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Geology of the Lawrence Livermore National Laboratory Site and Adjacent Areas

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Geology of the Lawrence Livermore National Laboratory Site and Adjacent Areas

Abstract

In April 1979, geoscience personnel at the Lawrence Livermore National Laboratory (LLNL) began comprehensive geologic, hydrologic, and seismologic studies of the LLNL site and nearby areas. These studies had two objectives:

1) To provide data for technical input to the Final Environmental Impact Report prepared for LLNL operations pursuant to the National Environmental Policy Act.

2) To provide geologic and seismological data for refining the design-basis earthquake for LLNL, and for assessing other geologic hazards pertinent to the site.

LLNL is located in the southeastern portion of the Livermore Valley, a structural and topographic depression that trends normal to the structural grain of the Central California Diablo Range within which it is located. The site slopes gently toward the northwest with a gradient that generally does not exceed 3%.

The Diablo Range consists predominantly of a core of metamorphic and igneous rocks of the Mesozoic Franciscan Assemblage. These rocks are flanked and locally tectonically overlain by sequences of oceanic crustal and marine sedimentary rocks of late Mesozoic through late Tertiary ages. These contrasting terranes appear to have been juxtaposed by large-scale movements along an extinct subduction zone known as the Coast Range Thrust Fault System.

Livermore Valley itself is underlain by an accumulation of predominantly continental alluvial deposits of latest Tertiary and Quaternary age that locally exceed 1 km in thickness. These sediments reflect a complex pattern of regional deformation, uplift, erosion, and deposition. The effects of variations in late Pleistocene and Holocene climates can be seen in the younger portions of this sedimentary sequence. These variations provide a basis for establishing the relative ages of deposits for which absolute age data are sparse. One absolute age date has been obtained by the ^{14}C method during project studies, and several dates of pedogenic carbonate formation have been obtained by the $^{230}Th/^{234}U$ method. In most cases, these dates correlate well with the relative ages deduced for the sediments from which the samples were obtained.

The relative and absolute age data indicate that alluvium ranging in age from about 35,000 to more than 100,000 yr underlies LLNL at depths of less than 1 to about 5 m. Older materials occur at greater depths, and an erosion surface (formed at least 300,000 yr ago) is believed to lie about 12 to 21 m beneath LLNL, based on the analysis of borehole data.

Located as it is in a seismically active region, LLNL would experience strong ground shaking as a result of a major earthquake on the active San Andreas, Hayward, and Calaveras Fault Zones. Strong shaking would also occur as a result of earthquakes on the active Greenville and Las Positas Fault Zones which bound the eastern and southeastern margins of the Livermore Valley, respectively. The Greenville Fault Zone was the source of damaging earthquakes that occurred late in January 1980. Geologic evidence demonstrates Holocene movements along strands of the Las Positas Fault Zone, and recently recorded microseismicity appears to correlate with this fault zone.

LLNL may also experience ground shaking as a result of earthquakes on the Concord-Green Valley Fault Trend and on the Verona and Williams Faults; all of these are known or postulated to be active. About 20 other faults have been identified or postulated in the Livermore Valley region. Direct geologic evidence rules out the existence of some of these faults and portions of others, at least as near-surface features. Others exist near the surface, but appear to be either inactive or of an uncertain status. These faults have not been investigated in detail, since considerations of their length and location demonstrate that they are not potentially important contributors to the seismic hazard at LLNL.

Regional geologic studies suggest the presence of an old fault deep beneath LLNL, which we have named the "ancestral" Greenville Fault. This fault has no geomorphic expression and no discernible effect on groundwater levels and late Quaternary alluvial deposits. The fault appears to be displaced by branches of the active Las Positas Fault Zone. The fault juxtaposes contrasting Jurassic-to-Cretaceous basement rocks and—where exposed in hills southeast of LLNL—appears to offset latest Tertiary and possibly early Quaternary deposits. No geologic or seismologic evidence for movement along the ancestral Greenville Fault was observed following the January 1980 earthquakes on the subparallel modern Greenville Fault Zone.

No strands of the modern Greenville and Las Positas Faults cross LLNL. Therefore, the possibility of surface fault rupture within the Laboratory during a major earthquake on either of these faults is nil. The possibility of ground rupture along the ancestral Greenville Fault is regarded as very remote since it is judged to be inactive.

Secondary seismic effects at LLNL, such as soil liquefaction, are judged very improbable based on the characteristics of alluvial deposits and depths to groundwater beneath the Laboratory. Landsliding at the site is precluded by the lack of slopes within LLNL. Some erosion and sloughing could occur along drainage ditch and stream channel banks during major storms. Localized sheet flooding and erosion could occur near the Arroyo Seco Channel at the southwest corner of LLNL during a catastrophic storm. Furthermore, most of the LLNL site could experience sheet flooding resulting from a failure of the South Bay Aqueduct, which is located about 0.4 km southeast of LLNL at its point of closest approach.

Introduction

Objectives and Scope of Project Studies

In April 1979, comprehensive geologic, hydrologic, and seismologic investigations of the LLNL site and nearby areas were begun by LLNL geoscience personnel. These studies were undertaken at the request of Laboratory management and were designed to provide an in-depth appraisal of aspects of site and regional geology pertaining to safe operation of site facilities. The area studied includes the Livermore Valley, the western portion of the Altamont Hills, and the northern margin of the Diablo Range south of LLNL.

The geologic and seismologic investigations particularly emphasized identification and location of faults near the Laboratory as well as the development and assessment of geologic and seismologic data concerning fault activity and motion. Other geologic hazards, such as slope stability and the potential for ground failure during a major earthquake, have also been assessed. The hydrologic studies examine the locations of aquifers, the transmissive characteristics of materials beneath the LLNL site, and the potential for groundwater contamination in the event of a significant on-site spill of radionuclides or toxic chemicals. These hydrologic studies are ongoing.

Geologic, hydrologic, and seismologic studies provided technical input to the Final Environmental Impact Report prepared for LLNL operations pursuant to the National Environmental Policy Act. The geologic and seismologic studies also provided data for refining the LLNL design-basis earthquake. The design-basis earthquake parameters will, in turn, be used to evaluate the adequacy of the seismic resistive designs of new Laboratory buildings and, if necessary, to reevaluate existing critical buildings.

Objectives and Scope of This Report

The objective of this report is the presentation of the results of comprehensive geologic investigations within and adjacent to LLNL from 1979 to 1982. These investigations are outlined below:

Literature Review

A thorough review and evaluation of existing geologic, geophysical, and seismic literature pertinent to the LLNL site and vicinity was completed.

Photographic Studies

Five sets of black-and-white stereoscopic aerial photographs of the LLNL site and vicinity were examined to identify features indicative of faulting. Photo sets examined include flights in 1940 (scale 1:20,000), and flights in 1958, 1968, 1970, and 1972 (scale 1:12,000). Black-and-white and false-color infrared (IR) photos in 1974 (scale 1:24,000) were also examined. (A list of these photographs is provided in Appendix A.)

Geologic Mapping

Geologic maps, scale 1:12,000, were made for the vicinity of the Laboratory and for an area of complex geologic structure located southeast of LLNL. Subsurface interpretations were also made based on well and geophysical data in an effort to extend mapped bedrock structures beneath the alluvial deposits within the Livermore Valley. The results of geologic mapping in the vicinity of the Laboratory are discussed in the main text. The subsurface work is discussed in Appendix B, and the results of mapping southeast of LLNL are discussed in a comprehensive report by Sweeney and Springer (1981).

Geophysical Surveys

Reconnaissance geophysical surveys were made within the LLNL site and vicinity to seek subsurface features that may indicate the presence of faults. An attempt was made to identify and determine the extent of subsurface marker horizons and the top of the zone of saturation as a means of developing more detailed structural and stratigraphic data. These geophysical surveys are discussed in Appendix C.

Geologic Exploration

Field investigations were conducted within and near the LLNL site to examine near-surface materials in areas where previous investigators had postulated faults or where geologic or geophysical studies identified anomalies suggestive of faults. The investigations included the excavation and detailed geologic logging of seven exploratory trenches and four test pits. An outcrop along the west bank of the Arroyo Seco within the Sandia National Laboratory (SNLL) property in Livermore was cleaned and logged in detail, as were two cuts along Greenville Road southeast of LLNL. Also, the south and east faces of the excavation for additions to LLNL Building 391 were logged in detail. Several adjacent sewer trenches were examined and logs of geologically significant segments were prepared when circumstances permitted. Logs of these trenches, test pits, and other excavations examined are included in Carpenter *et al.* (1982). While project studies were in progress, several other laboratory sewers were replaced or extended, and other excavations were made. Project personnel inspected these excavations and made reconnaissance examinations of the materials exposed.

Subsurface Studies

All known subsurface data previously obtained for the LLNL site were collected and reviewed. These data consisted primarily of logs from exploratory borings made during foundation design studies for major buildings at LLNL. As part of the site analysis, 23 exploratory boreholes were drilled and logged, using both conventional geologic logging techniques and downhole geophysical logging methods. All holes were logged with natural gamma and resistivity tools. Some holes were also logged with self-potential and caliper tools. Similar logs were made for 16 groundwater observation and monitoring wells drilled as part of the hydrologic investigation. Samples were obtained and logs made for three deep boreholes drilled within LLNL by others during the period in which project studies were in progress. Also, close contact was maintained with geotechnical contractors who were periodically at LLNL to perform building foundation and other investigations. Data obtained from their borings have been used during this investigation. Logs of holes drilled under the supervision of LLNL personnel are included in Carpenter *et al.* (1982).

Soil Dating

Samples of carbonaceous materials and caliche were obtained from exploratory trenches and exposures, and these were evaluated as to suitability for radiometric dating by the ^{14}C and $^{230}Th/^{234}U$ dating methods. Dating of suitable specimens has been completed (see Appendix D). Geologic interpretations of the dates obtained are presented in this report. Soil-stratigraphic studies were performed at LLNL by Dr. Roy J. Shlemon (Roy J. Shlemon and Assoc., Inc.) to obtain additional data on the ages of the alluvial deposits that underlie LLNL and the vicinity. Dr. Shlemon's findings appear in Appendix E of this report.

Other Project Reports

This report is one in a series being issued by the Site Seismic Safety Project to report the results of its investigations. Other reports in the series are

- Sweeney, J. J., and J. E. Springer (1981), *Geology of the Southeastern Livermore Valley, Alameda County, California*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53200.
- Taylor, S. R., and J. F. Scheimer (1981), *Seismological Investigations in the Livermore Valley Region, California, Part I: Geologic Setting and P-Velocity Models*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53169.
- Scheimer, J. F., M. L. Sharp, and S. R. Taylor (1982), *Seismological Investigations in the Livermore Valley Region, California, Part II: Seismicity of the Livermore Valley Region, 1900–1981*, Lawrence Livermore National Laboratory, Livermore, CA (in progress).
- Shakal, A. F., and R. C. Murray (1981), *Earthquake Strong-Motion Instrumentation at Lawrence Livermore National Laboratory*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53246.

D. W. Carpenter *et al.* (1982) have written a companion to this publication entitled *Geologic Data Report, Lawrence Livermore National Laboratory Site*, which has been prepared and issued in limited quantities. This report contains the detailed logs of exploratory trenches, boreholes, excavations, and other exposures studied during this investigation. Copies of the report have been provided to peer and independent review board personnel, as well as to several public agencies (listed in Appendix F). A copy has also been placed in a public file at the LLNL Visitor's Center, where it may be consulted by interested parties.

Lawrence Livermore National Laboratory Site

The LLNL site is in the southeastern portion of the Livermore Valley, approximately 65 km (40 mi) east of San Francisco. It is located in Sec. 12 (projected), T3S, R2E, Mt. Diablo Base and Meridian. The site and its environs are shown on the map in Fig. 1.

Physiographic Setting

LLNL has been constructed on a rather smooth land surface that slopes gently downward to the northwest. Elevations within the laboratory vary from a low of 174 m (570 ft) at the northwest corner of the site to 206 m (675 ft) at the southeast corner. Total relief is 32 m (105 ft) over a distance of 1.9 km (6234 ft). Slopes on the site are relatively uniform and generally do not exceed 3%. Exceptions are the banks of the Arroyo Seco Channel and the side slopes of various open drainage ditches within LLNL. These slopes average about 50%. Site topographic features are shown in Fig. 2.

The southwestern part of LLNL is drained by Arroyo Seco Creek, a minor stream that flows briefly, following major winter storms. The northern and eastern parts of LLNL were originally drained by the Arroyo Las Positas. However, in 1965, as part of an erosion control program, the Arroyo Las Positas was channeled north to the northeast corner of the site and from there west along the north perimeter to an outlet at the northwest corner. This outlet, which also serves as the outlet for the laboratory's surface drainage system (storm and irrigation), empties into a channel that runs north to the Western Pacific Railroad tracks and then westward to a junction with the Arroyo Seco.

Livermore Valley itself is an east-west oriented topographic and structural depression that trends at nearly right angles to the strike of the Central California Coast Ranges within which it is located. The valley is approximately 25 km (16 mi) long (east to west) and averages 11 km (7 mi) in width (north to south). It rises gradually from an approximate elevation of 92 m (302 ft) at the drainage exit along the Arroyo de Laguna southwest of Pleasanton to an approximate elevation of 220 m (722 ft) along its eastern margin.

The relief of the Livermore Valley is slight except for occasional hills, which rise to about 46 m (150 ft) above the valley floor. One group of such hills is located about 1 km (0.6 mi) south of LLNL. A second group of hills is located approximately 3.4 km (2 mi) northwest of the laboratory. Geologic studies [California Department of Water Resources (CDWR), 1966, 1974; Herd, 1977] indicate that some of these hills are results of uplifts of older materials along faults.

The Livermore Valley is drained by westward-flowing intermittent streams. These streams join west of Pleasanton (see Fig. 1) to form the south-flowing Arroyo de Laguna, a tributary to the Alameda Creek drainage system. Winter flows that are not captured and used for groundwater recharge flow out of the valley and eventually enter San Francisco Bay at Union City by way of Alameda Creek.

The natural Livermore Valley drainage system was originally somewhat restricted. Storm runoff periodically overflowed and formed a shallow intermittent lake where northwestern Pleasanton is now located. Near the beginning of this century, the lake was drained to permit agricultural development, and additional drainage works were later constructed to permit urbanization. An area of enclosed drainage still exists in the northeastern Livermore Valley, where winter stormflows accumulate in an intermittent pond known as Frick Lake.

Geologic Setting

The Livermore Valley is located within the California Coast Range Province. The Coast Range Province consists chiefly of a system of subparallel mountain ranges and valleys that mostly trend north-northwest. The Livermore Valley itself is an exception; it lies within the Diablo Range as an east-west trending structural basin.

The regional pattern of northwest-trending Coast Range relief aligns with the majority of active faults and reflects the regional deformation that the province is experiencing. While many of the faults are relatively minor, there are three major fault systems that have been fundamental in the tectonic history of the province. These are the San Andreas, the Sur-Nacimiento, and the Coast Range thrust. These fault

Fig. 1. Location of Lawrence Livermore National Laboratory (LLNL).

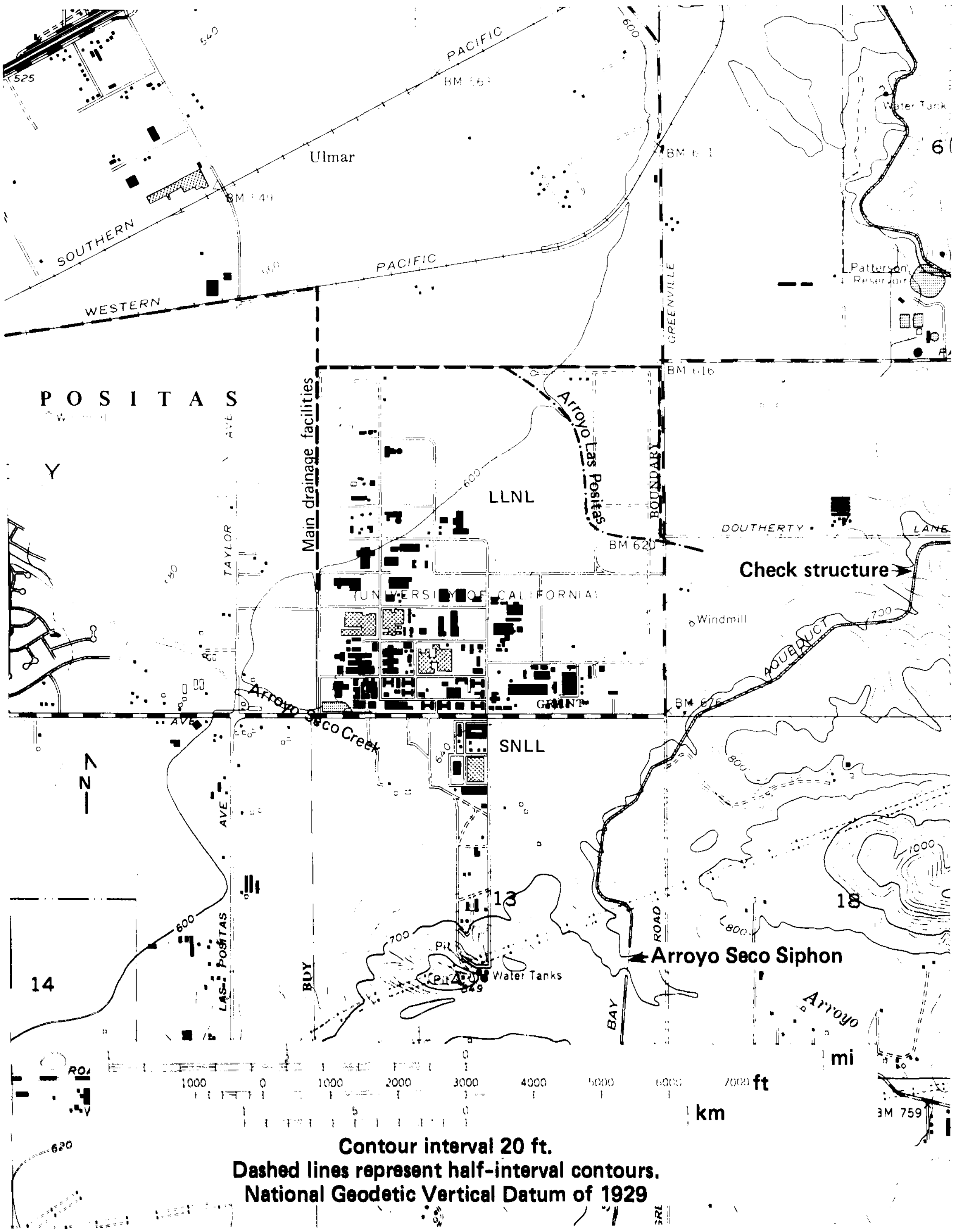

Fig. 2. Topographic setting of LLNL site (from U.S. Geological Survey, Altamont, CA, 7.5 min. Quadrangle, 1968 edition).

systems delineate three completely different lithologic blocks. As shown in Fig. 3, the Salinian Block lies between the Sur-Nacimiento and the San Andreas Faults and is composed primarily of granitic and metamorphic rocks. The second block lies to the east between the San Andreas and the Coast Range thrust fault and is composed primarily of deformed marine clastic and volcanic rocks of the Franciscan Assemblage. The third block consists of late Mesozoic through late Tertiary marine sedimentary rocks ("Peripheral Rocks" in Fig. 3) deposited on a complex basement of ancient oceanic and continental crust. This block lies mainly along the eastern margin of the Coast Range Province, but in places (for instance, the East Bay Hills west of Livermore Valley) remnants of this block are preserved within the core of the Coast Range Province. The stratigraphic column for these rocks, modified from Huey (1948) and pertinent to the Livermore Valley Region, is presented in Fig. 4.

The juxtaposition of these three distinct lithologic blocks presents structural and chronologic problems that have not been completely resolved. Many problems arise from the complexity of the Franciscan Assemblage and its unusual contacts with the surrounding rocks.

The Franciscan Assemblage (otherwise known as a Complex or Formation) is composed of graywacke, metagraywacke, shale or argillite, blueschist, greenstone, some chert and limestone, and mafic and igneous rocks forming a lithologically heterogeneous and structurally complicated unit. In most areas of exposure, the unit has been extensively deformed and dismembered into a melange.

The Franciscan Assemblage forms the basement rock in the Livermore Valley region and is exposed to the north in Mt. Diablo and to the south in the Diablo Range (Fig. 3).

Structurally overlying the Franciscan Assemblage is the Great Valley Sequence [or Great Valley Group (Ingersoll, 1981)] consisting of stratified sedimentary clastic rocks that have been little deformed and affected only by mild burial metamorphism. Great Valley Sequence rocks are exposed on the flanks of the Diablo Range and Mt. Diablo. They are also exposed east of Livermore Valley in the Altamont Hills and to the west in the East Bay Hills. Along the eastern edge of the Coast Ranges the Great Valley Sequence is generally exposed as an eastward dipping homocline.

No simple depositional contact has ever been observed between the contemporaneous Jurassic-to-Cretaceous-age (Fig. 4) Franciscan Assemblage and Great Valley Sequence rocks (Dickinson, 1965). The contact surface is commonly a juxtaposition of rocks of different layering attitudes and degrees of metamorphism. For this reason, the contact is generally considered to be a fault, usually referred to as the Coast Range thrust. Highly altered mafic and ultramafic rocks are found along the fault surface, and a klippe of the Great Valley Sequence overlying the Franciscan has recently been mapped in the Diablo Range (Bauder and Liou, 1979).

Structural, petrologic, and plate tectonic considerations suggest that the Franciscan Assemblage is an accretionary prism formed at the leading edge of an east-dipping subduction zone that existed off the coast of western North America during the late Mesozoic (Hamilton, 1969; Ernst, 1970; Hsu, 1971). The Great Valley Sequence is thought to have formed in a late Mesozoic forearc basin separating a westward-lying trench (in which the Franciscan was accumulating) from an eastward-lying Andean-type arc in the Sierras. The ultramafic and mafic rocks that commonly separate these two sequences represent the oceanic crust and the upper mantle lying below the base of the Great Valley Sequence. Probably beginning in the late Jurassic and continuing into Tertiary time, the Franciscan Assemblage was subducted beneath the oceanic crust and the Great Valley Sequence. The Coast Range Thrust may mark the location of the subduction zone or be related to overthrusting of the Great Valley Sequence following cessation of subduction (Page, 1981).

In most places this fault has itself been affected by subsequent folding, thrusting, or high-angle faulting during and after later Tertiary time. The Tesla and Ortigalita Fault Zones, located to the southeast of Livermore Valley, are remnants of this major structural and lithologic boundary.

Eocene-Upper Miocene marine sediments occur within the Livermore Valley and outcrop in the Altamont Hills to the east, and the East Bay Hills to the west (Fig. 5). The units studied as part of this investigation can be significantly deformed and are primarily composed of sandstones and shales, with some tuffs and conglomerates (Sweeney and Springer, 1981). These units unconformably overlie Upper Cretaceous rocks of the Great Valley Sequence (Huey, 1948; Dibblee and Darrow, 1981). The Tertiary sequence contains abundant volcaniclastic sediment, whose source was probably in the Sierras (Page, 1966) or in one of the other volcanic centers existing in Miocene time (Dickinson and Snyder, 1979). The sediments probably accumulated in a forearc basin differing slightly in structure from the Mesozoic basin in which the Great Valley Sequence was deposited (Dickinson and Seely, 1979). Exploratory drill holes

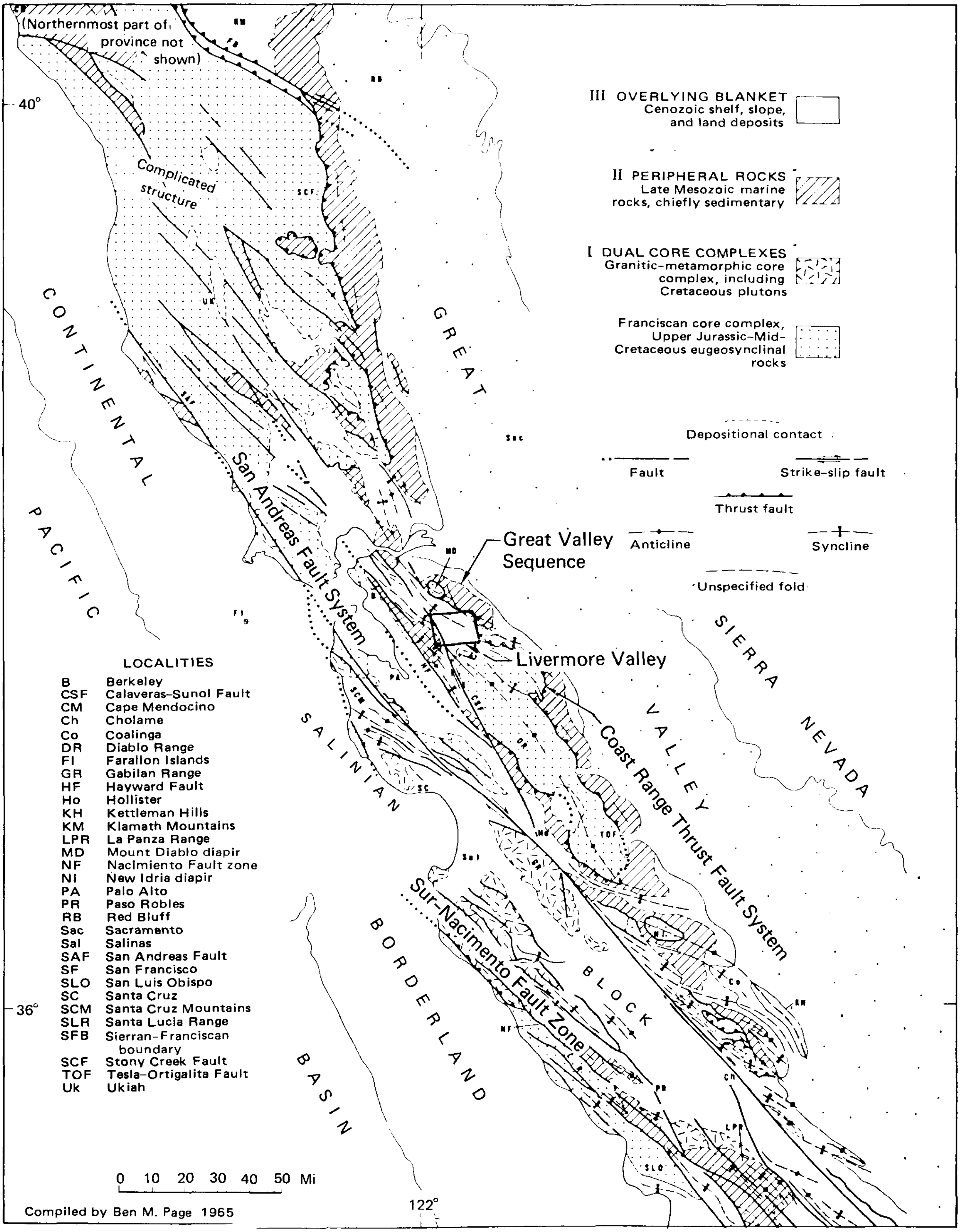

Fig. 3. Structure of the Coast Range Province (modified from Page, 1966).

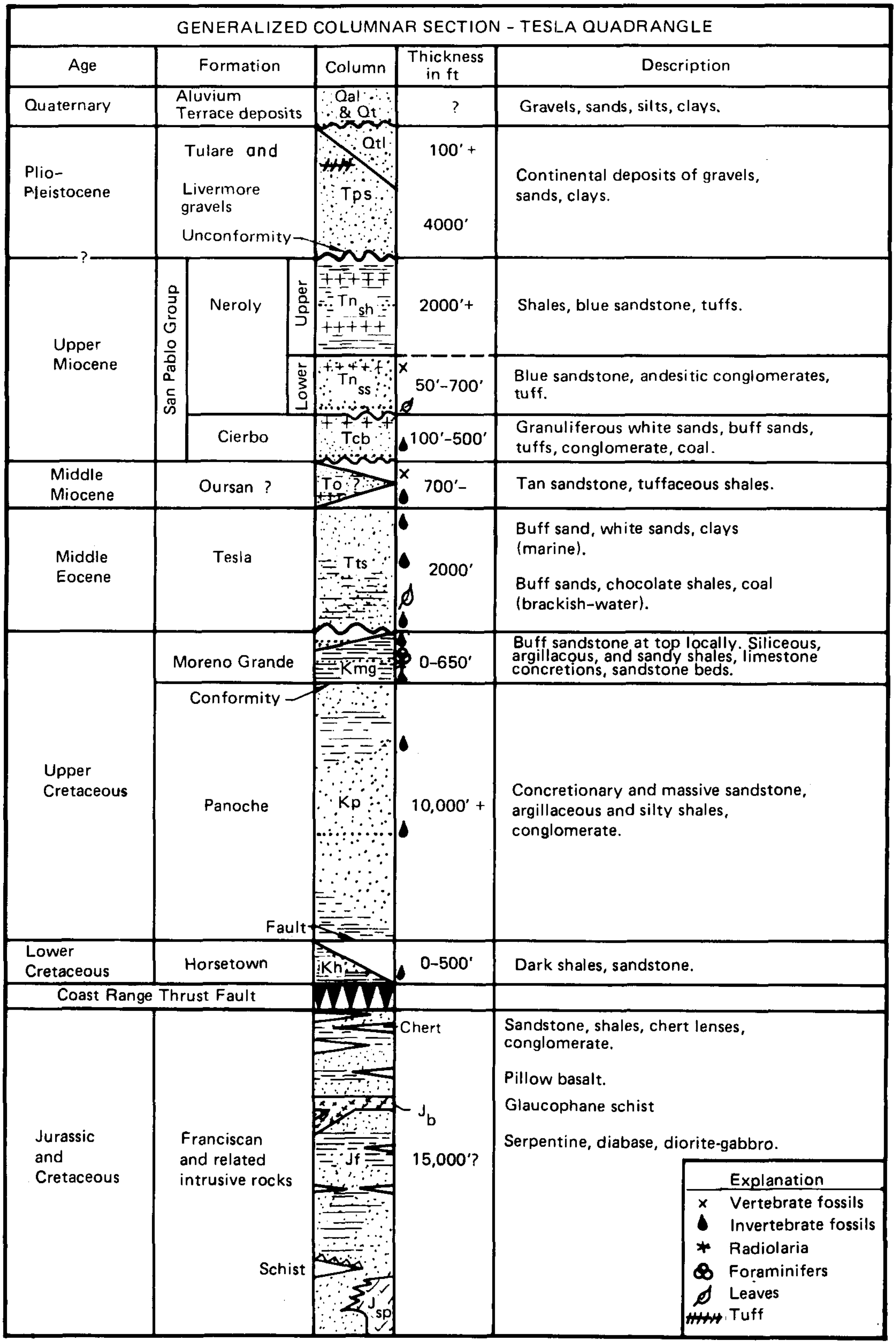

Fig. 4. Stratigraphic column for the Livermore Valley (modified from Huey, 1948).

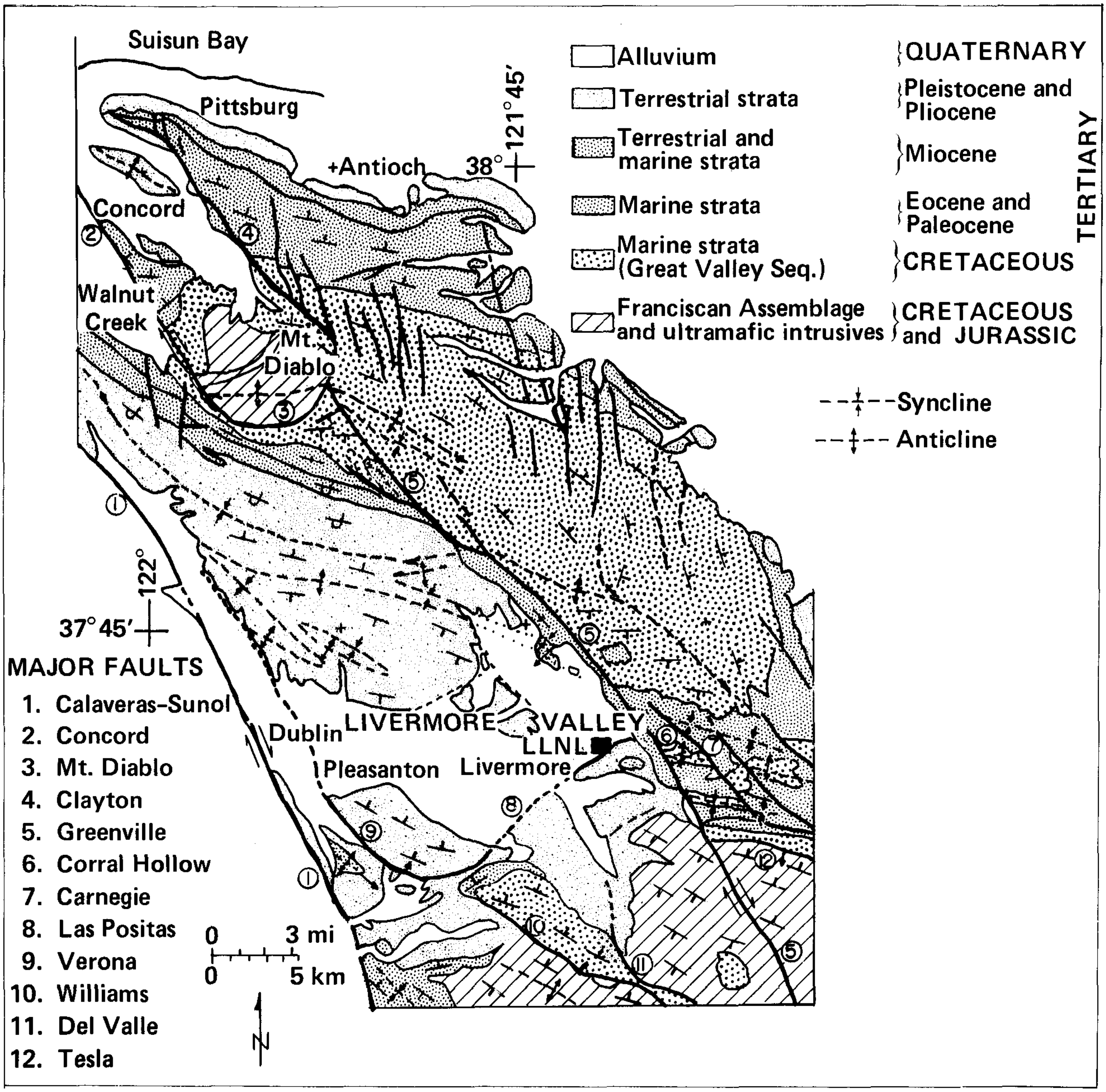

Fig. 5. Simplified geological map of the Livermore Valley area (after Dibblee and Darrow, 1981).

just north of the Livermore Valley indicate that the entire Cenozoic basin-fill sequence exceeds 5 km (3 mi) in depth (Dibblee and Darrow, 1981).

The youngest lithologies in the Livermore area are the Pliocene to Holocene lacustrine and fluvial deposits. These mostly coarse-grained sediments are poorly consolidated and are composed mainly of Franciscan debris eroded from the Diablo Range. These deposits locally exceed 1.2 km (4000 ft) in thickness (CDWR, 1974). The alluvial deposits rest unconformably on deformed Tertiary rocks. They exhibit minor folding and are downwarped towards the valley center, suggesting synorogenic deposition (Carpenter *et al.*, 1980).

The mid-Cretaceous-to-Tertiary tectonics of Northern California are dominated by the northward passage of the Mendocino triple junction and a transformation from subduction to transform motion

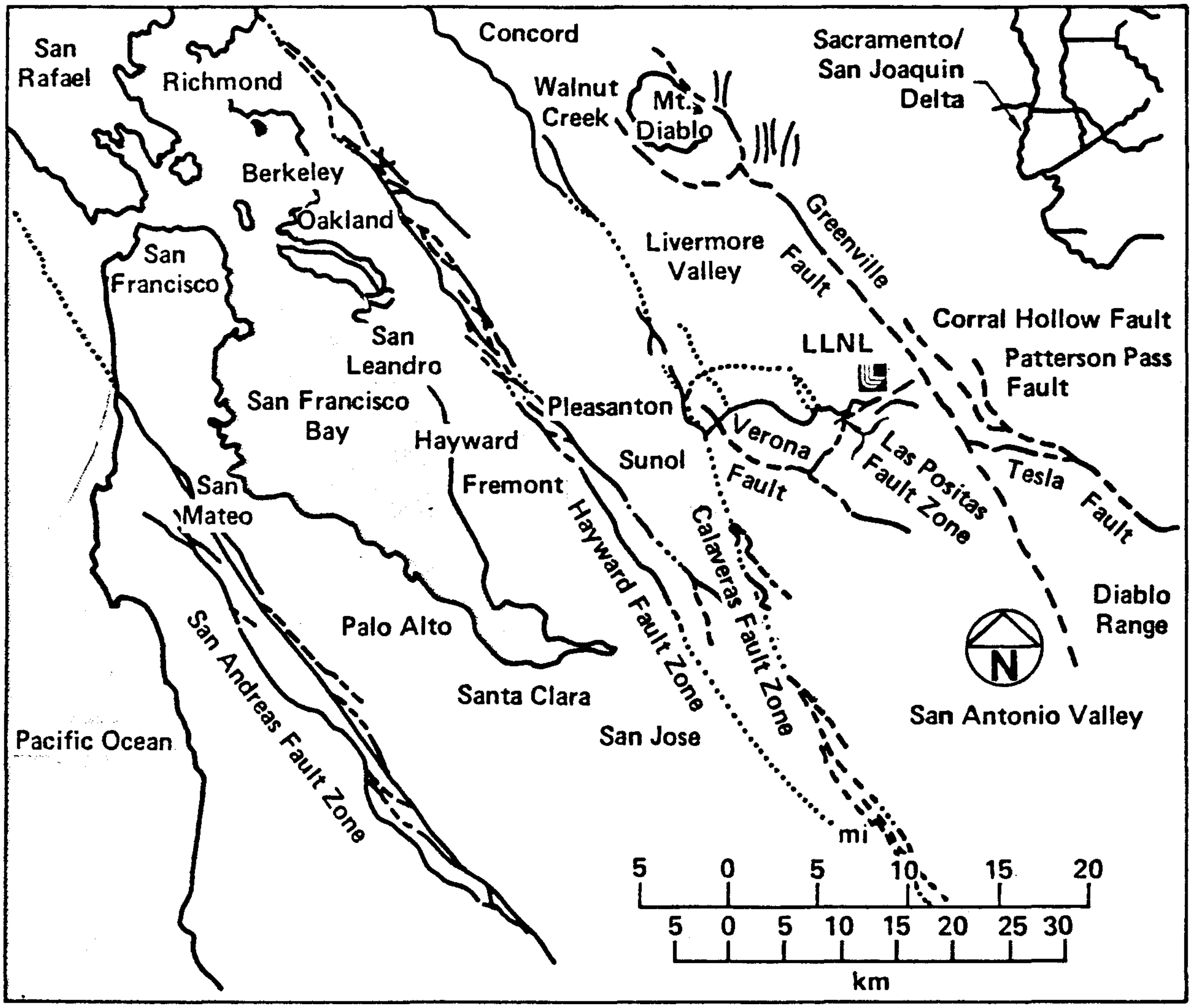

Fig. 6. Major fault zones of the San Francisco Bay Area.

between the Pacific plate and North America (Atwater, 1970; Dickinson and Snyder, 1979). The northward migration of the Mendocino triple junction resulted in extensional deformation associated with rapid subsidence of local sedimentary basins and local volcanic activity (Dickinson and Snyder, 1979; Blake *et al.*, 1978). This time period was also accompanied by renewed uplift of the Coast Ranges and inception of movement along the San Andreas Fault system.

The San Andreas Fault and its associated branches are one of the best known geologic features of the Coast Range Province. The fault system extends at least 1200 km (750 mi) from the Gulf of California north to Shelter Cove, CA (Wesson *et al.*, 1975). Based on a paleogeographic reconstruction of the depositional site of the Cantua sandstone (Nilsen, 1979), approximately 305 km (190 mi) of post-Eocene right-lateral displacement has occurred along the San Andreas Fault. Activity continues today along this major fault system and its principal branches, the Hayward and Calaveras Fault Zones (Figs. 5 and 6). These faults, described in more detail in the following section, probably began moving when the triple junction passed the latitude of the Livermore region about 6 million yr ago (Atwater, 1970). This correlates in time with the change from marine to continental deposition in the Livermore region and the initiation of subsidence of the Livermore basin.

Major Active Bay Area Faults

Major active faults in the San Francisco Bay Area include the San Andreas Fault System and two of its principal branches, the Calaveras and Hayward Fault Zones.* The Calaveras Fault Zone traverses the western margin of Livermore Valley and is, therefore, of local as well as regional interest. Locations of these major regional Fault Zones are shown in Figs. 3 and 6.

The Concord-Green Valley Fault Trend and the Greenville Fault Zone represent other major active Bay Area faults. The Concord-Green Valley Fault Trend may be tectonically related to the Calaveras Fault Zone, but it is separated from it by a distance of several kilometers (Earth Sciences Associates, 1982).

San Andreas Fault

The 1200-km-long (750-mi) San Andreas Fault System passes approximately 58 km (36 mi) southwest of LLNL at its point of closest approach. This system has generated two great earthquakes during recorded California history (Wesson *et al.*, 1975; Sieh, 1978).

Jennings (1975) indicates evidence for historic ground movement along most of the mapped traces of the San Andreas Fault, and Sieh (1978) provides evidence for repeated faulting at Pallett Creek in Southern California. Sieh determined that nine events disturbed the Pallett Creek site during the period extending backwards from the 19th to the 6th century, A.D. The average recurrence interval for earthquakes large enough to cause surface faulting was 160 yr, but varied from about a half century to roughly three centuries (Sieh, 1978).

The great San Francisco Earthquake of 1906 caused structural damage in Livermore Valley communities (Lawson *et al.*, 1908; Nason, 1982) and resulted in two instances of ground failure along the northern margin of Livermore Valley [Youd and Hoose, 1978; Nason, 1982 (locations 166 and 167 in Fig. 7)]. Neither of these cases involved the LLNL site.

Wesson *et al.* (1975) used empirical length-magnitude relationships to predict a maximum probable earthquake of magnitude 8.5 for the San Andreas Fault System. Wight (1974) estimated that an earthquake of magnitude 8.3, the largest in history experienced on the San Andreas Fault, could generate a peak bedrock acceleration of 0.4 g at LLNL.

Recent trilateration studies performed in the San Francisco Bay region (Prescott *et al.*, 1981) indicate strain accumulation along the San Andreas Fault equivalent to about 12 mm of right-lateral slip annually. Based on historical precedents, this strain energy will some day be released during a major earthquake.

Hayward Fault

The Hayward Fault is located generally along the eastern margin of the San Francisco Bay plain and passes about 26 km (16 mi) southwest of LLNL at its closest approach (Fig. 6). The length of the Hayward Fault Zone has been estimated as 72 km (45 mi) by Wesson *et al.* (1975). Other estimates (Slemmons and Chung, 1982) hypothesize the Hayward Fault Zone being as long as 280 km (175 mi), if its hypothesized northern extension is included.

Historic accounts of strong earthquakes along the Hayward Fault Zone in 1836 and 1868 (Slemmons and Chung, 1982) provide evidence for its activity. Right-lateral tectonic creep (Slemmons and Chung, 1982) and microseismic activity (Ellsworth and Marks, 1980) have been documented along the Hayward Fault Zone in recent years.

Trilateration studies (Prescott *et al.*, 1981) indicate that strain equivalent to about 7 mm (0.3 in.) of right-lateral slip is imposed on the Hayward Fault Zone annually. Their studies indicate that this strain is

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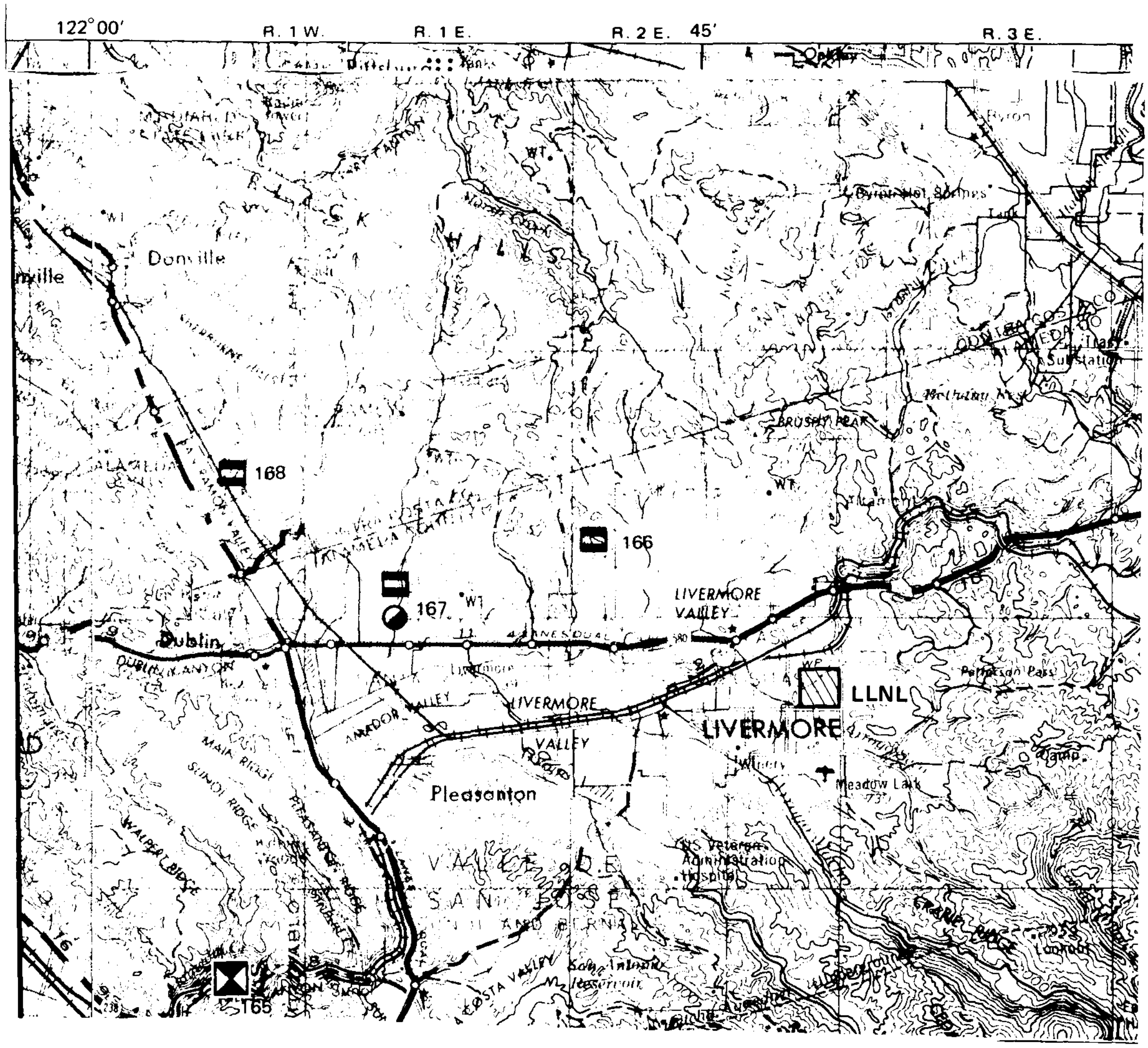
* Various criteria have been proposed to define what an "active fault" is for seismic hazard assessment. Suggestions for definitions have been made by the California State Mining and Geology Board (Hart, 1980b) for most classes of construction and by the U.S. Nuclear Regulatory Commission for commercial nuclear power reactors (10 CFR, Part 100). The State of California definition maintains that a fault shall be considered active if it shows evidence of most recent displacement within the last 11,000 yr of Earth history. The USNRC defines a fault as active if it shows evidence of a single displacement within the last 35,000 yr or multiple displacements within 500,000 yr. After considerations of these definitions, the Site Seismic Safety Project staff has decided to consider a fault as active if it shows evidence of having displaced materials approximately 35,000 yr or younger in age. It should be noted that this definition of an active fault is the same as that adopted by the U.S. Army Corps of Engineers for evaluation of critical facilities for which it has responsibility.



