map and cross section F-F', pl. 2.4).

The Topanga Formation, as exposed at Raymond and Grace Hills and along the Arroyo Seco north of the Raymond fault, consists of interbedded conglomerate, siltstone, and sandstone. All the exposed deposits are highly deformed by both folding and faulting. A more complete description of these units was given by Lamar (1970).

The area north of the fault zone between the Arroyo Seco and the Eaton Canyon flood plains is regarded as the southernmost part of the Altadena fan. This area is underlain by unit 3 deposits, consisting predominantly of massive poorly sorted fine-grained alluvial sand and sandy silt and lesser amounts of fluvial sand and gravel. These deposits appear to be very thin just north of the fault scarp because unit 4 alluvium crops out in several of the canyons that cross the scarp. Unit 4 alluvium has also been exposed in several excavations for foundation footings on the upper surface of the scarp.

Within and south of the fault zone in this same area, the alluvial deposits are younger and generally different in composition from those north of the fault (pl. 2.5; see subsection below entitled "Fault Displacement"). The topography indicates that fan building has occurred south of the fault; the fan heads are at the base of the scarp. Exposures in trenches 7, 14, 14A, and 15 showed that these deposits generally are much better sorted and bedded than those north of the fault (pl. 2.5).

In the past, faulting created ponds or small lakes large enough to allow accumulation of massive fine-grained silty sand and clayey sandy silt to a thickness of several meters. North of the fault, deposits of this type are associated with unit 4 gravel on the Patton estate west of the Huntington Library, and with unit 3 deposits at the Sunny Slope Reservoir, where they grade upward into Holocene marsh deposits rich in organic material (sample C-6, table 2.2). Eastward from the Eaton Wash concrete-lined channel, nearly all the surficial deposits along the Raymond fault zone are of unit 1 and consist of fluvial sand and gravel derived from the Eaton, Little Santa Anita, and Santa Anita drainages.

SEISMIC HISTORY

Careful examination of sedimentary features and deposits, as exposed in trenches 7, 14, and 14A (pl. 2.4; trench logs 7 and 14, pl. 2.5), has revealed significant new information on the seismic history of the Raymond fault zone. This information, along with ^{14}C ages on 11 samples collected from these trenches (pl. 2.5; table 2.2), allows an age or age limit to be assigned to the seismic events recognized.

Five events have been identified in the three trenches. In only one place—the southern break in trench 7 (pl. 2.5)—can the faulting features and ^{14}C ages be confidently combined to date the seismic event. In all other places, either a ^{14}C -dated feature is thought to record a seismic event (although it could have been from an earthquake on another fault), or faulting is recognized that can only be bracketed by dated units deposited an unknown period before or after the event.

Trench 7 at the Sunny Slope Reservoir exposed two separate faults (see trench log, pl. 2.5). The southern fault, which comes to within 3.3 m of the present ground surface and has a vertical displacement of only 6 cm, appears to record a single seismic event. The shaking that accompanied the event is indicated by the contorted and discontinuous silty-clay layers, which were probably still saturated and unconsolidated at the time of the event. The three $25,500 \pm 600$ -yr ages on samples C-3, C-4, and C-5 (table 2.2) precisely date this event.

The northern fault, which can be traced to within 1.3 m of the surface, terminates just short of a series of fingerlike fissures extending down from and filled with black marsh deposits rich in organic material. Sample C-6 (table 2.2), taken from one of these cracks, gave an age of $2,160 \pm 105$ yr B.P. Although this fissure could not be proved to be caused by faulting, this sample age is close to the age of $2,920 \pm 180$ yr B.P. on a similar sample collected from a fissure within the fault zone by Converse Consultants in a nearby trench (Payne and Wilson, 1974). The absence of correlatable units on both sides of the northern fault and the grossly different lithologies on either side indicate that multiple events have occurred along this fault.

San Marino High School trench 14 (see trench log, pl. 2.5), excavated by Le Roy Crandall & Associates, exposed two separate branches of the Raymond fault, 4 m apart. The considerably greater detail exposed in this trench adds significantly to the data on the seismic history of this fault. An age of $35,800 \pm 1,300$ yr B.P. was obtained on highly distorted clayey peat (sample C-16, table 2.2) at a depth of 3.8 m. The peat and surrounding deposits have the appearance of having been deformed by liquefaction (Sims, 1973, 1975; K.E. Sieh, oral commun., 1977) and by faulting. An age of $29,100 \pm 400$ yr B.P. was obtained on another deformed clayey peat with flame structures (sample C-17), 80 cm above sample C-16; the deformation of this layer also has the appearance of being due to liquefaction. This peat bed may record an event that occurred shortly after its deposition, or it may have been deformed during the event that caused the liquefaction features in the deposits 15 cm higher in the section. This upper set exhibits flame structures, slump structures, and a possible sandblow, 1.5 m south of the fault, that was

ejected from below and that also deformed and dislocated the surrounding silt beds.

An age of $10,600 \pm 160$ yr B.P. was obtained on a peaty silt (sample C-18, table 2.2) 1.9 m below the ground surface south of the southern fault trace. The reverse faulting of this layer records an event that occurred after its deposition but before deposition of the overlying 1.1 m of fluvial deposits, which record a subsequent normal-faulting event that dropped a fault-bounded wedge of these deposits downward to the north (pl. 2.5).

Sample C-19 (table 2.2), collected from the faulted lower part of the thick A horizon of the Holocene soil, yielded an age of $6,060 \pm 110$ yr B.P. This age and the age of 10,600 yr B.P. on sample C-18 bracket at least two events along the southern fault trace. The age of $6,060 \pm 110$ yr B.P. also places a maximum limit on the date of the event that displaced sample C-19.

Trench 14A, also excavated by Le Roy Crandall & Associates, 200 m west of trench 14, exposed a single branch of the Raymond fault. An age of $1,630 \pm 100$ yr B.P. was obtained on an apparently unfaulted paleosol (sample C-21, table 2.2) overlying the fault. A second sample (C-20) from a faulted paleosol, 30 cm lower than sample C-21 and south of the fault trace, yielded an age of $3,575 \pm 100$ yr B.P. These two ages appear to bracket the last movement at this locality and are consistent with the date associated with the youngest event seen in trench 7 (pl. 2.5).

FAULT DISPLACEMENT

Determination of the sense and extent of displacement on the Raymond fault has proved difficult, owing to the absence of exposures and of reliable subsurface data. That the Raymond is a high-angle reverse fault with considerable vertical slip is indicated by its high scarp and by its exposures in trenches; however, assessment of the total extent of vertical slip is more difficult.

Well logs were used to construct two cross sections across the Raymond Basin (pl. 2.4). The log of the Standard Oil Co. Live Oak Well No. 1, located 2.8 km south of the fault in San Gabriel, and logs from deep water wells in the central part of the basin were utilized to draw cross section G-G' (pl. 2.4), which shows the relations across the fault. The Live Oak well log indicates that the base of the alluvium is at a depth of 1,180 m; basement was penetrated at 2,460 m, with 1,280 m of intervening Tertiary sediment. Wells do not extend deep enough north of the fault to penetrate basement rock in the vicinity of cross section G-G'. A few driller's logs from wells north of the fault suggest Tertiary sediment at a depth of 230

m, but this information is questionable. Assuming south-dipping basement surfaces on either side of the fault, as much as 775 m of vertical displacement is possible. The gravity data of Sanford (1958) and Kingsley (1963) suggest that 190 m of post-Miocene displacement has occurred.

In the western part of the Raymond basin, however, evidence for vertical displacement is equivocal and somewhat contradictory. Three coreholes drilled by the California Department of Transportation (loc. 40; cross section *F-F'*, pl. 2.8) indicate diorite within 73 m of the surface south of the Raymond fault but no basement rocks within 107 m of the surface north of the fault. This relation is difficult to explain unless a significant amount of lateral displacement has also occurred.

Contrary to these data is some evidence that unit 4 alluvium north of the fault has been displaced vertically about 135 m, north side up. This evidence consists of notations of red clay and sand beds in drillers' logs for three wells south of the Raymond fault—beds considered to be equivalent to the unit 4 alluvium exposed at the top of the scarp.

We estimated the extent of vertical displacement during the past 36,000 years in the San Marino area as follows. Sedimentation rates were calculated from the ^{14}C ages on the deposits in trenches 7, 14, and 14A (table 2.2). We assumed that the sedimentation rate south of the fault equals the vertical slip rate, so that a constant gradient is maintained on the ground surface across the fault. The value used for the sedimentation/slip rate was 0.13 mm/yr—a weighted average from the data listed in table 2.2. Thus, at this rate, the estimated total vertical displacement during the past 36,000 yr is 4.7 m. This extent of displacement would indicate 0.58 m per seismic event, assuming eight events, or 0.39 m per event, assuming a 3,000-yr recurrence interval (see subsection below entitled "Fault Activity and Recurrence Interval Between Major Earthquakes"). This value is corroborated by the 0.66-m vertical offset of a sand bed (north side up) along what appeared to be a single break exposed in a Sunny Slope Water Co. pipeline trench (22, table 2.1).