Scale 1:250 000

5 0 5 10 15 20 mi

5 0 5 10 15 20 25 30 km

Contour interval 200 ft
with supplementary contours at 100-ft intervals.
Transverse mercator projection

Fig. 7. Locations of reported historical ground failures within the Livermore Valley and nearby areas. The failures shown resulted from the great San Francisco earthquake, April 18, 1906 (locations 165-167), and from an earthquake in 1861 (location 168), probably on the Calaveras Fault (from Youd and Hoose, 1978). Location 165 was a case of railroad tunnel distress and change in tunneling conditions. Locations 166 and 168 were cases of random ground fracturing not clearly associated with landsliding, lateral spreads, settlement, or primary fault movements. Location 167 included a minor streambank slump.

being relieved by tectonic creep along strands of the Hayward Fault and by periodic small-to-moderate earthquakes such as the magnitude (M_L) = 4.1 event that struck the Niles District of Fremont, CA, on March 3, 1981, and the M_L = 3.2 event on March 26, 1982, near San Leandro, CA.

The October 22, 1868, earthquake caused surface faulting along the Hayward Fault Zone from the Warm Springs District in Fremont northward to San Leandro and possibly as far as Berkeley (cf. Fig. 6) (Wesson *et al.*, 1975). Ground failures as far away as San Francisco were caused by this earthquake. None, however, were reported from the Livermore Valley, which was then sparsely settled (Youd and Hoose, 1978).

Wesson *et al.* (1975) indicate a maximum probable earthquake of magnitude 7.0 for the Hayward Fault Zone, based on empirical length-magnitude relationships. By using a variety of methods, Slemmons and Chung (1982) estimated the maximum credible earthquake for the Hayward Fault Zone (including northerly extensions) to be $M_s = 7 \pm 0.25$. The earthquake on October 22, 1868, is believed to have had a magnitude of 7 ± 0.5 (Wesson *et al.*, 1975) and was, therefore, probably a near-maximum event for the Hayward Fault Zone. Wight (1974) estimated that an earthquake on the Hayward Fault of magnitude 7.5, at a distance of 42 km (26 mi) from LLNL, could generate a peak bedrock acceleration of 0.35 g at the laboratory.

Calaveras Fault

The Calaveras Fault Zone branches from the San Andreas system near Hollister (a short distance south of the limits of Fig. 6) and trends northwest to the San Ramon Valley—a distance of about 115 km (72 mi) (Wesson *et al.*, 1975). Slemmons and Chung (1982) linked the Calaveras and Concord-Green Valley Fault Zones, creating a zone about 280 km (175 mi) long. Most other investigators have not linked these faults, and some (Shedlock *et al.*, 1980) have restricted the length of the Calaveras Fault Zone more than did Wesson *et al.* The Calaveras Fault Zone forms the western margin of Livermore Valley and is located about 17 km (11 mi) west of LLNL at its closest approach (Figs. 5 and 6).

The Calaveras Fault Zone has been historically active and a major earthquake in 1861 (estimated magnitude 6+) within either the Livermore or San Ramon Valley has been attributed to it (Radbruch, 1968; Fig. 8). Evidence for Holocene and probably historic surface faulting has been seen along the Calaveras Fault in the Dublin area (Burkland and Associates, 1975c; Earth Sciences Associates, 1971) and in the vicinity of the Castlewood Country Club, southwest of Pleasanton (Judd Hull and Associates, 1975). Hart (1980a) has questioned whether the geologic features seen in the Castlewood Country Club area are actually the result of faulting. Revised maps issued by the State of California (Davis, 1982a) have deleted strands of the Calaveras Fault Zone from the floor of the Livermore Valley in favor of traces on the easterly flank of Pleasanton Ridge about 1 km (0.6 mi) to the west (Fig. 8).

Ground failure appears to have occurred in the San Ramon area during the 1861 earthquake (location 168 on Fig. 7; Youd and Hoose, 1978).

The Calaveras Fault constitutes a groundwater barrier in the Dublin area (Burkland and Associates, 1975c), with water levels higher on the west side of the fault zone. Displaced stream channels and topography in the Dublin area indicate dominantly right-lateral strike-slip movement along the Calaveras Fault Zone, but with some uplift west of the fault. Up to 15 mm (0.6 in.) per year of right-lateral tectonic creep has been measured along the segment of the Calaveras Fault Zone south of Sunol (Wesson *et al.*, 1975; Page, 1982) and considerable microseismicity is associated with this portion of the Calaveras Fault Zone (Ellsworth and Marks, 1980). North of Sunol microseismic activity is sparse and tectonic creep has not been detected (Ellsworth and Marks, 1980).

A moderate earthquake (M = 5.7) occurred on the Calaveras Fault near Coyote Reservoir north of Gilroy on August 6, 1979 (Kerr, 1979). The earthquake struck in a lightly populated area and caused relatively little damage. Minor surface faulting occurred in the vicinity of the epicenter (Kerr, 1979). An M_L = 4.0 earthquake occurred on August 24, 1982, on the Calaveras Fault near Calaveras Reservoir southwest of Livermore Valley. This earthquake was felt in the Livermore Valley and southern San Francisco Bay areas, but caused no damage or casualties.

A larger earthquake ($M_L = 6.0\pm$) occurred on April 24, 1984, along the Calaveras Fault northeast of Morgan Hill, Ca. This earthquake struck closer to populated areas than the previous two events and therefore caused significant structural damage to homes and other buildings at several locations near Morgan Hill.

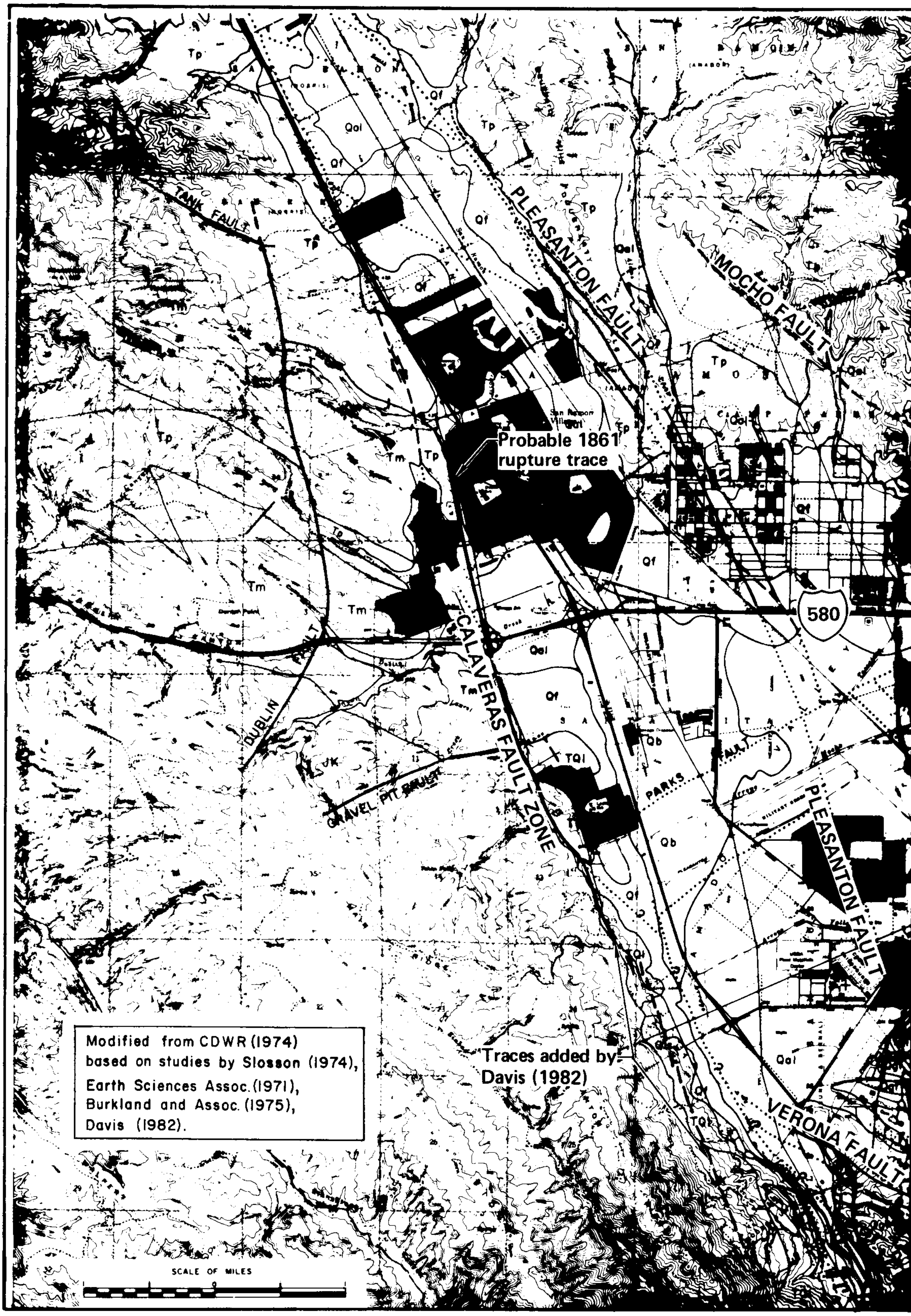


Fig. 8. Faults in the western Livermore Valley (adapted from CDWR, 1974).

Wesson *et al.* (1975) indicate a maximum probable earthquake of magnitude 7.3 for the Calaveras Fault Zone based on empirical length-magnitude relationships. Slemmons and Chung (1982) used various methods to estimate the maximum credible earthquake for the Calaveras Fault Zone (conservatively assumed to include the Concord-Green Valley Fault Trend) as $M_s = 7 \pm 0.25$. Wight (1974) estimated that an earthquake on the Calaveras Fault of 7.5 magnitude at a distance of 17 km (11 mi) could generate a peak bedrock acceleration of 0.5 g at LLNL.

Trilateration studies by Prescott *et al.* (1981) indicate that strain equivalent to about 7 mm (0.3 in.) of right-lateral slip is being imposed on the Calaveras Fault Zone and a region extending a few kilometers on either side of it. Available data suggested to Prescott and his colleagues that the strain energy is being dissipated through tectonic creep and small earthquakes.

Concord-Green Valley Fault Trend

The Concord-Green Valley Fault Trend extends from the southwest flank of Mt. Diablo (Fig. 6) northwest to the vicinity of Wooden Valley in the mountains east of Napa (Fig. 1). The trend is defined by two distinct faults, the Concord Fault south of Suisun Bay and the Green Valley Fault and its branches north of the Suisun Bay (Earth Sciences Associates, 1982).

The Concord Fault was first mapped and described by Sharp (1973). The fault has an exposed length of about 18 km (11 mi) from its south end to the point where it becomes concealed by marsh deposits south of Suisun Bay. Displacement along it is right-lateral with an east-side-up component.

Sharp (1973) documented episodes of intermittent tectonic creep along the Concord Fault. Galehouse (1981) also recently reported that about 1 cm (0.4 in.) of right slip occurred along the Concord Fault between the times of surveys in October and November 1979, but that the fault had not moved perceptibly since then.

In 1955 an earthquake of 5.4 magnitude occurred between Walnut Creek and Concord. The Concord Fault was the probable source of this earthquake although no surface faulting was observed (Wesson *et al.*, 1975).

Earth Sciences Associates (1982) suggested that the Concord Fault appears to be the most active fault east of the San Andreas at the latitude of Concord and that, therefore, some strain from both the Calaveras and Greenville Faults is being transferred to it. Earth Sciences Associates speculated that this transfer may occur via the crustal shortening and uplift of the Mt. Diablo antiform and the diffuse zone of faulting beneath San Ramon Valley that was the apparent source of the Danville earthquake swarm in 1970.

Wesson *et al.* (1975) calculated a maximum probable earthquake of M = 6.3 for the Concord Fault based on empirical length-magnitude relationships. Prescott *et al.* (1981) did not identify any strain accumulation in their trilateration network that could be directly associated with the Concord Fault. However, such strain accumulation could be included in that identified for the Calaveras Fault Zone and its environs.

Strands of the Green Valley Fault Zone extend northward from Suisun Bay to the vicinity of Wooden Valley [a distance of about 28 km (17 mi)]. The Green Valley Fault Zone shows evidence of right-lateral fault line morphology with an east-side-down vertical component (Earth Sciences Associates, 1982). Evidence for tectonic creep along the Green Valley Fault Zone is ambiguous (Earth Sciences Associates, 1982).

Wesson *et al.* (1975) report that historic seismicity (possible M = 4 to 5) is associated with the Green Valley Fault Zone. They calculated a maximum probable earthquake of M = 6.6 for the zone based on empirical length-magnitude relationships.

Earth Sciences Associates (1982) regarded the Concord and Green Valley Faults as separate features for the following reasons:

- Each has a distinctive, persistent strike and these differ by about 11°.
- The two faults do not line up directly. Instead, the Green Valley steps east about 1.5 km (0.9 mi) from a projected northward extension of the Concord.
- The vertical component of movement between the faults is opposite.

Greenville Fault

The Greenville Fault Zone is a major northwest striking zone of faults that extends southeast from Mt. Diablo for about 90 km (56 mi) to San Antonio Valley (see Figs. 5 and 6). Older-appearing strands of the Greenville Fault Zone are located about 425 m (1400 ft) northeast of the northeastern corner of LLNL. A recently active strand of the Greenville Fault Zone is located about 1.1 km (3500 ft) northeast of LLNL.

The Greenville Fault was first referred to as the Riggs Canyon Fault by Vickery (1925). At that time it was mapped as a fault marking the western margin of the Altamont Hills and extending from the east side of Mt. Diablo to about 4.8 km (3 mi) south of Altamont Pass. The Riggs Canyon Fault was included by Clark (1930) in a series of cross sections of the Coast Range; Clark gave it the same location as did Vickery (1925). Huey (1948) used the name "Greenville Fault" for the portion of the Riggs Canyon Fault south of Mt. Diablo. Huey's mapping of the fault at this time was similar to that of Vickery and Clark, and he cited its age as "post-Neroly" (i.e., post-late Miocene).

Herd (1977; see Fig. 9) mapped the Greenville Fault Zone along the eastern boundary of the Livermore Valley and reported geomorphic evidence for recent activity and displacement of his late Pleistocene unit (Qoa_2) along it. He concluded that the Greenville Fault continues southeast of Livermore Valley, buried beneath the Livermore Formation and younger alluvium, and that it truncates the Carnegie and Tesla Faults in that area.

A good exposure described by Huey (1948) of a strand of the Greenville Fault occurs in the Western Pacific Railroad cut in Sec. 25, T2S, R3E. There, horizontal slickensides give evidence for strike-slip displacement. Herd (1977) described the cut, but did not show it as being on a strand of the Greenville Fault.

Unquestionable evidence for activity along the Greenville Fault Zone was provided at 11:00 a.m. PST on Thursday, January 24, 1980, when an earthquake of $M_L = 5.8$ (U.S. Geological Survey) struck approximately 17 km (11 mi) north of Livermore on the Marsh Creek Fault (Cockerham *et al.*, 1980). The earthquake caused discontinuous surface faulting along and near several strands of the Greenville Fault Zone as mapped by Herd (1977) and by Brabb *et al.* (1971). Locations and descriptions of surface faulting were compiled by the U.S. Geological Survey (Bonilla *et al.*, 1980). Further details concerning surface faulting in the region near LLNL were reported by Carpenter *et al.* (1980).

Wight (1974) assumed a length of 42 km (26 mi) for the Greenville-Riggs Canyon Fault Zone based on regional data then available. He computed a maximum earthquake magnitude of 6.7 for the zone, based on empirical fault length-rupture length and length-magnitude relationships developed by Albee and Smith (1966), but did not provide an estimate of peak acceleration at LLNL. Shedlock *et al.* (1980) estimated the maximum earthquake for the Greenville Fault Zone as $M = 6.7$ based on fault length criteria. Earth Sciences Associates (1982) estimated maximum credible earthquakes for each of the three segments of the Greenville Fault Zone recognized during their study. Magnitudes estimated were $M_s = 6.25$ for the Clayton segment located east of Mt. Diablo and north of LLNL and $M_s = 6.5$ for both the Marsh Creek-Greenville and Arroyo Mocho segments. The Marsh Creek-Greenville segment is located northeast and east of LLNL and is the segment closest to the laboratory. The Arroyo Mocho segment is located in the Diablo Range southeast of LLNL. Because of insufficient data, Wesson *et al.* (1975) did not attempt to characterize the activity of the Greenville-Riggs Canyon Fault Zone.

Estimates of the maximum credible earthquake for the Greenville Fault Zone based on present studies are presented in a later section.

Pursuant to the requirements of the Alquist-Priolo Special Studies Zone Act of California, Hart (1981a) described the Greenville Fault as, "... [a] well-defined, more or less continuous fault that extends for 33 mi (52 km) from the Tassajara Quadrangle to the eastern edge of the Eylar Mountain Quadrangle." The report commented on the paucity of evidence for Holocene displacement, except for the area near Livermore Valley where, "...sharp tonal lineaments in Holocene alluvium align with well defined scarps and other recent geomorphic features."

The Greenville Fault as it was mapped by Dibblee (1980a,c,d,e; 1981) extends from the southeast side of Mt. Diablo, along the eastern side of Livermore Valley, into the Diablo Range to the south. Sweeney and Springer (1981) mapped the fault in the Altamont Quadrangle, and additional mapping of the fault zone is shown in Fig. 10. These recent studies show the Greenville Fault as a major young tectonic feature of the area, which truncates or offsets dextrally all other faults and fold trends crossing it, with the exception of branches of the Las Positas Fault Zone which appear to displace some of the older, westerly strands of the Greenville Fault Zone (Fig. 10).

Dibblee and Darrow (1981) describe the Greenville Fault as, "...in part, a zone of closely spaced faults that extends from Mt. Diablo southeastward through the Livermore Valley, into the central Diablo Range for a total distance of some 83 km (52 mi)."

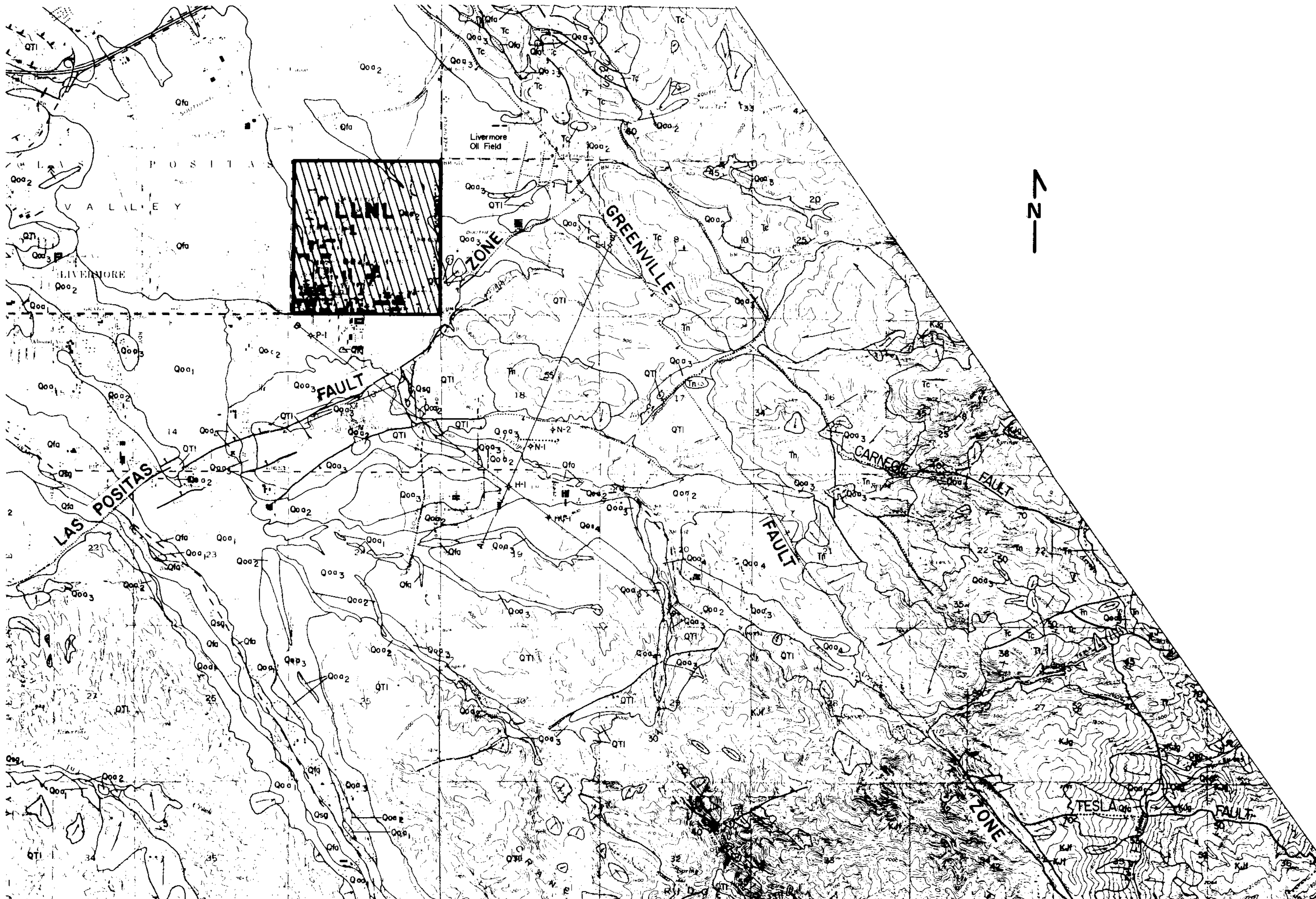


Fig. 9. Geology and faulting, as mapped by Herd (1977), showing the northwest-trending Greenville Fault Zone and the northeast-trendin Las Positas Fault Zone. For Herd's interpretation of geologic cross section A-A' cf. Fig. 25.

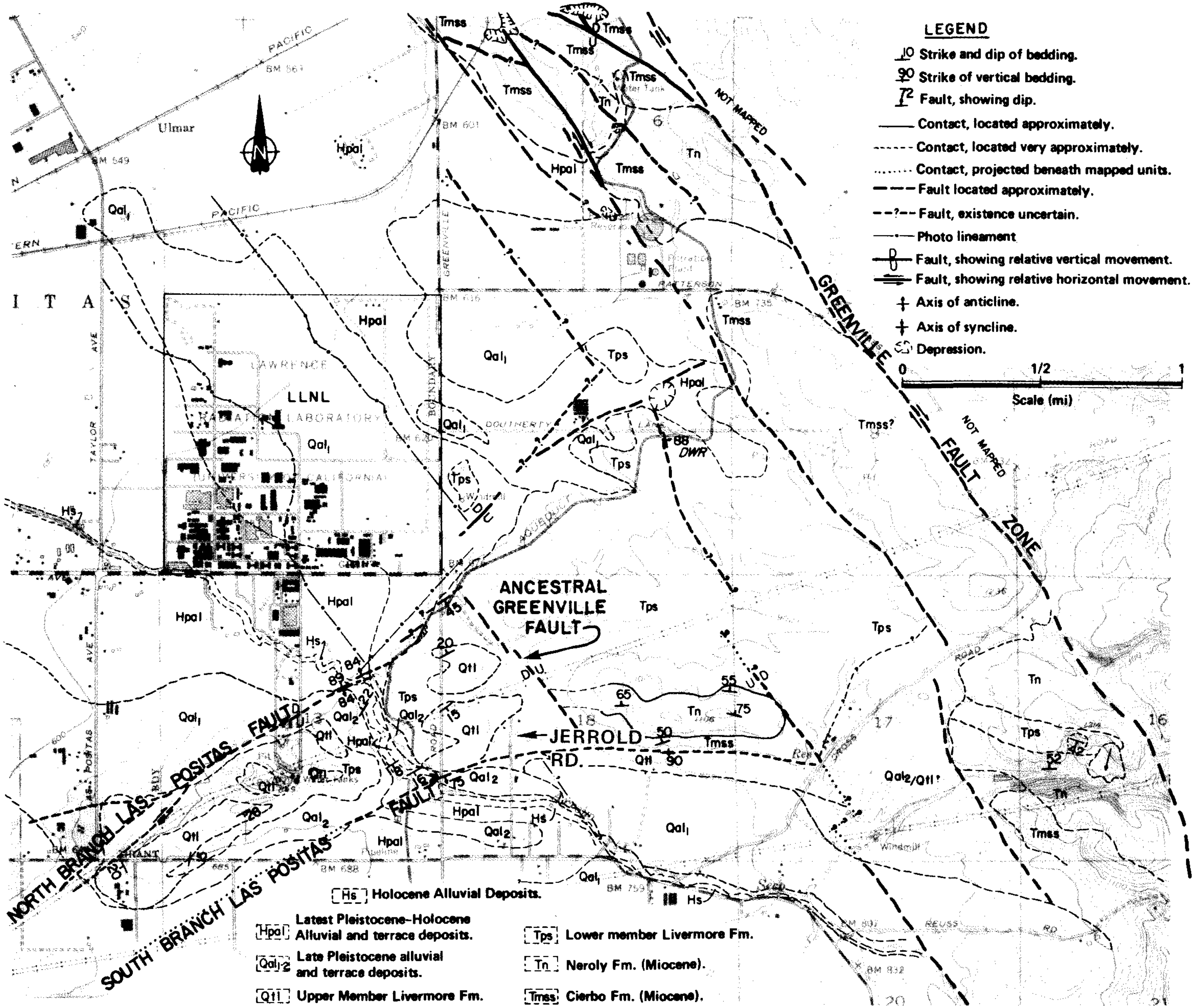


Fig. 10. Geologic map of southeastern Livermore Valley showing the Las Positas and Greenville Fault Zones.

During a seismotectonic study for Contra Loma Dam [located about 1.6 km (1 mi) south of Antioch (Fig. 1)], Earth Sciences Associates (1982) performed an extensive investigation of the Greenville Fault Zone. In the study, Earth Sciences Associates defined the Greenville Fault as a zone containing three distinct segments which they refer to as the Clayton, Marsh Creek-Greenville, and Arroyo Mocho. These segments extend from the Clayton Fault northeast of Mt. Diablo southward at least 90 km (56 mi) to San Antonio Valley within the Diablo Range. The most southerly segment, the Arroyo Mocho, was found to extend from San Antonio Valley 36 km (22 mi) north-northeastward to the southeast corner of Livermore Valley. Based on offset stream terraces, the slip rate on the Arroyo Mocho trend was estimated to be 0.5 to 0.7 mm/yr (0.02 to 0.03 in./yr) (Earth Sciences Associates, 1982). Earth Sciences Associates believed that the Marsh Creek-Greenville segment located north of the Arroyo Mocho segment steps to the east along the east side of Livermore Valley and extends 34 km (21 mi) north to the Clayton Fault. The slip rate on this segment was estimated at 0.1 to 0.3 mm/yr (0.004 to 0.01 in./yr), based on an offset paleosol in ESA exploratory trench G-10 located about 5.3 km (3.3 mi) southeast of LLNL in the south half of Sec. 16, T3S, R3E. Further north the trace of the fault zone then jumps back to the west by about 2 km (1.2 mi) and becomes the Clayton Segment. Earth Sciences Associates (1982) concluded that the Clayton Segment is the currently active northern segment of the Greenville Fault Zone rather than the Concord Fault, as concluded by Dibblee and Darrow (1981).

The extension of the Greenville Fault to the south into the Diablo Range is suggested by a prominent photo lineament recognized by Rogers (1966). The lineament was included in a map by Cotton (1972), and was shown as an approximately located fault by Hanna and Brabb (1979). Dibblee (1981) mapped the lineament as the Greenville Fault in the Mendenhall Springs Quadrangle, and Dibblee and Darrow (1981) showed the Greenville Fault extending well to the south in the Diablo Range (Fig. 6).

The geomorphic expression of the Greenville Fault trace has been studied by Earth Sciences Associates (1982) and Clark (1982). The trace is marked by offset drainages, eroded fault scarps, sag ponds, notches, and other airphoto lineaments indicative of an active fault trace.

On the San Jose Sheet State Map of California (Rogers, 1966) two areas of Mesozoic ultramafic-intrusive rocks are shown in the northeastern part of the Diablo Range (Fig. 11). The northern unit, in the Cedar Mountain Quadrangle, is truncated to the southeast by the aerial photo lineament and the southern one, in the Mt. Boardman Quadrangle, is truncated on the west by the same lineament mapped by Dibblee (1981) as the Greenville Fault and referred to by Earth Sciences Associates (1982) as the Arroyo Mocho segment of the Greenville Fault.

The Cedar Mountain ultramafic unit (serpentinite) has been mapped and interpreted as a dismembered ophiolite by Bauder and Liou (1979). In their interpretation, the ophiolite represents oceanic crust overlain by Great Valley Sequence sediments, and is exposed as a klippe in the midst of Franciscan Assemblage rocks of the Northern Diablo Range (see Fig. 12).

The Red Mountain ultramafic unit (serpentinite) in the Mt. Boardman Quadrangle is exposed in Del Puerto Canyon and was mapped by Maddock (1964). In a more recent study by Evarts (1977) the unit is described as a dismembered ophiolite at the base of the Great Valley Sequence in contact with Franciscan Assemblage rocks along the Coast Range Thrust Fault.

Shown in Table 1 is a comparison of the petrology of the Cedar Mountain (Bauder, 1975) and Red Mountain (Evarts, 1977) ultramafic units. It is clear that, although the Cedar Mountain series has several missing units, the two ultramafic bodies have very similar petrology. Such similar petrology for the two ophiolite units is to be expected and does not conclusively prove that they were once continuous. However, the close proximity of the units and the close match of the shapes of their truncated margins support the hypothesis of Ernst (1971) that the lineament represents a right-lateral fault that has offset a once continuous ophiolite unit.

Aeromagnetic data for the Diablo Range southeast of LLNL (shown in Fig. 13) reveals magnetic highs associated with the Cedar Mountain and Red Mountain ophiolites. The highs are probably related to a higher concentration of magnetic minerals in the serpentinite and ultramafic rocks of the ophiolite units. The sharply truncated boundaries of the magnetic anomalies closely follow the geological boundaries and suggest offset due to faulting. The magnetic high east of Cedar Mountain is associated with a large antiform (see Fig. 14) and may be due to serpentinite near the surface not revealed by erosion.

Stronger evidence for offset along the Greenville Fault in the northern Diablo Range is seen on examination of structures within the Franciscan Assemblage rocks. Figure 14 is a tectonic map based on mapping by Dibblee (private communication, 1981) and work by others, such as Bauder (1975), Cotton

(Continued on p. 26)

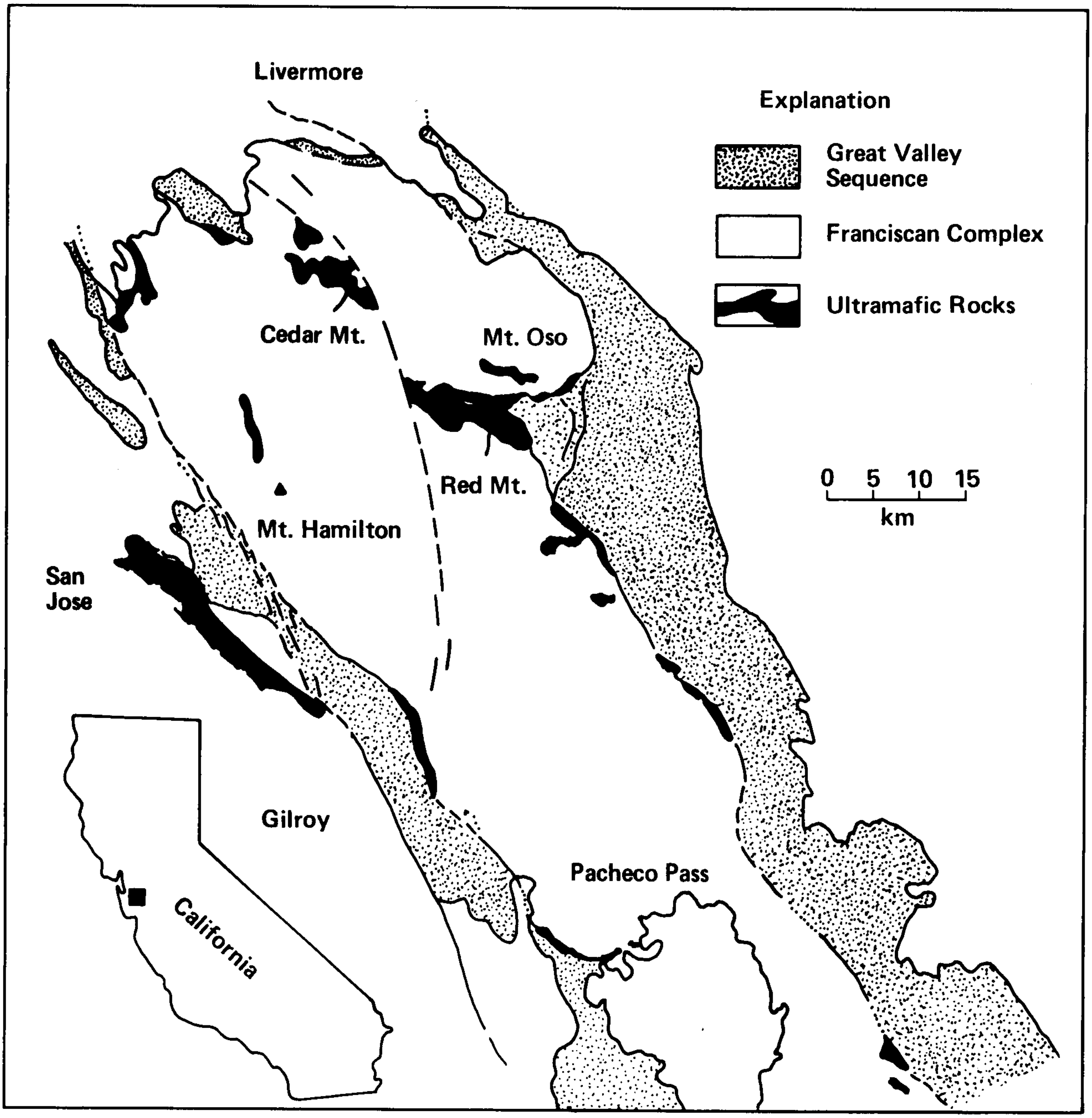


Fig. 11. Map showing locations of ultramafic units within the northern Diablo Range.

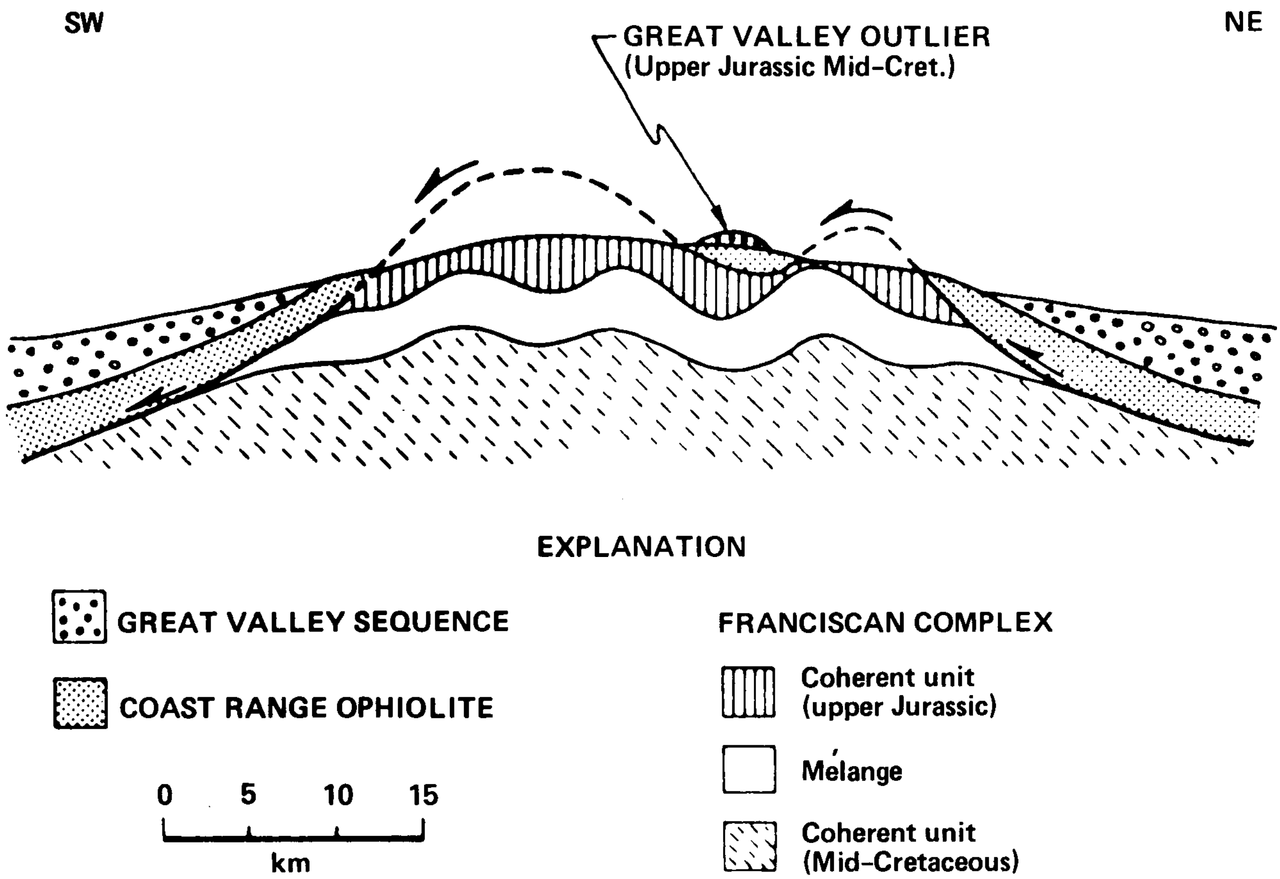


Fig. 12. Diagrammatic cross section through Cedar Mountain in the Diablo Range prior to Neogene high-angle faulting (after Bauder and Liou, 1979).

Table 1. Petrology of the Cedar Mountain and Red Mountain ophiolites.

Cedar Mountain	Red Mountain
Missing	Chert and volcaniclastic sandstone
Minor keratophyre	Volcanic member
	Altered basalts, andesites and dacites
	Quartz keratophyre sills
Gabbroic sections	Plutonic member
Diorites	Hornblende (quartz diorites)
Gabbros (hornblende and plagioclase, cumulus texture)	Hornblende gabbros with pyroxene cumulates
Plagiogranites	Gabbro cumulates with diabase, and plagiogranite intrusives
Dismembered ophiolite (serpentinized alpine ultramafics)	"Alpine peridotite member"
Missing	Black serpentinite
Dunite (contains chromite and interlayers of pyroxenite)	Dunite-wehrlite (partly serpentinized, contains podiform chromites and pyroxenite dikes)
Harzburgite (olivine and orthopyroxene, minor clinopyroxene and chromium spinel, partly serpentinized)	Harzburgite-olivine and orthopyroxene (minor chromium spinel and clinopyroxene, partly serpentinized), highly sheared serpentinite at margins

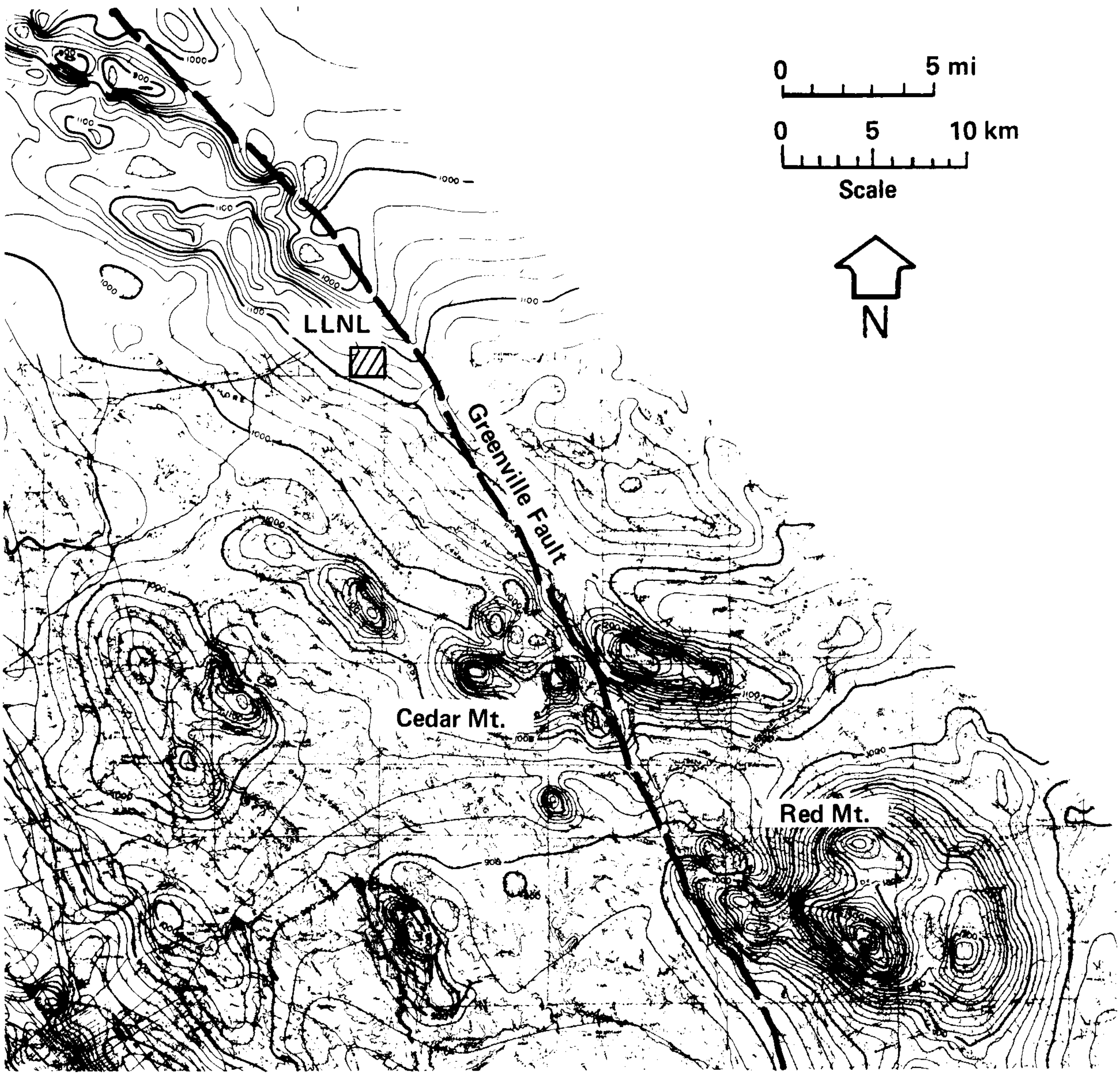


Fig. 13. Magnetic anomaly map of southeastern Livermore Valley and the northeastern Diablo Range. Contours are total magnetic intensity relative to datum (cf. Hanna and Brabb, 1979).

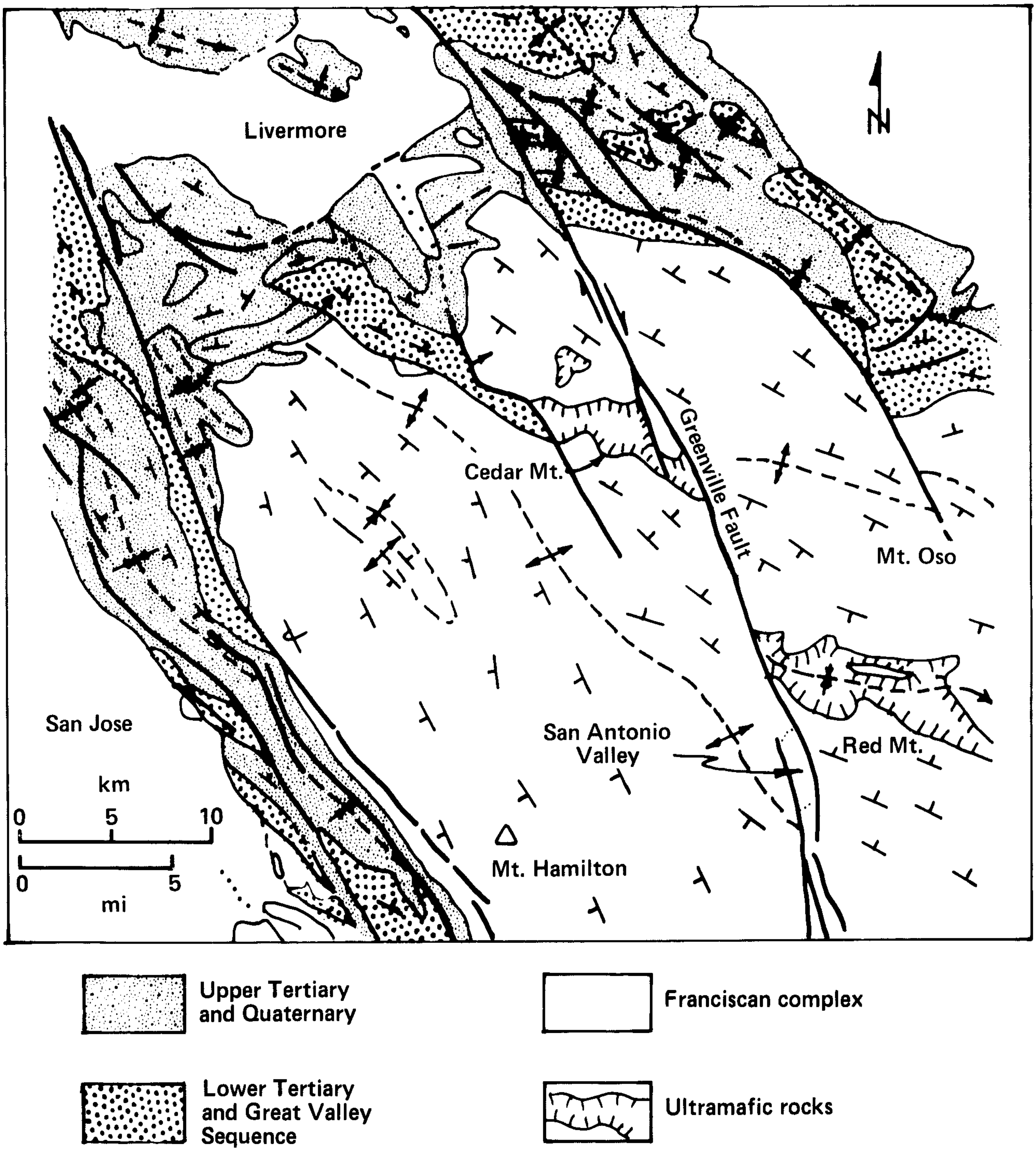


Fig. 14. Simplified geologic map of the northern Diablo Range showing locations of Cedar Mountain and Red Mountain ultramafic units and generalized fold trends.