Lateral displacement along the Raymond fault is much more difficult to assess. As noted above, the basement-surface relations across the west end of the fault suggest an unknown but significant amount of lateral slip, as do the apparent left-lateral displacements of small drainages. Lateral slip is also suggested by the drag features seen in trench 15 and by the variations in thickness of correlatable beds across several minor faults.

In summary, the total extent of displacement along the Raymond fault is unknown. The vertical displacement may range from 135 to 775 m, and the lateral displacement is unknown.

FAULT ACTIVITY AND RECURRENCE INTERVAL BETWEEN MAJOR EARTHQUAKES

We derived recurrence intervals and displacement rates for the Raymond fault from ^{14}C ages with analytical uncertainties ranging from ± 80 to $\pm 1,300$ years (at one standard deviation). All these ages were obtained from silt, clay, or soil, rich in organic material (table 2.2). The ages obtained on the soil samples are not the true ages of the soil but determinations of the mean residence time of the contained organic materials and thus are too young by an indeterminable amount. Thus, the dates for some events are minimums.

Even with no radiometric dates, the Raymond fault would appear to be considerably more active than the strands of the Sierra Madre fault zone along the range front. This greater activity is indicated by the abruptness of the Raymond fault scarp, the presence of several closed depressions along it, and the clear involvement of relatively young deposits. All these features contrast sharply with those at the base of the main mountain front. It might be argued, of course, that in the Pasadena area the Raymond fault is currently taking up the north-south compression that would otherwise be expressed in more activity along the Sierra Madre fault zone, but this hypothesis does not explain the seeming absence of Holocene activity along either fault zone for some distance eastward from Monrovia.

More definitive evidence for fault activity along the Raymond fault zone comes from the numerous radiocarbon ages obtained on materials from within the deformed zone, as discussed in detail in the preceding section. These trench data suggest as many as eight individual seismic events along the Raymond fault within the past 36,000 yr. Five of these events are reasonably well documented, whereas evidence for the remaining three is only suggestive; moreover, additional events might well have occurred for which evidence does not remain or has not been found.

Sample C-16 suggests a seismic event at 35,800 yr B.P., which we term event 1. Event 2, at 25,500 yr B.P., is demonstrated by samples C-4 and C-5. Sample C-17 may also record event 2. Samples C-18 and C-19 bracket events 3 and 4 between 10,600 and 6,060 yr B.P., and sample C-19 also places a maximum date of 6,060 yr B.P. on event 5. We assume that event 5 is also the event that affected samples C-6, C-20, and CDA-1, which is bracketed at between 2,160 and 1,630 yr B.P. by samples C-6 and C-21.

There is some indication that the event that disturbed sample C-17 predated event 2; this event is here termed "event 1A." An additional event, 2A, may be recorded in the possible liquefaction and faulting of the organic

clayey silt 1 m below sample C-18. Another event, 4A, may be recorded in the inclined fault above sample C-18, bounding the south side of the downdropped wedge and subsequent to event 4 on the vertical fault bounding the north side of the wedge.

Thus, the eight suggested events, from the oldest to youngest, are as follows:

| Event | Date (yr B.P.) |
|-------|--------------------------------------|
| 1 | $35,800 \pm 1,300$ |
| 1A | $29,100 \pm 400$ |
| 2 | $25,500 \pm 600$ |
| 2A | $29,100 \pm 400$ to $10,600 \pm 160$ |
| 3 | $10,600 \pm 160$ to $6,060 \pm 110$ |
| 4 | $10,600 \pm 160$ to $6,060 \pm 110$ |
| 4A | — |
| 5 | $2,160 \pm 105$ to $1,630 \pm 100$ |

If these eight events represent all the major earthquakes during this 36,000-yr period, then the average recurrence interval between such events is 4,500 yr. Assuming that some events were undetected in our study, the true recurrence interval is probably somewhat less, possibly 3,000 years. In comparison with the Sierra Madre fault zone to the north, it is particularly significant that at least three events occurred within Holocene time—the most recent about 2,200–1,500 yr B.P. Before jumping to the conclusion that the Raymond fault is highly active, however, we note that the apparent recurrence interval between major earthquakes on the adjacent segment of the San Andreas fault, 35 km to the north, is about 160 years (Sieh, 1978), perhaps only a 20th of the interval on the Raymond fault.

Estimation of the maximum credible earthquake on the Raymond fault must be based almost entirely on maximum rupture length, inasmuch as we have no other realistic basis for judgement. Assuming a fracture length of 15 km from Monrovia to the Arroyo Seco, and using the regression relation of Slemmons (1977), we derive an average magnitude of 6.5. The regression analysis of Mark and Bonilla (1977) gives a magnitude of 6.9 for that same fault length that illustrates the uncertainties in this type of approach. We prefer the basic data set of Slemmons, and, in our judgment, a magnitude (M_L) of $6\frac{3}{4}$ represents a realistic maximum credible earthquake for the Raymond fault—albeit an exceedingly unlikely one.

SUMMARY OF SEISMIC-HAZARD EVALUATION

All the major faults within the study area may be considered active in the sense that they cut Quaternary rocks, and, indeed, the total Quaternary displacement on some breaks may be several kilometers. The very existence of the San Gabriel Mountains and their steep south face testifies to this continuing tectonic activity. Of far greater

relevance to seismic-hazard evaluation, however, is the surprising variation in the fault activity of the various faults within the study area. Furthermore, the current fault activity of many of these faults may differ considerably from that averaged over all of Quaternary time, and so we have concentrated our attention on the Holocene and very latest Pleistocene fault-movement histories in the belief that this very recent history is most relevant to hazard evaluation. Abundant worldwide evidence suggests that faults which have been most active in the recent geologic past are those with which we must be concerned in planning for the near future (Allen, 1975).

Increased awareness of earthquake hazards in the greater Los Angeles area (for example, Environmental Research Laboratories, 1973) has in recent years led to several new Government regulations, such as those of the Alquist-Priolo Act (Hart, 1974) and in the requirements for local seismic-safety elements (Wiggins, 1974; Envicom Corp., 1975). The results of our studies generally reinforce the need for such regulations. In particular, we agree that most of the Raymond fault is sufficiently active and well located that it should be included under the coverage of the Alquist-Priolo Act, and we agree with the current tentative proposal that only parts of the Sierra Madre fault zone should be so designated.

As discussed in detail in the preceding sections, we consider the maximum credible earthquake on the Sierra Madre fault system between Dunsmore and San Gabriel Canyons to be of magnitude (M_L) 7 and to have a recurrence interval between major events of more than 5,000 yr. No demonstrable Holocene displacement has occurred along this segment, in sharp contrast to the San Fernando segment to the west. Also in contrast, the Raymond fault, which lies 5 km south of the Sierra Madre fault in Pasadena but converges with it toward the east, has had at least three displacements associated with significant earthquakes within Holocene time; at least eight such events have occurred within the past 36,000 years. The recurrence interval between major events on the Raymond fault may be 3,000 yr, and we judge the maximum credible earthquake on this fault to be of magnitude (M_L) $6\frac{3}{4}$.

It is interesting to compare our estimates with those of other workers. Greensfelder (1974) proposed a magnitude of 7.5 for the maximum credible earthquake on the "Malibu-Santa Monica-Raymond Hill" fault. However, this large-magnitude assignment results from assuming a total length for the active fault zone that we do not believe is supported by geologic studies, particularly that of Lamar (1970). We see no evidence that the Raymond fault extends westward as an active feature much beyond the Arroyo Seco in Pasadena. For the Sierra Madre fault, Greensfelder (1974) assigned a magnitude of 6.5 to the

maximum credible earthquake, but this value is apparently based on the assumption that the short segment north of Pasadena is independent of segments farther east and west. In contrast, Wesson and others (1974) assigned a magnitude of $7\frac{1}{2}$ to $7\frac{3}{4}$ to the "maximum expectable earthquake" on the Sierra Madre fault, primarily on the basis of the assumed 130-km length of this fault and on comparisons with the 1952 Kern County earthquake, generally assumed to be of magnitude 7.7. We take an intermediate position on the basis of our studies and recognize distinct salients within the fault zone that appear to have limited mechanical independence, partly following Ehlig (1975). Furthermore, as discussed earlier, we consider it inappropriate to directly compare the Sierra Madre fault with the White Wolf fault, whose movement caused the 1952 Kern County earthquake. Although both faults are thrust faults and are, to some degree, mirror images of one another across the "big bend" of the San Andreas fault, they differ significantly in their detailed geometry and in their degree of Holocene activity. Additionally, recent studies by Kanamori and Jennings (1978) indicated an M_L of about 7.2 for the 1952 event and that the magnitude of 7.7 earlier assigned by Gutenberg (1955) is more nearly a surface-wave magnitude (M_S). Not only is M_L the magnitude that should be compared with those of other earthquakes in the southern California catalog (for example, the magnitude of 6.4 for the 1971 San Fernando earthquake), but M_L is measured at frequencies of ground motion much more relevant to the evaluation of engineering damage than is M_S .