(1972), Maddock (1964), Soliman (1965), Crawford (1975), and Raymond (1973). As shown in Fig. 14, the Cedar Mountain and Red Mountain ophiolite units occur in the synclinal core of a large fold that has apparently been offset dextrally along the Greenville Fault. When the two sides of the fault are palinspastically restored with the ophiolite units juxtaposed (shown in Fig. 15) the large-scale structural elements match up. Note that San Antonio Valley may possibly represent a pull-apart basin along the Greenville Fault. In Fig. 15, the restored movement along the fault is about 9 km (5.6 mi) along the bearing 327°.

Our investigations into the geomorphic, field, and structural relations of the Greenville Fault lead us to conclude that it extends south into the Diablo Range. The displacement of an ophiolite sequence in the core of a synform suggests at least 9 km (5.6 mi) of dextral movement. The timing of this movement cannot be precisely determined from presently available data. The ultramafic rocks in the Red Mountain ophiolite have been dated at 160×10^6 yr old (Lamphere, 1971), making this the maximum age of faulting. The most reasonable assumption to make is that movement on the Greenville Fault is closely tied with the movement of the San Andreas System. Movement on the San Andreas may have begun as early as the late Eocene Age, as suggested by Dickinson, Ingersol, and Graham (1979). In Fig. 4 of their paper (p. 1469), they show a northerly branch of the "proto" San Andreas Fault that corresponds to the present trace of the Greenville Fault. Interpretations of ocean-floor magnetic lineations (Atwater, 1970) and poles of plate rotation (Minster and Jordan, 1978) indicate a present-day slip rate of 55 mm/yr (2.16 in./yr) along the Pacific Plate-North American Plate boundary. This movement is believed to have been initiated during Miocene time. Projecting the Mendocino triple junction back to the latitude of the northern Diablo Range indicates inception of the fault system in the Bay Area no later than 6.5×10^6 yr ago. The minimum average slip rate on the Greenville Fault, based on the previous arguments, could range from 0.23 mm/yr (0.01 in./yr) (initiation in late Eocene, 40 million years ago) to 1.4 mm/yr (0.05 in./yr) beginning 6.5 million years ago).

Further information about offset on the Greenville Fault is gained from detailed mapping in the Corral Hollow area by Dibblee (1980c,d,e) and Sweeney and Springer (1981). Figure 16 is a geologic map of the area southeast of LLNL based on Dibblee (1980c,d) and modified according to observations by Sweeney and Springer (1981), and more recent work by other LLNL personnel. The youngest materials clearly offset by the Greenville and Corral Hollow Faults are Plio-Pleistocene alluvial deposits (Tps) appearing in the hinge area of an overturned syncline. However, artificial exposures have revealed strands of the Greenville Fault offsetting younger materials including Holocene alluvium (Earth Sciences Associates, 1982). Figures 6 and 16 also show that the Tesla Fault is truncated to the west by the Greenville Fault where Franciscan Assemblage rocks (Kjf) have been offset dextrally.

A more detailed view of the bedrock geology of the area immediately adjacent to LLNL is shown in Figs. 10 and 17. In Fig. 17, an outcrop of Miocene sediments (Tm) occurs on the southerly limb of a syncline about 1 km (0.6 mi) southeast of LLNL. The attitude of the layering and proximity to the syncline of these rocks are quite similar to an outcrop east of the Greenville Fault in Corral Hollow, seen in the southeast corner of Fig. 17. There is an apparent right-lateral offset of the syncline of about 2 km (1.2 mi) along the branches of the Greenville Fault shown in Fig. 17. If an estimate is made of 4×10^6 yr for the age of the Plio-Pleistocene sediments (Tps) in the core of the syncline, the average slip rate for this segment of the Greenville Fault Zone is about 0.5 mm/yr (0.02 in./yr). A tuff bed of about this age is exposed within lower Livermore Formation beds north of Del Valle Reservoir (Dibblee, 1981, Sarna-Wojcicki, 1976).

This analysis is highly subject to the presumed location of the buried syncline east of LLNL and west of the presently active trace of the Greenville Fault Zone. In Appendix B, the discussion of borehole data concludes that 2.5 to 3 km (1.5 to 1.8 mi) of offset of the syncline across the two strands is possible, and that 2 km (1.2 mi) should be considered to be a lower bound. Therefore, the net average horizontal slip rate for the last 4 million years is 0.5 to 0.75 mm/yr (0.02 to 0.03 in./yr) across the Greenville Fault Zone.

Also shown in Fig. 17 are five oil and gas exploration holes south and southeast of LLNL. Wells P1, N1, H1, and HC1 reached Franciscan Assemblage rocks after drilling through 730 to 850 m (2400 to 2800 ft) of Plio-Pleistocene sediments. The drilling thus confirms that the Franciscan Assemblage rocks exposed east of the Greenville Fault in the southeastern corner of the valley shown in Fig. 14 continue at least as far north as the southern boundary of LLNL, buried under Plio-Pleistocene and Holocene materials. Well N2 encountered the Panoche Formation (Great Valley Sequence) under 850 m (2800 ft) of sediments and is, therefore, north of the Tesla Fault, which forms the west-northwest trending boundary

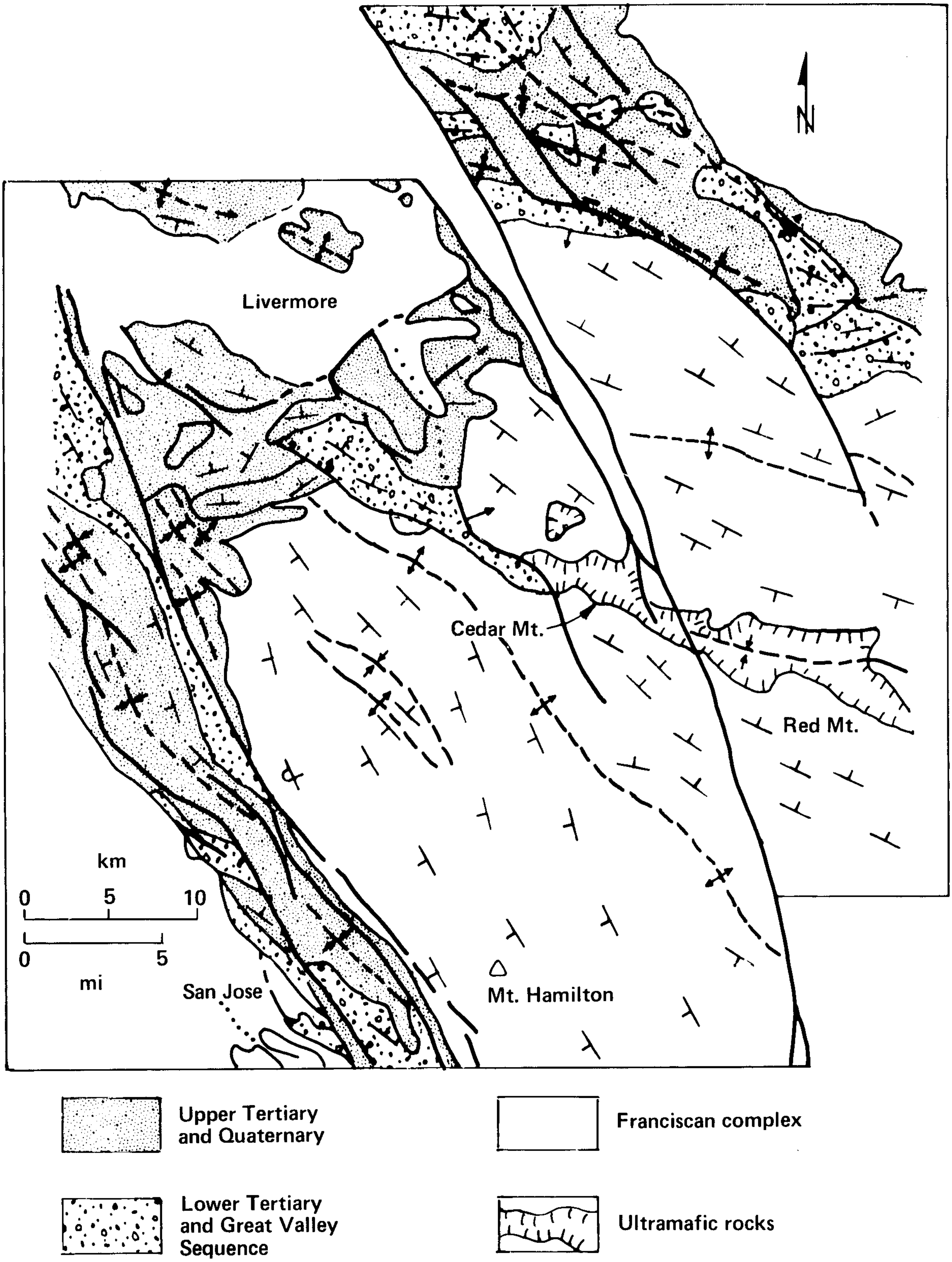


Fig. 15. Map showing Cedar Mountain and Red Mountain ultramafic units palinspastically restored to form a continuous unit.

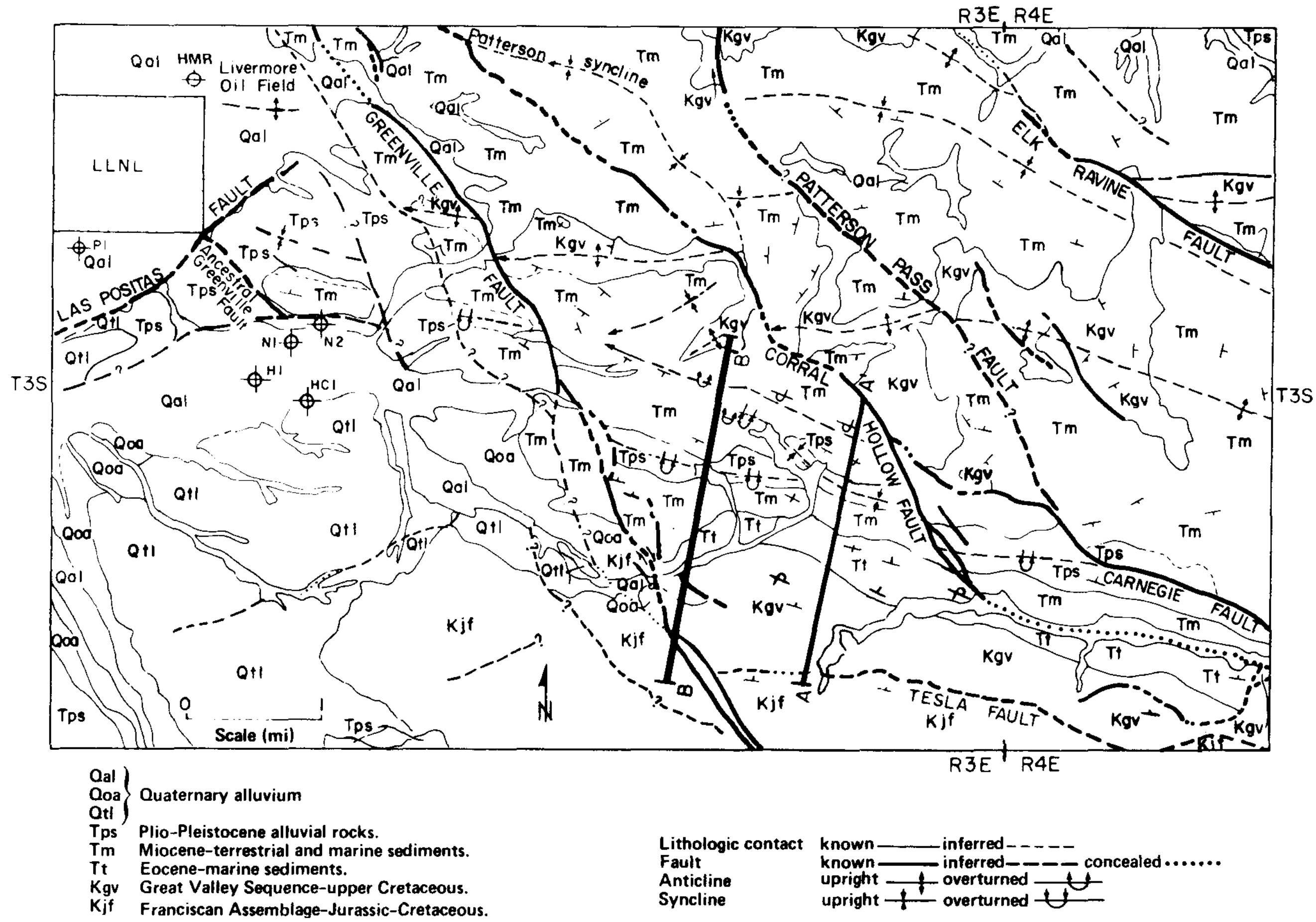


Fig. 16. Geologic map of area southeast of LLNL (modified from Dibblee, 1980c,d). Geologic cross sections A-A′ and B-B′ are shown in Fig. 23.

between Franciscan Assemblage to the south and Great Valley Sequence to the north. Wells P1, N1, H1, and HC1 are south of the subsurface extensions of the Tesla Fault.

The east-west strike of the Tesla Fault is sharply truncated by the Greenville Fault (shown in Fig. 17). The borehole and structural evidence given above requires the trace of the Tesla Fault to be north of well P1 and south of well N2. Previous investigators (Huey in Blume, 1972; URS/Blume, 1978) chose to make a sharp change in strike of the Tesla Fault, having it run along a north-northwest bearing between wells N1 and N2. The trends of the folds discussed above do not change orientation significantly across the Greenville Fault, therefore it is unlikely that the strike of the Tesla Fault, which parallels the fold axes in Corral Hollow (see Fig. 16), would drastically change across the Greenville Fault trace. The simplest explanation of the data is that the east-west striking Tesla Fault has been offset dextrally along an ancestral Greenville Fault trace, now mostly buried by 730 to 850 m (2400 to 2800 ft) of Plio-Pleistocene and younger sediments, that extends from southeastern Livermore Valley, goes between wells N1 and N2, and extends on to the northwest. The westward continuation of the Tesla Fault thus would trend east-west somewhere north of well P1.

A possible segment of the ancestral Greenville Fault is exposed in the hills southeast of LLNL (Figs. 10 and 16). Here, the fault juxtaposes a northerly dipping sequence of Miocene marine strata overlain by beds of the lower member of the Livermore Formation against beds of the lower and upper members of the Livermore Formation that have been folded into a southwest plunging anticline. The age of last movement is definitely after the deposition of the lower member of the Livermore Formation, e.g., post-Pliocene. The upper member has been eroded away along the trace of the fault but is present a few

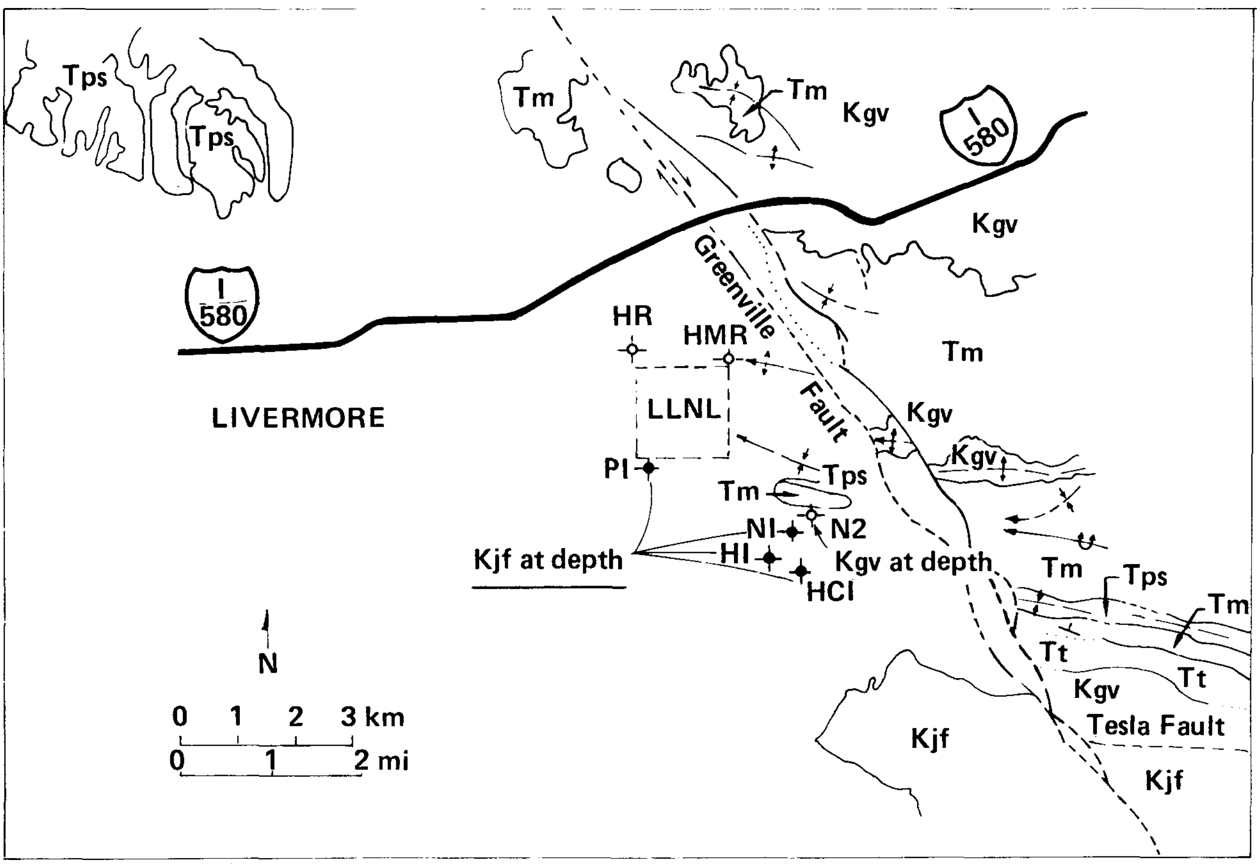


Fig. 17. Simplified geologic map of southeastern Livermore Valley showing locations of boreholes discussed in text. Solid symbols represent boreholes with Franciscan Assemblage rocks at total depth. Open circles are boreholes with Great Valley Sequence or Tertiary rocks at total depth. Other symbols are explained in Fig. 16 (modified from Dibblee, 1980c).

hundred feet west of it. Late Pleistocene alluvial deposits, probably 300,000 yr or older, are not visibly disturbed across the northward projection of the fault beneath the northeastern portion of LLNL. The exposed portion of the ancestral Greenville Fault was mapped by John A. Blume and Associates (1972) as a part of their "Ramp Thrust Fault." This exposed segment is truncated on the north and south by branches of the active Las Positas Fault Zone, and very limited subsurface data suggest that it is displaced laterally along these branches.

The minimum amount of displacement on the ancestral Greenville Fault is constrained to 8.5 km (5.3 mi) by the offset of the Tesla Fault from where it is truncated by the Greenville Fault to immediately north of well P1 (ignoring effects of movement on the Las Positas Fault). This agrees well with the offset of structures in the Diablo Range discussed above. The timing of this movement is unknown, except that at least 2 km (1.24 mi) of movement has occurred along the more easterly, presently active Greenville Fault Trace, offsetting folded Plio-Pleistocene units. There is some indication (see Appendix B) that Plio-Pleistocene folds are affected by movements on the ancestral Greenville Fault, and considerable movement probably occurred between 4×10^6 and prior to 300,000 yr ago. Without more information about the timing of events and spacial relations between folding and faulting in southeastern Livermore Valley and uplift and faulting in the Diablo Range, it is difficult to put constraints on the pre-Holocene slip rate for the ancestral Greenville Fault. No Holocene movement is postulated, based on the previous discussion and on the fact that the currently active Las Positas Fault cuts across the trace of the ancestral Greenville Fault.

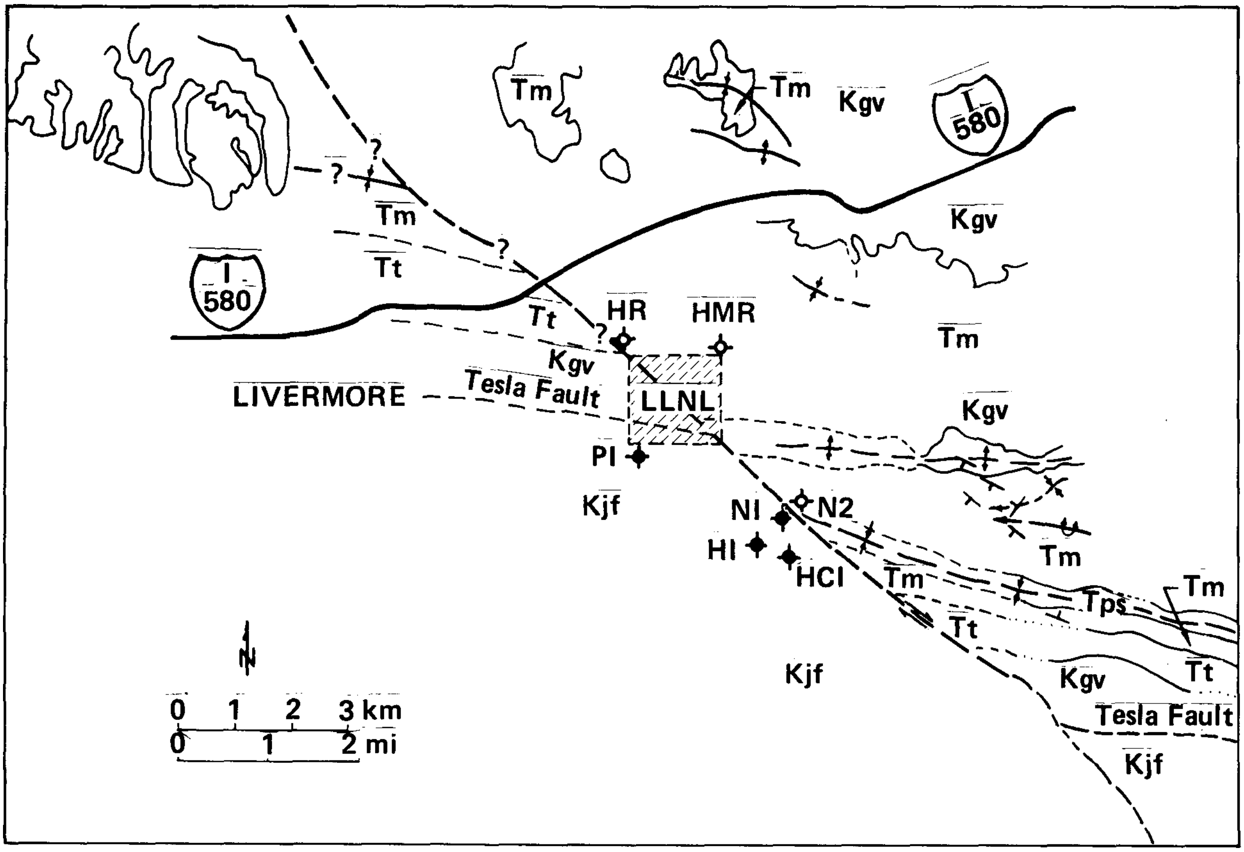


Fig. 18. Geologic sketch of bedrock geology following 7 km (4.3 mi) of movement on the ancestral Greenville Fault. Structures in solid lines and LLNL are fixed reference with respect to present-day locations. Location of the ancestral Greenville Fault is constrained by borehole and reflection seismic data (see Appendix B). Symbols used are explained in Figs. 16 and 17.

Figures 18 and 19 illustrate, by means of palinspastic reconstruction, the probable structural development of the Greenville Fault system in the southeastern part of Livermore Valley. The location of an ancestral Greenville Fault is generalized and any interaction with the Las Positas Fault is ignored. The exact trace is unknown although some surface evidence, well data, and seismic reflection data (see Appendix B) exist that constrain its location to the vicinity of the alignment shown in Figs. 18 and 19. The scene in Fig. 18 represents probable bedrock relations after Plio-Pleistocene folding (about 2-to-4 $\times$ 10^6 yr ago). Prior to (and possibly contemporaneous with) the folding, 6 to 7 km (3.7 to 4.5 mi) of right-lateral movement occurred on the ancestral trace of the Greenville Fault. The Tesla Fault is shown displaced to the southern part of what is now the location of LLNL, with the conjectured folded Great Valley Sequence and overlying Tertiary sediments to the north. Following the 6 to 7 km (3.7 to 4.3 mi) of movement, 730 to 850 m (2400 to 2800 ft) of alluvial deposits blanketed the area as uplift continued in the Diablo Range to the south and the Mt. Diablo antiform to the north and east. Movement was also occurring at this time along the Calaveras Fault on the west side of Livermore Valley and large thicknesses of Plio-Pleistocene sands and gravels were filling in the western part of the valley. At some period during the depositional events, an additional 2 to 3 km (1.2 to 1.9 mi) of right-lateral movement occurred to the east of the ancestral Greenville Fault trace, along the strands of the modern Greenville Fault shown in Figs. 16 and 19. Movement did not occur along a single slip plane, but rather along a series of anastamosing branches. Some blocks were rotated and uplifted between fault strands and, in general, there is about a 1:3 ratio of dip-slip to strike-slip motion, east side up (Earth Sciences Associates, 1982). Figure 19 shows the present-day bedrock configuration with the conjectured positions of the buried Tesla Fault and accompanying

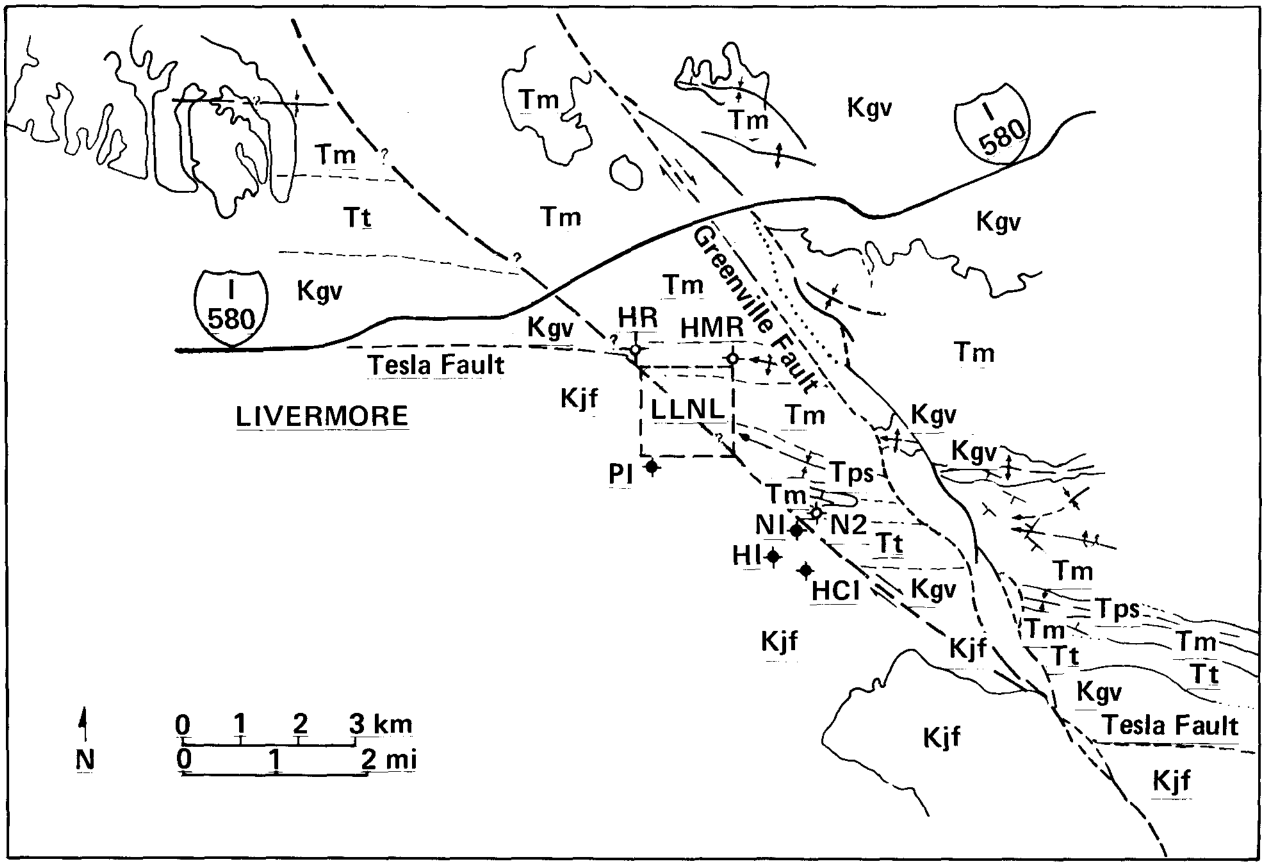


Fig. 19. Present-day bedrock geology of southeastern Livermore Valley after 2 km (1.2 mi) of movement along the modern Greenville Fault Zone. Location of the ancestral Greenville Fault and the offset of the Tesla Fault are discussed in the text and Appendix B. For clarity, the Las Positas Fault has been omitted from the drawing. The symbols used are explained in Figs. 16 and 17.

folded Great Valley Sequence and overlying strata. The position of the anticline northeast of LLNL with a core of Great Valley Sequence flanked by Miocene rocks coincides with the Livermore Oil Field (see Dibblee and Darrow, 1981).

The structural interpretation of Fig. 19 is based on drillhole and reflection seismic data (see Appendix B), structural relations across the Greenville Fault, and the offset of ophiolite units in the Diablo Range. All that is known for certain is that a significant structural boundary exists between wells N1 and N2 and that Franciscan Assemblage rocks are found at depth as far north as well P1, but were not found in well HR (Fig. 17), putting the westward extension of the Tesla Fault between P1 and HR.

Estimates of the maximum credible earthquake that the Greenville Fault Zone may be capable of generating are presented in Table 2. These estimates follow methods outlined by Slemmons and Chung (1982). Estimated magnitudes vary from $M_s = 5.8$ to 6.8. The estimated maximum credible earthquake based on the magnitude of the maximum historic earthquake, which occurred on January 24, 1980, is measurably lower than the estimated maximum credible earthquakes based on other methods. Therefore, it is doubtful that the January 24, 1980, event represents the maximum credible earthquake for the Greenville Fault Zone, and for this reason this estimate was eliminated from the average of the values listed in Table 2. As shown in Table 2, the maximum credible earthquake for the Greenville Fault Zone is $M_s = 6.6 \pm 0.2$. This estimate compares closely with previous estimates made by Wight (1974), Shedlock *et al.* (1980), and Earth Sciences Associates (1982).

In summary, the Greenville Fault Zone is a major structural feature extending from southeast of Mt. Diablo, along the eastern side of Livermore Valley, and into the Diablo Range for a total distance of about

Table 2. **Estimates of the maximum credible earthquake, Greenville Fault Zone.**[a]

Method	Maximum credible earthquake
Maximum historic earthquake (January 24, 1980)	5.8[b]
Fractional fault length (15.2 km)	6.4
Segmentation (35 km)	6.7[c]
Rupture segment length (14.3 km)	6.3
Total displacement (0.6 m)	6.8
Total fault length (90 km)	6.7
Fault slip rate (0.6 mm/yr)	6.5
Relative magnitude	6.8
Average	6.6 ± 0.2

[a] Methods as outlined by Slemmons and Chung (1982), except fault slip rate which is from Woodward-Clyde Consultants (1979).

[b] Probably not maximum credible earthquake.

[c] Assuming linkage of Arroyo Mocho and Marsh Creek-Greenville segments as identified by Clark (1982).

90 km (56 mi). As is typical of strike-slip faults in California (Allen, 1981), the fault is not a single trace, but contains numerous splays and en-echelon segments. Earth Sciences Associates (1982) have identified three such segments. Observable geomorphic features suggest that activity has shifted from the "ancestral" trace eastward to the presently-active trace. The fault is active at least as far south as Corral Hollow, and estimates of current slip rates, based on offset geologic structures and geomorphology, are in the range of 0.5 to 0.7 mm/yr (0.02 to 0.03 in./yr). The maximum credible earthquake estimated for the Greenville Fault Zone, based on several methods of analysis, is $M_s = 6.6 \pm 0.2$.

Livermore Valley Geology

Previous Studies

An extensive review of previous geologic studies of the LLNL site and vicinity has been provided by Carpenter *et al.* (1980). This review is updated in Sweeney and Springer (1981). Following is a brief summary of studies applicable to the LLNL site and its vicinity.

As noted by Carpenter *et al.* (1980), previous investigations have differed greatly as to data and interpretations and these differences were a major reason for the detailed investigations undertaken by the Site Seismic Safety Program.

Early geologic work in the Livermore Valley and adjacent areas was performed by A. Huey (1948). Huey mapped the geology of the Tesla 15-min Quadrangle and named a number of presumed strands of the Tesla, Greenville, and related faults in the hills east and southeast of LLNL.

In 1966, CDWR evaluated the geohydrology of the Livermore and Sunol Valleys. Their work included an appraisal of regional geology, including fault locations. The study identified a number of presumed groundwater barriers believed to be the results of fault displacements. In 1974 CDWR made some revisions and extensions to their previous work. Some of the faults postulated by the CDWR represented projections into the valley of faults mapped by Huey. Others were new features in valley geology.

In 1971, John A. Blume and Associates prepared a geotechnical investigation report concerning additions to the LLNL Plutonium Handling Facility, Bldg. 332. This study drew largely on existing CDWR data but included excavation of an exploratory trench east of Bldg. 332. Inspection of the trench revealed no feature suggestive of faulting.

In 1972, Blume was retained by LLNL to investigate faulting at and near the LLNL site. In the report (John A. Blume and Associates, Inc., 1972), Huey provided background geologic information and extrapolated several of his previously mapped faults from the hills into the Livermore Valley.

John A. Blume and Associates performed gravity, magnetometer, and seismic refraction studies in an effort to locate faults extrapolated by Huey. They also reviewed geodetic leveling data to detect ground movements within the Livermore Valley. The study did not include exploratory trenching or drilling within LLNL, although a utility trench excavated in Sec. 13, T3S, R2E (Fig. 2), was inspected for evidence of faulting.

On the basis of their investigation, John A. Blume and Associates added several faults to Valley geologic literature but also concluded that geophysical evidence indicated that the Corral Hollow Fault, projected beneath LLNL during their 1971 study, did not extend west of Greenville Road.

In 1977, D. Herd, U.S. Geologic Survey (USGS), published a new geologic map based largely on airphoto interpretation. Herd introduced a new element into Valley geology, a northeast trending fault zone located in the southern and southeastern portions of the Livermore Valley. Herd named this feature the Las Positas Fault Zone. The Las Positas Fault Zone is of particular interest in that its trend is at almost right angles to the previously recognized fault pattern. Herd's interpretation of the geology of the eastern Livermore Valley is shown in Fig. 9.

Herd's study showed no strands of the Tesla Fault Zone as projected northwest by Huey (John A. Blume and Associates, 1972) and the CDWR (1974). In contrast, Herd considered the Tesla to be truncated by the Greenville Fault Zone and showed the two faults merging in the NE 1/4 Sec. 34, T3S, R3E (Fig. 9).

In 1978, URS/John A. Blume and Associates (URS/Blume) did a field study for SNLL. URS/Blume's general picture of areal geology changed little from that published in 1972 except that one postulated strand of the Tesla Fault Zone was deleted from their maps.

URS/Blume stated that they were unable to confirm the presence of the Las Positas Fault identified by Herd. However, they observed features in several of their exploratory trenches that could be interpreted as having been caused by faulting.

In July 1979, the CDWR released a geologic study that included an assessment of the seismic safety of Patterson Reservoir, Del Valle Dam, and Lake Del Valle. This study was based on review of previous reports, field checking and reconnaissance mapping, reexamination of preconstruction exploration and construction records, and a limited trenching program.

The 1979 investigation resulted in a fault pattern generally similar to previous CDWR studies, but with some modifications. The CDWR recognized the northeast trending Las Positas Fault, but restricted its extent to the area between the Arroyo Mocho on the southwest and the Arroyo Seco on the northeast. The CDWR mapped the Livermore Fault northwest across the central portion of the Livermore Valley, based on data from exploratory trenches near Del Valle Dam and on an analysis of water-well data from the Livermore area.

In 1980 and 1981, T. H. Dibblee, Jr. of the U.S. Geological Survey, released a series of 7-1/2-min Quadrangle maps to Open File (Dibblee, 1980a-g; Dibblee, 1981). These maps are the result of Dibblee's review of work by others and his own field studies performed at intervals during 1975–1978. A general discussion of Dibblee's work and his interpretation of local tectonics are given in Dibblee and Darrow (1981).

Mapping of rock units, folds, and fault patterns by Huey (1948), Herd (1977), and Dibblee (1980c,d) in the area southeast of LLNL has been compared in an independent study by Sweeney and Springer (1981). Their work confirmed the findings of Dibblee (1980c) and Herd (1977) on the location of the Tesla Fault and its truncation by the Greenville Fault. The location of the Carnegie Fault given by Huey (1948) and Herd (1977) was not confirmed but was found by Sweeney and Springer (1981) to be an overturned stratigraphic contact on the southern limb of an anticline. Dibblee (1980c,d) also mapped this structure as an overturned anticline.

Another recent work pertinent to Livermore Valley geology is that of Prescott *et al.* (1981). This study demonstrates that almost all of the relative plate motion across the Bay Region (32.1 $\pm$ 7.4 mm/yr) is being accommodated by strain accumulation along the San Andreas Fault and slip along the Hayward and Calaveras Fault Systems. Only about 6 $\pm$ 1.5 mm of annual slip appears to occur on other faults in the Bay Region including those in the Livermore Valley. Prescott *et al.* also presented evidence that a crustal block, bounded by the Las Positas Fault on the north and the Calaveras Fault on the west, is rotating in a clockwise sense and deforming internally. Available geodetic data did not permit Prescott *et al.* to define the southern and eastern boundaries of the rotating block.

Stratigraphy

Stratigraphic units exposed in the Livermore Valley and adjacent areas may be discussed in terms of the following three general groupings:

1. A complex of igneous and metamorphic rocks mapped as the (Jurassic and Cretaceous) Franciscan Assemblage.
2. A sequence of primarily marine sedimentary rocks of Cretaceous through late Tertiary age.
3. Primarily continental rocks and alluvial deposits of latest Tertiary through Holocene age.

Each of these groupings will be discussed in following subsections.

As discussed earlier in this report under "Geologic Setting" (p. 5 ff), rocks of the Franciscan Assemblage and the earlier portions of the Cretaceous sedimentary sequence are equivalent in age, but were deposited in differing tectonic environments and appear to have been juxtaposed by subduction and later movements along the Coast Range Thrust Fault system.

A generalized stratigraphic section for the Tesla 15-min Quadrangle that includes LLNL was published by Huey (1948), and is reproduced in a modified form as Fig. 4. Brief descriptions of the formations described by Huey will be provided in the following paragraphs. Sweeney and Springer (1981) used the stratigraphic subdivisions of Huey, but did not subdivide the Great Valley Sequence (unmetamorphosed marine sedimentary rocks of Cretaceous age). Dibblee (1980a-g, 1981) mapped on the basis of a slightly more generalized regional stratigraphy and proposed no subdivisions seriously at variance with those originally proposed by Huey except that he separated the Livermore gravels of Huey into two mappable units, an older Plio-Pleistocene sequence (Tps) and a younger Quaternary sequence (Qtl).

Detailed geologic mapping of areas south and east of LLNL performed by Project Investigators supports the separation of the Livermore Formation in this area into two map units generally corresponding to those described by Dibblee. Distributions of these map units are shown in Fig. 10 accompanying this report and in Sweeney and Springer (1981). LLNL mapping of the area southeast of LLNL differs primarily from that of Dibblee (1980c) in that, while Dibblee believed that the upper portion of the Livermore Formation is exposed in the hills southeast of LLNL, our examination of the area, including some recent artificial exposures, indicates that most of it is underlain by beds closely resembling the lower unit (map unit Tps) described by Dibblee. This is similar to the interpretation of subsurface data by the CDWR (1974). The CDWR referred to a "clay facies" of the Livermore Formation flanking the eastern Livermore Valley.

Subdivisions of Quaternary geology have been proposed for the Livermore Valley by Helley *et al.* (1972) and Herd (1977); these will be described below. Late Quaternary units shown on the geologic map of the LLNL site and vicinity (Fig. 10) are considerably modified from those previously proposed, based on the more detailed data obtained during the Site Seismic Safety Study. This late Quaternary stratigraphy developed for the LLNL area is described in detail in a following section.

Jurassic and Cretaceous Igneous and Metamorphic Rocks

The basement rocks in the Livermore Valley region are the Franciscan Assemblage of Jurassic and Cretaceous age. These rocks are exposed throughout the entire southern part of the Diablo Range. Exposures extend north to Sec. 29, T3S, R2E about 5 km (3 mi) southeast of LLNL. Further to the north, beneath Livermore Valley, the Franciscan Assemblage is progressively buried by up to 1.2 km (4000 ft) of Plio-Pleistocene to Holocene alluvial deposits (CDWR, 1966, 1974). Regionally, the Franciscan Assemblage primarily consists of severely deformed and folded graywacke, shales, and cherts. However, diabase, pillow basalts, serpentine, and peridotite occur locally (Huey, 1948; Dibblee, 1980c,d).

In the vicinity of Livermore Valley, the Franciscan consists mainly of a weakly metamorphosed greenish-gray sandstone that weathers to a greenish-brown. The rock is generally massive bedded, but highly jointed, forming irregular blocks in outcrop. Some chert lenses are present and the rocks are often pervasively sheared.

Cretaceous-Late Tertiary Marine Sedimentary Rocks

A sequence of unmetamorphosed Cretaceous through late Tertiary marine sedimentary rocks occurs in fault contact with the Franciscan Assemblage throughout the Livermore Valley area. Huey (1948) separated the Cretaceous portion of this sequence of strata into a lower Cretaceous Horsetown Formation and an upper Cretaceous Panoche Formation. However, many later workers have preferred to combine these Cretaceous rocks into an undifferentiated Great Valley Sequence (Herd, 1977; CDWR, 1979; Sweeney and Springer, 1981). These Great Valley Sequence rocks typically consist of variably cemented, greenish-gray-to-brown concretionary sandstone interbedded with dark gray shale and occasional conglomerate.

Dibblee (1980c,d) used the name Panoche Formation for that portion of the Great Valley Sequence that consists chiefly of concretionary sandstone and micaceous shales.

Huey (1948) and Dibblee (1980c,d) mapped the late Cretaceous Moreno Grande Formation overlying the Panoche Formation in a band extending southeast from Sec. 27, T3S, R3E to Sec. 33, T3S, R4E (Fig. 16). The Moreno Grande Formation (Moreno shale of Dibblee) consists dominantly of dark, siliceous, argillaceous, sandy shale with some limestone concretions and friable sandstone interbeds. The formation is typically poorly exposed.

The Eocene Tesla Formation, which forms the base of the Tertiary sequence, is exposed in a narrow band along Tesla Road where numerous road cuts provide excellent exposures. The unit is characterized by massive white-to-buff quartz sands interbedded with brown shales and occasional lignite seams.

The Miocene Cierbo Formation unconformably overlies the Tesla Formation and is well exposed along Patterson Pass Road (Sec. 9, T2S, R3E; Fig. 16). It consists of poorly consolidated white-to-buff sands with iron-oxide-filled fractures and shale interbeds. A lithology similar to the Tesla Formation makes separation difficult in areas of deep soil cover. However, resistant conglomerate beds and fossils in the formation aid in tracing this unit.

The Neroly Formation overlies the Cierbo Formation. This unit is very distinctive, consisting mainly of a bluish sandstone with lenses of andesite-bearing conglomerate, minor tuff, and tuffaceous shale beds. The unit is easily mappable because of its distinctive purplish float.

Correlation of Tertiary units within the region has been hampered by structural complexity and the isolated nature of depositional basins. General discussions of regional stratigraphy are given by Dibblee and Darrow (1981) and Wagner (1978).

Late Tertiary to Holocene Sediments

Livermore Valley is a topographic and structural depression filled with fluviatile and lacustrine sediments of Pliocene through Holocene age (CDWR, 1966; Blume, 1972; Dibblee, 1980c,g). The total thickness of these deposits locally exceeds 1.2 km (0.75 mi) (CDWR, 1966). This thick sedimentary sequence has been subdivided into the Plio-Pleistocene Livermore Formation (Huey, 1948; CDWR, 1966) and variably further subdivided into late Pleistocene and Holocene alluvial deposits (Helley *et al.*, 1972; Herd, 1977; Dibblee, 1980c,g).

As previously noted, Dibblee subdivided the Livermore Formation into two mappable units and we have found this subdivision to be applicable during geologic mapping of areas south and east of LLNL. None of the previously proposed subdivisions of the late Pleistocene and Holocene alluvium have proven to adequately characterize these materials in the vicinity of LLNL. Therefore, we have developed a local stratigraphy for these deposits based on geomorphic positions, soil profile development and available age data. Some correlations exist between this local stratigraphy and areal stratigraphies proposed by previous workers; these will be described in a following section.