Recent reports by engineering consultants concerning earthquake-resistant design for dams in the foothills area have assigned values for the maximum credible (or equivalent) earthquake on the Sierra Madre fault that range from 7.0 to 7.5. Postulated recurrence intervals between such events have been approximately a few hundred years, much less than we now propose on the basis of the absence of demonstrable Holocene displacements along this segment of the fault zone.

A general conclusion from our study is that the magnitudes of the maximum credible earthquakes we propose do not grossly differ from those proposed by earlier workers. On the other hand, the projected recurrence intervals between major earthquakes on these two fault zones are far greater than those proposed earlier, particularly for the Sierra Madre fault zone in this area.

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- observed and the conclusions reached from each excavation. The initial numbers preceding each description correspond to the trench numbers.
1. *Foothills Junior High School, Arcadia*.—The trench was excavated in the athletic field across an apparent scarp of the Raymond fault as observed on 1929 Fairchild aerial photographs. The site was picked at the break in slope from original grading maps. Observations: A 1-m-high scarp-like feature was noted, and continuity of horizontal bedding was established for the entire length of the trench, although a thin sand lens with an anomalous steep southward dip was observed at the south end. Conclusions: The deposits exposed in the trench are probably unit 2 and are not faulted (loc. 60, pl. 2.4).
2. *Arroyo Seco, north of JPL Bridge, Pasadena*.—The trench was excavated in the stream bottom just north of the east bridge pier. The site was picked to reinterpret relations uncovered previously by Converse Consultants of Pasadena. Observations: A branch of the Sierra Madre fault zone was exposed; Mesozoic basement rock is thrust over unit 3 alluvium. The fault zone consists of 30 cm of clay gouge and as much as 150 cm of crushed rock, with one main and several minor fault surfaces; the zone strikes N. 40° W. and dips 30°-40° N. The unit 3 alluvium contains highly weathered diorite clasts, some of which have been smeared out by faulting. Conclusions: This trench exposes one of the major fault branches at the mountain front. Recent alluvium did not seem to be faulted, as had previously been suspected (loc. 24, pl. 2.2).
3. *Eaton Canyon, Pasadena*.—The trench was excavated along the inside edge of the old Mount Wilson Toll Road, approximately 46 m west of the bridge, between outcrops of unit 3 alluvium and quartz monzonite. Observations: A branch of the Sierra Madre fault zone was exposed; Mesozoic basement rock is thrust over unit 3 alluvium. The fault zone consists of 13 cm of clay gouge and 60 cm of crushed granitic rock. Three separate fault surfaces were observed; the zone strikes N. 70° W. and dips 45° N. The upper several centimeters of unit 3 alluvium is well indurated. The fault contact between granitic rock and unit 3 alluvium is very sharp. Conclusions: This fault branch could not be traced upward in unit 3 alluvium and probably has not been recently active; it is only one of several thrust faults at the mountain front in this area (loc. 35, pl. 2.2).
- 3A. *Eaton Canyon, Pasadena*.—This trench was excavated along the inside edge of a road, 10 m below the southeast end of trench 3 and on the strike of the fault exposed in trench 3. Observations: Unit 2 alluvium, consisting of loose moderately well bedded sand and gravel, was exposed. Continuity of bedding was established for the entire 21 m of trench. Conclusions: Unit 2 alluvium once filled Eaton Wash to an elevation of 8 to 9 m above the present channel. The absence of faulting in these deposits indicates only pre-Holocene movement for this fault branch.
4. *East of Pasadena Glen, west of Hastings Canyon, Pasadena*.—Excavation consisted of scraping off the existing roadcut where a thrust fault had previously been mapped; Mesozoic basement rock is thrust over unit 4 alluvium. Observations: The exposure showed banded gneiss overlying unit 4 alluvium along an indistinct contact. Fault gouge is absent. Conclusions: This thrust fault is one of several along the Sierra Madre fault zone at the mountain front; at least one additional branch lies to the south (loc. 44, pl. 2.2).
5. *Clairbourn School, San Marino*.—A 33-m-long trench was excavated by Leighton & Associates, Inc., perpendicular to an east-west-trending lineament observed on a 1929 Fairchild aerial photograph. Observations: An old filled-in east-west-trending gully was exposed. Continuity of bedding in older alluvium was established along the entire trench length. Conclusions: The southern branch of the Raymond fault probably does not extend westward to this site. The lineament is probably an erosional feature.
- 6 and 6A. *Los Angeles County Arboretum, Arcadia*.—Both trenches were excavated at the base of the north slope of the pressure ridge between two branches of the Raymond fault. Observations: Bedding in the alluvium dips 15° N. Unit 3(?) alluvium and younger colluvium ap-