Huey (1948) described the Livermore gravels of Plio-Pleistocene age as "... continental deposits of gravels, sands, [and] clays" (see Fig. 4). Dibblee (1980c,d) subdivided the equivalent strata into a Pliocene unit (Tps) consisting of "... weakly indurated pebble conglomerate, sandstone, and greenish-gray claystone," and an overlying unit (Qtl) consisting of "... light reddish-gray cobble-pebble gravel containing debris from Franciscan rocks: minor to major amounts of claystone."

Units corresponding fairly closely to those described by Dibblee are exposed in the hills south and east of LLNL (Fig. 10). Greenish- to bluish-gray, dominantly fine-grained sediments believed correlative with unit Tps of Dibblee have been encountered in exploratory boreholes and monitoring wells drilled in the eastern and southeastern portions of LLNL at depths ranging from 7 to 58 m (23 to 190 ft) Materials equivalent to surface unit Qtl have not been definitely identified in boreholes within LLNL, but these materials are lithologically identical to the younger alluvial deposits making subdivision in a borehole virtually impossible. Age data and considerations of net sedimentation rates based on soil profile interpretations (Shlemon, Appendix E of this report) indicate that much of the oxidized alluvium beneath LLNL and vicinity is probably correlative with unit Qtl of Dibblee.

Field reconnaissance reveals that the contact between units Tps and Qtl is variable but often unconformable. The probable contact is visible at three locations near LLNL and is different at each. Immediately west of the water tanks in the south half of Sec. 13, T3S, R2E, the contact appears roughly conformable. Along Greenville Road about 610 m (2000 ft) south of its intersection with East Avenue (Fig. 10), unit Qtl appears to occupy a broad channel eroded into unit Tps. About 610 m (2000 ft) further south along Greenville Road, a strong angular unconformity exists between the two units. At this last location, relationships are greatly complicated by multiple erosion events, intense deformation, and active faulting.

During detailed geologic studies in the southwestern Livermore Valley, Earth Sciences Associates (1979) recognized three members within the Livermore Formation exposed in that area. These members were believed to reflect the tectonic history of the region and to be the result of increasing uplift and erosion of the Diablo Range during Plio-Pleistocene time.

Earth Sciences Associates (1979) described a lower member consisting of predominately fine-grained lacustrine sediments, a middle conglomerate member, and an upper member of complexly interlensed coarse and fine-grained sediments. The lower lacustrine member corresponds to unit Tps of Dibblee and this investigation, while the middle and upper members defined by ESA appear correlative with unit Qtl of Dibblee and this investigation.

Herd and Brabb (1980) suggested ages for the Livermore Formation ranging from a minimum of between 300,000 and less than 600,000 yr to a maximum of about 5 million yr. Wagner (1978) suggested that basal Livermore Formation beds may be as old as 9 million yr.

Late Quaternary alluvial deposits are exposed as a series of terraces flanking major drainages that enter Livermore Valley from the south. These terrace deposits consist of oxidized sediments that range from clay to cobble and boulder-bearing gravel. Similar materials underlie the valley at shallow depth. Herd and Brabb (1980) indicate a probable maximum age of about 300,000 yr for the oldest of these deposits; deposition has occurred discontinuously up to the present day.

The CDWR (1966) examined logs of well drillers and noted a vague decrease in grain size with increasing depth. The CDWR suggested that the decrease of grain size may mark the contact between the Livermore Formation and the Quaternary Alluvium. Clasts from both the Livermore Formation and the younger alluvial deposits are similar and consist mainly of resistant Franciscan rock types such as chert, graywacke, metavolcanic rock, and quartzite. Other Cretaceous and Tertiary rocks described in the previous sections are generally poorly cemented and are not preserved, at least in the coarser fractions.

CDWR examination of well logs revealed spatial variations in the composition of the Quaternary alluvial deposits. In the southern portion of the Livermore Valley adjacent to present day major stream channels (Arroyo Valle, Arroyo Mocho), the Quaternary alluvial deposits consist dominantly of sand and gravel. This portion of the valley is a major groundwater recharge area (Alameda County Planning Department, 1979).

Alluvial deposits along the northern margin of the valley are dominantly fine-grained and represent deposition from small streams draining from the hills north and east of the valley. These streams carry sediments derived by weathering and erosion of predominately fine-grained Cretaceous and Tertiary age rocks. The resulting alluvial deposits consist chiefly of silt and clay beds, with occasional lenses and stringers of sand and gravel (CDWR, 1966).

In the eastern portion of the Livermore Valley, well logs show that the alluvium is composed of interfingering deposits of gravel, sand, silt, and clay. Individual layers are typically not extensive enough to permit correlations between wells. The heterogeneous nature of the alluvium is largely the result of deposition from many small streams (CDWR, 1966).

In the western half of the Livermore Valley, extensive gravel layers deposited by ancestral Arroyo Del Valle alternate with thick clay beds deposited when lakes were present in the area. These lakes appear to have formed as a result of periodic interference with valley drainage, probably related to movements on the Calaveras Fault Zone (CDWR, 1966).

The thickness of the Holocene portion of the Quaternary alluvial sequence is uncertain. The CDWR (1974) estimates that from a few feet to as much as 200 ft (61 m) of Holocene alluvium may underlie various parts of the valley, and that the Holocene alluvium is thickest in the western portion of the Livermore Valley.

A ^{14}C-age of 5100 $\pm$ 200 yr was obtained from a sample taken at a depth of about 5.5 m (18 ft) in the Arroyo Mocho flood control channel north of Pleasanton (Burkland and Associates, 1975a, 1975b). The sample was obtained from fine-grained sediments deposited in the former playa lake area. If the rate of net sedimentation indicated by the age of the ^{14}C sample is representative of rates in the western valley in general (about 3.5 ft/1000 yr), then the indicated thickness of Holocene alluvium (last 11,000 yr) in the area would be about 11.6 m (38 ft), roughly 20% of the maximum amount estimated by the CDWR.

Recent studies by Wahler and Associates (1981) also provide ^{14}C data on the ages of alluvial deposits in the western Livermore Valley. They obtained an age of about 9770 $\pm$ 400 yr B.P. for a specimen recovered from a depth of 11.2 ft in an exploratory trench located north of Pleasanton. This site is near the northeast margin of the playa investigated by Burkland and Associates. Several other specimens from trenches in the area gave younger but stratigraphically reasonable ages. Net sedimentation rates indicated by the Wahler and Associates data are about 0.9 ft/1000 yr. These data also suggest that the thicknesses of Holocene materials in the Livermore Valley are quite limited and that most of the post-Livermore Formation materials in the Livermore Valley area are late Quaternary in age.

In the vicinity of LLNL, geomorphic features, soil series distributions, and age data permit the recognition of four surface units of late Quaternary to Holocene age. The stratigraphic sequence is not as well defined as in areas nearer the major streams entering Livermore Valley from the south. This is, in part, a reflection of the fact that the local drainages, Arroyo Seco and Arroyo Las Positas, are minor streams with limited depositional capabilities. Also (as will be discussed more in the following section) some areas south and east of LLNL appear to be undergoing active uplift and deformation resulting in accelerated erosion and the removal of older materials.

The oldest post-Livermore Formation materials recognized near LLNL are terrace deposits standing about 3 to 10 m (10 to 33 ft) above the present bed of the Arroyo Seco. Distributions of these terrace deposits (map symbol Qal_2) are shown on Fig. 10.

Unit Qal_2 consists dominantly of silty clay and silty-to-clayey gravel of Franciscan origin. Clasts are typically subangular to subrounded and are slightly-to-moderately weathered. A mature soil profile has formed within these materials (Shlemon, Appendix E) and is believed to reflect a period of landscape stability about 80,000 to 125,000 yr ago. The age of these sediments is believed to be 125,000 to 195,000 yr. Knauss (1981, Appendix D) obtained a series of $^{230}Th/^{234}U$ ratio ages from pedogenic carbonates within correlative materials that group at about 100,000 yr B.P. consistent with the data of Shlemon.

Map unit Qal_1 is a slightly younger accumulation of valley fill and terrace deposits. In exposures along the Arroyo Seco in the southern portion of Sec. 18 and the NE1/4 Sec. 19, T3S, R3E (Fig. 10), these materials consist of reddish-brown silty gravels. Correlative alluvial deposits underlie LLNL at shallow depth. Exposures in trenches, test pits, and in samples recovered from drill holes indicate that these materials consist of reddish and yellow-brown silty gravels and sands generally capped by yellow and light-brown sandy clays and silts. Soils of the Pleasanton series have formed on these alluvial deposits near the Arroyo Seco southeast of LLNL; soils of the Rincon series occur on these materials near and within LLNL (Welch *et al.*, 1966).

Based on relative age criteria and soil profile development, Shlemon (Appendix E) indicates that unit Qal_1 was probably deposited about 60,000 to 70,000 yr ago. Soil profiles developed on these materials reflect a period of landscape stability about 35,000 to 40,000 yr ago.

Knauss (1981, Appendix D) obtained $^{230}Th/^{234}U$ ages in the range of 7,000 to 20,000 yr B.P. for samples taken from exploratory trenches E-5 and E-6 (see Fig. 20 for locations) in materials mapped as Qal_1, based on soils and geomorphic continuity. Shlemon (Appendix E) expresses the opinion that these younger ages are superimposed on older materials as a result of groundwater percolation through gravel beds during the latest Wisconsin Age pluvial period.

Helley *et al.* (1972) mapped unit Qal_1 as "Older Alluvial Fan Deposits (Qof)." The older terrace deposits along the Arroyo Seco (Qal_2, this investigation) were included with areas underlain by the Livermore Formation, probably because the scale of their map would not allow more detail.

Herd (1977) mapped the portion of unit Qal_1 underlying the Livermore Valley floor and the low terraces along the Arroyo Seco as unit Qoa_2. The older terrace deposits along the Arroyo Seco were mapped as unit Qoa_3.

Two younger geologic units occur in the vicinity of LLNL. These are a sequence of low terrace and correlative alluvial deposits judged to be of latest Pleistocene to Holocene age (map symbol Hpal, Fig. 10) and local accumulations of flood plain and stream channel deposits (Map unit Hs, Fig. 10). Terrace surfaces developed on unit Hpal lie an average of about 2 m (6.5 ft) above the Arroyo Seco and do not appear to be affected by modern floods. These terrace deposits consist of silty gravels and sands capped by sandy-to-clayey silts. Downslope, boreholes within LLNL indicate that these materials grade to silty-to-sandy clay and sandy silt with occasional lenses of clayey sand and gravel. Soils are typically immature, dark brown to brown and organic-rich.

Adjacent to the Arroyo Seco, soils developed on these deposits include the Livermore, Zamora, and locally the Yolo series. A ^{14}C date of 17,400 $\pm$ 250 yr was obtained during this investigation for a wood specimen recovered from unit Hpal in exploratory trench E-3 (Robinson, 1980; see Fig. 21 for location). The specimen was obtained from a depth of 11 ft (3.3 m) probably near the base of the deposit.

Soils of the San Ysidro series have formed on correlative deposits of the Arroyo Las Positas within northeastern LLNL and to the east of the laboratory (Welch *et al.*, 1966). These materials consist of sandy-to-silty clay and show increased but not mature soil profile development. The Arroyo Las Positas drains the arid Altamont Hills and probably has caused little net erosion or sedimentation during latest Pleistocene to Holocene time, permitting more advanced soil profile development.

The youngest unit identified in the vicinity of LLNL (map unit Hs) consists of active stream channel deposits along the Arroyo Seco and adjacent flood plain and very low terrace deposits that stand about 15 to 50 cm (6 to 20 in.) above the present bed of the Arroyo. These materials consist chiefly of gravelly sands and dominantly fine gravels. Welch *et al.* (1966) identified soils formed on unit Hs as Riverwash and locally Livermore series.

A few small lenses of sand and gravel occur within the poorly defined Arroyo Las Positas Channel east of LLNL. These materials are correlative with unit Hs, but are too limited in extent to map at the scale of Fig. 10.

Units Hpal and Hs vary in total thickness from a thin colluvial veneer overlying all older materials to about 10 to 17 ft (3 to 5 m) based on trench and borehole data. Where shown in Fig. 10, these units are believed to generally exceed 5 ft (1.5 m) in thickness.

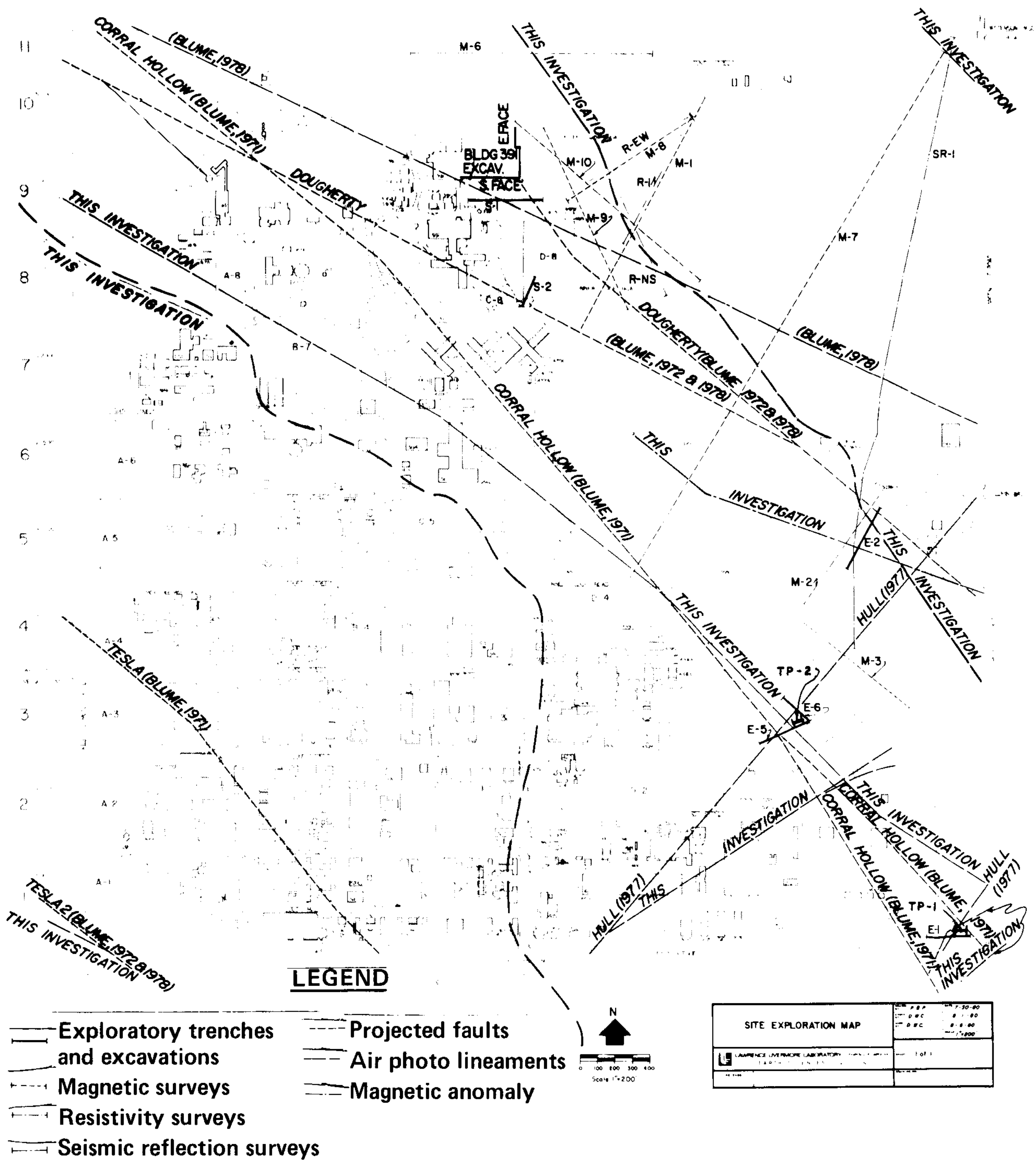


Fig. 20. LLNL site map showing locations of postulated faults, airphoto lineaments, excavations studied, and geophysical surveys made.

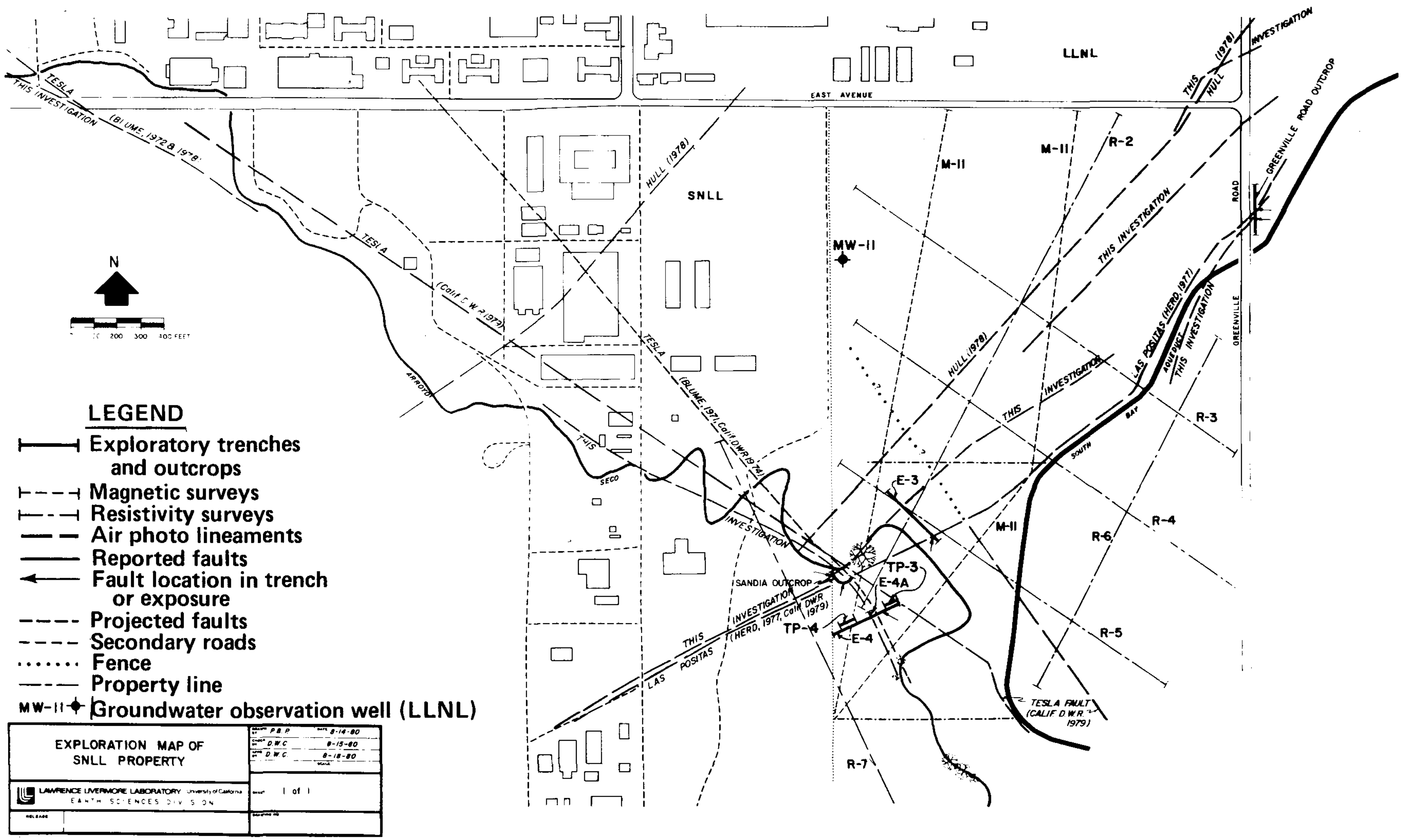


Fig. 21. SNLL site map showing locations of postulated faults, airphoto lineaments, excavations studied, and geophysical surveys made.

Materials mapped as Hpal and Hs during this study occur in areas mapped as both Older and Younger Alluvial Fan deposits (Qof, Qyf) by Helley *et al.* (1972). They underlie areas mapped by Herd (1977) as Qoa_2, Qfa (recent flood plain alluvium) and Qsg (recent stream gravel).

Structure

Folding

On a regional scale, Livermore Valley is a depositional basin bounded by the Calaveras Fault on the west and the Greenville Fault on the east (see Fig. 5). To the south, the Diablo Range is a large, doubly plunging, northwest trending, antiform with a core of Franciscan Assemblage rocks. Great Valley Sequence and Cenozoic rocks flank the sides. The northern end of the Diablo Range plunges beneath Livermore Valley where Miocene and Quaternary age rocks locally onlap the Franciscan Assemblage and Great Valley Sequence rocks (Dibblee, 1980f, 1981). To the north of Livermore Valley, Mt. Diablo forms another doubly plunging antiform with a core of Franciscan Assemblage. Cretaceous and Tertiary age rocks dip moderately into the Great Valley to the north, but are steep-to-overturned on the southwest flank of Mt. Diablo. The Mt. Diablo structure is interpreted as an anticlinal uplift with counterclockwise rotation between strands of the Greenville-Clayton and Concord Faults (Dibblee and Darrow, 1981). The Mt. Diablo antiform, with a core of Great Valley Sequence rocks, continues to the southeast along the east side of the Greenville Fault Zone to the Corral Hollow area. South of Mt. Diablo and north of Livermore Valley in the Tassajara hills there are a series of northwest trending, tight, overturned folds that terminate abruptly north of I-580 and east of the San Ramon Valley.

The Livermore Valley itself is a complex, geologically young, synclinal structure (CDWR, 1966, 1974; Blume, 1972). Geologic cross sections published by the CDWR (1974) show a general thickening and downwarping of beds toward the center of the Valley, indicating syntectonic deposition.

John A. Blume and Associates (1972) mapped a secondary syncline, called the Livermore syncline, across the northeastern portion of LLNL (Fig. 22). They reported that benchmark releveling within and near LLNL showed an area of maximum subsidence approximately coincident with the axis of the syncline and showed minimal subsidence elsewhere. They interpreted the data as indicative of continuing tectonic downwarping of the Livermore syncline.

Dibblee (1980c,d) and Sweeney and Springer (1981) mapped a series of overturned folds in the area near Corral Hollow and to the north (T3S, R3E) as shown in Fig. 23. These folds have been translated dextrally along the Corral Hollow Fault and the Greenville Fault as shown in Fig. 16 and have been previously discussed. The tight, overturned folding in the Corral Hollow area becomes upright and open to the north within about 2 km (1.2 mi). Folds east of the Corral Hollow Fault of Dibblee (1980d) plunge gently east, while those west of the Corral Hollow Fault plunge gently west. The style of folding in the Corral Hollow area closely resembles that in the Tassajara Hills, if the removal of a considerable amount of Plio-Pleistocene cover in the Corral Hollow area is allowed.

Folding in the area has occurred in at least two, and probably three time periods. The great structural and lithologic contrast between the Jurassic-Cretaceous Franciscan Assemblage and the Great Valley Sequence has been mentioned above. Disconformities between Great Valley Sequence strata and Miocene and Eocene rocks indicate periods of deformation during Oligocene time and possibly during Paleocene time. Plio-Pleistocene rocks commonly occupy cores of synforms and often occur in disconformity with underlying Miocene rocks, indicating a period of intense deformation during and following their deposition. This Plio-Pleistocene period of deformation is undoubtedly related to the wrenching of crustal blocks between the series of right lateral faults in the region and probably is continuing in many areas at the present time.

Evidence for youthful folding is further provided by the geologic structure in the hill area immediately south and east of SNLL. As shown in Fig. 10, beds of the Plio-Pleistocene Livermore Formation are deformed into a southwest plunging anticline bounded by strands of the Las Positas Fault Zone on the north and south. The anticline is abruptly terminated along its eastern margin by a northwest trending fault regarded as a segment of the ancestral Greenville Fault and is juxtaposed against the south limb of the Livermore syncline across this fault.

Evidence that this anticline may still be growing is provided by the presence of an abandoned valley, probably an ancestral course of the Arroyo Seco. This valley ends abruptly at its southeastern end, about

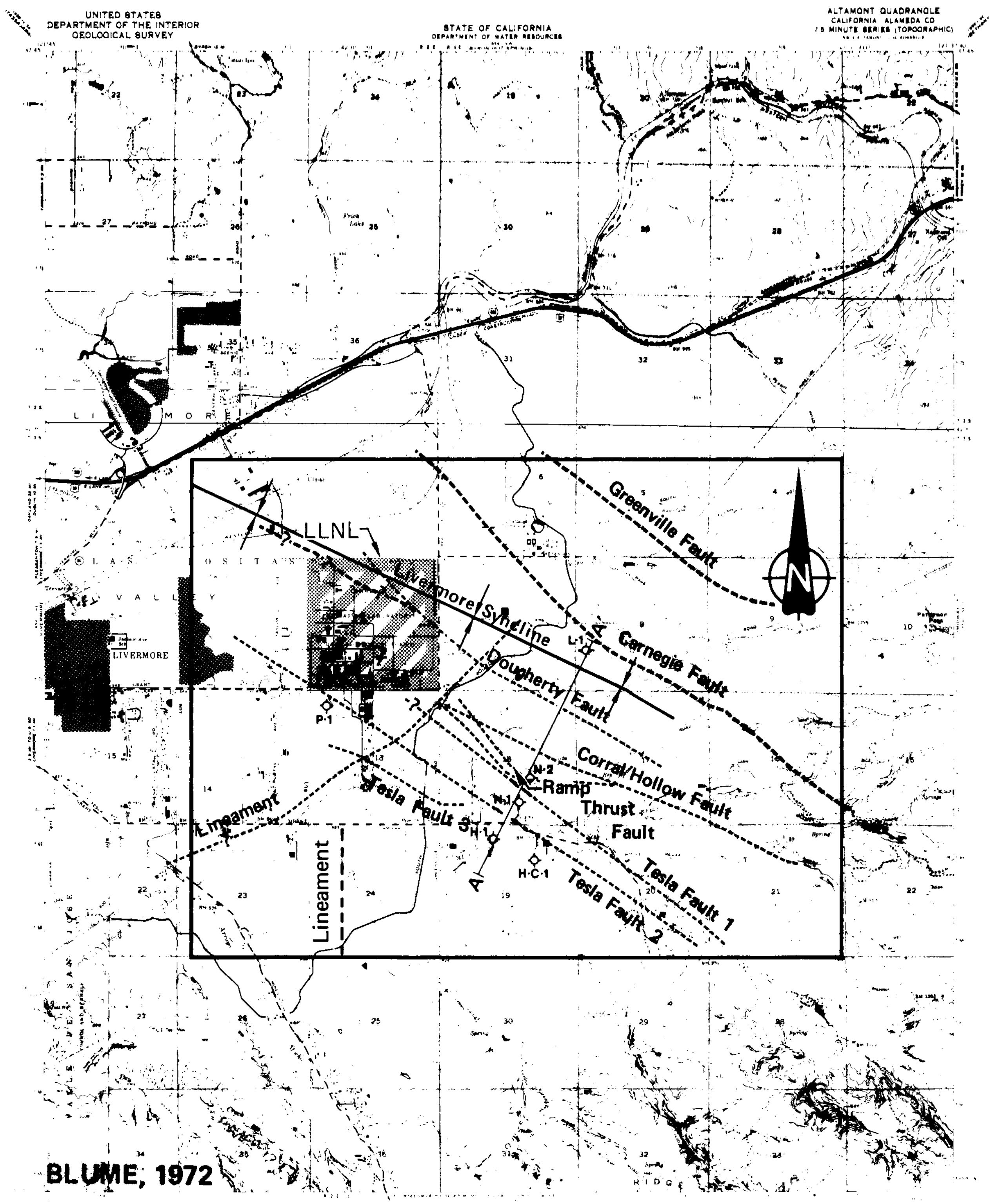


Fig. 22. Folding and faulting as mapped by Blume (1972). Cross section A-A′ is shown in Fig. 25.

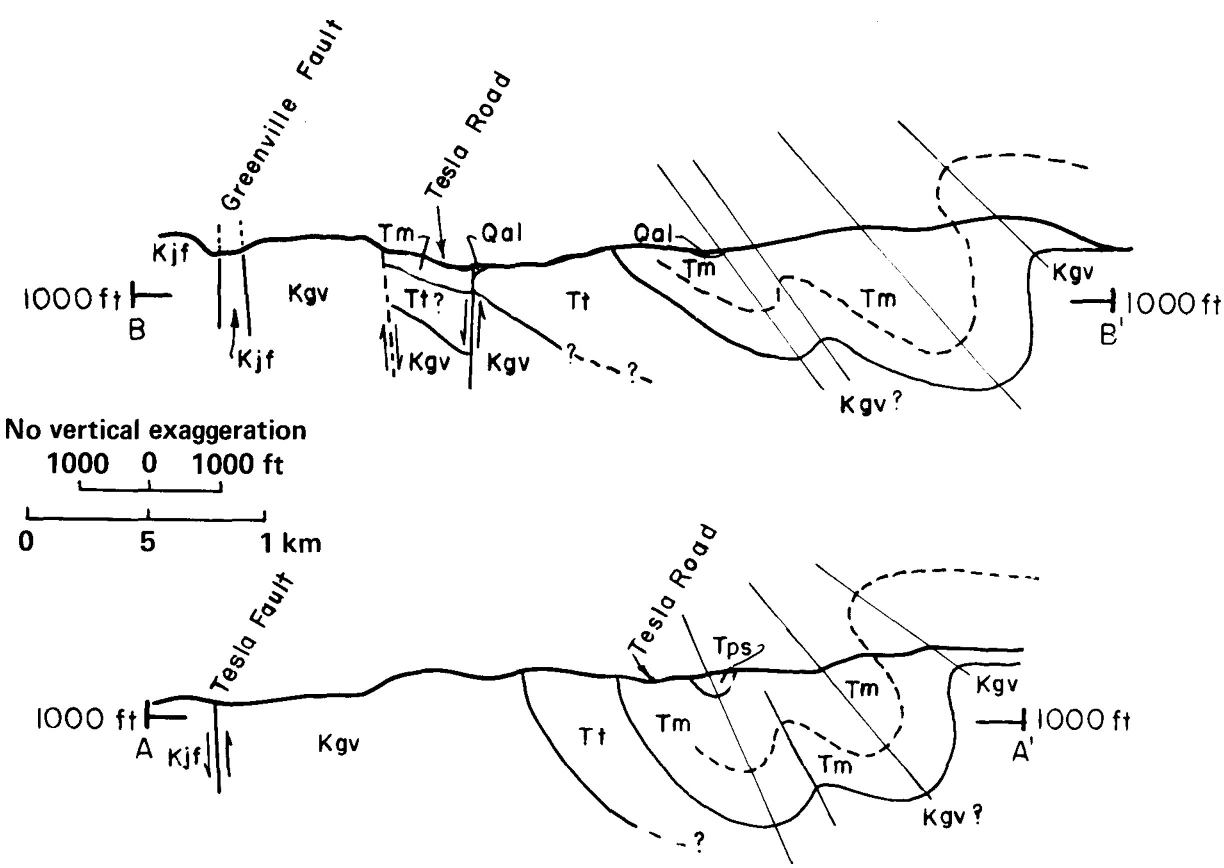


Fig. 23. Cross sections across the Corral Hollow area. Both sections trend northeast, with section B to the west of section A. See Fig. 16 for locations.

15 m (50 ft) above the present course of the Arroyo and appears oversteepened toward the northwest, down the dip of the north flank of the anticline. Rincon series soils, similar to those formed on unit Qal_1, are preserved within the lower part of the valley suggesting that the valley was an active drainage course during at least part of the time of deposition of unit Qal_1.

Faulting

In addition to the Calaveras and Greenville Faults, two other active faults have been identified in the Livermore Valley area and 20 other faults have been identified or postulated in the area as well. These latter faults are either apparently inactive or their activity status is uncertain. These evidently inactive faults have not been investigated in detail since considerations of their length and location based upon literature review and field reconnaissance demonstrate that they are not potentially important contributors to the seismic hazard at LLNL. Also, microseismic data (Taylor and Scheimer, 1981) suggest the presence of several short, active faults within the extreme southeastern corner of the Livermore Valley and adjacent Diablo Range foothills. None of these faults appear to be more than a few kilometers in length.

The Calaveras and Greenville Fault Zones have been previously discussed. Descriptions of all other known and postulated faults in the Livermore Valley area are presented in the following sections.

Active Faults

Las Positas Fault. The northeast-trending Las Positas Fault Zone was first mapped by Herd (1977) based on geomorphology, airphoto interpretation, a groundwater barrier, and two fault exposures (one on the west bank of the Arroyo Seco and the other in a cut along Greenville Road, about 100 ft (30 m) north of the South Bay Aqueduct). The northerly branch of the Las Positas Fault Zone, as mapped by Herd (Fig. 9), crosses the southern portion of SNLL and coincides with a break in slope separating the nearly flat valley floor to the north from an area of terraces and hills to the south. It bounds the northwestern side of a young anticline described in a previous section.

Herd also mapped an arcuate southerly branch of the Las Positas Fault Zone approximately coincident with the southern boundary of the hill area south of SNLL. This strand is roughly 0.8 km (0.5 mi) south of the main fault zone and bounds the southerly flank of the anticline.

Features that Herd used to postulate the Las Positas Fault Zone are concentrated in an area that extends roughly 2 km (1.2 mi) northeast and southwest from SNLL.

Approximately 3.2 km (2 mi) northeast of SNLL, Herd mapped the Las Positas Fault Zone as ending abruptly at the Greenville Fault Zone in an area of complex structure. Herd also mapped a series of strands of the Las Positas Fault Zone extending from the area of most prominent expression southwestward for a distance of about 9.6 km (6 mi) to a point about 1.2 km (0.8 mi) northeast of San Antonio Reservoir. The Las Positas Fault Zone is not well defined in the area of postulated southwestward extension and its existence in this area has been the subject of conflicting opinions as will be discussed in later paragraphs.

The Las Positas Fault Zone was not detected during geophysical surveys conducted by John A. Blume and Associates (1972). Most of the gravity, magnetometer and seismic refraction profiles run by Blume were oriented subparallel to the Las Positas Fault Zone and would have been unlikely to detect the fault. However, two gravity profiles crossed the fault at high angles; no anomalies appeared on either profile at fault crossings.

URS/Blume (1978) excavated 10 trenches within SNLL across the postulated trace of the Las Positas Fault. URS/Blume found evidence suggestive of faulting in some trenches, but not in others. Geophysical and trenching investigations on property approximately 0.8 km (0.5 mi) southwest of SNLL produced data that suggested faulting (Judd Hull and Associates, 1977; Carpenter, 1977) within materials believed then to be the Livermore Formation, but mapped during this investigation as unit Qal_2.

To obtain more data concerning the Las Positas Fault, LLNL geoscience personnel performed an extensive field study described in detail by Carpenter *et al.* (1980). Explorations performed are shown in Figs. 20 and 21. The results of the 1980 study as modified by subsequent investigations may be summarized as follows:

Two faults were noted in an enlarged creek bank exposure located on the southwest side of the Arroyo Seco within SNLL. These faults displace the contact between northwest dipping beds of the Livermore Formation and overlying colluvial and terrace deposits. The southerly fault has offset the erosion surface developed across the dipping Livermore Formation beds vertically by about 60 cm (2 ft). Material overlying the erosion surface consists of remnants of an older terrace deposit (Qal_2, this report, Qoa_3, Herd, 1977) and colluvium. These materials appear to have been displaced in part as well. The fault strikes N49°E and dips 84°SE. Faint slickensides preserved on the fault plane plunge 19° northeast indicating oblique, but dominantly strike-slip movement. The movement appears to have occurred sometime between 3,000 and 80,000 yr ago (Shlemon, Appendix E).

Vertical movement along the northerly strand is north side down. The slip surface offsets the Livermore Formation, an overlying reddish-brown colluvial gravel and extends upward into the organic-rich surficial colluvium. The base of the reddish-brown (older) colluvial gravels has an apparent vertical offset about 90 cm (3 ft) and a scarp of this height may have existed or been formed progressively by a series of smaller movements. The northerly fault extends upward into late Holocene colluvium and faulting may have occurred possibly 500 to 1000 yr ago (Shlemon, Appendix E). The northerly fault strikes N58°E and dips 89°NW; no slickensides are visible.

Trench E-3, excavated about 23 m (75 ft) northeast of Arroyo Seco Creek (Fig. 21), encountered a zone of faulting approximately 6 m (20 ft) wide at the hill front near its southerly end. The faulting displaces alluvium (Hpal, this report) against steeply dipping Livermore Formation beds. A wood sample obtained at a depth of 11 ft (3.3 m) in Trench E-3 has been dated by the ^{14}C method at 17,400 ± 250 yr (Robinson, 1980). The alluvial unit from which the wood sample was obtained cannot be directly traced to the fault zone. However, correlative and overlying alluvium traceable to the fault has been displaced, indicating movement at less than 17,400 ± 250 yr. Much of the displaced alluvium has been altered by hydrothermal fluids or natural gas in a zone extending approximately 37 m (120 ft) northwest from the faulted section.

However, a pocket of young appearing, unaltered alluvium abruptly terminates along a 15-cm (6-in.) step within the fault zone suggesting minor very late Pleistocene or Holocene movement. Colluvial soils overlying the fault zone are thickened but have not been displaced. A detailed log and description of Trench E-3 is included in Carpenter *et al.* (1980).

Ambiguities exist at the Greenville Road cut site shown in Fig. 21. This road cut provides one of the principal exposures that Herd (1977) used to postulate the existence of the Las Positas Fault Zone. The northern branch of the Las Positas Fault, as mapped by Herd, is exposed along the eastern side of Greenville Road as a zone of highly fractured claystone containing pods of greenish clay. The zone strikes about N80°E where visible in the road cut. Colluvial soils are thicker north of the fracture zone than the south of it and a gravel bearing bed (unit Qal_1?) is terminated at the fracture zone and along a line that strikes N35°E across Greenville Road. Pedogenic carbonate data provide evidence for a groundwater barrier at this location approximately 60,000 yr ago (Knauss, 1981; Appendix D). However, no direct evidence of faulting such as slickensides or pebbles upturned relative to bedding planes can be seen along this northeast striking feature. A number of small faults cut Livermore Formation beds exposed in the road cut and 1 ft of apparent vertical displacement of topsoil appears to have occurred along at least one of them. The individual small faults strike from about N35°W to N73°W and dip variously northeast and southwest. These small faults were described by John A. Blume and Associates (1972) and were regarded as evidence for either the Corral Hollow or Ramp Thrust Faults as these were then mapped. As discussed previously, these small faults trend parallel to the postulated ancestral Greenville Fault mapped about 400 ft east of the road cut (Fig. 10). Two of the northwest-striking small faults terminate against the N80°E striking fracture zone. The others daylight in the face of the roadcut; their relationship to the northeast-trending fracture zone cannot be determined.

Several vague airphoto lineaments subparallel to the Las Positas Fault were identified crossing the southeastern portion of LLNL. Exploratory trenches E-1, E-5, and E-6 were excavated across these lineaments (Carpenter *et al.*, 1980). Trench locations are shown in Fig. 20. No faults were found in any of these trenches. Alluvial deposits in these trenches include materials for which a minimum age of approximately 100,000 yr has been established by the $^{230}Th/^{234}U$ ratio method applied to pedogenic carbonate (Knauss, 1981; Appendix D of this report) and by soil profile methods (Shlemon, Appendix E). Shlemon suggests that, based on late Pleistocene history, the probable depositional age of these deposits is 125,000 to 195,000 yr.

Subsequent to these initial phase studies reported by Carpenter *et al.* (1980) and modified herein, additional investigations have been conducted by LLNL geoscience personnel. These investigations consisted of geologic mapping (see Fig. 10), further airphoto interpretation and the logging of a cut on Greenville Road about 1.2 km (0.8 mi) south of LLNL. This cut crosses the south strand of the Las Positas Fault Zone as identified by Herd (1977) and by this investigation. A detailed log of the road cut is presented in the geologic data report (Carpenter *et al.*, 1982) prepared as a supplement to this document. Figure 24 presents an extract from the detailed log showing the most recently active strand. Geology exposed in the southerly road cut is discussed in more detail in following paragraphs.

These field investigations show that the Las Positas Fault Zone in the vicinity of LLNL consists of two well-defined branches, referred to here as the northern and southern branches, respectively. Both branches are characterized by discrete, relatively short [mostly less than 1 km (0.6 mi) long] shears.

Shears defining the north branch are concentrated in a northeast-southwest striking zone roughly 150 m (500 ft) wide. The zone departs from the Greenville Fault in the SW 1/4, NE 1/4 Sec. 7, T3S, R3E (Fig. 10) at an angle of about 60° to the Greenville system. A linear, northeast striking valley along the Las Positas Fault intersects an east-facing scarp and semienclosed depression at the probable point of junction. The scarp and depression are on strike with an older strand of the Greenville Fault exposed in the South Bay Aqueduct about 520 m (1700 ft) to the southeast. The north branch of the Las Positas Fault Zone is tangent to LLNL at the laboratory's southeastern corner and, as previously noted, crosses SNLL property along a well-defined slope break.

Bonilla *et al.* (1980) had suggested minor sympathetic motion along the north branch of the Las Positas Fault during the earthquakes on January 24 and 26, 1980 generated by the Greenville Fault. During field studies in December 1981, a pattern of crudely en-echelon, right-stepping cracks were noted at the intersection of East Avenue and Greenville Road immediately southeast of LLNL (Fig. 10). These cracks overlie an area where one of the shears defining the north branch of the Las Positas Fault Zone is believed

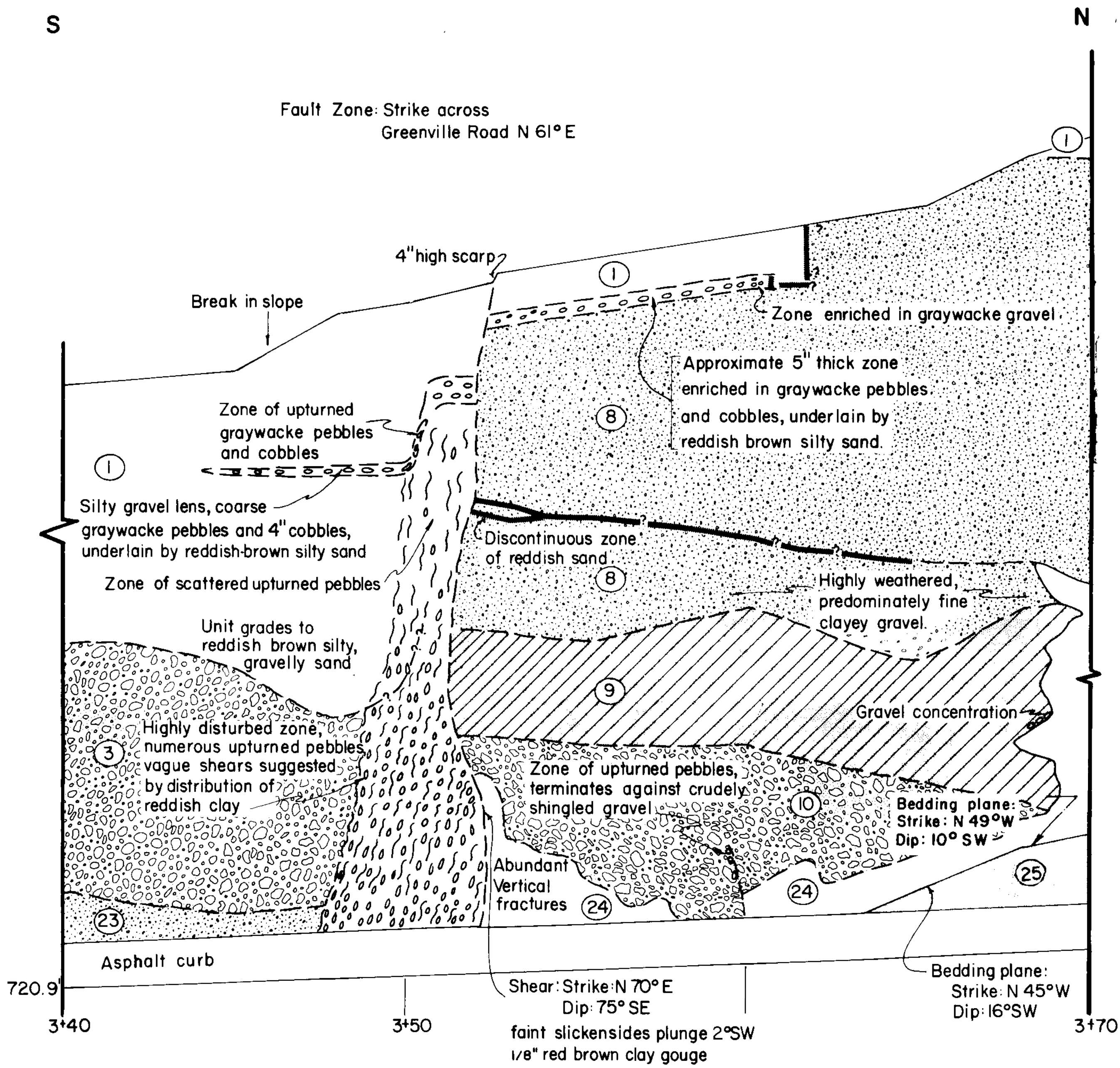


Fig. 24. Log of Greenville roadcut (south) from Sta. 3 + 40 to Sta. 3 + 70 showing south branch, Las Positas Fault Zone. For descriptions of numbered geological units see Carpenter *et al.*(1982).

to be located and suggest that areal stress readjustments following the 1980 earthquakes may have initiated aseismic slip along part of the north branch of the Las Positas Fault Zone. Scheimer *et al.* (1982) report that some microseismic events plot near the north branch of the Las Positas Fault.

The south branch of the Las Positas Fault Zone is well exposed in a deep cut along Greenville Road approximately 140 m (460 ft) north of the Arroyo Seco (Fig. 10) about 1.2 km (0.8 mi) south of LLNL. Faults are exposed on both sides of the road and a right-stepping pattern of en-echelon cracks in the road pavement link the two faults. The cracks appeared sometime between early April and late May 1981 and suggest aseismic slip along a portion of the south branch as well.

A zone of coarse gravel and cobbles interpreted by Shlemon (Appendix E) as a latest Pleistocene stoneline (e.g., erosion surface) and estimated at 15,000 to 20,000 yr of age is offset vertically about 85 cm

(33 in.) across the fault (south side down). There is also evidence for a throughgoing shear in the overlying modern colluvium as well (see Fig. 24). Shlemon (Appendix E) states that observed geologic features support the belief that the south branch has ruptured to the surface during historic time. Scheimer *et al.* (1982) report that epicenters of a number of microearthquakes and one locally felt event ($M_L = 3.2$) plot along the south branch of the Las Positas Fault Zone.

The south branch strikes N61°E across Greenville Road; exposed shears dip steeply southeast. Numerous other faults are exposed in the road cut, but none of these clearly offset unit Qal_2 or younger materials (Carpenter *et al.*, 1982).

Airphoto interpretation and field reconnaissance indicate that the south branch strikes southwestward through a landslide on the east bank of the Arroyo Seco and beneath two enclosed depressions within unit Hpal (Fig. 10). Further southwest, airphoto data, cracks, and repairs in the lining of the South Bay Aqueduct suggest that the fault consists of a series of en-echelon, right-stepping shears.

The south strand appears to continue southwestward with decreasing definition and probably crosses Tesla Road about 0.8 km (0.5 mi) west of Greenville Road (Fig. 10). Further southwest, the location of the south branch becomes progressively more uncertain.

Except at Greenville Road, Herd (1977) and Dibblee (1980c) map the south branch of the Las Positas Fault slightly north of the locations described in this report. Their maps show the fault following tonal lineaments that appear to us to correspond to the boundary between steeply dipping Livermore Formation beds and remnants of unit Qal_2. Minor faults within Livermore Formation beds are exposed on the north side of Tesla Road about 1.6 km (1 mi) west of Greenville Road near the fault mapped by Herd. It is likely that the south branch, like the north branch, actually exists as a zone of shears several hundred feet wide.

East of Greenville Road, the south branch of the Las Positas Fault can be traced nearly east-west for about 1.6 km (1 mi). Evidence for the fault in this area consists of a linear swale visible west of Jerrold Road (Fig. 10) and the juxtaposition of vertically dipping upper Livermore Formation (Qtl) beds against a northwest dipping sequence of Miocene and Pliocene strata exposed upslope to the north. The northwest dipping sequence forms the south limb of the Livermore syncline.

The south strand of the Las Positas Fault appears to curve southeastward and join the Greenville Fault Zone somewhere in the southwest 1/4 Sec. 17, T3S, R3E (Fig. 10). There are no exposures or geomorphic features in this area to clearly establish the probable point of intersection, although a spring that has been developed into a small reservoir occurs near the probable point of linking.

East of Greenville Road, the south branch of the Las Positas Fault, as we have mapped it, lies slightly north of the location shown by Herd (1977), but follows the same trend. Dibblee (1980c) did not map the south branch east of Greenville Road.

The south branch may change dip in the area east of Greenville Road. Huey (in John A. Blume and Associates, 1972) reported on a directionally drilled gas exploration well that extended beneath the exposures of the Neroly Formation north of the Las Positas Fault [thought to be a "ramp" (e.g., thrust) fault by Huey]. The well penetrated a thick sequence of Livermore gravels and "Orinda" Formation (equivalent to unit Tps of Dibblee and this investigation) before bottoming in Great Valley Sequence rocks (Figs. 25 and 26). No other Tertiary strata were encountered. Examination of Huey's cross section suggests that a low-angle thrust fault would not be necessary to fit the well data, but that a high-angle north dipping fault would be needed. Changes of dip direction are not uncommon along high-angle strike-slip faults.

The extension of the Las Positas Fault Zone southwest of Arroyo Mocho has been the subject of considerable controversy. Conflicts in data and interpretations become evident when reports by Herd (1977), Earth Sciences Associates (1979), and Herd and Brabb (1980) are compared. Rice *et al.* (1979) and T. C. Smith (1981) provide reviews of the problem.

T. C. Smith (1981) evaluated the Las Positas Fault to determine if it should be included with the list of active faults requiring study pursuant to the provisions of the State of California, Alquist-Priolo Act. The study by T. C. Smith included an evaluation of previous reports and interpretation of aerial photographs.

Between the Arroyo Mocho and Arroyo Valle the front of the Diablo Range foothills is very linear. T. C. Smith (1981) noted linear tonal patterns, straight drainages and possible deflected drainages and ponded alluvium in this area. Similar features were observed by LLNL geologists when airphotos of the area were studied (see Fig. 27).

Features suggestive of faulting cannot be seen disturbing active floodplain deposits along the Arroyo Valle, but reappear in more subdued form southwest of it. Immediately southwest of the Arroyo Valle

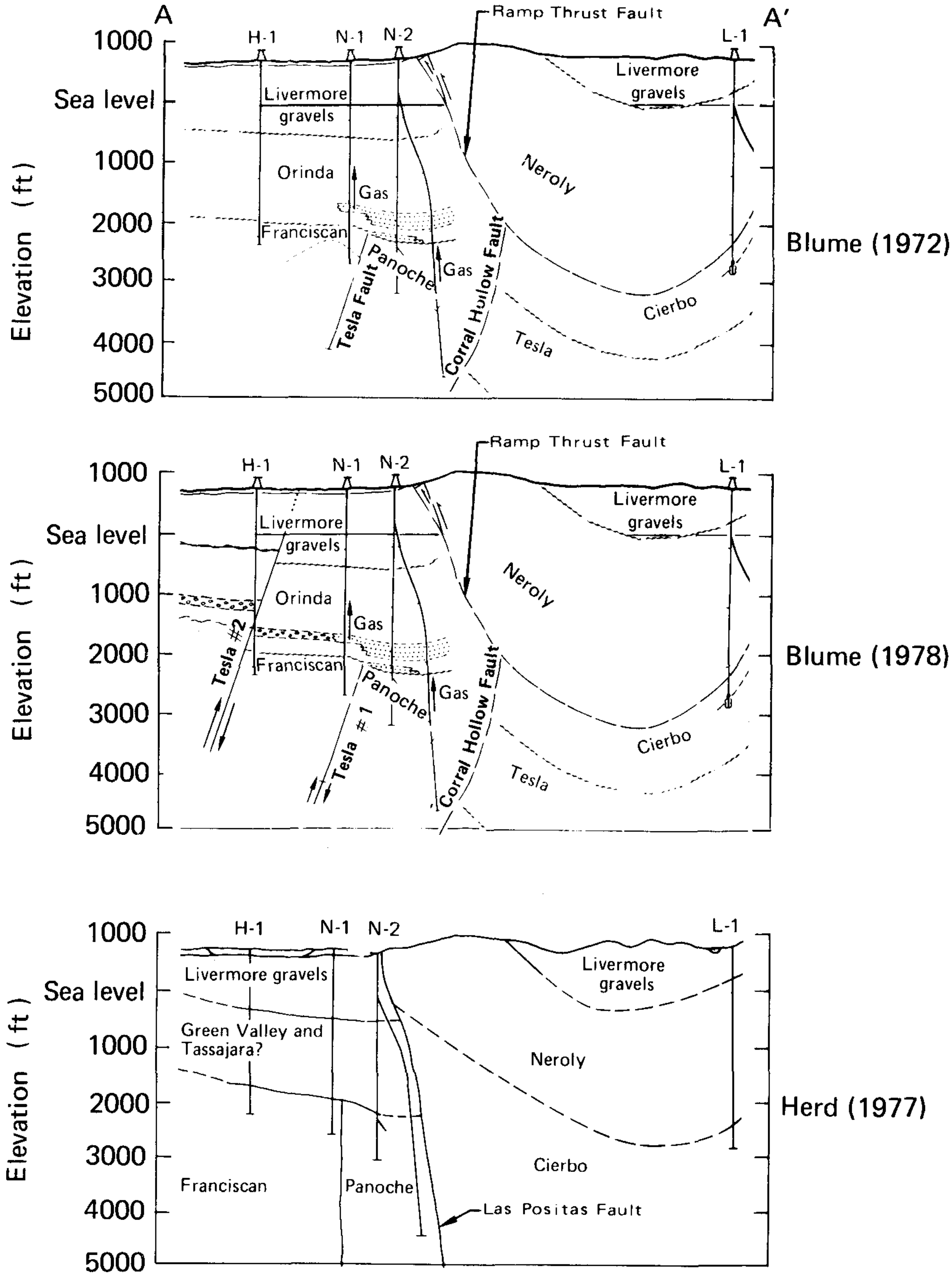


Fig. 25. Section A-A′ as shown in John A. Blume and Associates (1972), in URS/Blume (1978), and in Herd (1977). See Fig. 22 for location.

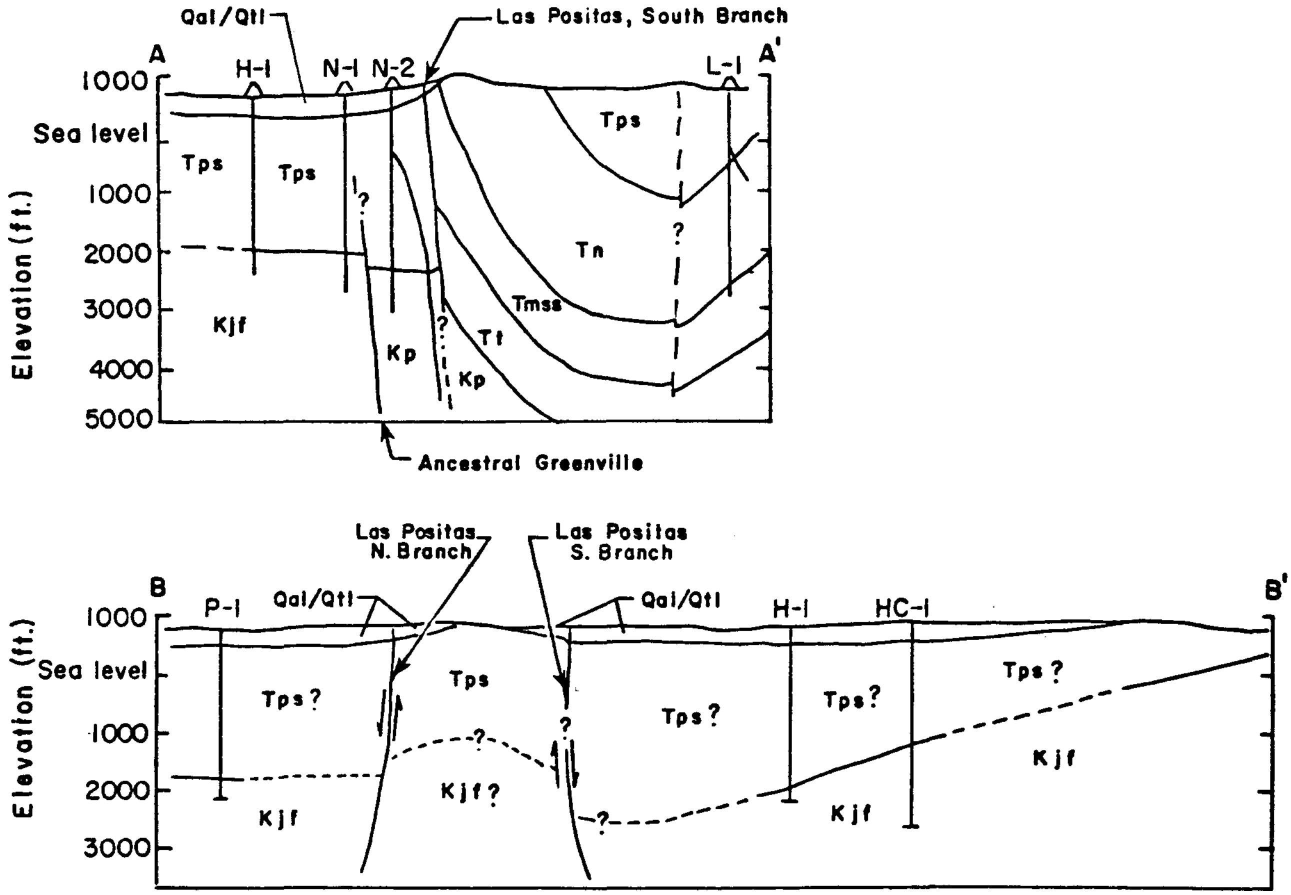


Fig. 26. Cross-section interpretations as a result of this investigation. For locations of sections, see Fig. 16.

floodplain, T. C. Smith (1981) detected a short, yet well-defined scarp, which cuts materials mapped by Herd (1977) as Qoa_3.

Further southwest, features were less continuous and less well-defined. T. C. Smith (1981) stated:

"These features tend to be 'softer' data, consisting of tonals, benches, linear drainages, and one possible deflected drainage, all of which could conceivably be of nontectonic origin . . .".

However, T. C. Smith (1981) noted that these features could be followed southwest into the La Costa Valley Quadrangle where Herd and Brabb (1980) postulated a link between the Las Positas and Verona Fault Zones. As shown in Fig. 27, LLNL geoscientists have made similar observations.

After evaluating available data, the State of California (Davis, 1982b) established a "Special Studies Zone" along strands of the Las Positas Fault northeast of the Arroyo Mocho to a point about 230 m (750 ft) east of Greenville Road. Within Special Studies Zones, parties subject to the jurisdiction of the State of California are required to have active fault location studies performed before building permits can be issued for most classes of construction.

No Special Studies Zone was established for postulated strands of the Las Positas Fault southwest of the Arroyo Mocho since the evidence for these strands was not sufficient to justify zoning under State of California criteria (T. C. Smith, 1981). Initially, no zoning along the south branch of the Las Positas Fault was proposed (T. C. Smith, 1981). However, zonation was recommended following observations by Hart (1981b) of the southerly Greenville Road cut exposure and the evidence for possible aseismic slip also visible at this location.

Data are very limited from which estimates of the slip or activity rate of the Las Positas Fault Zone can be made. Shedlock *et al.* (1980) estimated a geologic slip rate of 0.2 mm/yr for the Las Positas Fault

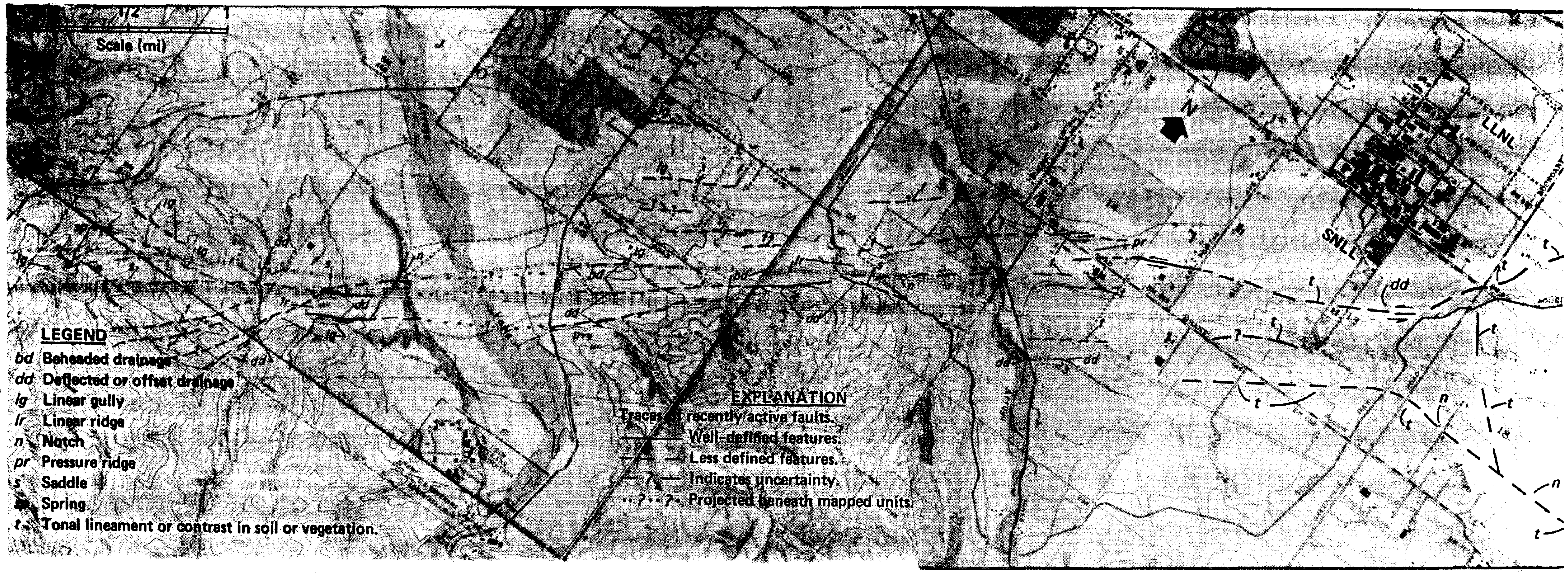


Fig. 27. Interpretation of aerial photo data: Las Positas Fault Zone, Arroyo Mocho area, and southwest of Arroyo Valle.

Zone based on a presumed tectonic connection with the Verona Fault. Prescott *et al.* (1981) gave no estimates of geodetic slip rates along the Las Positas Fault.

Vertical offsets can be determined for several geologic features whose relative ages can be estimated. These features are listed in Table 3. However, it is difficult to convert these vertical offsets into total offsets. Total offsets along strike-slip faults, such as the Las Positas is believed to be (Herd, 1977), usually are several times larger than the observable vertical offsets alone. Herd (1977) believed that geomorphic features along the fault indicated left-lateral motion, and the clockwise rotation of the block south of the fault detected by Prescott *et al.* (1981) would require left-lateral motion along the fault zone.

Slickensides are preserved on two fault surfaces exposed during detailed geologic studies. Slickensides on one shear exposed during clean-up of the creek bank southwest of the Arroyo Seco (Fig. 21) plunge 19° northeast (indicating a ratio of horizontal-to-vertical motion of 2.9:1). Along this shear, the northwest side is displaced up, a feature difficult to reconcile with the overall geology along the north branch where the northwest side is downthrown.

Slickensides plunging 9° southwest were observed on a northeast-striking shear encountered in Trench E-4 (Fig. 21) and believed to be a strand of the Las Positas Fault Zone (Carpenter *et al.*, 1980). The horizontal-to-vertical ratio indicated by the plunge of these slickensides is 6.3:1.

The average horizontal-to-vertical ratio based on the two sets of preserved slickensides is 4.6:1, and this ratio has been used to convert observed vertical offsets to estimated total offsets from which geologic slip rates can be estimated. The resulting estimated total offsets are also included in Table 3. The average slip rate calculated for the north branch of the Las Positas Fault Zone is 0.4 mm/yr; the range of rates obtained (shown in Table 3) is 0.02 to 0.9 mm/yr.

Table 3. Slip rate estimates for the Las Positas Fault Zone.

Feature	Age (yr)	Observed vertical offset (m)	Calculated total offset (m)	Slip (mm/yr)
North branch				
Offset erosion surface on lower member of Livermore Formation (elevation difference between position in wells MW-11 and MW-19 and exposures south of fault)	1,000,000	60	281[a]	0.3
Offset surface on unit Qal_2	100,000	6	28.1[a]	0.3
Base, late Pleistocene colluvium, southerly shear, North Branch, Arroyo Seco outcrop	3,000-80,000 (range)	0.6	1.84[b]	0.6-0.02 (range)
Base, late Pleistocene colluvium, northerly shear, Arroyo Seco outcrop	80,000	0.9	4.2[a]	0.05
Base, modern colluvium, northerly shear, North Branch, Arroyo Seco outcrop	500-1,000 (range)	0.1	0.47[a]	0.9-0.5 (range)
South branch				
Offset eroded contact between Livermore Fm and unit Qal_2	195,000	6.6	66.5[c]	0.3
Offset latest Pleistocene stoneline at base of colluvium	18,000	0.85	8.5[c]	0.5

[a] Based on average 4.6:1 horizontal-to-vertical offset ratio deduced from geologic data (see text).

[b] Based on 19° plunge of slickensides preserved on fault surface.

[c] Based on 10:1 horizontal-to-vertical offset ratio deduced from separation and uplift of paleodrainage along fault.

Data for the south branch are equally sparse and uncertain. A stoneline at the base of the latest Pleistocene-Holocene colluvial layer has been offset 85 cm vertically by movements along the south branch, and the erosion surface between Livermore Formation beds and overlying unit Qal_2 has been offset about 6.6 m (21.5 ft) vertically across the fault zone.

Horizontal components of motion are highly uncertain. About 0.8 km (0.5 mi) east of Greenville Road a gully "hangs" on the hillside at the point where the gully is crossed by the south branch (see Fig. 10). About 305 m (1000 ft) farther east, a deep gully exists below the 900-ft contour, but has no expression higher on the slope. The point of apparent disruption of the gully is about 30 m (100 ft) above the present valley floor, suggesting a ratio of about 10:1 horizontal-to-vertical motion along the south branch. Estimated slip rates for the south branch, shown in Table 3, have been calculated based on the above observations and interpretations. The average slip rate for the south branch of the Las Positas Fault is 0.4 mm/yr (0.016 in.)—the same as for the north branch.

The overall slip rates for the Las Positas Fault Zone are similar to those calculated for the Greenville Fault Zone. As discussed above, these two fault zones appear to intersect and, therefore, movements on the larger Greenville Fault Zone may be triggering approximately equivalent amounts of sympathetic motion and seismicity on strands of the Las Positas Fault Zone.

Shedlock *et al.* (1980) calculated a maximum earthquake for the Las Positas Fault Zone of M = 6.2 based on fault length criteria. Earth Sciences Associates (1982) estimated that the maximum credible earthquake for the Las Positas Fault Zone is about 6.0. Table 4 presents a range of the estimates of the maximum credible earthquake for the Las Positas Fault Zone based on methods reviewed by Slemmons and Chung (1982). The values estimated are based on eight different methods of analysis and range from $M_s = 5.4$ to 6.7. The average estimated magnitude is 6.0 ± 0.5.

In summary, airphoto data reviewed during this investigation support a subdued continuation of the Las Positas Fault southwest to the vicinity of the Williams Fault, as mapped by Dibblee (1980f). The Las Positas Fault Zone is then roughly 18 km (11 mi) long including the south branch. Plots of microseismicity within the southeastern Livermore Valley show events near both branches of the Las Positas Fault (Scheimer *et al.*, 1982). The estimated slip rate for the Las Positas Fault Zone is 0.4 mm/yr (0.016 in./yr); the maximum credible earthquake is $M_s = 6.0 \pm 0.5$.

Verona Fault. The CDWR (1966) mapped the Verona Fault south of Pleasanton (Figs. 6 and 8) and reported evidence for displacement of the Livermore Formation as well as the existence of a groundwater barrier in alluvium where the fault crosses the narrow canyon of the Arroyo de Laguna.

Herd (1977) placed the Verona Fault southwest of the position shown by the CDWR and close to the General Electric Corporation's Vallecitos Nuclear Center. The investigation by Herd led to an extensive study of the Vallecitos area (Earth Sciences Associates, 1979).

Table 4. Estimates of the maximum credible earthquake, Las Positas Fault Zone.[a]

Method	Maximum credible earthquake
Maximum historic earthquake (June 11, 1903)	5.5[b]
Fractional fault length (2.9 km)	5.6
Segmentation (6.4 km)	5.7
Rupture segment length (2.79 km)	5.4
Total displacement (0.47 m)	6.7
Total fault length (18.1 km)	6.6[c]
Fault slip rate (0.4 mm/yr)	6.3
Relative magnitude (maximum historic event plus 1 magnitude unit)	6.5
Average	6.0 ± 0.5

[a] Methods outlined by Slemmons and Chung (1982), except fault slip rate method which is from Woodward-Clyde Consultants (1979).

[b] Event plots within Las Positas Fault Zone; quality of location uncertain.

[c] Maximum value, data point at lower limit of regression curve.

The Verona Fault as mapped by Herd and several subparallel shears were identified during the Earth Sciences Associates investigation. These shears were found to dip at low angles to the northeast leading the U.S. Geological Survey (Herd and Brabb, 1980) to postulate thrust faulting, and Earth Sciences Associates (1979) to postulate that the features represented the soles of large, degraded landslides.

Rice *et al.* (1979) reviewed the evidence concerning the Verona Fault and related shears and concluded that multiple displacements have occurred during the past 70,000 yr. Some shears displace early Holocene materials and individual displacements have occurred in increments of about 1 m (3 ft) or less. The cause of the displacements could not be definitely determined. However, Rice and others favored the landslide hypothesis over tectonic faulting.

The Verona Fault mapped by Herd (1977) is approximately 10 km (6 mi) long. Rice *et al.* (1979) concluded from available data that there was little likelihood that the Verona Fault continues beyond these limits to the northwest or east. They also concluded that a postulated connection between the Verona Fault and the Las Positas Fault (Herd and Brabb, 1980) was not supported by field data.

D. P. Smith (1981) reviewed geologic and geomorphic evidence from the Vallecitos Nuclear Center area and concluded that the Vallecitos Hills northeast of the site have been tectonically elevated. However, he also concluded that the landscape in the vicinity of the Vallecitos Nuclear Center has been modified by large scale landslides that have been periodically triggered and transected by fault movements. The Verona Fault envisioned by D. Smith is a high-angle fault different from that postulated by Herd and Brabb.

Subsequently, the California Division of Mines and Geology reevaluated data concerning the Verona Fault Zone and concluded that the segment of the fault from the Vallecitos Nuclear Center to Sycamore Road, about 1.6 km (1 mi) south of Pleasanton, is sufficiently well-defined to require zoning under provisions of the Alquist-Priolo Act (Hart, 1980a, 1981b; Davis 1982c). The segment zoned is approximately 5.65 km (3.5 mi) long. Postulated northwestward connections with the Calaveras Fault Zone and southeastward connections with the Las Positas Fault Zone were again judged not to be supported by the geologic data (Hart, 1980a, 1981b).

Ellsworth and Marks (1980) reported minor microseismicity in the vicinity of the Verona Fault. Some thrust-faulting events were observed in the microseismicity.

Other Faults

In addition to the active faults described previously, investigators have mapped or postulated the existence of 20 additional faults in the Livermore Valley region. Some of these faults have been formally named; others have not. Carpenter *et al.* (1980) provide a comprehensive review of previous work. The following is summarized from this previous review, with additions reflecting recent studies, where appropriate. These other known or postulated faults are described in alphabetical order.

Carnegie Fault. Huey (1948) mapped the Carnegie Fault in the hills east of LLNL and reported evidence near its northwestern limit for a faulted contact between the Livermore Formation and the Cretaceous Panoche Formation (Great Valley Sequence). He did not recognize effects of the fault on Quaternary alluvial deposits along its projection and, therefore, mapped it as buried and dying out beneath alluvial cover within eastern Livermore Valley.

Dibblee (1980d) and Sweeney and Springer (1981) mapped an overturned anticline along the westerly portion of the Carnegie Fault as mapped by Huey (1948). They found no evidence for faulting in this area. Dibblee (1980d) mapped the Carnegie Fault southeastward from Sec. 24, T3S, R3E to a junction with the Tesla Fault in Sec. 2, T4S, R4E (Fig. 16), a distance of about 10 km (6 mi). Dibblee (1980d) showed the fault juxtaposing lower Livermore Formation (Tps) against older rocks but buried beneath alluvial deposits.

The CDWR (1979) mapped the Carnegie Fault along the northeastern margin of the Livermore Valley and across the Livermore oil field northeast of LLNL. Features used by the CDWR to define the Carnegie Fault within northeastern Livermore Valley were regarded by Herd (1977) as associated with the Greenville Fault Zone and are so regarded by our study (see Fig. 10).

In summary, the Carnegie Fault appears to be a local fault in the southern Altamont Hills related to a complex zone of folding and faulting north of the Tesla Fault. The fault does not extend into eastern Livermore Valley as postulated by some previous investigators. No features suggesting post-Pliocene movement have been seen along it.

Corral Hollow Fault. Huey (1948) mapped the Corral Hollow Fault as locally displacing the Livermore Formation in the Altamont Hills, but showed the fault as dying out before reaching the valley. During early studies, the CDWR (1966, 1974) projected the Corral Hollow Fault northwest across the Livermore Valley as a subsurface feature (Fig. 28). However, in 1979, the CDWR mapped the Corral Hollow Fault essentially as it had been mapped by Huey. John A. Blume and Associates (1971) followed the CDWR in projecting the Corral Hollow Fault northwest across Livermore Valley beneath the eastern portion of LLNL but later (1972) deleted this projection from their maps.

Dibblee (1980d) mapped the Corral Hollow Fault in the Altamont Hills as a northwest-trending strike-slip fault oriented subparallel to segments of the Tesla and Greenville Fault Zones. The Corral Hollow Fault of Dibblee is located entirely northeast of the Greenville Fault Zone and trends southeast from SW 1/4, Sec. 32, T2S, R2E to Corral Hollow (SE 1/4, Sec. 25, T3S, R3E) and then easterly beneath alluvium in Corral Hollow to an inferred junction with the Carnegie Fault in Sec. 33, T3S, R4E (see Fig. 16).

Dibblee (1980d) showed the Corral Hollow Fault as offsetting the axis of the Corral Hollow syncline about 0.6 km (0.4 mi) in a right-lateral sense. Beds of lower Livermore Formation (Tps) are preserved in the core of the syncline.

In 1979 LLNL geoscience personnel excavated exploratory trench E-5 across the Corral Hollow Fault as projected beneath LLNL by John A. Blume and Associates (1971) and CDWR (1966) (see Fig. 20). The trench showed no offsets suggestive of faulting (Carpenter *et al.*, 1980) in alluvial deposits believed to be 125,000 to 195,000 yr old (Shlemon, Appendix E). Average resolution during the trenching investigation was about one inch (2.5 cm).

Dougherty Fault. John A. Blume and Associates (1972) postulated the Dougherty Fault* as crossing the northeastern portion of LLNL based on their interpretation of geophysical data (Fig. 22). Gravity data indicated that the northeast block appeared displaced up and seismic refraction data suggested a groundwater barrier along the postulated fault (John A. Blume and Associates, 1972).

The Dougherty Fault shown by John A. Blume and Associates (1972) has no physiographic expression either in valley alluvium or in lower Livermore Formation beds exposed in the hills southeast of LLNL. However, URS/John A. Blume and Associates (1978) reported a night infrared (IR) lineament near the suspected fault trace (Fig. 20) and LLNL geoscience personnel have seen a similar feature during photogeologic studies, but have given it a different trend.

In 1979 LLNL geoscience personnel examined an exploratory trench, two storm drain trenches, and a deep building foundation excavation located across the postulated Dougherty Fault as mapped by John A. Blume and Associates (1972). These exposures showed no offsets (Carpenter *et al.*, 1980) in materials mapped as late Pleistocene to about 195,000 yr old (see Shlemon, Appendix E, and the discussion in the section entitled "Geology of LLNL Site").

Geophysical data obtained by John A. Blume and Associates (1972) and attributed to the Dougherty Fault appear to be locally associated with the ancestral Greenville Fault Zone previously described. However, in most cases the data cannot be clearly associated with any fault mapped during this investigation. Contours on the top of the saturated zone near LLNL (see Fig. 42, this report) provide no evidence for a groundwater barrier across the trend of the Dougherty Fault as postulated by John A. Blume and Associates (1972). No stratigraphic discontinuities that may be attributed to a Dougherty Fault appear on geologic cross sections compiled from drill holes within LLNL (Figs. 29 to 31). Locations of these geologic cross sections are shown in Fig. 32.

Therefore, detailed investigations provide no support for the existence of the Dougherty Fault postulated by John A. Blume and Associates (1972) in materials at least as old as 195,000 yr and probably significantly older. Indirect geophysical data are either inconclusive with respect to the Dougherty Fault or may reflect the presence of other faults.

Livermore Fault. The CDWR (1966) identified the Livermore Fault based on a well-defined groundwater barrier between the Livermore and Santa Rita Subbasins. They showed three strands of the fault passing through the western portion of Livermore (CDWR, 1974) (see Fig. 33). An outcrop of the easternmost strand was recognized in Oak Knoll, a hill composed of the Livermore Formation and located in

* Called "Doutherty Fault" in the report by John A. Blume and Associates (1972).

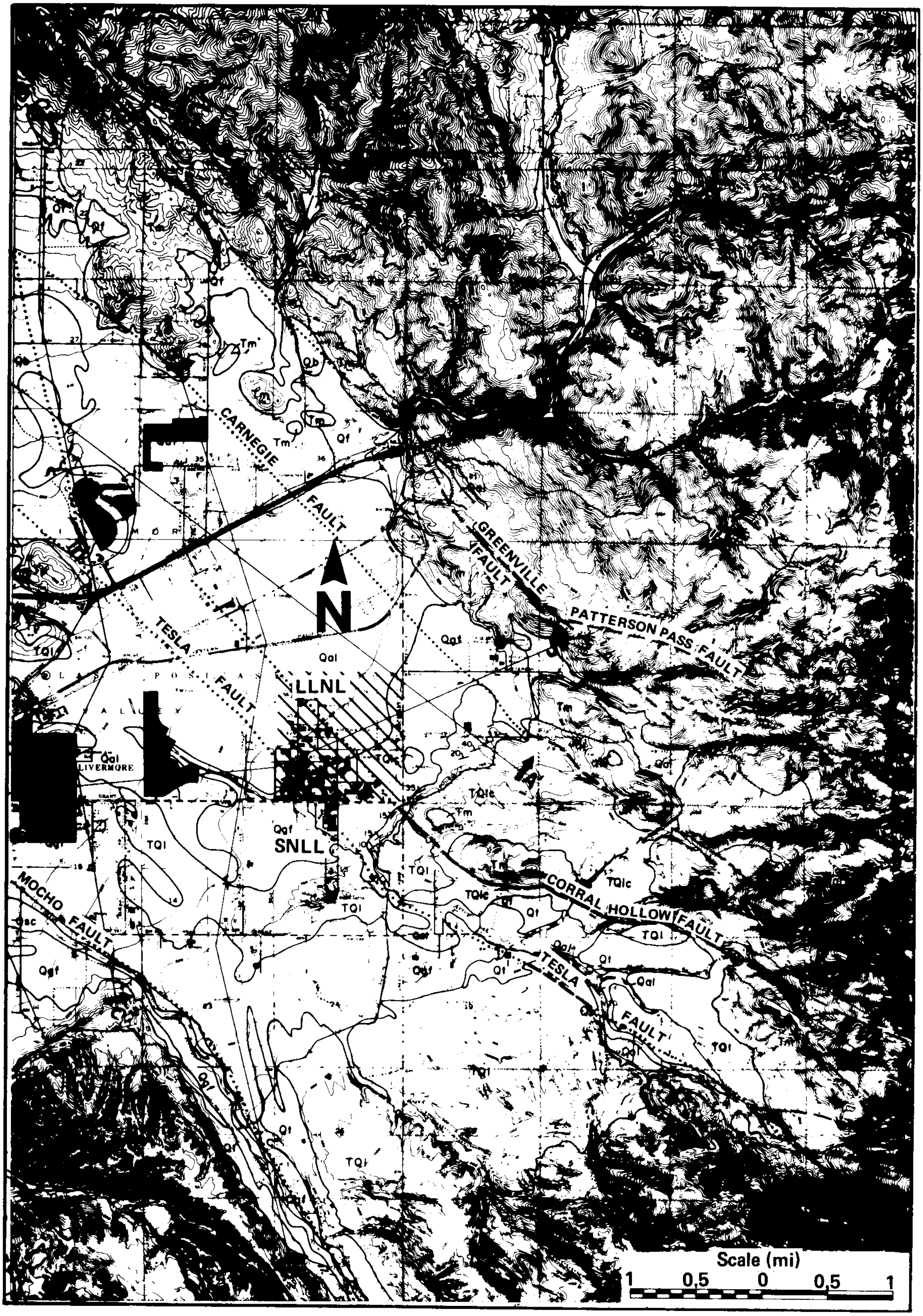


Fig. 28. Geologic map of Southeastern Livermore Valley (CDWR, 1974).

western Livermore. Preliminary LLNL field reconnaissance studies disclosed another possible outcrop of the Livermore Fault along Arroyo Road a short distance north of Marina Avenue. An airphoto lineament links the locations of these two outcrops. As presently mapped, the closest approach of the Livermore Fault to LLNL is about 5 km (3.2 mi) southwest of the laboratory.

Subsequently, the CDWR (1979) excavated two exploratory trenches east of Del Valle Reservoir, examined water level data obtained during the spring of 1978 in the vicinity of the postulated Livermore Fault, examined aerial photographs, and performed field mapping studies along the postulated fault trace. One well-defined groundwater barrier was detected and the fault was observed in a cut-slope north of the Del Valle Reservoir spillway, in an exploratory trench, and along the shoreline of Del Valle Reservoir in the southeast 1/4 Sec. 11, T4S, R2E (where it has been uncovered by wave erosion).

In the shoreline exposure, the fault zone is reported to consist of five parallel shears within the Livermore Formation. In the spillway cut slope, the fault reportedly juxtaposes the Livermore Formation and the Miocene Cierbo sandstone. In the exploratory trench, the Livermore Formation was displaced at two locations, but the weakly developed soil profile in colluvium overlying the Livermore Formation and the fault zone was not displaced (CDWR, 1979). Examination of the trench log published by the CDWR revealed some thickening of the colluvium over the more easterly shear exposed in the trench. A local zone of carbonate accumulation in the base of the "C" horizon of the soil profile developed in the colluvium ends at the shear.

The CDWR (1979) judged that the Livermore Fault should be considered active because it cuts through geologically young sediments and appears to be associated with moderate seismic activity.

Herd (1977) did not map or discuss the Livermore Fault, although it occurs within the area of his investigation. His map shows Oak Knoll composed of the Livermore Formation, while the Arroyo Road exposure is in an area mapped as an Older Alluvial Deposit (Qoa_4). Herd (1979) has stated that the presence of an active Livermore Fault would be inconsistent with his tectonic model for the Livermore Valley, which postulates right-lateral strike-slip movement on the Greenville Fault, left-lateral strike-slip movement on the Las Positas Fault, and thrusting along the Verona Fault (see Figs. 6 and 8).

Merrill and Seeley, Inc. (1980), reviewed evidence regarding the Livermore Fault on behalf of the City of Livermore and concluded that the Livermore Fault was potentially active. They recommended that the city require geologic studies adjacent to probable locations of the Livermore Fault Zone pending State of California review of available data. The CDMG (Hart, 1981b) conducted a review and concluded that because no geomorphic expression of the Livermore Fault could be seen in areas underlain by alluvial deposits, the fault should not be zoned as requiring detailed geologic studies pursuant to State statutes.

Mocho Fault. The CDWR (1966) postulated the existence of the Mocho Fault, based on geomorphic features southeast and north of the Livermore Valley, and mapped it (1974) as extending northwestward from the Arroyo Mocho Valley across central Livermore and into the Tassajara Hills north of Camp Parks (see Figs. 28 and 33). As mapped, the fault crosses the Mocho Groundwater Subbasin and is described as having some effect on groundwater levels beneath Livermore, but not farther to the southeast where the presence of thick, coarse alluvium may prevent the formation of a groundwater barrier.

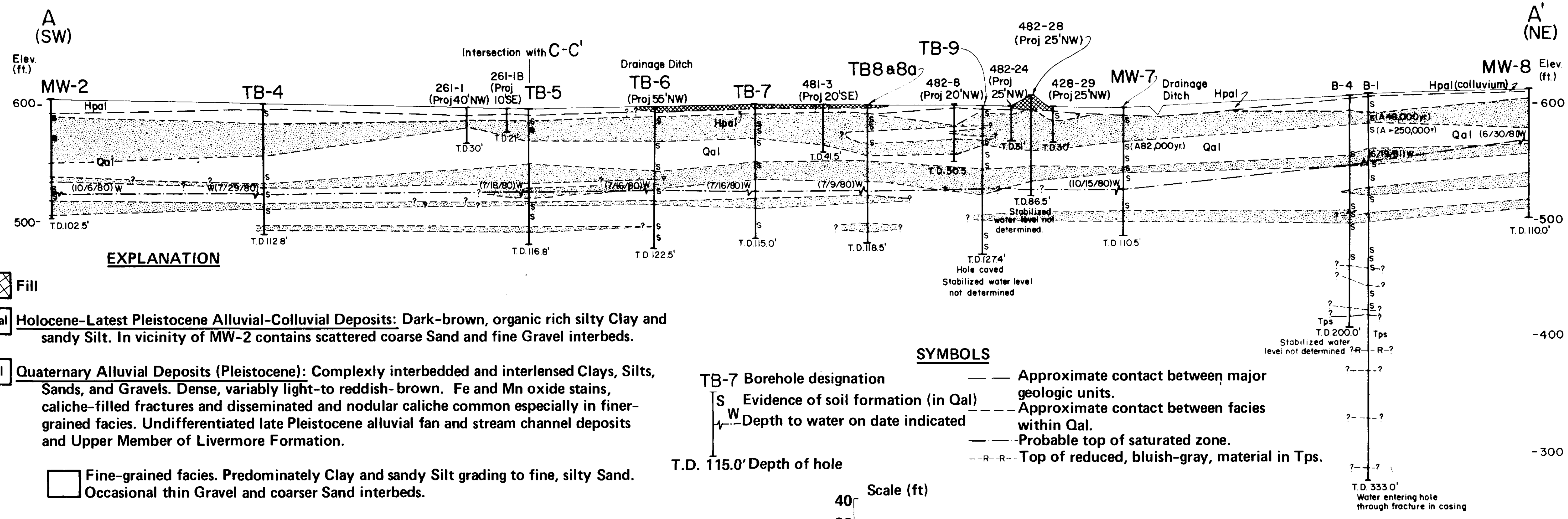
There is no known surface expression of the Mocho Fault, and geophysical studies by Cooper-Clark and Associates (1973) were inconclusive regarding its presence. Huey (1948) and Herd (1977) mapped the area southeast of Livermore where the Mocho Fault has been postulated, but neither showed the fault on their maps. The CDWR did not show the Mocho Fault on its 1979 map. Airphoto lineaments in the Tassajara Hills north of the Livermore Valley, previously ascribed to the Mocho Fault, were regarded by the CDWR in its 1979 report as a portion of the Livermore Fault Zone.

During geotechnical studies for a land development project north of the Livermore airport, Purcell, Rhoades and Associates (1981) encountered a fault in Pliocene Age Tassajara Formation deposits (beds roughly equivalent to unit Tps of Dibblee and this study). The fault is located in the general vicinity of the projected Mocho Fault and has a northwest strike. However, the fault does not displace colluvial deposits and was, therefore, judged by Purcell, Rhoades and Associates to be inactive and not a hazard to the proposed land development.

No relationship has been established between the fault observed by Purcell, Rhoades and Associates and the postulated Mocho Fault aside from the general areal relationship. The extent of the fault discovered by Purcell, Rhoades and Associates is unknown.

The CDMG (Hart, 1981c) evaluated the postulated Mocho Fault and concluded that its existence was largely inferential and that there was no surface evidence for Holocene faulting.

(Continued on p. 62)



EXPLANATION

Fill

Hpal Holocene-Latest Pleistocene Alluvial-Colluvial Deposits: Dark-brown, organic rich silty Clay and sandy Silt. In vicinity of MW-2 contains scattered coarse Sand and fine Gravel interbeds.

Qal Quaternary Alluvial Deposits (Pleistocene): Complexly interbedded and interlensed Clays, Silts, Sands, and Gravels. Dense, variably light-to reddish-brown. Fe and Mn oxide stains, caliche-filled fractures and disseminated and nodular caliche common especially in finer-grained facies. Undifferentiated late Pleistocene alluvial fan and stream channel deposits and Upper Member of Livermore Formation.

Fine-grained facies. Predominately Clay and sandy Silt grading to fine, silty Sand. Occasional thin Gravel and coarser Sand interbeds.

Coarse-grained facies. Predominately fine-to-coarse, silty and clean Sand, and silty-to clayey Gravel. Some poorly sorted Clay and Silt interbeds.

Tps Latest Tertiary Sediments (Lower Member of Livermore Formation): Interbedded, lenticular Clay, Silt, Sand, Gravel. Dense, locally lithified. Finer grained material dominately greenish-bluish gray, coarser materials variably oxidized brown to reduced, bluish gray.

SYMBOLS

TB-7 Borehole designation

S Evidence of soil formation (in Qal)

W Depth to water on date indicated

T.D. 115.0' Depth of hole

Approximate contact between major geologic units.

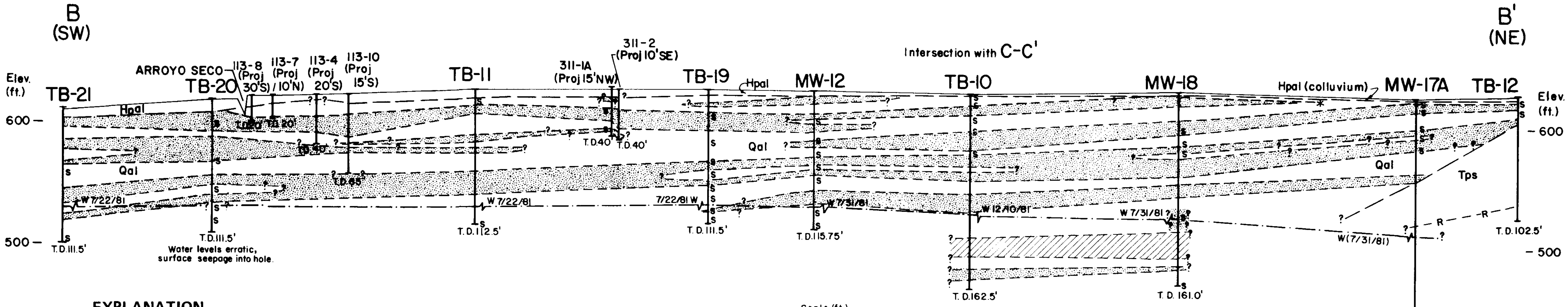
Approximate contact between facies within Qal.

Probable top of saturated zone.

--R--R-- Top of reduced, bluish-gray, material in Tps.

Scale (ft)
40, 20, 0; 200, 400

Fig. 29. Geologic cross section A-A' (for location of section, see Fig. 32).



EXPLANATION

[Hpal] Holocene–Latest Pleistocene Alluvial-Colluvial Deposits: Dark-brown, organic rich silty Clay, sandy Clay, sandy Silt, occasional lenses of clayey Sand and Gravel.

[Qal] Quaternary Alluvial Deposits (Pleistocene). Complexly interbedded and interlensed Clays, Silts, Sands, and Gravel. Dense, variably light- to reddish-brown. Fe and Mn oxide stains, caliche-filled fractures and disseminated and nodular caliche common especially in finer-grained facies. Undifferentiated late Pleistocene alluvial fan and stream channel deposits and Upper Memberof Livermore Formation.

- Fine-grained facies. Predominately silty Clay and sandy Silt grading to fine, silty Sand. Occasional thin Gravel and coarser Sand interbeds.
- Zone consisting of alternating beds of gravelly Sand, Silt, and sandy Clay (mostly 2- to 5-ft thick).
- Coarse-grained facies. Predominately fine-to-coarse silty and clean Sand, and silty-to-clayey Gravel. Some poorly sorted Clay and Silt interbeds.