APPENDIXES

TRENCHING

A total of 33 trenches and pits were excavated for this project: 23 by backhoe, 6 by tracked front-end loader, 1 by Poclain excavator, and 3 by hand (table 2.1). This section summarizes the important features

pear to lie unconformably over unit 4(?) alluvium. Both trenches had a planar feature, striking N. 70° E. and dipping 50° to 75° S., that shows a lithologic and color change only. There was no evidence of displacement or fault-generated debris. Conclusions: Although warping of the sediment is apparent, the main branch of the Raymond fault was not penetrated; it may be beyond the north end of the trenches (loc. ⑥, pl. 2.4).

7. *Sunny Slope Reservoir, Pasadena.*—The trench was excavated across the northern branch of the Raymond fault at a site adjacent to trenches dug previously by other workers. Observations: Two separate fault planes were exposed, both cutting marsh deposits of different ages, rich in organic material. Distinct lithologies were found on either side of the north trace. The fault zone strikes N. 70°–85° E. and dips 30°–80° N. The most recent soil appears to have been affected by faulting. Several samples were collected for ^{14}C dating. Conclusions: This trench exposed the main branch of the Raymond fault. There is evidence of Holocene faulting, and the lithologic relations observed and ^{14}C ages obtained have added significantly to our knowledge of the seismic history of this fault (see trench log, pl. 2.5; loc. ⑥, pl. 2.4).

8. *Lacy Park, San Marino.*—A 14.5-m-long trench was excavated on the slope between the fault scarp and the old Wilson Lake site. Observations: A 6-m-thick deposit of colluvium was exposed. No fault features were observed, and continuity of bedding was established along the entire length of the trench at depth. Conclusions: The Raymond fault does not cut these deposits and probably lies a short distance beyond the north end of the trench (loc. ⑧, pl. 2.4).

9. *JPL, northwest of Building 32, Pasadena.*—The trench was excavated by Le Roy Crandall & Associates. Observations: A branch of the Sierra Madre fault zone was exposed, showing Mesozoic basement rock thrust over unit 3 alluvium (fig. 2.8). The fault zone consists of several splay faults; the main fault contains 1 to 2 cm of clay gouge. The basement rock is highly crushed for 3 m above the fault, and the alluvium is moderately indurated for 12 cm below the fault. The fault strikes N. 85°–90° E. and dips 29°–33° N. The fault is overlain by colluvium derived from unit 2 alluvium upslope. Conclusions: This trench exposes the same major branch of the fault as that seen in trench 2. The fault does not cut later Holocene colluvium at this site (loc. ⑨, pl. 2.1).

10. *JPL, Building 150, Pasadena.*—The original exposure was made during construction of Building 150 and was reexposed by hand. Observations: Mesozoic basement rock is thrust over unit 4 alluvium; several fault surfaces and a landslide complicate the picture. Conclusions: This splay of the main fault branch appears to be quite old because the fault does not displace the soil developed on unit 4 alluvium upslope.

11. *Gully west of Passionist Fathers Monastery, Sierra Madre.*—This exposure was excavated by hand. Observations: The excavation exposed Mesozoic basement rock thrust over unit 4 alluvium. The fault plane strikes N. 70° W. and dips 50° N. The upper part of the fault surface dips south, owing to downhill sliding or creep, and is overlain by fresh (unit 1?) colluvium and bedded sand. Conclusion: This is a major branch of the Sierra Madre fault zone, but it has not displaced the overlying slide debris or unit 1(?) alluvium (loc. ⑩, pl. 2.2).

12. *Gould Canyon, La Canada.*—This exposure was excavated by hand in the bottom of Gould Canyon. Observations: The excavation exposed Mesozoic basement (diorite) rock thrust over unit 4 alluvium. The fault surface strikes N. 5° W. and dips 20° W., and consists of 2 to 10 cm of clay gouge. Conclusions: The attitude of the fault surface is anomalous and appears to be part of a gravity-controlled thrust-rooted slide. This fault is a major branch of the Sierra Madre zone (loc. ⑪, pl. 2.1).

13 and 13A. *West of Van Tassel Canyon, Duarte.*—Trenches were excavated parallel to, and within 3 m of, two of seven trenches dug previously by a consulting firm. The logs prepared by the consultant for all seven of these trenches showed one or two traces of the Sierra Madre fault zone displacing alluvium. Our intent was to log the trenches in more detail and to collect soil rich in organic material, shown on the

consultant's logs, for ^{14}C dating. Observations: No evidence of faulting was seen in either trench, and continuity of bedding was established for the entire length of both trenches. Conclusions: The subtle lithologic changes interpreted by other workers as faulting are probably due to depositional variations. The Sierra Madre fault zone, located in this area on magnetic surveys of other workers, is buried by a minimum of 3.5 m of undisturbed unit 2(?) alluvium (loc. ⑫, pl. 2.3).