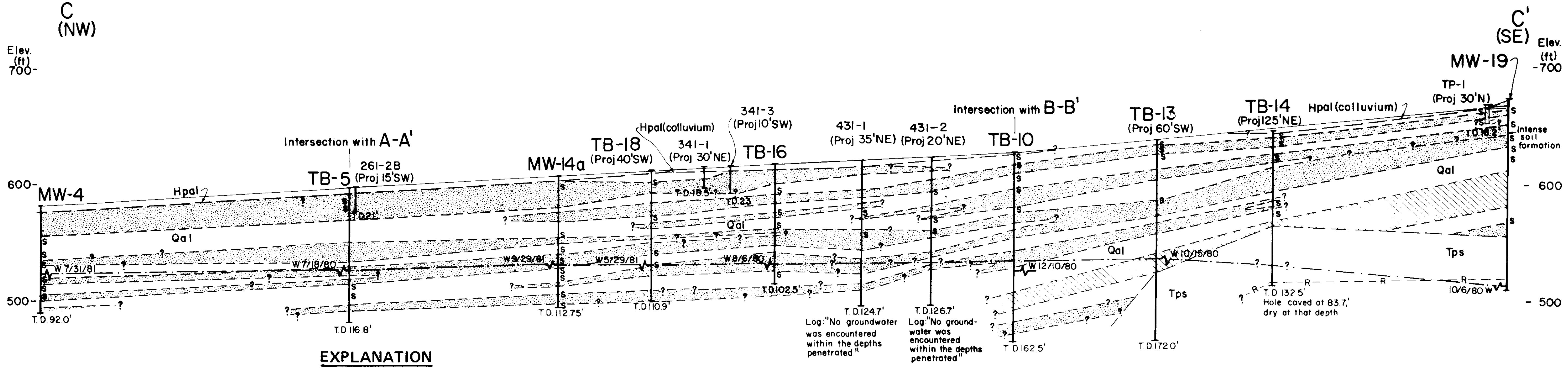
[Tps] Latest Tertiary Sediments (Lower Member of Livermore Formation): Interbedded, lenticular Clay. Silt, Sand, some Gravel. Dense, locally lithified. Finer grained materials predominately greenish-gray grading bluish-gray with depth; coarser materials commonly mottled green, brown, orange, grading blue-gray with depth.

SYMBOLS

TB-11 Borehole designation
S W Evidence of soil formation (in Qal)
Depth to water on date indicated
T.D. 112.5' Depth of hole

——— Approximate contact between major geologic units.
------ Approximate contact between facies within Qal.
—•—•— Probable top of saturated zone.
—R—R— Top of reduced, bluish-gray material in Tps.

Fig. 30. Geologic cross section B-B' (for location of section, see Fig. 32).



EXPLANATION

Fill

Hapl Holocene-Latest Pleistocene Alluvial-Colluvial Deposits: Dark-brown, organic-rich silty Clay, sandy Clay, sandy Silt, occasional thin Sand beds and traces of Gravel.

Qal Quaternary Alluvial Deposits (Pleistocene): Complexly interbedded and interlensed Clays, Silts, Sands, and Gravels. Dense, variably light to reddish-brown. Fe and Mn oxide stains, Caliche-filled fractures and disseminated and nodular Caliche common especially in finer grained facies. Undifferentiated late Pleistocene alluvial fan and stream channel deposits, and Upper Member of Livermore Formation.

Fine-grained facies. Predominately silty Clay and sandy Silt grading to fine silty Sand. Occasional thin Gravel and coarser Sand interbeds.

Zone consisting of alternating beds of gravelly Sand, Silt and sandy Clay (mostly 2-5-ft thick)

Coarse-grained facies. Predominately fine-to-coarse silty and clean Sand and silty-to-clayey Gravel. Some poorly sorted Clay and Silt interbeds.

Tps Latest Tertiary sediments (Lower Member of Livermore Formation): Interbedded, lenticular Clay, Silt, Sand, some Gravel. Dense, locally lithified. Finer grained materials dominately greenish-gray grading bluish-gray with depth, coarser materials commonly mottled, gray-green, brown, orange.

SYMBOLS

TB-16 Borehole designation

s Evidence of soil formation (in Qal)

Depth to water on date indicated

T.D. 102.5' Depth of hole

— — — Approximate contact between major geologic units.

- - - - - Approximate contact between facies within Qal.

—·—— Probable top of saturated zone.

- -R- -R- - Top of reduced, bluish-gray, material in Tps.

Scale (ft)

Fig. 31. Geologic cross section C-C' (for location of section, see Fig. 32).

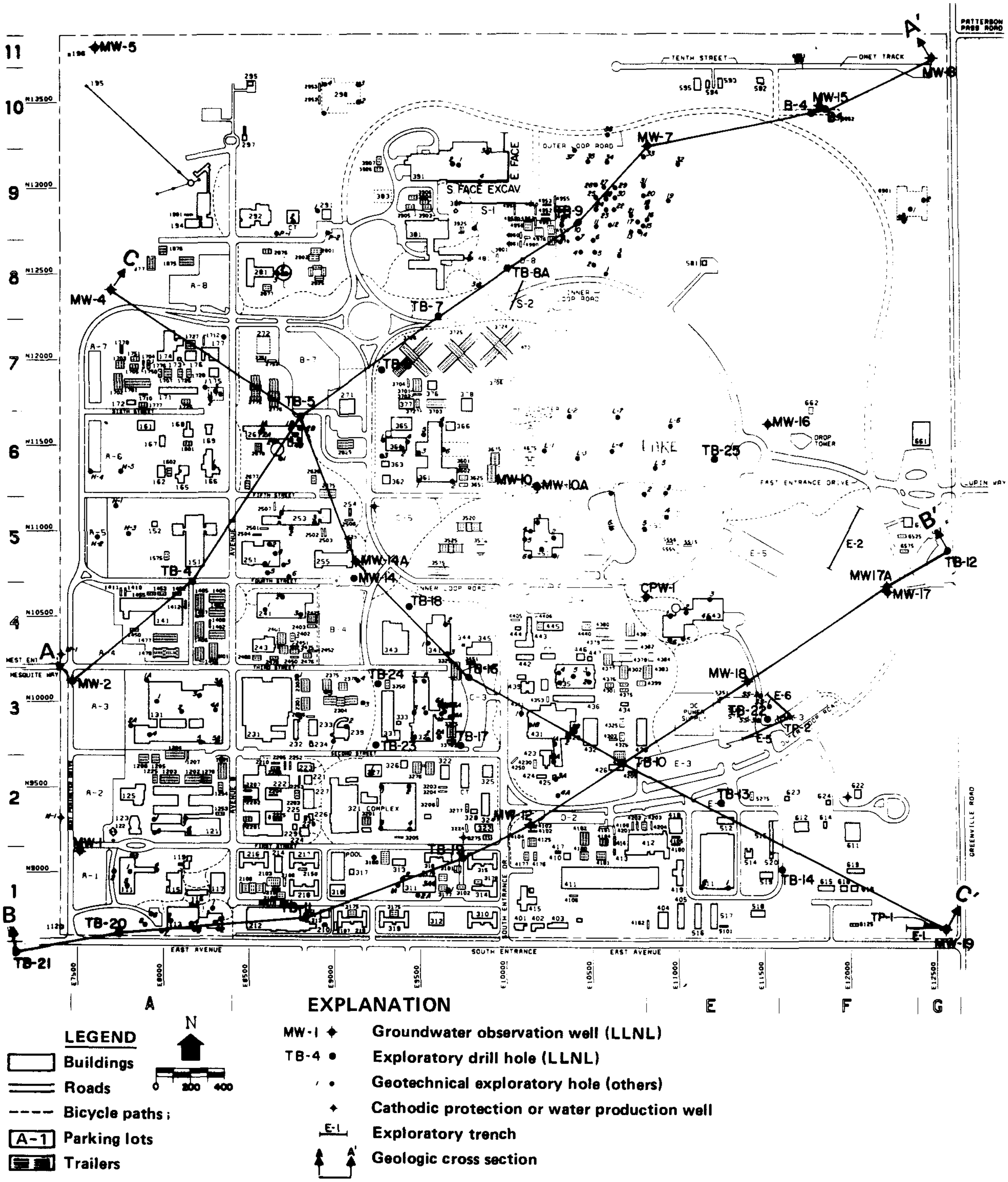


Fig. 32. LLNL site map showing all known boreholes, wells, and locations of detailed geologic cross sections A-A′, B-B′, and C-C′. Detailed drawings of these cross sections are presented in Figs. 29, 30, and 31, respectively.

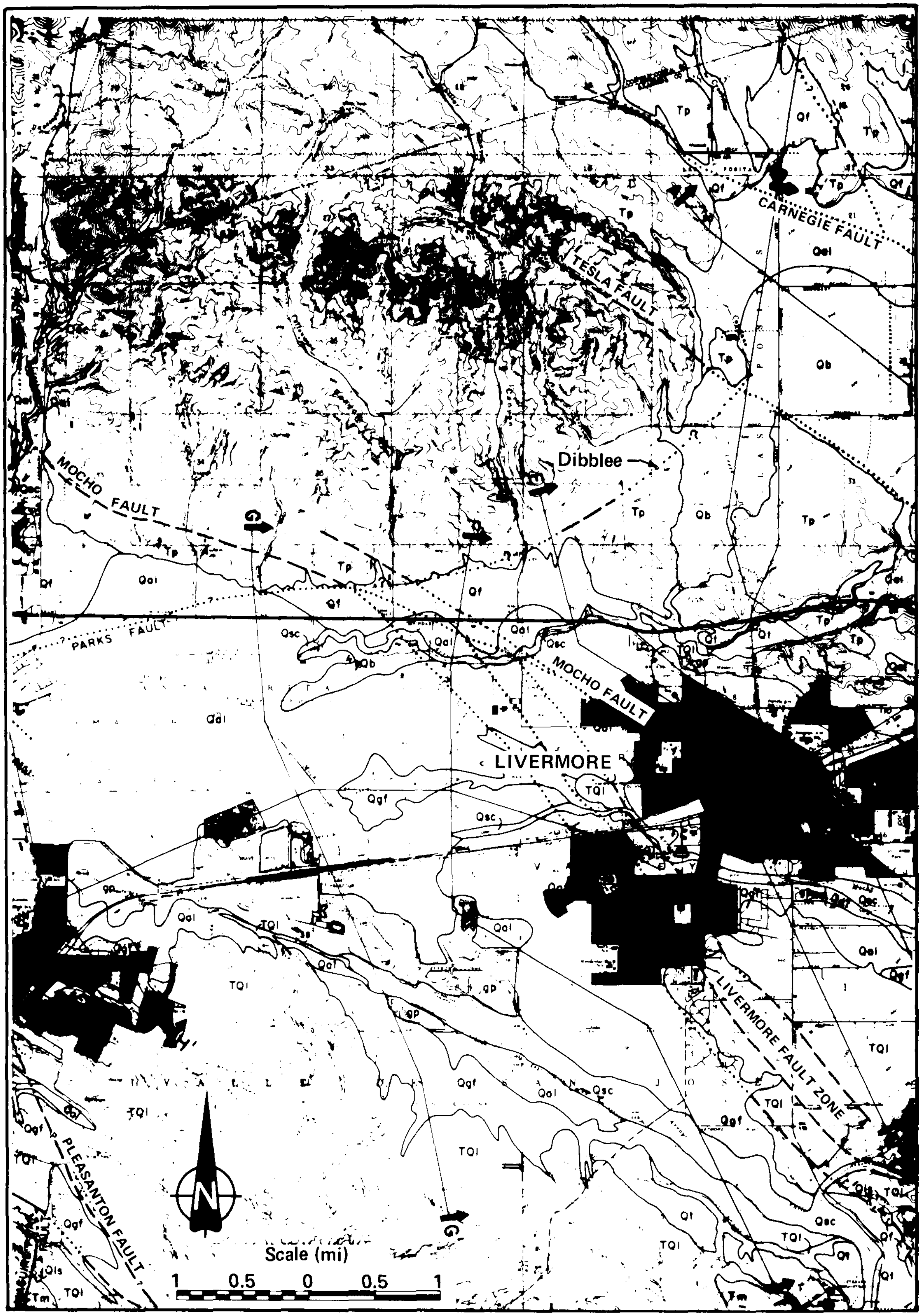


Fig. 33. Faults in central Livermore Valley (CDWR, 1974; Dibblee, 1980g).

Parks Fault. The near east-west trending Parks Fault, as postulated by the CDWR (1966), was based on changes in water levels and quality. The postulated fault occurs in the northwest Livermore Valley (see Figs. 8 and 33) and separates the Dublin and Camp Subbasins on the north from the Bernal and Amador Subbasins to the south. The CDWR stated that there was no surface evidence for the Parks Fault, but that the fault appears to offset Quaternary alluvium in the subsurface and strongly influences groundwater movement near it. The CDWR did not include the Parks Fault on its 1979 map. CDMG (Hart, 1981c) concluded that, as with the Mocho Fault, evidence for the Parks Fault was largely inferential and that there was no surface evidence for Holocene faulting.

Patterson Pass Fault. Huey (1948) mapped the Patterson Pass Fault in the Altamont Hills northeast of LLNL. He showed it as a bedrock fault branching eastward from the Greenville Fault. Dibblee (1980c,d) mapped the Patterson Pass Fault as a branch of the Carnegie Fault but did not show a connection with the Greenville Fault Zone (see Fig. 16).

The best expression of the Patterson Pass Fault appears to be in portions of Secs. 10 and 11, T3S, R3E where springs and a low, north-facing scarp occur near its mapped trace. However the fault cannot be traced westward from this area to the postulated link with the Greenville Fault (Carpenter *et al.*, 1980).

The CDWR (1979) stated that the Patterson Pass Fault branches from the Carnegie Fault in Corral Hollow and extends northwest 13 km (8 mi) to an apparent junction with the Greenville Fault. The CDWR noted that both the Patterson Pass Fault and the Greenville Fault show pronounced horizontal components of movement and steep dips, but they are upthrown on opposite sides. Because of apparent linkage with the Greenville Fault and reported seismic activity along its trace, the Patterson Pass Fault was regarded as active by the CDWR.

As mapped by Dibblee (1980c,d), the Patterson Pass Fault is about 7.4 km (4.6 mi) long.

Pleasanton Fault. The Pleasanton Fault was mapped by CDWR (1966, 1974) in the western Livermore Valley, based on a reported groundwater barrier and airphoto interpretation. The postulated fault location is shown in Figs. 8 and 33. The fault was delineated north of I-580 in aerial photographs, but its extension south across the Livermore Valley toward Pleasanton was based on perceived groundwater effects.

Reports of evidence for tectonic creep along the Pleasanton Fault trace led the California Division of Mines and Geology (Slosson, 1974) to zone the Pleasanton Fault as one requiring geologic studies prior to the issuance of building permits for structures in its vicinity. Subsequently, numerous investigations were conducted along the postulated trace of the Pleasanton Fault without any definite evidence being found for faulting in Holocene materials or the Livermore Formation. A thorough review of these investigations is provided by Hart (1981c).

Subsequently, CDMG (Davis 1982a) limited the Pleasanton Fault Zone to an area within Camp Parks (Fig. 8) where well-defined airphoto lineaments that may be fault-related occur within Holocene materials. Previous zones south of Camp Parks were eliminated, based on the results of the numerous site-specific studies. The Pleasanton Fault Zone as remapped by CDMG, is approximately 2.6 km (1.6 mi) long. It remains uncertain whether geologically young faulting has occurred within this remaining Special Studies Zone.

Ramp Thrust Fault. John A. Blume and Associates (1972) mapped the Ramp Thrust Fault as a local structure in the hills southeast of LLNL (see Fig. 22). John A. Blume and Associates mapped the fault from Greenville Road southeast across Secs. 17 and 18, T3S, R3E to Cross Road, a distance of about 2.2 km (1.4 mi). They indicated that displacement of the fault is demonstrated by deep hydrocarbon exploratory wells and that evidence for surface faulting along its trace was observed. The surface faulting cited was the faulted exposure on Greenville Road north of the South Bay Aqueduct (Figs. 10 and 21). This road-cut has subsequently been interpreted as an exposure of the Las Positas Fault Zone (Herd, 1977; this investigation) with possible contributions from minor faults parallel to the ancestral Greenville Fault Zone.

Studies by LLNL geoscience personnel indicate that the Ramp Thrust Fault of Blume was the result of linking two faults of dissimilar age and possibly dissimilar tectonic characteristics.

The northwesterly segment is an area of surface expression of the ancestral Greenville Fault that could be a normal fault, strike-slip fault, or possibly high-angle thrust fault (northeast side up) based on available field data. This fault juxtaposes folded beds of both the upper and lower members of the Livermore Formation exposed southwest of the fault against a north-dipping sequence of late Tertiary strata to the northeast. John A. Blume and Associates (1972) noted a northwesterly termination of the Ramp Thrust Fault just southeast of LLNL. The point of termination reported by Blume coincides with the point where the ancestral Greenville Fault is truncated by the younger Las Positas Fault and is overlapped by late Pleistocene alluvial deposits (unit Qal_1 of this investigation).

The southeasterly segment of the Ramp Thrust Fault coincides with the active south branch of the Las Positas Fault as mapped during this investigation. This segment is either a steeply north-dipping strike-slip fault or a high-angle thrust fault, north-side up, based on possible interpretations of surface and subsurface data shown on geologic cross sections (Figs. 25 and 26). The eastern limit of the Ramp Thrust Fault of Blume occurs where the south branch of the Las Positas Fault probably intersects a strand of the Greenville Fault Zone.

Tesla Fault. The Tesla Fault (Huey, 1948) is the northernmost segment of a complex of faults of varying ages that bound the eastern flank of the Diablo Range from Livermore Valley south to Panoche Valley and beyond. These faults are probably remnants of the ancient Coast Range Thrust Fault system. As previously stated, this system appears to have ceased functioning as a major element in California tectonics during Miocene time. At that time, subduction along the Pacific Plate-North American Plate boundary was replaced by right-lateral strike-slip movement along the San Andreas Fault system.

Huey (1948) mapped the Tesla Fault north-westward across the central portion of the Tesla 15-min Quadrangle as a boundary fault between the Franciscan rocks to the south and the Knoxville and Panoche Formations (Great Valley Sequence) to the north. Near the east boundary of Sec. 28, T3S, R3E, he mapped the fault as separating the Livermore Formation from the Miocene Cierbo sandstone. LLNL field reconnaissance in this area revealed no geomorphic features suggestive of geologically young movements (Sweeney and Springer, 1981; Carpenter *et al.*, 1980) although the boundary between the Great Valley Sequence and the Franciscan Assemblage can be mapped with good precision.

To the southeast, in Sec. 27, the trace of the Tesla Fault cannot be inferred on geomorphic grounds except locally by stream channel orientation. Therefore, geomorphic evidence for faulting is only weakly suggested. In any case, there is no evidence for geologically recent movement. Northwest of Sec. 28, Huey (1948) mapped the Tesla Fault as buried beneath the Livermore Formation and Quaternary alluvial deposits. Field reconnaissance in this area revealed no evidence for displacement of the Livermore Formation or younger sediments.

The CDWR (1974) reported evidence for displacement of the Livermore Formation, and evidence of influence on groundwater movement and quality along a projection of the Tesla Fault beneath Livermore Valley. Their studies indicated possible displacement of Quaternary alluvial deposits north of I-580. A cross section in the 1974 CDWR report showed the Tesla Fault displacing Quaternary alluvium to within about 18 m (60 ft) of ground surface.

Cooper-Clark and Associates (1973) noted that the northwestward projection of the Tesla Fault across a proposed subdivision area about 3.2 km (2 mi) north of Livermore was visible on aerial photographs as a linear contact between the Pliocene Orinda Formation and younger alluvial deposits. A distinct left-lateral jog in Collier Canyon, roughly 8 km (5 mi) northwest of Livermore, aligns with the projected fault trace and was cited as possible evidence for left-lateral offset along the Tesla Fault.

Interest in the subdivision project was dormant for several years but has recently been revived. Cooper-Clark and Associates now regard their previous report as dated (Baker, 1982) and are reevaluating their data based on more recent geological studies and the now known active status of the Greenville Fault Zone.

Cooper-Clark and Associates (1973) reported 40-to-160-gamma variations in magnetic intensity across the Tesla Fault north of I-580 as projected by the CDWR. They also cited indications of possible fault "creep" at two unspecified locations along the South Bay Aqueduct southeast of LLNL. Their inspections of the locations revealed that creep movement was not well-defined and could be the result of unstable soil conditions in the vicinity of the presumed fault zone. Cooper-Clark and Associates stated that at one location a recent landslide had obviously contributed to the cracking of the aqueduct, while at the other location, pressures resulting from storm water seepage along a drainage swale could account for damage done to the aqueduct's lining.

John A. Blume and Associates (1972) mapped three strands of the Tesla Fault System, based on geomorphic features and interpretation of geophysical data obtained by magnetometer, seismic refraction, and gravity methods (see Fig. 22). John A. Blume and Associates (1972) stated that Strand 1 of the Tesla Fault Zone had not undergone movement since deposition of the Livermore Formation and, therefore, was not considered a potential hazard. Strand 1 of the Tesla Fault coincides with the projected position of the ancestral Greenville Fault where it crosses Blume's section A-A' (Fig. 25).

John A. Blume and Associates (1972) reported that Strand 2 of the Tesla Fault is a geologically young feature, based on geomorphic and gravity profile evidence. They reported an exposure of Strand 2 in a utility trench on SNLL property. However, this exposure coincides with the mapped location of the Las Positas Fault. URS/Blume (1978) excavated an exploratory trench in alluvium across the postulated location of Strand 2 of the Tesla Fault within SNLL and found no evidence of faulting.

To further investigate the postulated Strand 2 of the Tesla Fault, LLNL geologists excavated exploratory Trench E-4 across the mapped fault trace at a location south of the north branch of the Las Positas Fault (Fig. 21) (Carpenter *et al.*, 1980). The trench log is presented in Carpenter *et al.* (1980, 1982).

Trench E-4 was oriented approximately at right angles to the mapped trace of the Tesla Fault and crossed a distinct slope break between two terrace levels. The trench penetrated the deposits underlying both terraces and exposed beds of the underlying Plio-Pleistocene Livermore Formation. A northeast trending fault within the Livermore Formation, probably related to the Las Positas Fault Zone, was encountered in Trench E-4 but no evidence for the mapped northwest trending Strand 2 of the Tesla Fault was observed in the trench. The oldest materials encountered in Trench E-4 ranged from Livermore Formation beds in most of the trench to late Pleistocene sediments at the east end. Subsequently test pit TP-3 was excavated adjacent to Trench E-4 (Fig. 21). Shlemon (Appendix E) examined TP-3 and determined that the oldest materials exposed in it were probably deposited about 60,000 to 70,000 yr ago. There is, therefore, no evidence for a young strand of the Tesla Fault in materials ranging in age at various locations from about 60,000 yr to possibly 4 to 5 million yr.

Strand 3 of the Tesla Fault system was mapped by John A. Blume and Associates (1972; Fig. 22) as a local fault in the hills within the southern portion of SNLL and nearby areas. In 1978, URS/Blume reevaluated previous evidence and removed the fault from their maps.

Herd (1977) mapped the Tesla Fault as truncated by the Greenville Fault Zone in Sec. 27, T3S, R3E about 6.4 km (4 mi) southeast of LLNL (Fig. 9). Dibblee (1980c) showed the same interpretation. Studies by LLNL geoscience personnel (Sweeney and Springer, 1981) confirm the mapping by Herd and Dibblee in the area of postulated truncation. Further LLNL studies previously discussed suggest that the westerly extension of the Tesla Fault has been displaced about 9 km (4.6 mi) northwestward by movements along the active Greenville Fault and its ancestors. This displaced segment is believed to underlie alluvial deposits probably including the Livermore Formation somewhere in the vicinity of I-580 about 2 to 3 km (1.2 to 1.9 mi) north of LLNL (Fig. 19). This postulated westerly segment is isolated tectonically from the main Tesla Fault Zone to the southeast and does not appear to be defined by valley microseismicity (Ellsworth and Marks, 1980; Scheimer *et al.*, 1982a).

The CDWR (1979) reported that numerous earthquake epicenters plot near the main Tesla Fault Zone southeast of Livermore Valley. However, as stated previously, features suggesting geologically young surface faulting have not been seen in the area.

Williams and Valle Faults. The CDWR (1974) mapped a complex of northwest and north trending faults within the lower slopes of the Diablo Range south and east of Del Valle Reservoir (see Fig. 34). The CDWR did not consider these faults further in its 1974 report since they did not influence valley geohydrology.

In its 1979 report, the CDWR stated that the Williams Fault (the more westerly of the complex) cuts Plio-Pleistocene Livermore gravels in the Hetch-Hetchy Tunnel. This observation (along with moderate seismic activity adjacent to its trace) suggested to the CDWR that the Williams Fault is active.

Ellsworth and Marks (1980) stated that seismologic data in the vicinity of the Williams Fault as projected north of the mapped Las Positas and Verona Faults are not compatible with postulated movement on the Williams Fault. South of these faults the data are poorly constrained, although some could be compatible with right-lateral movement on the Williams Fault. They noted that seismicity in the vicinity of the southerly portion of the Williams Fault scatters widely and is distributed on numerous faults.

The log of the Hetch-Hetchy Tunnel shows the easterly Valle Fault to separate rock described as granodiorite and Livermore gravels. Since the fault cuts Quaternary sediments, it is considered active under CDWR criteria. However, the CDWR noted that only three small earthquakes have occurred near its trace since 1900 and that their locations were plotted with a several kilometer uncertainty.

D. P. Smith (1981) examined geomorphic features along the Williams Fault and concluded that these features become increasingly youthful toward the southeast especially in the Mendenhall Springs Quadrangle south of Livermore Valley. D. P. Smith reported that to the northwest in the La Costa Valley

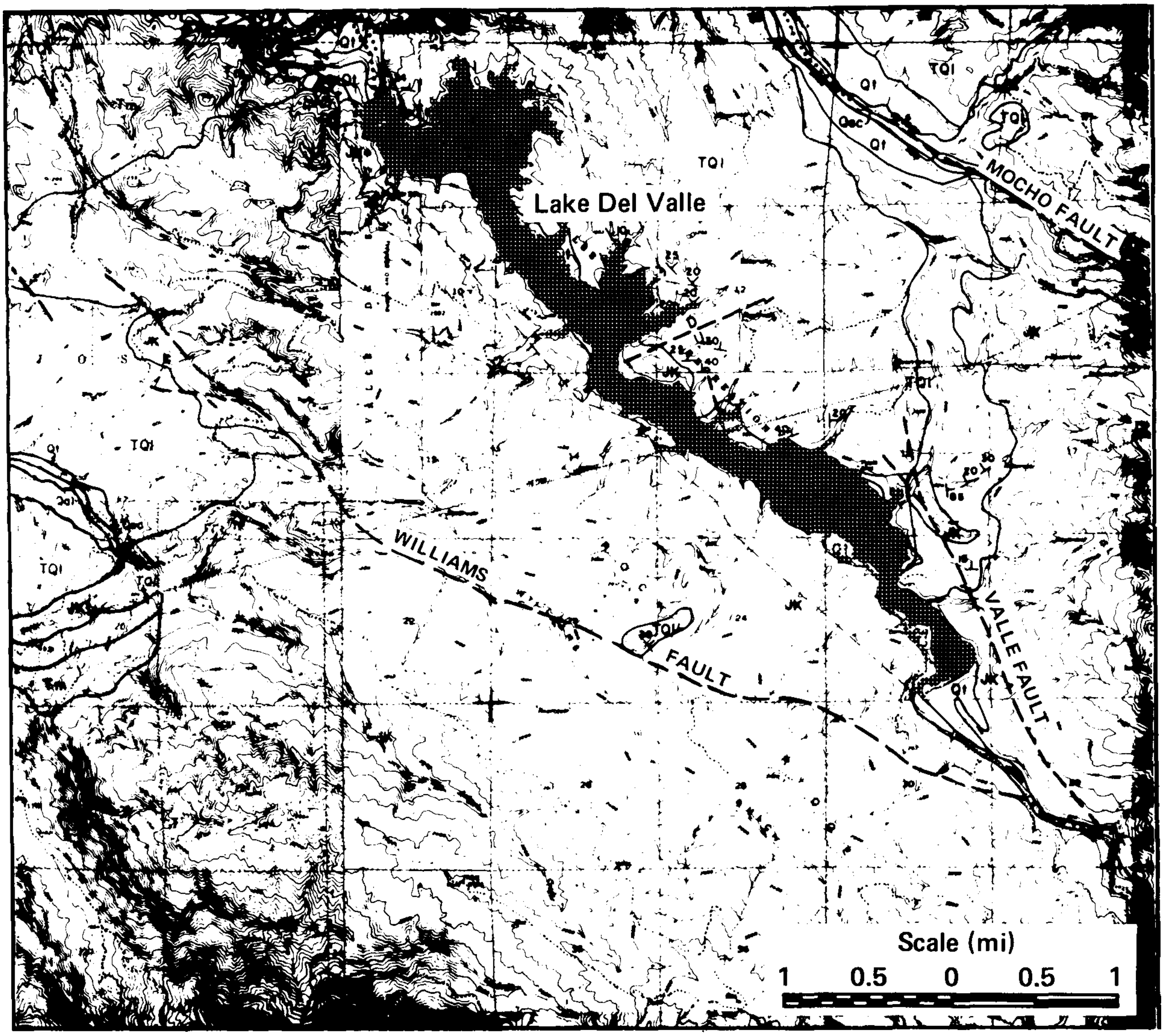


Fig. 34. Map showing locations of the Williams, Valle, and Mocho Faults mapped by CDWR (1974).

Quadrangle, the geomorphic features diminish in prominence and youthfulness of appearance. D. P. Smith also mapped the Williams Fault as splaying out to the northwest in an area about 4 km (2.5 mi) west of Lake Del Valle (Fig. 34) and south of the postulated southwestward extension of the Las Positas Fault Zone.

D. P. Smith noted that the geometry of the trace of the Williams Fault suggests that the fault dips to the southwest at an angle of 50° to 70°. Geomorphic and topographic features along the fault suggest right-lateral oblique motion with the southwest side of the fault down in a normal sense relative to the northeast side.

D. P. Smith (1981) recommended zonation of the southeasterly 3 km (1.9 mi) of the Williams Fault as an area requiring detailed geologic studies prior to issuance of building permits pursuant to State of California statutes. However, this recommendation was not adopted because the apparently active area coincides with the headwall scarp of a large landslide (Hart in D. P. Smith, 1981).

Dibblee (1980f; 1981) mapped the Williams Fault as extending southeastward from a point about 5 km (3 mi) west of Lake Del Valle (Fig. 34) for a distance of about 13.4 km (8.3 mi). At its northwestern end, Dibblee (1980f) showed the Williams Fault as intersecting the southwestern end of the Las Positas Fault

Zone at a high angle. At its southeastern limit, Dibblee (1981) mapped the Williams Fault as linking with or displaced by the Valle Fault.

The CDMG did not evaluate the Valle Fault for possible inclusion in a Special Studies Zone. Dibblee (1981) shows the Valle Fault as buried by sediments of the lower Livermore Formation (map unit Tps). Dibblee shows a tuff bed dated by the K/Ar method as 4.5 ± 0.5 million yr (Sarna-Wojcicki, 1976) as undisplaced across the postulated buried fault location.

Seismologic and geologic evidence suggests that the Williams Fault is active and, therefore, is a potential source of regional ground shaking. Geologic evidence presented by Dibblee (1981) strongly suggests that the Valle Fault is inactive at least immediately south of Livermore Valley.

Minor Unnamed Faults. The CDWR (1974) mapped several minor faults in the Las Positas Valley north of Livermore. Cooper-Clark and Associates (1973) identified seven possible minor faults in this same area, based on geophysical studies and field reconnaissance. Most of these local faults appeared to be branches of major faults mapped or projected into the area. As noted previously, Cooper-Clark and Associates are currently reevaluating their previous studies in the area north of Livermore.

Herd (1977) mapped several short east-west trending faults in the foothills south of the Livermore Valley. These showed evidence of displacement of the Livermore Formation and are located in an area of elevated microseismicity (Scheimer *et al.*, 1982a). None of these small faults are of sufficient length or are critically located so as to significantly influence the seismic hazard at LLNL. Microseismicity, possibly associated with these faults, is included with that for the Diablo Range source region in general (Scheimer et al, 1982a).

The CDWR (1979) mapped a number of small faults in the vicinity of Del Valle Dam and Reservoir. Several of these appear to branch from the Livermore Fault.

Dibblee (1980g) mapped a possible normal fault along the northern margin of the Livermore Valley (Fig. 33) extending from about 1 km (0.6 mi) northwest of the Livermore airport northeast for about 6 km (3.7 mi). As mapped by Dibblee, this possible fault appears to be a northeastward extension of the postulated Parks Fault.

Purcell, Rhoades and Associates (1981) excavated a series of trenches and test pits across the fault postulated by Dibblee without finding any evidence for it. The boundary between colluvial-alluvial deposits and underlying sediments of the Tassajara Formation slopes gradually southward toward Livermore Valley without any evidence of disturbance.

Geodetic Measurements

Benchmark surveys, triangulation and trilateration data for various areas within and near Livermore Valley have been reviewed and analyzed by Gibson and Wollenberg (1968), John A. Blume and Associates (1972), Alt (1979), the CDWR (1979), Bennett (1979), Crow (1983) and Prescott *et al.* (1981). We summarize their findings as follows:

- Vertical ground movements change from subsidence to uplift in the vicinity of the Calaveras Fault. Data indicate that the valley floor is still subsiding while the adjacent hills are rising, and that some of this differential movement is spatially related to the Calaveras Fault. John A. Blume and Associates (1972) believed that the data suggest strain accumulation along the Calaveras Fault and a potential for its release by earthquakes. However, Prescott *et al.* (1981) interpret trilateration data as indicating that the accumulating strain energy is being dissipated through tectonic creep and small earthquakes in a zone including the Calaveras Fault and a region extending a few kilometers on either side of it.
- Apparent tectonic creep along the Pleasanton Fault (Fig. 8) from 1964 to 1969 did not continue based on resurveys in 1974 and 1979 (Bennett, 1979). However, Bennett states that the 1964-69 creep episode appears real and may have been terminated by the Danville earthquake swarm in 1970 (Bennett, 1979). The Danville earthquake swarm was centered about 19 km (12 mi) north of the Camp Parks network within which the reported creep was detected. Relative subsidence of benchmarks located west of the postulated Pleasanton Fault continued from 1965 through 1975, but at a diminished rate relative to the subsidence observed from 1964 to 1965 (Bennett, 1979). Bennett (1979) attributed the observed subsidence to differential groundwater withdrawal on opposite sides of a fault.
- At the east margin of Livermore Valley near the LLNL site, a change from ground subsidence to uplift also takes place. John A. Blume and Associates (1972) indicated that the line of change coincides with the position of the postulated Dougherty Fault (Figs. 22 and 35), a geologic feature that has not been found to exist.

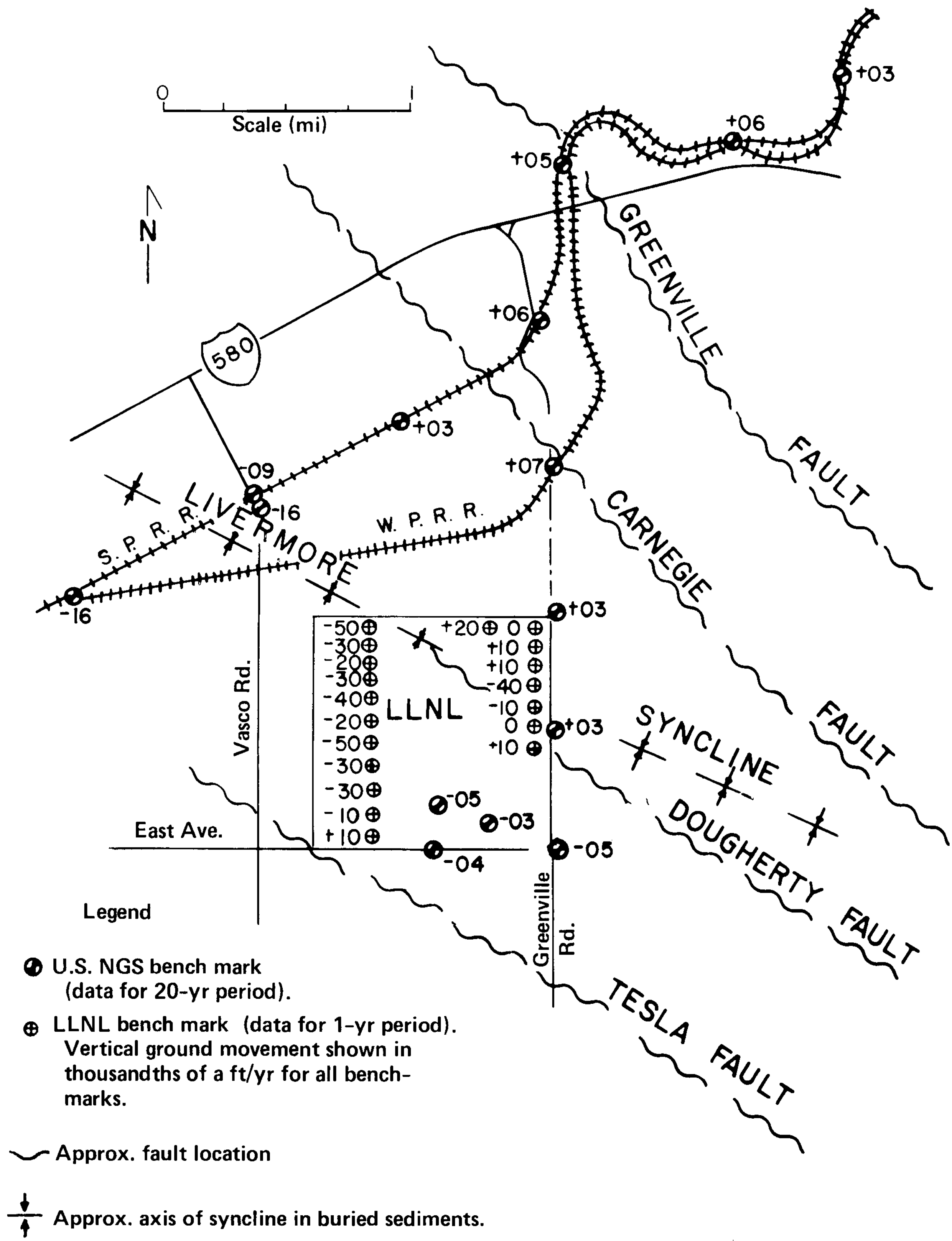


Fig. 35. Benchmarks and vertical ground movement within LLNL (from John A. Blume and Associates, 1972).

Benchmark survey data included surveys of laboratory benchmarks, as well as National Geodetic Survey (NGS) benchmarks (as shown in Fig. 35). Movements shown for the NGS stations are annual averages based on resurveying over a 20-yr interval. Data for LLNL benchmarks were for a 1 yr resurveying interval. Blume noted that resurveying of the LLNL benchmarks indicated higher apparent rates of movement than those calculated for the NGS marks. No explanation for the apparent differences in movement rates could be established, although it should be noted that the relative accuracy of the two surveys is probably different. The LLNL survey was probably made by standard engineering methods, whereas the NGS survey was reported to have employed first-order leveling. The significance, if any, of the survey data is uncertain although the LLNL data could be interpreted as reflecting relative subsidence near the axis of the Livermore syncline as mapped by John A. Blume and Associates (1972).

John A. Blume and Associates (1972) stated that groundwater withdrawal could be a factor in subsidence of the valley floor. They noted that subsidence caused by groundwater withdrawal would be superimposed on areal tectonic subsidence and that it would be difficult to separate the two phenomena. It should be noted that significant groundwater withdrawal has not occurred at LLNL itself for many years and that no major groundwater withdrawals are known to be presently occurring in the vicinity of the laboratory.

- A correlation appears to exist between subsidence in the area southwest of Patterson Reservoir and withdrawal of oil from the Livermore oil field (CDWR, 1979). Independent analysis of the CDWR data (Crow, 1983) confirms this opinion and indicates that subsidence largely ceased about 1975 when water injection reportedly began in the oil field. Representative pre- and post-1975 data are shown in Figs. 36 and 37, respectively. Since 1975, benchmark movements appear to be irregular. However, as shown in Fig. 37, a slight northward tilt of the area may be occurring (Crow, 1983). The subsidence area detected by the CDWR overlaps an area reported by John A. Blume and Associates (1972) to be rising. The reason for the discrepancy in data is not readily understandable, especially since both Blume and the CDWR conducted their measurements during the same period in the early 1970s. However, it should be noted that all leveling comparisons are relative to some benchmark or set of benchmarks, and an apparent change at any one spot is not absolute. Therefore, it would be possible to have relative uplift and relative subsidence at the same place and time for two different surveys if different points were held fixed.
- Within the Livermore Valley region, trilateration data provide no evidence for strain along any faults other than the Calaveras system (Prescott *et al.*, 1981). However, the network is very limited with respect to the Greenville Fault Zone and some regional strain (equivalent to about 6 mm of right-lateral slip annually) remains that is not accumulating on the San Andreas Fault or being released by movements along the Hayward and Calaveras Fault Zones. Portions of the Diablo Range south of Livermore Valley appear to be rotating in a clockwise sense relative to the Bay Region in general. The rotating block is bounded by the Las Positas Fault Zone on the north and apparently by the Calaveras Fault Zone on the west. The trilateration network is not extensive enough to permit definition of the eastern and southern boundaries of the block.

Tectonic Model of the Livermore Valley Region

In order to clarify the data concerning the activity of faults and their relation to various structural features, a tectonic model of the Livermore Valley area is presented here. The region under consideration is that bounded west and east by the Calaveras Fault and the Altamont Hills, respectively, and north and south by Suisun Bay and the Diablo Range, respectively (see Fig. 38). In this model the Calaveras Fault, Concord Fault, Greenville Fault north of the Las Positas Fault, north and south branches of the Las Positas, and Verona Fault are all considered to be active. The Mount Diablo Fault, Clayton Fault, Corral Hollow Fault, Carnegie Fault, Williams Fault, and Del Valle Fault are considered as unknown in terms of being currently active. The Tesla Fault is considered as probably inactive. The Livermore and Pleasanton Faults are not considered in the model because the status of their activity and existence is uncertain.

For the model (Fig. 38) the region has been divided into five distinct tectonic blocks. Block I, the Altamont Hills Block, consists of the area east of the Greenville Fault which contains the large Altamont antiform and the structures in Corral Hollow. The area appears to be acting as a rigid block with little or no internal deformation. There is presently only minor seismicity within the block.

Block II, the Livermore Valley–Tassajara Hills Block, is bounded by the Calaveras and Greenville Faults and by Mount Diablo and the Verona–Las Positas Faults. Folding of Livermore gravels, uplift in the Tassajara Hills, and thrusting on the Verona Fault are consistent with NNE-SSW compression of this

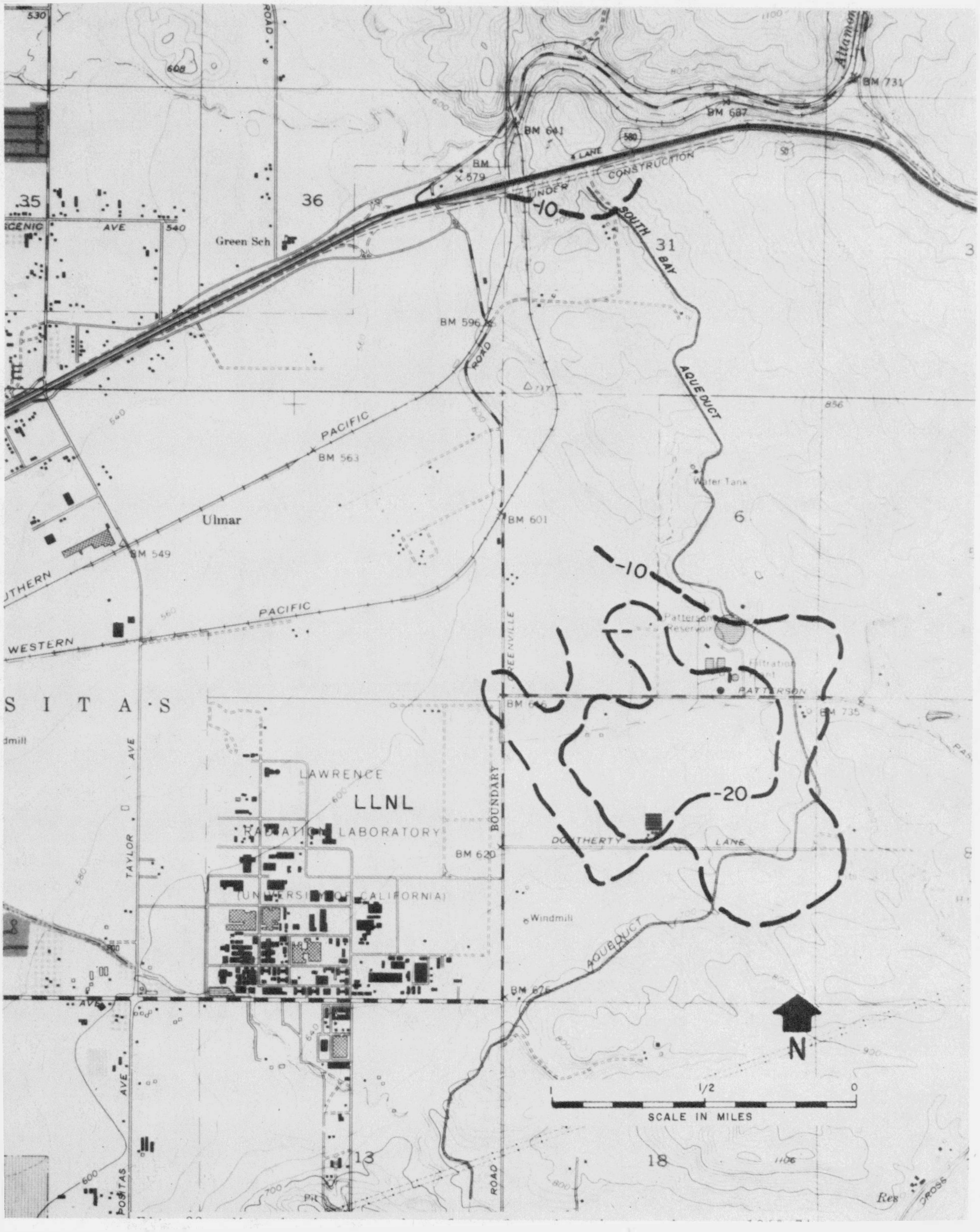


Fig. 36. Ground surface elevation changes (mm) from 1969 to 1974 (from CDWR data).

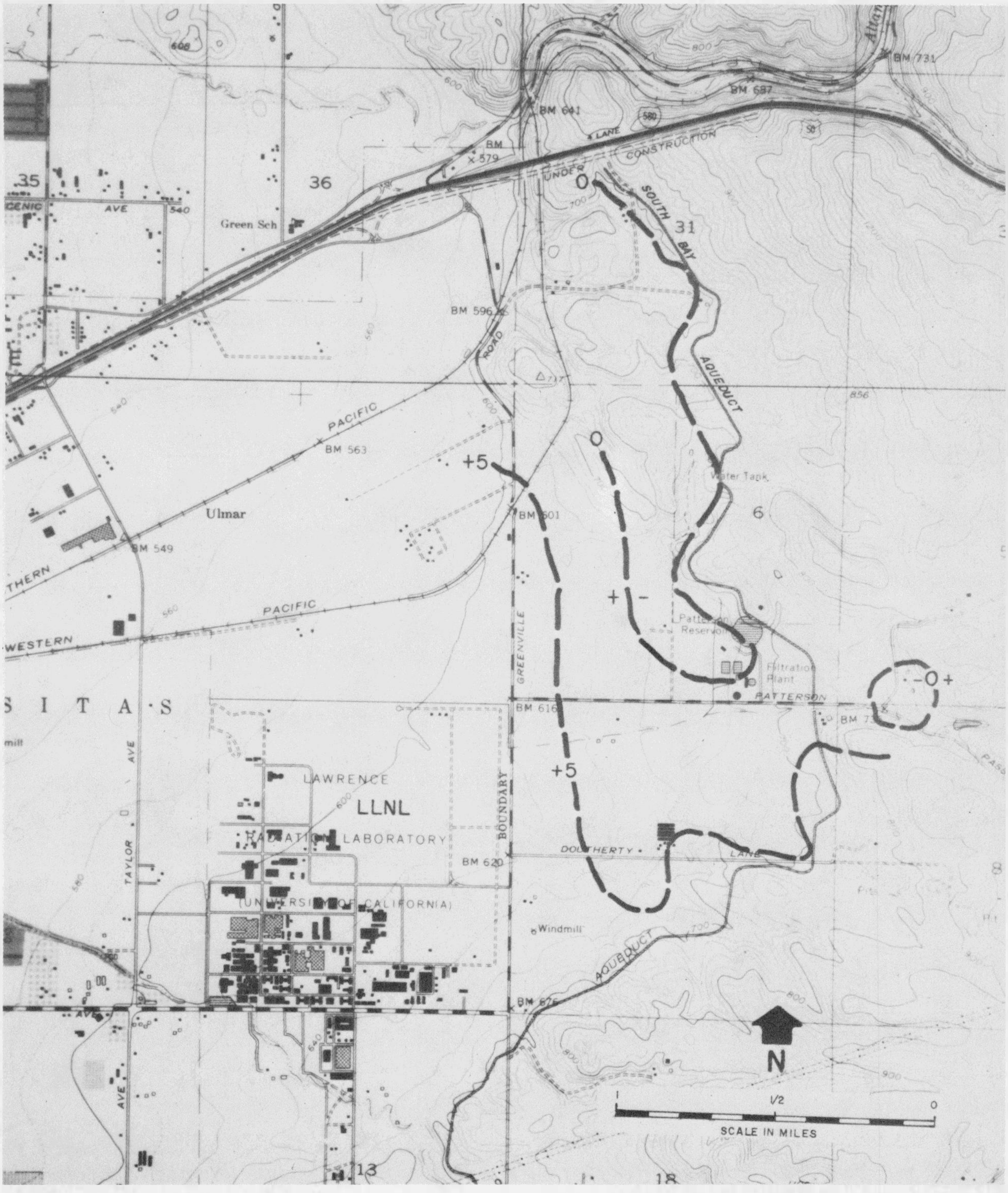


Fig. 37. Ground surface elevation changes (mm) from 1975 to 1977 (from CDWR data).

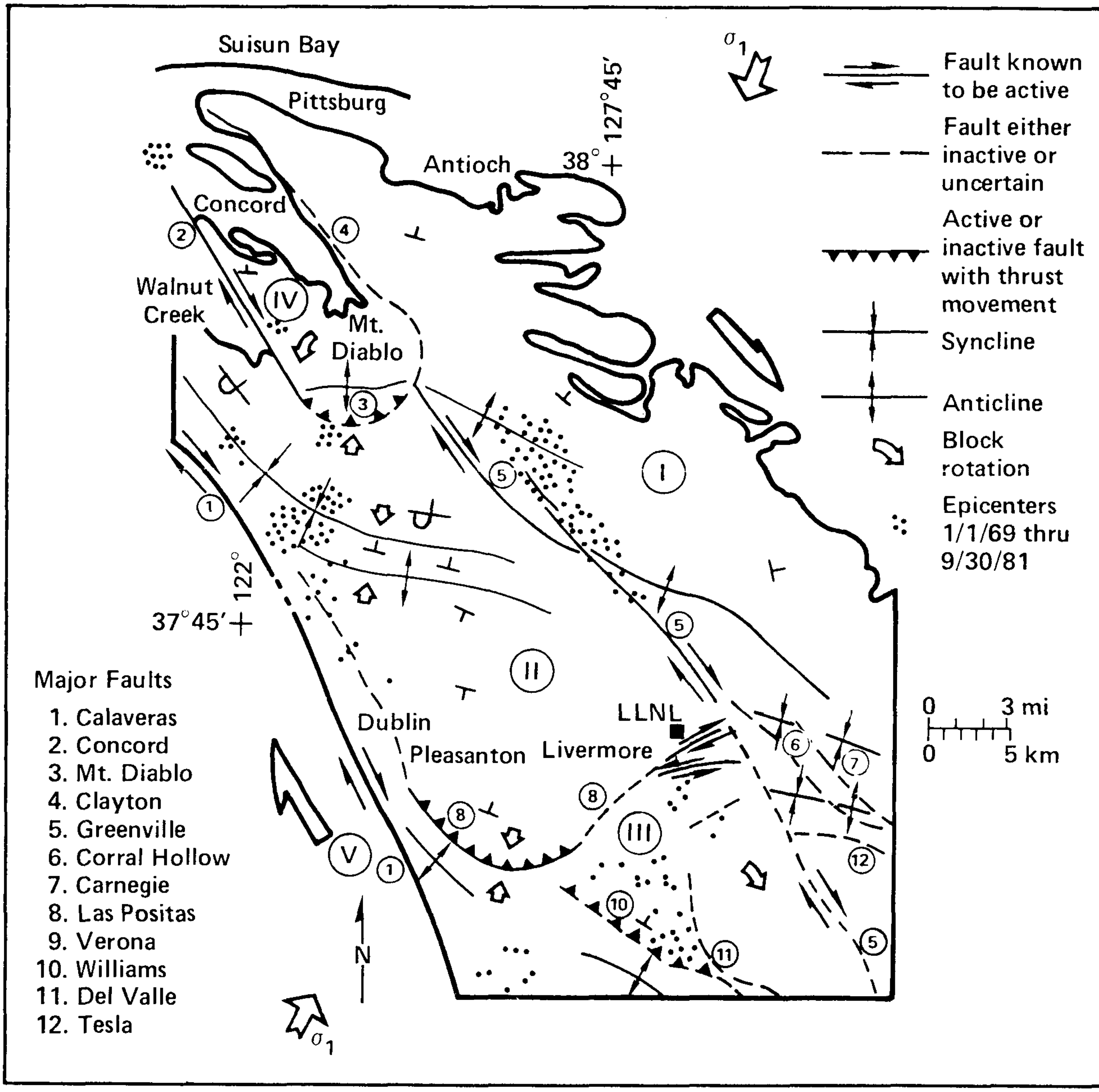


Fig. 38. Tectonic map of the Livermore Valley region showing the location of tectonic blocks I through V, as discussed in the text. Approximate direction of the regional principal compressive stress is indicated by large arrows labeled σ_1.

block. The Livermore Basin, deeply filled with Pliocene to Quaternary alluvium, is a subsiding area. The presence of a basin within an area of crustal shortening is an apparent contradiction, but it may simply be a compressive downwarp that has been filled in with sediment shed from the surrounding uplifts. In the southeastern corner of the block a small ridge is being uplifted between the north and south branches of the Las Positas Fault. The uplift is a result of oblique movement on the primarily left-lateral faults which converge along strike to the southwest. A small depression is being formed just north of this uplift which is probably a space effect related to the movement of the Greenville and Las Positas Fault systems.

Activity from the seismic events of the January 1980 Greenville Fault earthquakes was localized north of the Las Positas Fault, so it is not certain if the Greenville Fault to the south is active. The trend of seismicity at the northern end of the Greenville Fault in 1980 (shown in Fig. 38) was to the north of the mapped trace of the fault. Furthermore, there were two distinct sets of hypocenters for the events, indicating a possibility of detachment between the deeper Great Valley Group rocks and the shallower Cenozoic rocks (see Scheimer *et al.*, 1982b, and Wagner, 1978).

The Danville earthquake swarm of 1977 was located between the northern end of the Calaveras Fault and the southern end of the Concord Fault. These events may indicate transfer of strain from the Calaveras Fault to the Concord Fault—a right step of the trace of a right-lateral fault system. This type of stepover usually results in the development of a pull-apart graben; in this case, however, the evidence is for compression (folds) in the area. Perhaps the seismicity is related to slip on bedding planes due to tightening of the folds.

Block III, the Del Valle Block, consists of the area east of the Calaveras Fault and south of the Verona and Las Positas Faults. The block is probably attached to the northern end of the Diablo Range which is composed primarily of Franciscan basement rocks with younger rocks covering the edges. This block appears to be pushing into Block II from the southwest, with thrusting on the Verona Fault and lesser compression along the Las Positas Fault at its eastern end. The southern part of the Greenville Fault may or may not mark an eastern boundary of this block, depending on whether the fault is active there. The block shows evidence of possible internal deformation by means of thrusting, or at least oblique movement on the Williams Fault, and by current seismicity in the vicinity of the Valle Fault and along an unnamed fault parallel to and south of the south branch of the Las Positas Fault. Prescott *et al.* (1981) found a component of clockwise rotation for this block by looking at recent geodetic data.

Block IV, the Mount Diablo Block, is bounded by the Concord, Clayton, and Mt. Diablo Faults. Mount Diablo has an antiformal core of Franciscan rock which has pushed up through the Great Valley Group and younger rock cover. Strata on the southwestern side of Mt. Diablo have steep to overturned attitudes. The east-west-trending axis of the antiform in the core of Mt. Diablo (mapped by Dibblee) seems to be part of the northwest-trending Altamont antiform, which has apparently been rotated counterclockwise. This type of deformation could occur as a push-up between the ends of left-stepping right-lateral faults. In this case it indicates a possible transfer of motion from the northern part of the Greenville Fault to the Concord Fault. This would mean that the Concord Fault is more likely to be active than the Clayton Fault. An additional possibility is that some thrusting toward the south-southwest may occur on the Mt. Diablo Fault, as is suggested by its outcrop pattern.

Block V, the East Bay Hills Block, consists of everything west of the Calaveras and Concord Faults. In this model it is considered to be a rigid block, although it is internally deformed (Aydin, 1982). This block is sliding past the blocks to the east in a right-lateral sense, but there is probably a considerable NE-SW compressional component involved.

Most of the fold axes in the region have NNW-SSE trends consistent with NNE-SSW compression, but in places (most notably along the trend of the Calaveras Fault) seem to have been rotated to the NE. The more westerly trend of Altamont Hills folds intersects the trend of the Greenville Fault. This structural relation may result in a type of buttressing effect of the Altamont Hills Block which may be causing deformation of Block II and offset of motion from the Greenville Fault to the Concord Fault and the accompanying rotation and uplift of the Mt. Diablo Block.

In summary, Blocks II, III, and IV are being affected by the shear couple imposed by movement of Blocks I and V. Blocks II, III, and IV respond by internal deformation—uplift, folding, and thrusting—as well as downwarps and subsidence. Block II is being compressed from north to south with a combination of uplift and subsidence occurring at its eastern side. Blocks III and IV show evidence of possible rotation—clockwise for Block III and counterclockwise for Block IV. All of the above is consistent with a NNE-SSW imposed regional horizontal principal compressive stress, σ_1, as shown in the figure.

LLNL Site Geology

Stratigraphy

LLNL is underlain by a thick sequence of late Tertiary and Quaternary alluvial deposits and poorly lithified rocks of predominantly continental origin. Huey (in John A. Blume and Associates, 1972) reported that hydrocarbon exploratory well P-1, located near the southwest corner of LLNL (Fig. 17) penetrated 750 m (2470 ft) of these materials before reaching "basement" rocks of the Franciscan Assemblage. Two deep wells drilled just north of the north boundary of LLNL are reported to have bottomed in Tertiary rocks at depths of several thousands of feet (Fig. 17).

Previous subdivisions of portions of this alluvial sequence have been made by Helley *et al.* (1972) and Herd (1977). These subdivisions are reviewed in the section on Livermore Valley stratigraphy and their relationships to the local stratigraphy developed during the LLNL Site Investigation are also described in the preceding text concerning Valley geology.

As shown in Fig. 10, surface geology of the LLNL site itself is relatively simple.

Late Pleistocene and Holocene alluvial deposits (unit Hpal) underlie the southwestern and portions of the northeastern parts of LLNL. They occur generally adjacent to the former natural channels of the Arroyo Seco and Arroyo Las Positas. These materials consist chiefly of dark-brown, organic rich silty clay, sandy clay, and sandy silt with occasional lenses of sand and gravel. They also form (or formed prior to grading) a thin colluvial blanket over other portions of LLNL shown on Fig. 10 as underlain by older alluvial deposits (unit Qal_1). Logs of boreholes and excavations within LLNL suggest that the late Pleistocene and Holocene alluvial deposits vary in thickness from about 60 cm (2 ft) or less beneath the southeastern portion of the Lab to about 3 to 5 m (10 to 17 ft) beneath the southwestern portion of the site near the Arroyo Seco. Up to 3 m (10 ft) of Holocene to late Pleistocene alluvial deposits also underlie parts of the northern portion of the laboratory site adjacent to the former, natural course of the Arroyo Las Positas. The courses of these two modern streams can be seen in Fig. 39, a mosaic made from aerial photographs taken in 1940 prior to development of the LLNL site. A former course of the Arroyo Seco can also be seen located northeast of the present course.

The late Pleistocene and Holocene alluvial deposits are underlain by older alluvium. These materials are typically dense, thoroughly oxidized, with prominent soil profile development (Shlemon, Appendix E), and range in composition from clay to coarse gravel. Based on examination of test pits TP-1 and TP-2 excavated adjacent to exploratory trenches E-1 and E-5, respectively (Fig. 20), Shlemon (Appendix E) recognizes three periods of net deposition within the sedimentary record preserved in the test pits (maximum depth 4.9 m (16 ft) in TP-1). In general, this older sedimentation occurred during two periods of landscape instability roughly 60,000 to 70,000 yr ago and 125,000 to 195,000 yr ago. Test pit TP-2 also encountered some sediments that appear to have been deposited about 35,000 to 40,000 yr ago. Two primary periods of soil formation are recorded in the stratigraphic record; these occurred roughly 35,000 to 40,000 and 80,000 to 125,000 yr ago, respectively.

Exploratory drill holes and groundwater monitoring wells within LLNL (Fig. 29) penetrated up to 58 m (190 ft) of heterogeneous alluvial deposits similar to those exposed in the test pits and trenches (Carpenter *et al.*, 1982). The upper portion of the alluvial sequence has also been penetrated by numerous engineer's borings made during building foundation and other geotechnical studies at LLNL. Most of the LLNL drill holes and wells were still in these materials when bottomed at depths of about 27 to 40 m (90 to 130 ft). Geologic cross sections A-A' (Fig. 30), B-B' (Fig. 31), and C-C' (Fig. 32) show inferred subsurface profiles. Cross sections A-A' and B-B' trend northeast-southwest normal to the strikes of previously postulated faults (e.g., John A. Blume and Associates, 1972) while section C-C' trends northwest-southeast normal to site topography and to the strike of the Las Positas Fault Zone. There are no distinctive marker horizons within the alluvial sequence beneath LLNL. Therefore, the subsurface relationships shown in the cross sections are interpretive and some alternatives could be argued. However, the interpretations presented are believed to be the most consistent with the available data.

The alluvial deposits penetrated in boreholes and monitoring wells within LLNL include sediments correlative with the late Quaternary terrace and fluviatile sequences of previous investigators (Helley *et al.*, 1972; Herd, 1977) and surface units Qal_1 and Qal_2 as defined during this investigation. Also, since the stratigraphy and soil profiles determined by Shlemon (Appendix E) indicate a very slow net depositional

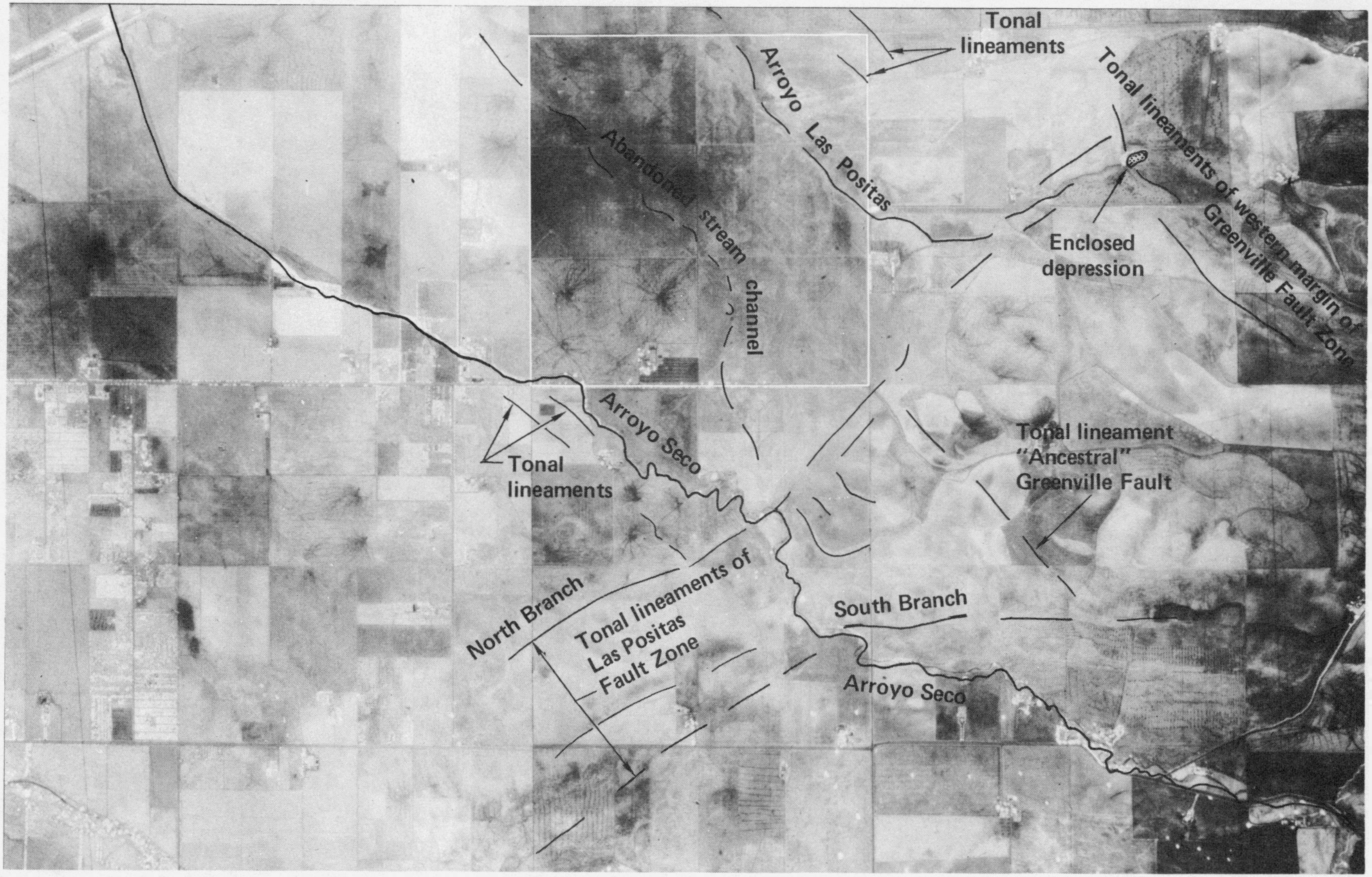


Fig. 39. **Airphoto mosaic of LLNL site in 1940 prior to initial development.**

LLNL Site Geology

Stratigraphy

LLNL is underlain by a thick sequence of late Tertiary and Quaternary alluvial deposits and poorly lithified rocks of predominantly continental origin. Huey (in John A. Blume and Associates, 1972) reported that hydrocarbon exploratory well P-1, located near the southwest corner of LLNL (Fig. 17) penetrated 750 m (2470 ft) of these materials before reaching "basement" rocks of the Franciscan Assemblage. Two deep wells drilled just north of the north boundary of LLNL are reported to have bottomed in Tertiary rocks at depths of several thousands of feet (Fig. 17).

Previous subdivisions of portions of this alluvial sequence have been made by Helley *et al.* (1972) and Herd (1977). These subdivisions are reviewed in the section on Livermore Valley stratigraphy and their relationships to the local stratigraphy developed during the LLNL Site Investigation are also described in the preceding text concerning Valley geology.

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During preparation of cross sections A-A', B-B', and C-C', it was noted that a stratigraphic horizon appeared at depths from about 12 to 21 m (40 to 70 ft) beneath much of LLNL. Across this horizon there seemed to be no suggestion of the interfingering relationships between finer and coarser materials observed in deposits above and below. This horizon is particularly noticeable in sections A-A' and B-B'. Samples obtained from clay and silt beds immediately above the horizon and from sands and gravel directly below it frequently showed evidence of soil profile development. While uncertain, it is possible that this horizon developed just beneath an erosion surface developed on the top of the upper sand and gravel member of the Livermore Formation. By careful examination it was possible to identify this horizon in most LLNL exploratory drill holes and groundwater monitoring wells. The presence of the horizon could be inferred from the logs of a number of deeper engineer's borings as well. Figure 40 presents a contour map drawn on the horizon. In general, the horizon slopes gently to the northwest, subparallel to the present land surface. A reentrant in the buried surface appears to underlie the western part of LLNL and may mark the location of a shallow, backfilled valley. The northeastern margin of the possible valley roughly coincides with the location of an abandoned course of the Arroyo Seco visible on 1940 aerial photographs.

During the exploration and monitoring of well drilling within the eastern and southeastern parts of LLNL, a sequence of predominantly fine-grained, dense, locally lithified continental sediments was encountered. These materials were characteristically greenish-gray or, where oxidized, showed evidence of relict greenish-gray colors. Blue clays and silts were commonly encountered at greater depths within these sediments that are believed to be the subsurface correlatives of the lower member of the Livermore Formation (unit Tps of Dibblee and this investigation).

Depths to sediments correlated with unit Tps vary from 7 m (23 ft) in borehole TB-12 (Fig. 32) near the eastern boundary of LLNL to 58 m (190 ft) in borehole B-1 near the northeast corner of the Lab grounds. Elevations of the top of unit Tps encountered beneath LLNL are shown in Fig. 41.

In addition to the LLNL boreholes, unit Tps may have been encountered in two deep water wells M_1 and N_1 drilled along the western boundary of the site during its initial development during World War II. Detailed driller's logs of these wells indicate beds of "blue clay" and "cement gravel" below depths of 111 m (365 ft) and 115 m (377 ft) in M_1 and N_1, respectively.

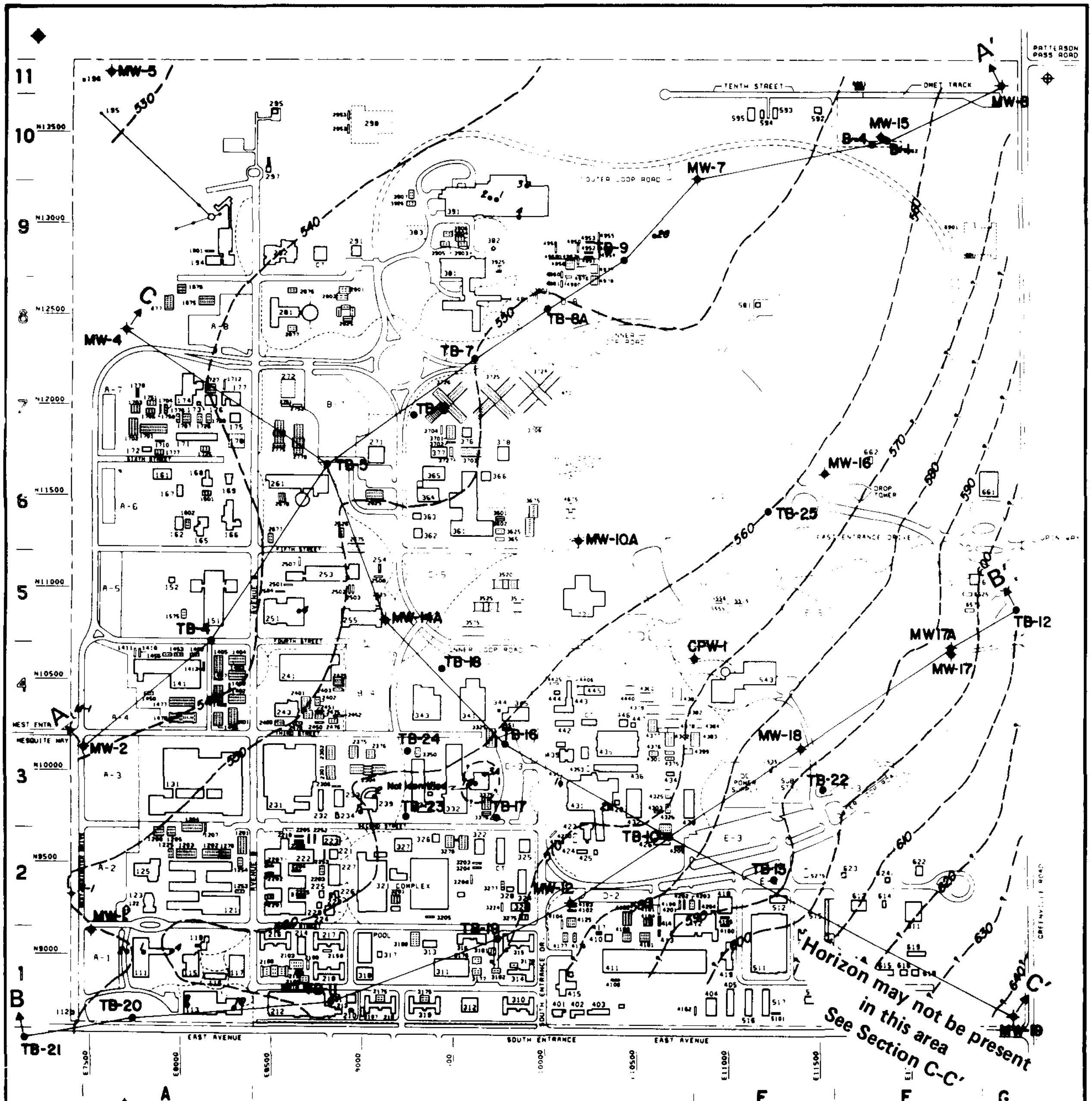
Several cathodic protection wells drilled within LLNL reached depths sufficient to encounter sediments of unit Tps, but the driller's logs of these wells provide insufficient detail to permit definite judgments.

Structure

As shown in Figs. 20 and 22, various investigators have postulated faults traversing the LLNL site. These include the Corral Hollow Fault (John A. Blume and Associates, 1971; CDWR, 1974), the Dougherty Fault (John A. Blume and Associates, 1972), and the Tesla Fault (John A. Blume and Associates, 1972; CDWR, 1974). Airphoto lineaments subparallel to the north branch of the Las Positas Fault Zone cross the southeast portion of LLNL (Judd Hull and Associates, 1977; this investigation).

As discussed previously, exploratory trenches have been excavated across the postulated locations of the Corral Hollow and Dougherty Faults within LLNL and across the north branch of the Las Positas Fault and the postulated location of the Tesla Fault on SNLL property. Two airphoto lineaments believed possibly related to the north branch of the Las Positas Fault were also trenched within LLNL.

No offsets have been found to suggest the presence of strands of any of the above postulated or known faults within LLNL or the postulated Tesla Fault within SNLL. These include trenches, test pits and other excavations made in materials at least 100,000 yr old (Knauss, 1981; Appendix D) and probably 125,000 to 195,000 yr in age for the postulated Corral Hollow and Tesla Faults and possible Las Positas strands within LLNL. No evidence for the Dougherty Fault has been found in alluvial deposits believed to



LEGEND

- Buildings
- Roads
- ---- Bicycle paths
- A-1 Parking lots
- Trailers

EXPLANATION

MW-1 ✦ Groundwater observation and other wells (LLNL).

TB-4 • Exploratory drill hole (LLNL).

2• Geotechnical exploratory hole (others). (only deeper holes that provided data for contouring are shown.)

A A' Geologic cross section.

540 Contours on subsurface horizon (possible erosion surface developed on upper member of Livermore Formation).

N

0 200 400

Fig. 40. Map of LLNL site showing contours on top of buried erosion surface (possible top of upper member of Livermore Formation, map unit Qtl).

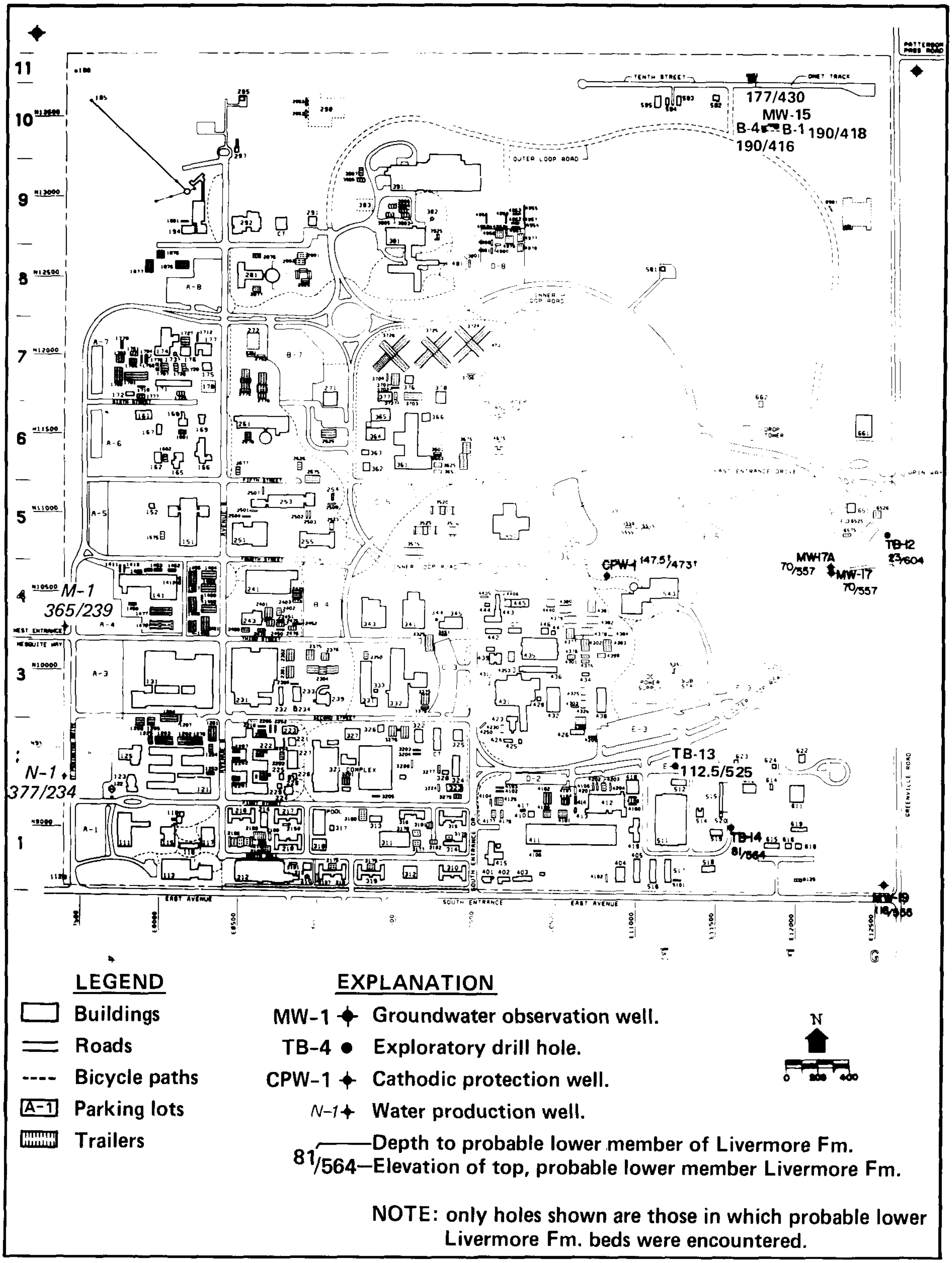


Fig. 41. Map of LLNL site showing depths to and elevations of top of lower member of Livermore Formation, map unit Tps.

be at least 35,000 yr old.* Interpretation of borehole and groundwater monitoring well logs strongly suggests (Figs. 29 to 31 and 40) that an erosion surface, possibly 300,000 yr old, has not been visibly disturbed by faulting, although the data are such that small movements would not be recognized.

Regional data strongly suggest that an older fault, herein named the ancestral Greenville Fault, is present at depth beneath the LLNL site. This fault has no geomorphic expression, nor does it appear to disturb alluvial deposits believed to be 300,000 yr or older (Figs. 29 to 31 and 40) although the quality of the data is insufficient to preclude minor offsets. No features that could be attributed to the ancestral Greenville Fault can be detected in groundwater levels or gradients (Fig. 42). Regional geologic data suggest an approximate trend for the ancestral Greenville Fault as shown in Figs. 18 and 19.

John A. Blume and Associates (1972) mapped a local fold structure (the Livermore syncline) across the northeastern portion of LLNL. This structure does not appear in cross sections A-A′ or B-B′. Rather, there is a gentle upwarp of beds in the area of the postulated syncline. Field mapping (Fig. 10) suggests that the axis of the Livermore syncline lies northeast of LLNL, although its location cannot be clearly established because of poor exposures.

Geodetic Data

Precise leveling surveys including all or part of the LLNL site have been reported and discussed by John A. Blume and Associates (1972) and CDWR (1979). Crow (1983) has reevaluated the CDWR data and noted apparent time-dependent effects (Figs. 36 and 37). As previously noted, discrepancies exist between the Blume and CDWR data raising doubts as to the significance of either data set.

Groundwater Data

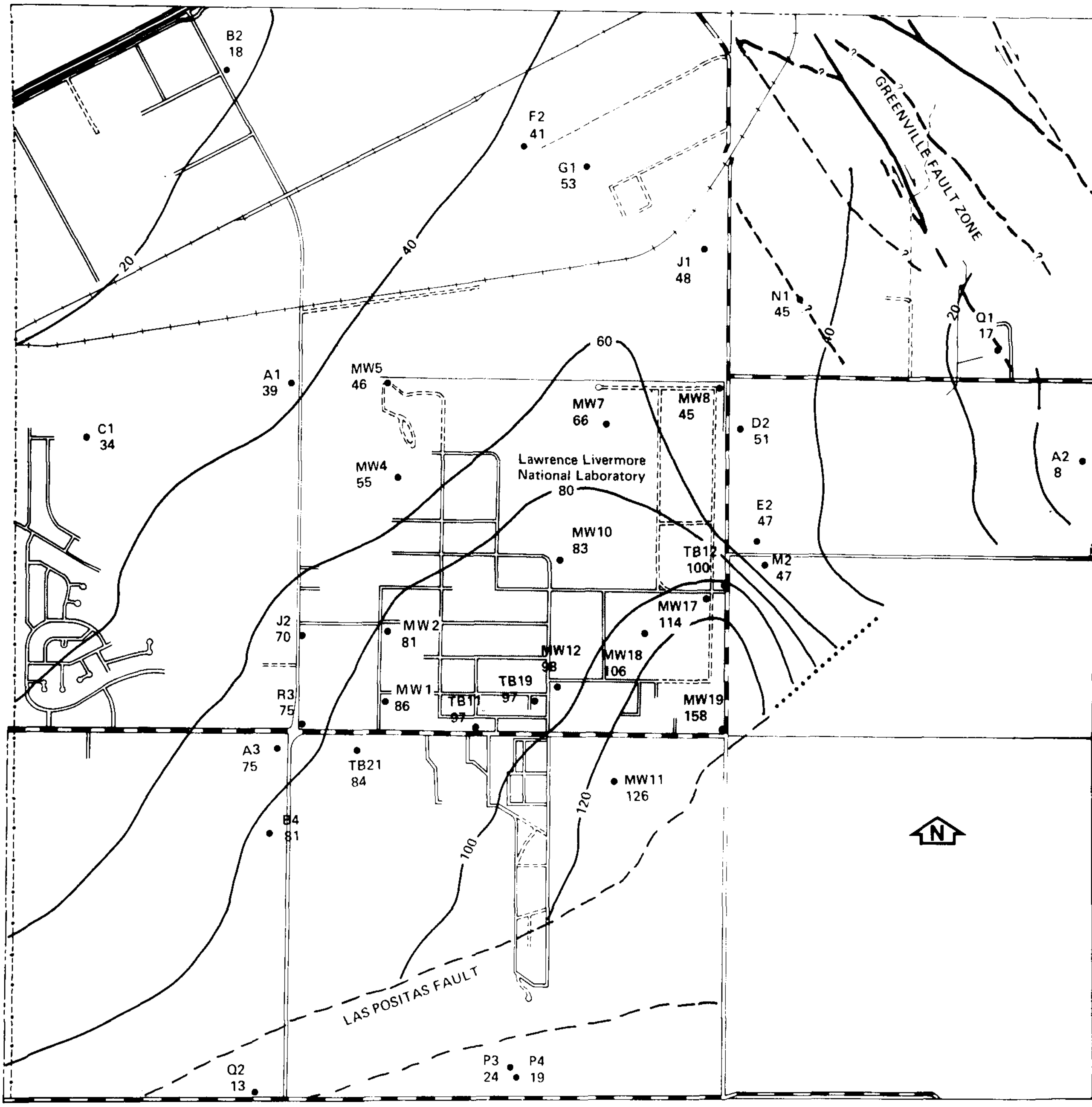
Depths to water-saturated sediments vary from about 13 m (43 ft) to about 49 m (160 ft) beneath LLNL. Depths to water, beneath portions of LLNL where major buildings are located, are mostly in the range of 18 to 30 m (60 to 100 ft). A water-table map is shown in Fig. 42. Groundwater gradients are gently to the west and northwest beneath most of the laboratory (Rogers, 1982). An area of increased gradient appears along the eastern boundary of the site and a groundwater depression exists beneath the southeastern portion of the laboratory and adjacent areas (Stone *et al.*, 1982). Areas of increased gradient and the groundwater depression appear to occur where the top of the saturated zone is within sediments of the lower member of the Livermore Formation (unit Tps). For a detailed discussion of the LLNL site geohydrology see Rogers (1982) and Stone *et al.* (1982).

No perched groundwater bodies were encountered during the subsurface investigations conducted as part of this study. Exploratory holes and groundwater monitoring wells used to collect subsurface data were drilled at various times during the periods of April through November 1980 and May through June 1981. Although holes drilled during the summer and fall of 1980 could have missed any local, seasonal, perched groundwater bodies, holes drilled during the spring of 1980 and in 1981, shortly after the ends of rainy seasons, would likely have detected perched groundwater had any been present.

Geologic Hazards

Geologic hazards potentially affecting safe operations and future building siting at LLNL are almost entirely related to regional seismicity. Lack of site relief, as well as landscaping and provisions for drainage, has made the potential for hazards related to slope instability or accelerated erosion negligible.

* This interpretation is based on the mapped continuity of alluvial deposits and soil types from the area of test pits 1 and 2 (studied by Shlemon, Appendix E) to trench E-2 and the excavation for Building 391. The log of trench E-2 also suggests that unfaulted sediments probably correlative with the 125,000 to 195,000 yr sediments identified by Shlemon were encountered locally in the lower portion of trench E-2 across the trace of the postulated Dougherty Fault.



LEGEND

D2 • 51	Water well and depth to water (ft below ground surface)
----	Fault located approximately.
--?---	Fault, existence uncertain.
⇄	Fault, showing relative horizontal movement.

0 — 1 mi

Contour interval 20 ft

Fig. 42. Depth to water table for LLNL site and surrounding sections (faults as mapped by Dibblee).

Ground Shaking

The LLNL site has experienced strong ground shaking during past historic earthquakes and can be expected to experience strong motions during future earthquakes. Potential sources of strong motion include the major active Bay area faults—the San Andreas, Hayward, and Calaveras Systems, and two local active faults, the Greenville and Las Positas Fault Zones. Geologic and seismologic evidence indicates that the LLNL site may also be shaken by earthquakes originating on the Concord, Green Valley, Williams, and Verona Faults. The site response study completed as part of the Site Study program considers probable site motions during earthquakes from all of the above sources plus motions arising from regional background seismicity, e.g., events of mainly low magnitude that cannot be clearly correlated with any particular active fault. Table 5 summarizes estimates of the extent, maximum credible earthquakes and slip rates of faults, which bear significantly on the ground shaking hazard at LLNL.

Ground Rupture

Surface displacements are frequently observed during major California earthquakes (Wesson *et al.*, 1975; Hart, 1980b). Surface faulting is believed to have occurred on the Calaveras Fault in western Livermore Valley during an earthquake in 1861 (Radbruch, 1968) and occurred within portions of the modern Greenville Fault Zone during earthquakes in January 1980 (Bonilla *et al.*, 1980; Carpenter *et al.*, 1980). Such displacements have been observed to closely follow identifiable faults (Hart, 1980b; Allen, 1981) and evidence for repetitive rupturing within a fairly narrow zone along the San Andreas Fault has been demonstrated by Sieh (1978).

Minor surface fracturing was observed at several locations within the Las Positas Fault Zone following the January 1980 earthquakes and was cited as evidence for possible sympathetic motion along the Las Positas Fault (Bonilla *et al.*, 1980). Minor pavement fracturing possibly reflecting tectonic creep along strands of the Las Positas Fault Zone was also observed during project studies.

None of the above active faults traverse LLNL. Therefore, the potential for surface faulting within LLNL as a result of a major earthquake on any of these active faults is nil.

Because of proximity to the north branch of the Las Positas Fault Zone, a small portion of the southeast corner of LLNL is now included in the Special Studies Zone for the Las Positas Fault recently defined by the California Division of Mines and Geology, pursuant to the Alquist-Priolo Act (Davis, 1252b). Figure 43 shows the affected area, a triangular parcel that extends 61 m (200 ft) west and 46 m (150 ft) north from the southeastern corner of the laboratory. Exploratory trench E-1 and test pit TP-1 were both excavated within the affected area and no fault strands were found.

As discussed previously, an old regional fault (herein named the ancestral Greenville Fault) is believed to underlie LLNL. This fault has no geomorphic expression, appears to have been segmented by movements along the Las Positas Fault, and does not appear to disturb the groundwater table or strata

Table 5. Principal active faults, San Francisco Bay Region.

Name	Length (km)		Maximum credible earthquake		Slip rate (mm/yr)	
	Recommended	Range	Recommended	Range	Recommended	Range
San Andreas	1200	–	8.3	7.5-8.5	12[a]	10-37
Hayward	96	72-280	7.0	6.7-7.7	7[a]	6-9.5
Calaveras	115	70-280	7.3	7.1-7.7	7[a]	5.6-7.5
Concord	20	18-20	6.0	5.0-6.3	1.5	0.4-6
Greenville	90[b]	42-200	6.6[b]	5.0-6.8	0.6[b]	0.1-1.4[b]
Las Positas	18.1[b]	6.0-29.4	6.0[b]	5.0-6.7	0.4[b]	0.02-0.9[b]
Verona	5.6	0-10	6.0	0-6.0	0.2	0-0.2

[a] These data are based upon short-term geodetic strain rates measured by Prescott *et al.* (1981) and converted to slip rates.

[b] These data are based chiefly on the results of this investigation. Some data for the Greenville Fault is from Shedlock *et al.* (1980) and from Earth Sciences Associates (1982). Other values are compiled from the following sources: San Andreas Fault—Wesson *et al.* (1975), Shedlock *et al.* (1980), Prescott *et al.* (1981); Hayward and Calaveras Faults—Wesson *et al.* (1975), Shedlock *et al.* (1980), Prescott *et al.* (1981), Slemmons and Chung (1982), Page (1982), and Lennert (1982) (Hayward Fault only); Concord Fault—Wesson *et al.* (1975), Shedlock *et al.* (1980), Earth Sciences Associates (1982); Verona Fault—Earth Sciences Associates (1982), Shedlock *et al.* (1980), and Davis (1982c).

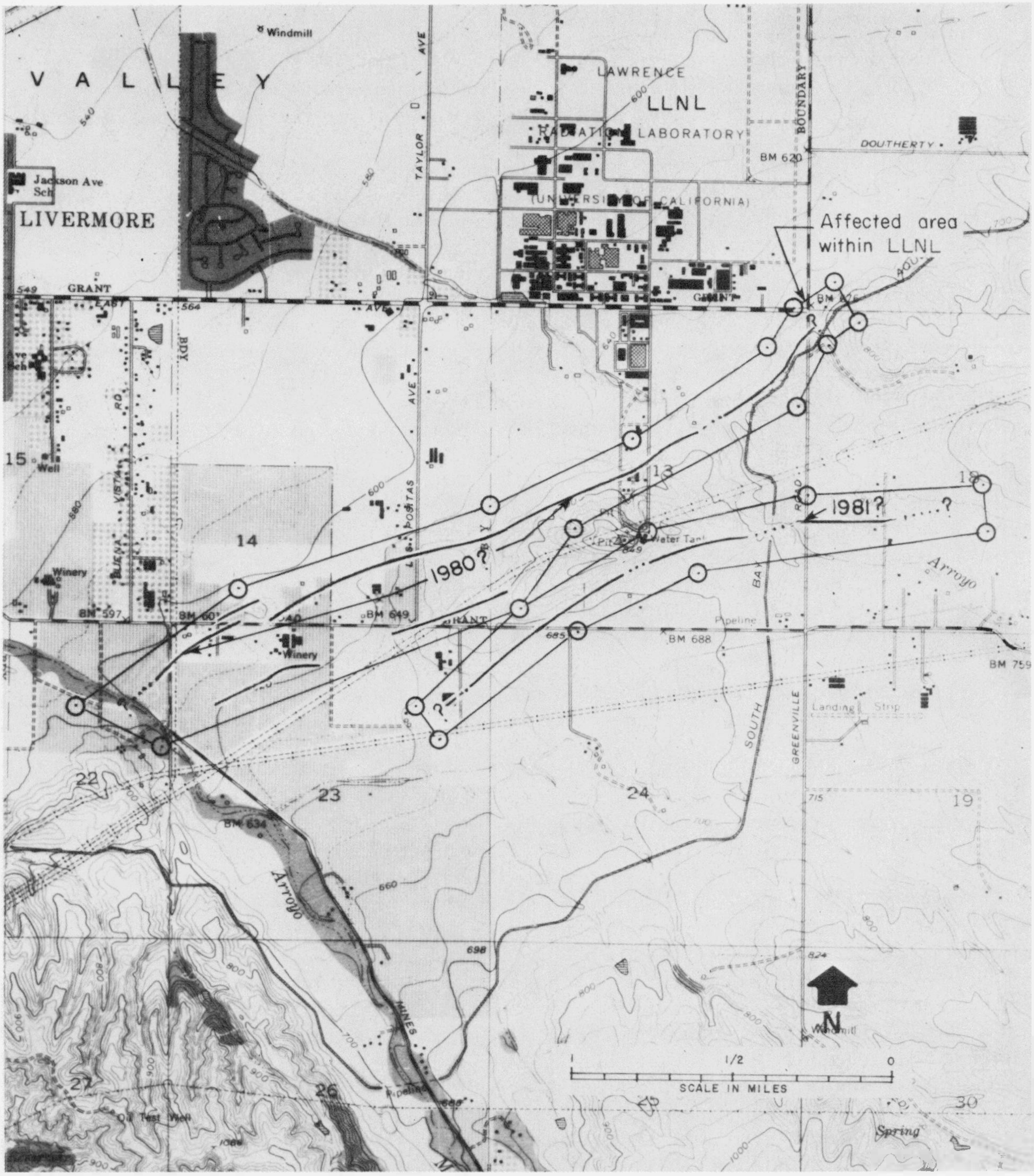


Fig. 43. Special studies zones, Las Positas Fault Zone (after Davis, 1982b). Note: 1980? and 1981? indicate locations of possible sympathetic surface faulting and tectonic creep, respectively.

beneath LLNL believed to be 300,000 yr and older (Figs. 29 to 31, 40, and 42). This fault is judged to be inactive based on criteria for fault activity used during project studies. However, because the ancestral Greenville Fault appears related to the tectonic environment in which the modern, active Greenville Fault exists, some form of sympathetic rupture might occur along this ancestral fault during a future earthquake (although none occurred during the 1980 earthquakes). The probability of such an event is very remote based on the lack of evidence for displacement of late Quaternary materials and geologic and seismologic evidence for the shift of seismic activity eastward to the modern Greenville Fault, at least during late Quaternary time.