14 and 14A. *San Marino High School, San Marino.*—Two trenches near the athletic field were excavated by Le Roy Crandall & Associates. The Raymond fault was exposed in both trenches. Observations: The easternmost trench exposed two separate fault traces within a complex sequence of clay, silt, sand, and gravel rich in organic material. Several faulting events are recognizable; the northernmost trace is the most recently active one and affects the B horizon of the modern soil. Lithologies differ strikingly across this trace: The north side consists of massive sandy clayey silt, and the south side of bedded sand and gravelly sand of fluvial origin. The fault strikes N. 70°–80° E. and dips 60°–90° N. Eight samples of clay and silt rich in organic material were collected for ^{14}C dating. Conclusions: The main branch of the Raymond fault zone locally consists of more than one fault trace. The most recent movement appears to be predominantly strike-slip. The lithologic relations seen and ^{14}C dates (table 2.2) obtained have added considerably to our knowledge of the seismic history of the Raymond fault (see trench log, pl. 2.5; loc. ⑬, pl. 2.4).

15. *Edison Company Powerline right-of-way, Chapman Woods, Pasadena.*—A single trench was dug across the Raymond fault under the powerlines and 100 m north of Huntington Drive. Observations: The major fault and several minor faults were exposed in this trench. South of the main fault, the units consist of bedded fluvial sand and gravel, with two interbedded paleosols. North of the fault, similar deposits contain several massive clayey sandy silt beds that are not found south of the fault. Correlation of units across the minor faults is generally possible at shallow depths but impossible in much of the lower half of the trench. Alluvial units within 0.3 m of the surface have been affected by faulting. Both strike-slip and dip-slip movement is evident. The fault zone is 11 m wide at this site; the fault surface strikes N. 50°–85° E. and dips 40°–90° N. Four samples were collected for ^{14}C dating. Conclusions: The Raymond fault zone is locally quite complex; it commonly consists of several discrete fault surfaces, the most conspicuous of which appears to be the one most recently active. Strike-slip displacement appears to be the predominant sense of movement (loc. ⑭, pl. 2.4).

16 and 16A. *Rubio Canyon, Altadena.*—Two trenches were excavated across a suspected fault trace within the upper part of the Rubio Canyon debris basin. The site was picked on the basis of the report by Saul (1977). Observations: The fault trace was not uncovered. Conclusions: The alluvium in the trenches has not been faulted, and the seeps noted by Saul were probably caused by water flowing on top of silt beds.

17. *Santa Anita Wash, Arcadia.*—A trench was excavated in unit 1 alluvium across the projected trace of a branch of the Sierra Madre fault zone. Observations: The fault was not uncovered; almost the entire trench was in artificial fill.

18A, 18B, and 18C. *Dunsmore Canyon, Glendale.*—Three trenches were excavated across the southernmost of two apparent scarps on the Dunsmore fan surface. The fault was exposed in all three trenches. Observations: The trenched scarp is 4 m high. A single fault plane, in places obscure, was exposed in each trench. There were some indications of multiple fault planes in trench B. The faulted deposits are of unit 2 alluvium. The fault surfaces contain no gouge, and commonly the only evidence of faulting is a color change or smeared clasts. Conclusions: The scarp height suggests multiple faulting events. This alluvium is the youngest for which movement is documented along the Sierra Madre fault zone within the study area east of the 1971 San Fernando earthquake zone. These observations indicate late(?) Holocene movement (see trench log, fig. 2.5; loc. ⑯, pl. 2.1).

TABLE 2.3.—*P*-wave velocities in clasts of Lowe Granodiorite from a sequence of alluvial deposits near the mouth of the Arroyo Seco

| Alluvial-deposit sequence | Average clast velocity (km/s) | Standard deviation of mean | Number of clasts measured |
|---------------------------|-------------------------------|----------------------------|---------------------------|
| A (oldest) | 1.20 | .06 | 52 |
| B | 1.41 | .07 | 28 |
| C | 1.58 | .06 | 36 |
| D | 1.77 | .06 | 48 |
| E | 1.60 | .09 | 17 |
| F (youngest) | 2.01 | .05 | 38 |

19. *Bradbury*.—A 52-m-long trench was excavated at the bottom of the prominent scarplike feature near the south boundary of the city of Bradbury. Observations: No definite fault features were exposed. Continuity of bedding was verified for the entire trench length. Conclusions: The trenched deposits are not faulted.

20A, 20B, and 20C. *Near Sierra Madre Villa Dam, east of Pasadena Glen, west of Hastings Canyon, Pasadena*.—Three trenches were excavated at two separate sites; the fault was exposed in all three trenches. Observations: In each trench, Mesozoic basement is thrust over unit 4 alluvium and younger colluvium of undetermined age. The fault surface strikes N. 55° W.–30° E. and dips 7°–20° N. The fault plane in trench C is truncated and overlain by 0.6 m of younger alluvium. A piece of wood was collected from the alluvium for ¹⁴C dating. Conclusions: This fault branch is probably the most recently active of the Sierra Madre fault zone in this area; however, it does not cut unit 2 alluvium that yielded an age of 2,200±80 yr (see fig. 2.9 and trench log, fig. 2.10; loc. 43, pl. 2.2).

21A, 21B, and 21C. *JPL, Pasadena*.—Three trenches were excavated in unit 2 alluvium across the projected trace of the fault exposed in trench 9. Observations: No faulting was observed in the exposed deposits. Conclusions: This branch of the Sierra Madre fault zone does not cut unit 2 alluvium and has not been active during Holocene time (see pl. 2.6).

22. *Sunny Slope Reservoir, Pasadena*.—The trench was excavated for a waterline by the Sunny Slope Water Co. Observations: The Raymond fault was crossed at a shallow angle and was difficult to distinguish because lithologies are similar on both sides of the fault surface. One major and several minor faults were exposed. One minor fault is associated with deposits rich in organic material that may be used to date a seismic event. A second minor fault displaces a sand bed 0.66 m vertically (north side up); movement appears to have occurred during a single event. The main fault strikes N. 75° E. and dips nearly vertically. Two samples of tree branches were collected north of the fault at depths of 4.3 and 4.9 m, and a peat sample was collected from the fault zone. Conclusions: This is the main branch of the Raymond fault. The Holocene soil could not be shown to be faulted.

MEASUREMENT OF PROGRESSIVE CLAST WEATHERING

It has long been known that alluvial clasts undergo progressive weathering, so that older alluvial units are distinguishable from younger ones by the greater degree of weathering shown by clasts of a given

lithology. We developed a new method during this study whereby the *P*-wave velocities of clasts (clast sound velocity [CSV]) of a specific lithology are measured. Preliminary results show that the CSV decreases progressively and significantly as a function of alluvial-unit age.

The CSV is obtained from traveltimes measurements made in the field with a DynaMetric Micro Seismic Timer model 217B. The instrument is portable and measures seismic traveltimes for a seismic compressional (*P*) wave generated by a hammerblow on the clast surface. The wave travels a predetermined distance through the clast. To avoid any possible systematic offset of origin time, apparent traveltimes for several different distances—generally four or more—were measured, and distance-time plots of the resulting data were used to determine the seismic velocity. Because of the range of path distances required, clasts had to be larger than 15 cm in greatest dimension. For each distance-time plot, a seismic velocity (slope) was determined by linear regression analysis. Without exception, the indicated correlation coefficient was high (greater than +0.98).

As a test of this method, six alluvial deposits in the Arroyo Seco were chosen that ranged in age from unit 1 (Holocene) through unit 4, as determined from geology and geomorphology. The CSV was measured on a group (17–52) of Lowe Granodiorite clasts from each deposit. All the CSV values from a given deposit were averaged to give an average CSV for the deposit. Statistical tests indicated that deposits corresponding to a single terrace level have the same CSV within the statistical resolution. All the CSV values corresponding to each terrace level were averaged to give an ensemble-average CSV for the deposit; table 2.3 lists the result. Statistical tests show that the separate deposits can be differentiated statistically by these CSV data at confidence levels (*t*-test) of 80 percent or greater.

Table 2.3 shows that the CSV decreases progressively with increasing alluvial age. This correlation holds for all the CSV data except those for deposit E, for which the CSV is low. This discrepancy may represent a statistical fluctuation because only 17 Lowe Granodiorite clasts from unit E could be measured, and so the resulting standard deviation of the mean CSV for that unit is high. The discrepancy may also have resulted from the relatively small sizes of the clasts available for measurement from unit E, compared to those from the other units. Nevertheless, the overall indication of a progressive decrease of CSV with age, as shown by table 2.3, is impressive and gives us reason to think that the CSV method holds promise for the relative-age determination of alluvial units.

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