Any estimate of the amount of sympathetic surface displacement that might occur along the ancestral Greenville Fault during a future earthquake is highly speculative owing to very infrequent observations of the reactivation of old faults during historic earthquakes. A possible worst-case example may be provided by Saul (1975). Saul observed up to 15 cm (6 in.) of displacement on portions of the Santa Susana Fault in Southern California following the 1971 San Fernando Valley earthquake ($M_L = 6.5$) triggered along the adjacent San Fernando Fault. Geologic evidence suggested that the Santa Susana Fault had been dormant for about 500,000 yr (Saul, 1975). It should also be noted that the Santa Susana Fault has expression in near surface materials, whereas the ancestral Greenville Fault is buried by at least 30 m (100 ft) of undisturbed Pleistocene and Holocene sediments (Figs. 29 and 30).

The Santa Susana Fault rupture is believed to represent a worst-case situation because of the geometric and tectonic relationships involved. Movement on the San Fernando Fault was primarily thrusting at relatively shallow depth, and the Santa Susana Fault appears to mark a lateral boundary of the shallow thrust slab (Saul, 1975). In the case of the modern and ancestral Greenville Faults, subparallel systems are involved with right-lateral strike-slip motions on near-vertical fault planes. Motions along the modern system do not necessarily impose stresses on the ancestral system. The absence of fracturing along the ancestral Greenville Fault following the 1980 earthquakes provides evidence for this opinion. It should also be noted that the active Las Positas Fault Zone truncates the ancestral Greenville Fault at two locations southeast of LLNL (Fig. 10) providing further evidence for its inactivity.

Ground Failure

The passage of seismic waves (in addition to causing ground shaking and rupture) can cause other damage in certain locations and in certain earth materials. These are called secondary effects and are generally limited to surface and near-surface materials.

Liquefaction (resulting in lurch cracking, sand boil formation, and lateral spreading) is a type of soil failure related to the presence of loose, water-saturated, relatively clean sands. Structures on or in such sands may sink or float, depending on their relative buoyancy. Fissuring occurs in overlying soils (lurch cracks), and water/sand mixtures may be expelled (sand boils). If a free face, such as a river bank, is present, the soil mass may slide toward the free face (lateral spreading). These effects occur chiefly in areas underlain by geologically young, alluvial deposits in which the top of the zone of saturation is near the ground surface. Areas underlain by shallow bedrock or dense, older alluvial deposits, as well as areas in which the saturated zone is deep, are generally not affected. Studies have shown that the duration of shaking as well as the relative density of the material is important. Long duration shaking during a great earthquake may cause liquefaction of materials that would be unaffected by a short, sharp earthquake even if peak accelerations are similar. Helley *et al.* (1979) provided a listing of factors and conditions controlling liquefaction. These are listed in Table 6.

Alluvial deposits underlying LLNL do not possess the physical properties of materials generally subject to liquefaction. Typically, the sediments beneath LLNL are older, weathered, poorly sorted, and often weakly cemented. Numerous standard penetration tests were performed during exploratory hole and observation well drilling at LLNL. These tests were performed to obtain samples for strata identification and to explore for loose saturated sands that are potentially subject to liquefaction. The results of standard penetration tests in sand beds beneath the LLNL site are presently in summary form in Fig. 44. Tests summarized in Fig. 44 are grouped in 10-ft increments. Blows required to drive the sampler during the first foot of penetration were determined from field data. The lowest, average, and highest number of blows required for samples within each 10-ft depth interval are shown in Fig. 44. Blow counts obtained during standard penetration tests in sand beds near and below the top of the saturated zone range from 12 to more than 96 per ft (Carpenter *et al.*, 1982). All but two of the blow counts obtained exceeded 20/ft.

Table 6. Factors and conditions controlling soil liquefaction (adapted from Helley *et al.*, 1979).

Factor	Conditions conductive to liquefaction	Conditions not conducive to liquefaction
Grain size of sediment	Coarse silt and fine sand	Clay, coarse sand, gravel
Sorting (variability in grain size)	Well sorted; uniform grain size clay-free (less than 3%)	Poorly sorted; nonuniform grain size; high clay content (more than 3%)
Cementation[a]	Uncemented, loose	Cemented, hard
Consolidation (compaction)	Unconsolidated; noncompacted; loose; low shear strength	Semiconsolidated to consolidated, moderately to highly compacted; high shear strength
Relative density[b]	Low relative density; less than 65% for small earthquakes	High relative density; more than 90% for largest earthquakes
Standard penetration[c]	Low	High
Geologic age[d]	Generally young; Holocene; Late Pleistocene	Generally older (Pleistocene and older)
Water saturation	Saturated; pore spaces filled; high groundwater table; bay deposits, flood basins, lower parts of alluvial fans	Partly unsaturated to dry; pore spaces not filled; low groundwater table; higher parts of alluvial fans
Pore-water pressure	High (greater than lithostatic load)	Low (less than lithostatic load)
Depth	Within 30 m (100 ft) of surface; low lithostatic load	Greater than 30 m (100 ft) depth; less than lithostatic load
Seismic activity	High seismic activity; high probability of moderate to great earthquakes	Low seismic activity; low probability of moderate to great earthquakes

[a] Particles may be cemented together by calcite, silica, iron oxides, or other materials.

[b] Relative density primarily reflects the degree of compaction in a sediment; 100% relative density means a sediment is at its maximum compaction (all the pore space is filled). Relative density of 0% means a sediment is at its minimum compaction (it is in its loosest condition and pore space is at a maximum).

[c] Standard penetration generally reflects the degree of induration, which is a combination of compaction and cementation. Low standard penetration values indicate a sediment that is neither compacted nor cemented.

[d] In a general way, the age of a deposit is reflected in certain physical properties, such as induration. Older alluvial deposits are generally more highly indurated than younger deposits.

As shown in Fig. 44, some tests were made that resulted in low blow counts/ft of penetration. These tests were almost entirely in the unsaturated zone within 30 ft of ground surface. It is probable that geotechnical engineering studies performed in advance of future building construction would detect similar low-density strata and that foundation designs and/or site treatment would reflect observed soil conditions. Low density materials above the water table do not contribute to the potential for liquefaction unless perched groundwater bodies are present. As discussed previously, no perched groundwater bodies have been detected during exploration beneath the LLNL site.

Shannon and Wilson, Inc. (1971) estimated relative densities in the range of 90 to 100% for sand beds beneath LLNL. Sand beds below the top of the saturated zone were believed to be at 100% of relative density (Shannon and Wilson, Inc., 1971). Sands with relative densities of 90% or above are judged by Helley *et al.* (1979) to have low liquefaction potentials. Youd and Hoose (1978) did not find any incidents suggestive of liquefaction in the eastern Livermore Valley as a result of historic earthquakes and none were noted following the January 1980 earthquakes.

Based on the soils engineering data provided by Shannon and Wilson, Murray and Tokarz (1973) evaluated the liquefaction potential at the LLNL pool-type reactor facility. They found that even a worst-case scenario for the reactor site did not suggest the potential for liquefaction.

Borehole data indicate general physical similarity of strata beneath the entire LLNL site to the materials studied by Shannon and Wilson, Inc. (1971) and used by Murray and Tokarz (1973) during their analysis. Depths to water are shallower along the north boundary of the laboratory (e.g., about 14 m+ (47 to 48 ft) in MW-5 and 13 m (43 ft) in MW-8, located at the northwest and northeast corners of the site, respectively). However, even in these areas, the top of the saturated zone is blanketed by more than 12 m (40 ft) of dense, poorly sorted sandy silts, clays, and silty, locally gravelly, sands. As stated previously,

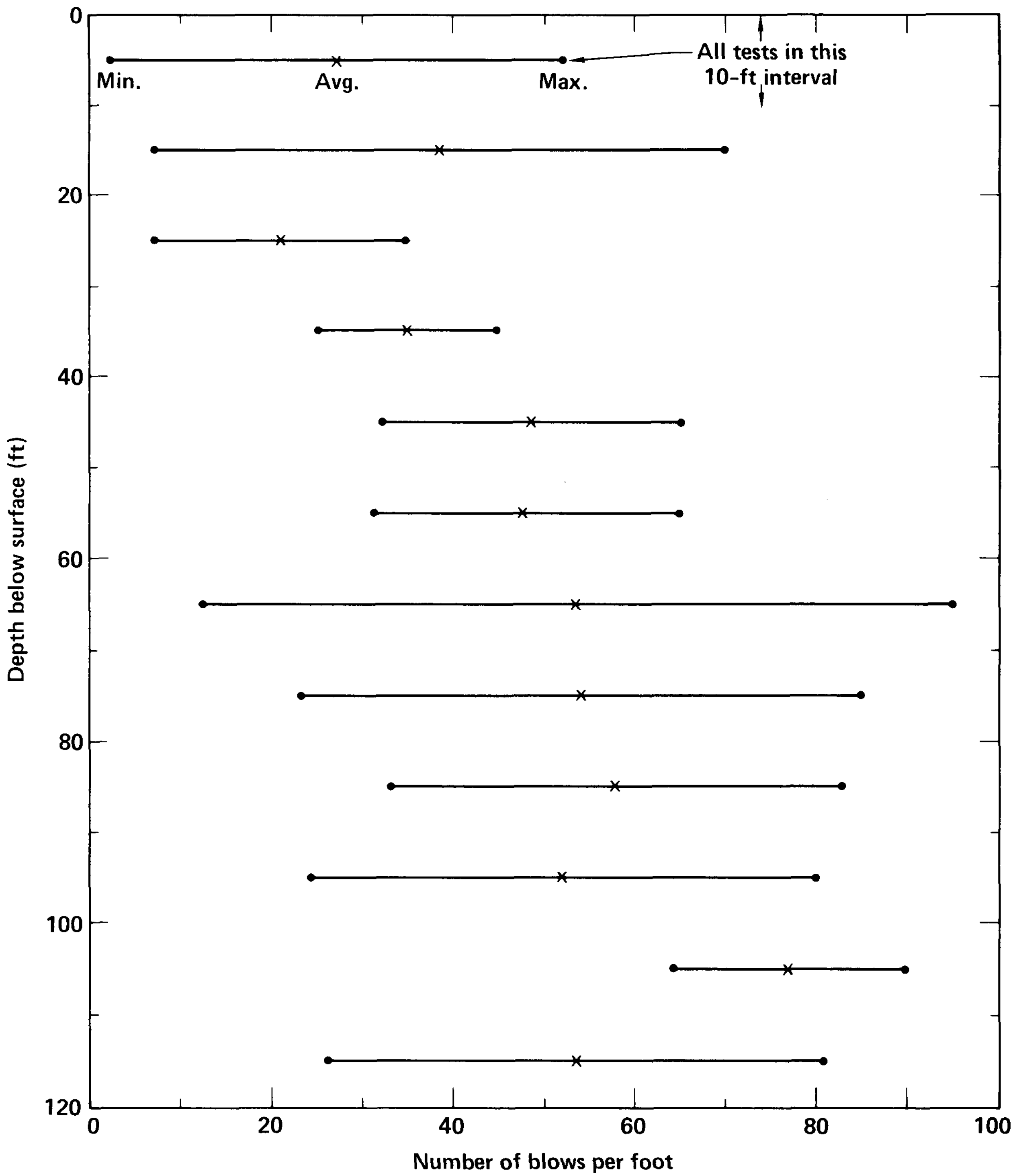


Fig. 44. Standard penetration test data of sand strata beneath the LLNL site.

depths to water beneath portions of LLNL occupied by major buildings generally range from 18 to 30 m (60 to 100 ft).

Based on soils data and historic experience, the potential for liquefaction and related phenomena at LLNL is remote. Potentials for structural damage as a result of vibrational compaction or differential settlement of soils during major earthquakes are regarded as low for the LLNL site, although some less critical structures constructed on shallow foundations could be affected by localized settlements of near surface soils. It has been general practice at LLNL for many years to have comprehensive foundation engineering studies performed for significant buildings (including all critical facilities). These studies minimize the risk of foundation damage as a result of settlement or insufficient bearing capacity.

Tsunamis and seiches are, respectively, marine "tidal waves" and smaller oscillations in closed lakes or bays. Both types of wave action can cause damage to near-shore structures, but are not potential hazards at LLNL because of the absence of nearby water bodies.

Soil Erosion and Slumpage

Natural slopes within LLNL do not exceed 3% and, therefore, the potential for any large-scale landsliding is nil. Minor erosion and sloughing have been experienced along drainage ditch and stream channel banks and at drainage outlets as a result of concentrated runoff following heavy rains. However, no structures have been endangered and the problems posed are those of periodic maintenance rather than hazard mitigation.

During the winter of 1982, following heavy rains, two landslides appeared along the southeast side of the State of California's South Bay Aqueduct, roughly 400 m (0.25 mi) southeast of LLNL. Neither slide disrupted aqueduct operations although one encroached on the top of the canal lining and posed the risk of siltation of aqueduct water. The CDWR promptly repaired this slide and unloaded the slope above the site to reduce the risk of future movements. The second slide affected the bank above the access road along the east side of the aqueduct, but did not encroach on the aqueduct prism itself. The CDWR subsequently repaired this slide as well.

In the unlikely event of a failure of the South Bay Aqueduct near LLNL, sheet flooding might be experienced across a portion of the LLNL site. The potential water volume would be limited to that between a check structure south of Dougherty Lane (Fig. 2) about 1.1 km (0.8 mi) east of LLNL and the Arroyo Seco Siphon located a similar distance southeast of the laboratory.

Site flooding as a result of overflow of the Arroyo Seco and Arroyo Las Positas channels has been previously considered (USDOE, 1978). Some potential for sheet flooding exists [15 mm (0.6 in.) maximum depth] as a result of overflow of the Arroyo Seco during a very large storm. This flow could cause localized erosion.

Summary and Conclusions

LLNL is underlain by a thick sequence of late Tertiary and Quaternary alluvial deposits overlying a complex basement of Mesozoic metamorphic rocks of the Franciscan Assemblage and late Mesozoic and Tertiary marine sedimentary rocks. An old fault, herein named the ancestral Greenville Fault, separates the Franciscan basement terrain from the late Mesozoic and Tertiary basement.

The late Tertiary and Quaternary alluvial deposits include lacustrine, alluvial fan, and stream channel deposits that accumulated in a continental environment. Rapid lateral and vertical facies changes are common within these sedimentary deposits although some correlations of coarser and finer zones have been possible for the LLNL site itself through interpretations of borehole logs.

Soil profiles and relative and absolute age data demonstrate that most of the near-surface materials beneath LLNL range in age from latest Pleistocene (15,000 to 20,000 yr) to 100,000 yr or greater. A low net sedimentation rate of about 30 $\pm$ 3 cm (1 $\pm$ 0.3 ft)/10,000 yr is indicated by the data. Therefore, deeper boreholes drilled within the site are believed to penetrate strata of the Pleistocene sand and gravel member of the Livermore Formation. Some holes located generally within the eastern portion of LLNL have probably reached the lower member of the Livermore Formation which is predominantly fine-grained and of Pliocene age.

Depths to groundwater beneath LLNL vary from about 13 m (43 ft) beneath the northeast corner of the laboratory to about 49 m (160 ft) beneath the southeast corner. Depths to water beneath portions of the laboratory where major buildings are located range from 18 to 30 m (60 to 100 ft).

LLNL is located in a seismically active region. Deformation of Quaternary materials and periodic seismicity support this conclusion. Historic seismicity has been experienced along the Calaveras and Greenville Faults that bound the Livermore Valley on the west and east, respectively, and also appears associated with the Las Positas Fault Zone. The Calaveras Fault is located approximately 17 km (11 mi) west of LLNL, and recently active strands of the Greenville Fault Zone are located approximately 1.1 km (3500 ft) northeast of the laboratory. Geologic evidence demonstrates Holocene activity along strands of the Las Positas Fault Zone that lie about 90 m (300 ft) southeast of LLNL at their point of closest approach. Pavement fracturing at the intersection of Greenville Road and East Avenue suggests that a strand of the Las Positas Fault may be located about 15 m (50 ft) southeast of the southeast corner of the laboratory.

Other potential sources of seismicity that could affect LLNL include two major regional faults, the San Andreas and the Hayward, as well as several local faults. These include the Concord, Green Valley, Williams, and (possibly) Verona Faults.

A number of other faults have been mapped in the Livermore Valley region, based on geologic discontinuities or inferred from groundwater data. Geologic studies of many of these postulated faults have demonstrated that either they do not disturb late Quaternary materials, and are therefore inactive, or that their existence is doubtful. Based upon considerations of their lengths and locations, none of these faults have the potential to materially influence the seismic hazard at LLNL.

No active faults underlie the LLNL site. One older, presently inactive fault (herein named the ancestral Greenville Fault) is believed to underlie the laboratory. Its position at depth is uncertain but is probably near the northwest-southeast alignments shown in Figs. 18 and 19, based on regional well data. Interpretations of borehole data and geologic cross sections suggest that this fault does not disturb strata 300,000 yr or older. The thickness of the undisturbed strata is at least 30 m (100 ft) based on borehole data.

The principal geologic hazard at LLNL is strong ground shaking as a result of a major earthquake on a large regional or local fault. Surface rupture as a result of sympathetic displacement of the inactive ancestral Greenville Fault is a remote possibility. Secondary seismic hazards, such as soil liquefaction, are not judged to be risks because of the nature of the alluvial deposits beneath the site and depths to saturated materials. Slope failures and major erosion damage as a result of flooding are not credible site hazards. Minor, localized erosion may be experienced.

Recommendations

The authors of this report believe that the findings presented represent a state-of-the-art appraisal of the geology of the Livermore Valley region and of potential geologic hazards to safe operations at LLNL. However, geologic knowledge is not static and is never complete because of observational limitations. It is, therefore, likely that future discoveries will be made that will have bearing on the seismic setting of the laboratory. In view of this we recommend the following:

- Earth Sciences Department personnel should remain in contact with other geoscientists working in the Livermore Valley area and be in a position to advise LLNL management regarding findings that may affect the LLNL site. In particular, any data concerning the position and activity status of the ancestral Greenville Fault should be obtained and promptly analyzed. Potential sources of information include geotechnical studies of project locations in the eastern Livermore Valley and geophysical exploration and drilling by petroleum and gas interests.
- If LLNL constructs any structures for human occupancy (as defined by the State of California) within the portion of LLNL zoned for Special Study pursuant to the Alquist-Priolo Act, a site-specific geotechnical investigation for the building must be completed prior to construction. Earth Sciences Department personnel should participate in the State-mandated review of the geotechnical report to determine its adequacy under State guidelines for such investigations (see Hart, 1980b).
- Earth Sciences Department personnel should have the opportunity to participate in studies of any future earthquakes in the Livermore Valley region similar to those conducted following the January 1980 earthquakes.
- While not judged critical to defining the seismic hazard at LLNL, some additional studies would be of benefit in further understanding Valley seismicity and tectonics. These studies would focus on the extent and evidence for Holocene activity along the Livermore and Williams Faults and further evaluate postulated links between the Las Positas Fault Zone and the Verona and/or Williams Faults.

Additional geologic studies of the seismically active area south of LLNL would be of benefit. These studies could be integrated with other investigations to develop an improved tectonic model of the Livermore Valley region. Such a model could generate beneficial data concerning the nature of strong ground motion in the region as well as provide better data concerning seismic sources. The possibility of establishing precise level and trilateration networks in the vicinity of LLNL to detect crustal movements that may reflect faults at depth and better quantify short-term slip rates along active faults should be given active consideration. These networks should incorporate existing benchmarks wherever possible.

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Woodward-Clyde Consultants has been retained by LLNL to provide professional review services in accordance with generally accepted professional practices and with the recommendations of the State of California Seismic Safety Commission for peer review of seismic hazards reports.

It must be emphasized that the aforementioned individuals and agencies have neither approved nor otherwise endorsed the findings and conclusions of this report. The findings and conclusions reported herein are solely those of the authors, who are members of the LLNL staff. The principal authors of this report are Registered Geologists in the State of California.

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WEC/BS/JS

Appendix A
Airphoto Interpretation

D. W. Carpenter

Five sets of black-and-white aerial photographs were studied during the Site Seismic Safety assessment program. Photographs were examined and interpreted for features suggestive of faulting. The region examined included all of the area within the perimeter of the Laboratory as well as neighboring areas.

Photographs examined were taken in 1940, 1958, 1968, 1970, and 1972. Two detailed monoscopic and stereoscopic analyses were made of each of the photo sets. The investigators worked independently so that the results of one study would not influence the other.

Tonal variations and linear patterns were observed in photographs of areas within and adjacent to the LLNL site. Such tonal variations and linear patterns could indicate surface expressions of faults, or they could indicate other geologic features, such as former stream channels. They may also reflect cultural features unrelated to geology, such as buried pipes, former fence lines, and farming patterns. Locations of all lineaments seen near LLNL are shown in Figs. 10, 20, 21, and 39 in the main text.

The majority of the tonal variations and linear patterns observed can be described as faint or ill-defined. However, well-defined lineaments were also identified to the south and the southwest of the Laboratory, and they coincide with the location of the Las Positas Fault. Airphotos taken in 1940 (Fig. 39), prior to the development of the LLNL site, do not show any lineaments subparallel to the Las Positas Zone within the area now occupied by the Laboratory. However, faint lineations crossing the southeast corner of the LLNL site can be seen on 1958 and 1972 airphotos.

The 1940 aerial photographs show a channel of Las Positas Creek in the area where faint lineaments and tonal variations, attributed to the Dougherty Fault (John A. Blume and Associates, 1972), can be seen on later photographs (Fig. 22, main text). Discontinuous lineaments and faint tonal patterns related to an abandoned course of the Arroyo Seco were observed in the area where Strands 1 and 2 of the Tesla Fault Zone were projected by John A. Blume and Associates (1972).

A band of faint and discontinuous tonal variations that cuts across the entire LLNL site was observed by one investigator. The southeastern portion of this band of tonal variations is indistinct in places but roughly coincides with the projected position of the Corral Hollow Fault trace as mapped by John A. Blume and Associates (1971). The northwestern segment diverges to the west of the projected fault trace and is probably part of a surface drainage channel. A short discontinuous and faint lineament was also observed to intersect the northeastern corner of the Laboratory's perimeter.

Subsequent detailed exploratory efforts discussed in the main text were concentrated along well-defined lineaments and in areas where previous investigators had postulated faults. As discussed in the main text, some northeast trending linear patterns seen within SNLL and southeast of LLNL were found to be expressions of the Las Positas Fault Zone. Other linear and tonal patterns were not found to be associated with faulting within materials of late Quaternary and Holocene ages.

Airphoto interpretation was an important part of later phases of Site Study investigations. As a preliminary to regional mapping efforts (Sweeney and Springer, 1981), Ramirez (1980) completed a comprehensive lineament study for an area bounded roughly by the town of Tassajara to the north, the Del Valle Reservoir to the south, Shadow Cliffs Regional Park to the west, and the area of Patterson Pass to the east. The 1972 black-and-white (scale 1:12,000) and the 1940 (scale 1:20,000) photos were examined during this study.

Wagoner (1980) and Clark (1982) reviewed several sets of aerial photographs of the Greenville Fault Zone and adjacent areas during project studies of that active fault, and Clark and Carpenter periodically examined aerial photographs during field mapping in the area adjacent to LLNL. The results of the mapping study are shown in Fig. 10 in the main text.

Table A-1 presents a listing of all aerial photographs examined by project investigators during the Site Study.

Table A-1. Aerial photographs examined during LLNL Site Seismic Safety Assessment program.

Agency	Type	Date	Scale	No.
NASA	IR B & W	1-74	1:24,000	0260-0272
NASA	IR Color	1-74	1:24,000	0260-0272
NASA	IR Color Pos.	3-71	1:63,000	349-353
Gov.	B & W	4-70	1:63,000	VCMI 1-134-138
USAF	B & W	7-68	1:160,000	066 and 067
Unknown	B & W	6-40	1:12,000	BUT 340 85-91 BUT 340 55-60
Alameda Co.	B & W	6-58	1:12,000	2-7-20-22 2-8-20-23 3-9-21-22
Alameda Co.	B & W	5-72	1:12,000	AC 10-28-36 to 10-28-43 10-29-32 to 10-29-40 12-23-32 to 12-23-34 12-26-33 to 12-26-35 12-27-33 to 12-27-35 and 14-25-33 to 14-25-36
U.S. Geological Survey	B & W	5-68	1:24,000	5-111 and 5-112

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Appendix B
Results of Examination of Well Logs and Reflection Seismic Data in Southeastern Livermore Valley

J. J. Sweeney

Contents

Exploration for oil and gas over the last 30 to 40 years by various companies has resulted in considerable data bearing on the interpretation of geologic structures in southeastern Livermore Valley. The data consists of borehole, sonic, induction, lithologic, density and dip meter logs, and three lines of reflection seismic data leased by the LLNL Site Seismic Safety Program from Hershey Oil Company. The borehole logs were obtained from the California Division of Oil and Gas, Department of Conservation. The borehole data was purchased only for holes drilled deeper than 2000 to 3000 ft. Complete sets of logs are not available for each hole; the most commonly available logs are induction, sonic, and lithologic description.

The essential elements of the geologic structure of southeastern Livermore Valley can be worked out from logs from Section 16, T3S, R3E, Section 8, T3S, R3E, the Livermore Oil Field, and seven other wells within a 1 mi radius of LLNL.

Northeast Corner of Section 16, T3S, R3E

There have been three boreholes drilled in this area, shown in Fig. B-1. Two holes are west of the eastern strand of the Greenville Fault (Dibblee, 1980, and Sweeney and Springer, 1981), labeled T1 and T12 in Fig. B-1, and one hole is east of the fault strand (T5 in Fig. B-1). The logs of these holes reflect the major geologic discontinuity present across the fault shown on the map. Well T5 was drilled in an area with Panoche sandstone of the Great Valley Sequence (Kps) near the surface and only Kps was encountered throughout the 3910 ft total depth drilled. Figure B-1 shows that the unconformable contact between Cierbo Formation (Tmss) and Kps outcrops close to well T5. Note that there is no Eocene Tesla Formation (Tt) here between units Tmss and Kps as is seen in Corral Hollow.

In contrast, wells T1 and T12 have been drilled in an area with Neroly Formation (Tn) near the surface and penetrated a typical section of Tmss, Tt, and Kps. The presence of Tt at depth (top of Tt about 2200 ft depth) in T1 is proved by descriptions in the lithologic log of a 100-ft-thick section of coal at a depth of 2700 ft. The coal is also easily identified on the sonic and induction logs. In the Corral Hollow area, no coal seams thicker than about 10 ft have been seen (Huey, 1948). Therefore the seam in well T1 is probably dipping 70° or more. Well T12 only has an induction log for comparison. It was not deep enough to encounter the coal seam seen in T1, but the induction log correlates well with T1 and shows the (probable) Tmss-Tt contact about 100 ft shallower. This indicates that bedding dips to the southwest towards the core of the syncline shown in Fig. B-1. This syncline is the offset continuation of the syncline shown east of the fault in the southeast corner of Fig. B-1. The net horizontal component of offset of this syncline is 5150 ft (1.57 km).

A short distance north-northwest of wells T1 and T12, Dibblee has mapped an area of Kps (?) directly underlying Tmss. Exposure in this area is poor and thus the Kps (?) is conjectured. If the mapping is

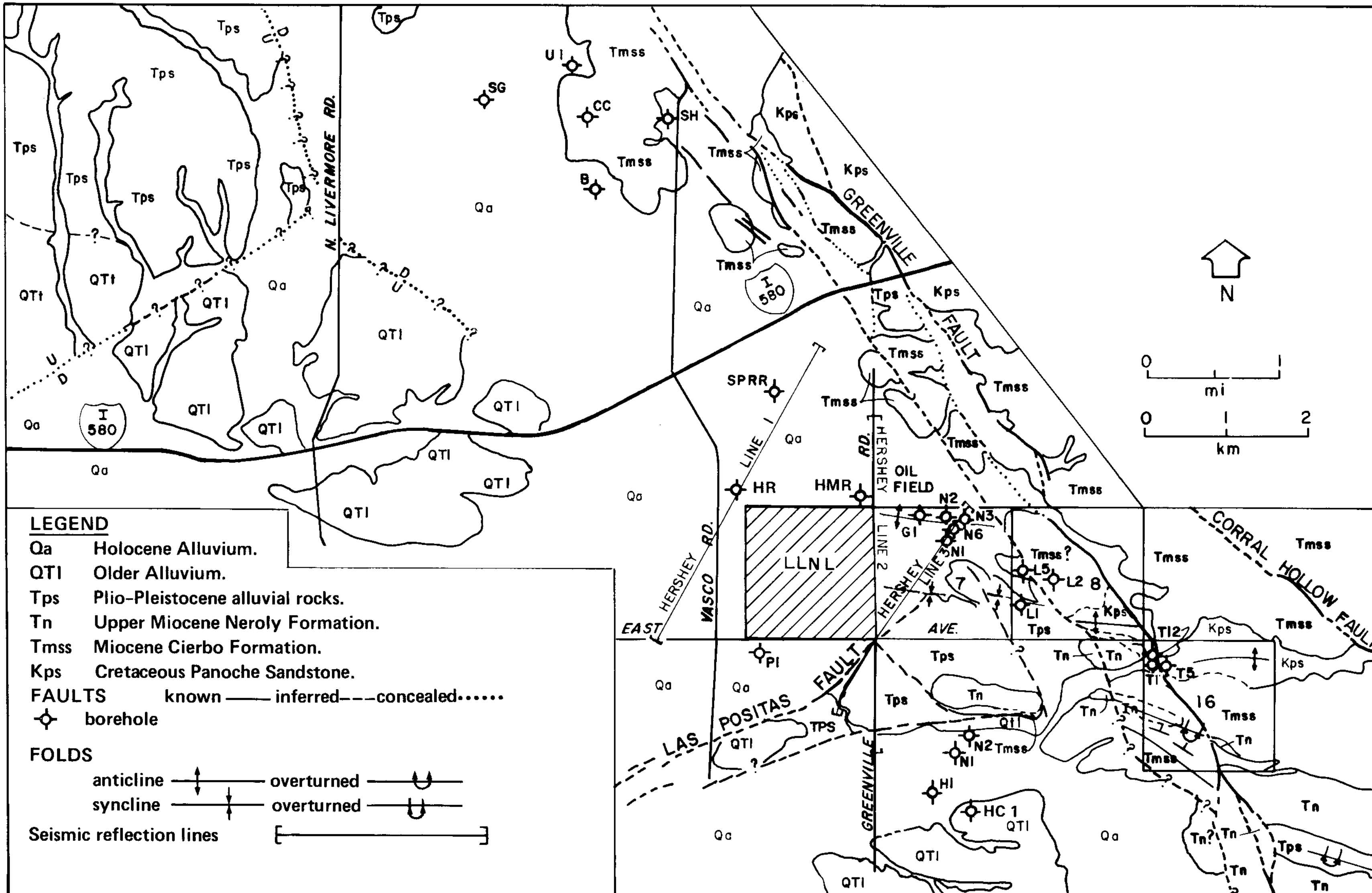


Fig. B-1. Generalized geologic map of southeastern Livermore Valley, showing locations of boreholes and seismic reflection lines discussed in the text [primarily after Dibblee (1980c) and Sweeney and Springer (1981)].

correct, the Tt seen in T12 must pinch out extremely rapidly toward the north, otherwise it would be exposed between units Tmss and Kps on the southern limb of the anticline. Furthermore, dips here have to be about 80° SW to bring the top of Kps from 3400 ft depth (as seen in T1) to the surface over a horizontal distance of 600 ft. Such steep dips are in accordance with observations about the coal seam discussed above.

Section 8, T3S, R3E

The writer examined logs from three boreholes in Section 8, shown in Fig. B-1. Borehole L2 (an oil producing well) is located east of the inferred western strand of the Greenville Fault and holes L1 and L5 are west of the strand and do not produce oil. L2 was drilled through Tmss near the surface and down into Kps. The unconformable contact between Tmss and Kps is at a depth of about 1000 ft, with no Tt present at this location. The lithology of L2 is consistent with the well being on the north flank of the anticline in the southeast corner of Section 8 shown in Fig. B-1.

Wells L1 and L5, west of the fault strand, are much different from L2. The top of Tmss is seen at about 1700 ft depth in L5; the top of Tt is at about 2300 ft; and the top of Kps is at about 3500 ft. Lithology for L1 is similar to L5, but the contacts tend to be 200 to 300 ft deeper in L1. The lithologic log for L1 reports coal at a depth of 3400 to 3700 ft, confirming the presence of Eocene Tesla Formation. The sonic and induction logs for well T1 in Section 16 and L5 (redrill) in Section 8 are quite similar, with contacts in L5 being about 100 ft lower. Therefore, boreholes L1 and L5 appear to be located on the northern limb of the same syncline in which the southern limb was penetrated by wells T1 and T12. The dextral offset of the syncline is about 5000 ft (1.52 km) based on this data. This gives a total horizontal component of offset across the two strands of the Greenville Fault of about 10,150 ft (3.09 km). Error in this estimate is due to difficulty in accurately locating the core of the syncline and is probably on the order of 0.5 km.

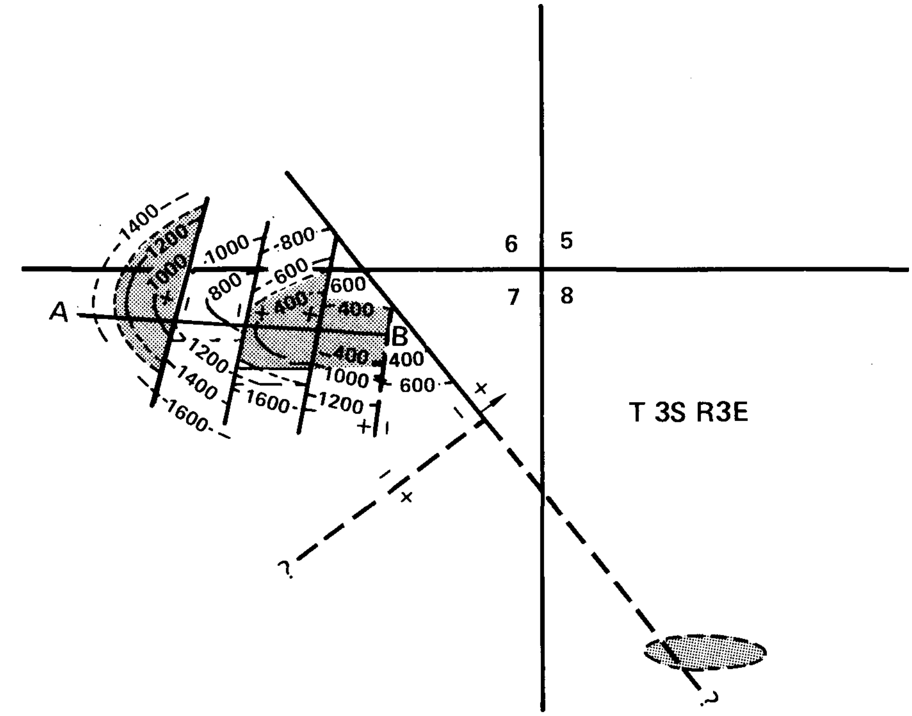
Livermore Oil Field

The Livermore Oil Field, consisting of 10 producing wells along the southern edge of Section 6, T3S, R3E and the northern edge of Section 7, T3S, R3E has been interpreted as a complexly faulted westerly plunging anticline (Dibblee and Darrow, 1981) that continues east of the Greenville Fault south of L2 and at T5 (see Fig. B-1). Figure B-2 shows an interpretation of the structure of the oil field by the California Division of Oil and Gas (1973). Note that the longest fault, shown extending into Section 8, lies to the east of the trace of the Greenville Fault mapped by Dibblee (cf. Figs. B-1 and B-2). If the fault shown in Fig. B-2 exists, it is probably a branch of the Greenville, parallel to the trace shown in Fig. B-1. The faults shown trending nearly north-south, which would be perpendicular to the fold axis, are contrary in trend to any known mapped faults in the region. It is more likely that the offsets shown in Fig. B-2 can be accounted for by primarily northwest-southeast trending faults parallel to the Greenville trend with possibly some subsidiary faulting parallel to the Las Positas trend. The writer has attempted to interpret available logs and the seismic reflection data with this in mind. However, the data is insufficient to make definite determinations of fault locations. What is important is that the Livermore Oil Field marks the possible location of a buried anticline that may have been offset dextrally 2.5 to 3.0 km across the Greenville Fault Zone.

An intriguing aspect of the oil field data is the presence of the Tesla Formation, which is not seen in the continuation of the anticline to the east across the fault. The writer has no good explanation of this, but can think of two possibilities:

1. Presence of Tt in the oil field indicates that it is an anticline that does not match the anticline east of the eastern Greenville Fault trace shown in Fig. B-1, but rather some other (buried) anticline not shown, and lying to the south of the ones that are. This would affect determination of total slip along the fault zone.

2. An irregularity in the areal extent of deposition of the Tesla Formation could account for its presence in the Livermore Oil Field. It seems fortuitous that a change in the depositional area coincides with the fault trace, unless the fault was active during Eocene time.



Contours on top of Greenville sands.
Scale 1 in. = 2000 ft.

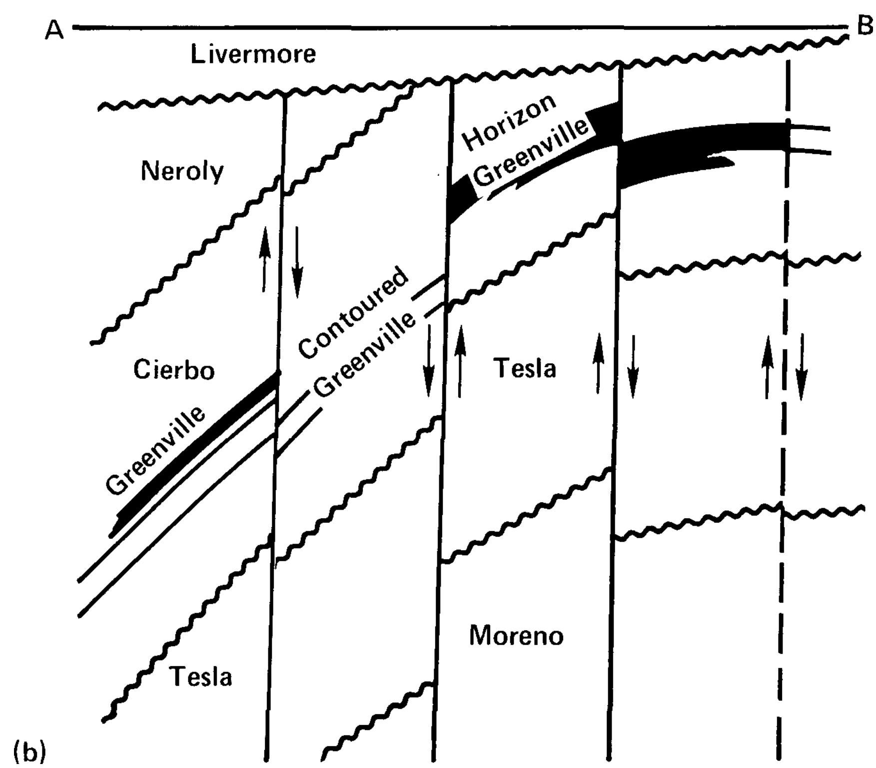


Fig. B-2. Interpretation of the structure of the Livermore Oil Field by the California Division of Oil and Gas (1973). The Greenville sands are a zone of hydrocarbon accumulation marked by an anomaly in the induction logs.

Other Boreholes Within One Mile of LLNL

The significance of holes P1, H1, N1, N2, and HC 1 (shown in Fig. B-1) southeast of LLNL for the interpretation of the ancestral Greenville Fault has been discussed in the main text. Three wells have been drilled north of LLNL that also bear on the location of an ancestral Greenville trend, Hershey-Rhodes (HR), Hershey-Miller-Richards (HMR), and a well near the Southern Pacific Railroad line (SPRR). All three wells penetrated Tertiary formations. Tt was reported at about 6000 ft in HMR and is probably about 3000 ft deep in SPRR. Hershey-Rhodes did not penetrate Tt. However, a fault was encountered at about 3500 ft, possibly resulting in a repetition of part of the section. Franciscan Assemblage rocks were not found in the 5442-ft-deep well HR.

The significance of the HR borehole is that it constrains the location of an ancestral Greenville Fault between well P1, southwest of LLNL, and well HR, north of LLNL. Further information concerning the trace of the ancestral Greenville Fault is seen in the seismic reflection data, discussed below.

Hershey Oil Company Seismic Reflection Data

Three lines of reflection seismic data were leased from Hershey Oil Company. Locations of the lines are shown in Fig. B-1. The data were of generally poor resolution, but several obvious reflectors are visible for data to which amplitude coherency processing was applied. Norm Burkhard, LLNL Earth Sciences Department, made an initial pick of the reflectors for each line. Depths to the reflectors were then calculated using the average moveout velocities given on the seismic lines and an apparent depth section was prepared as shown in Figs. B-3, B-4, and B-5.

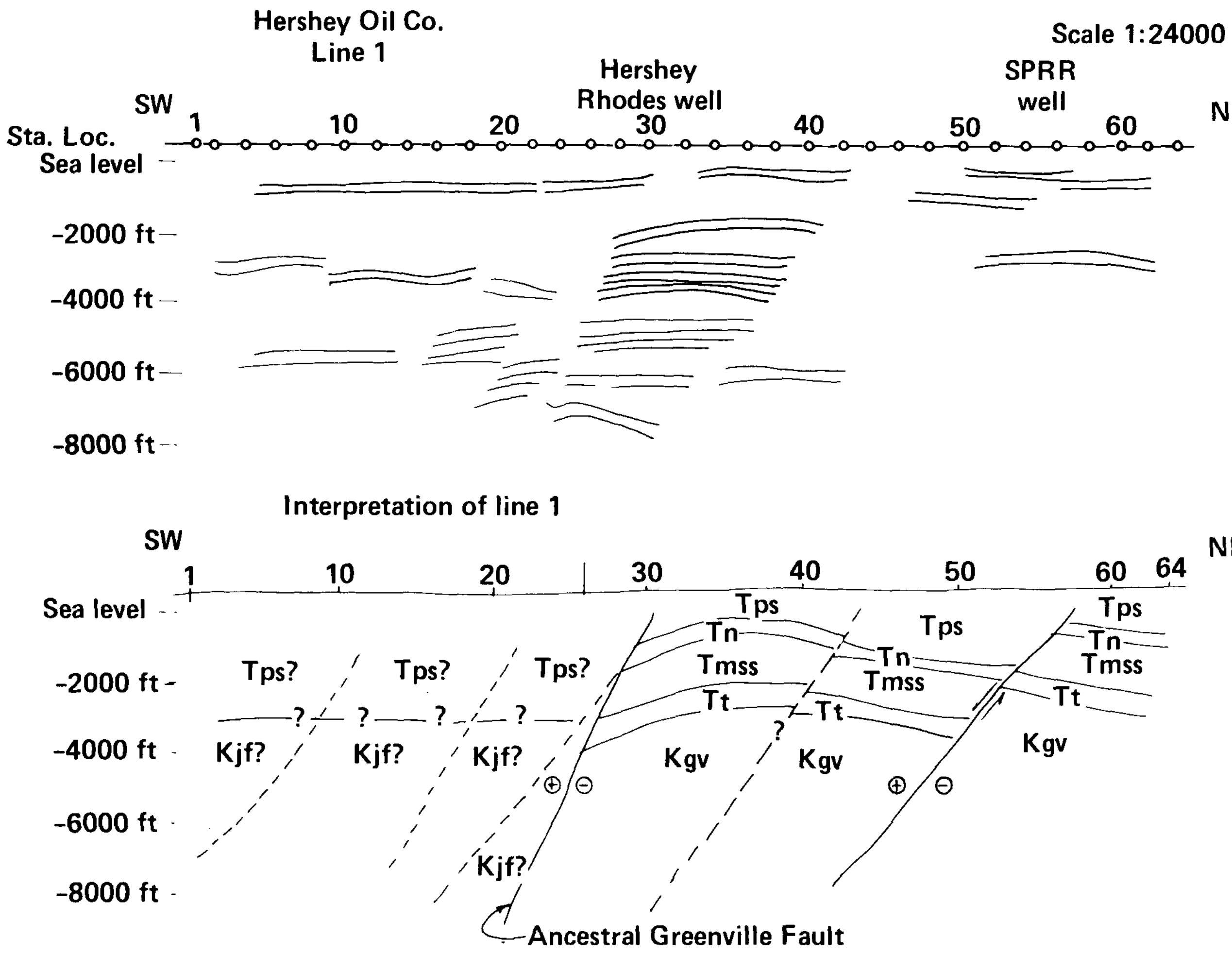


Fig. B-3. Apparent-depth seismic-reflection line 1 (top) with corresponding geologic section (bottom).

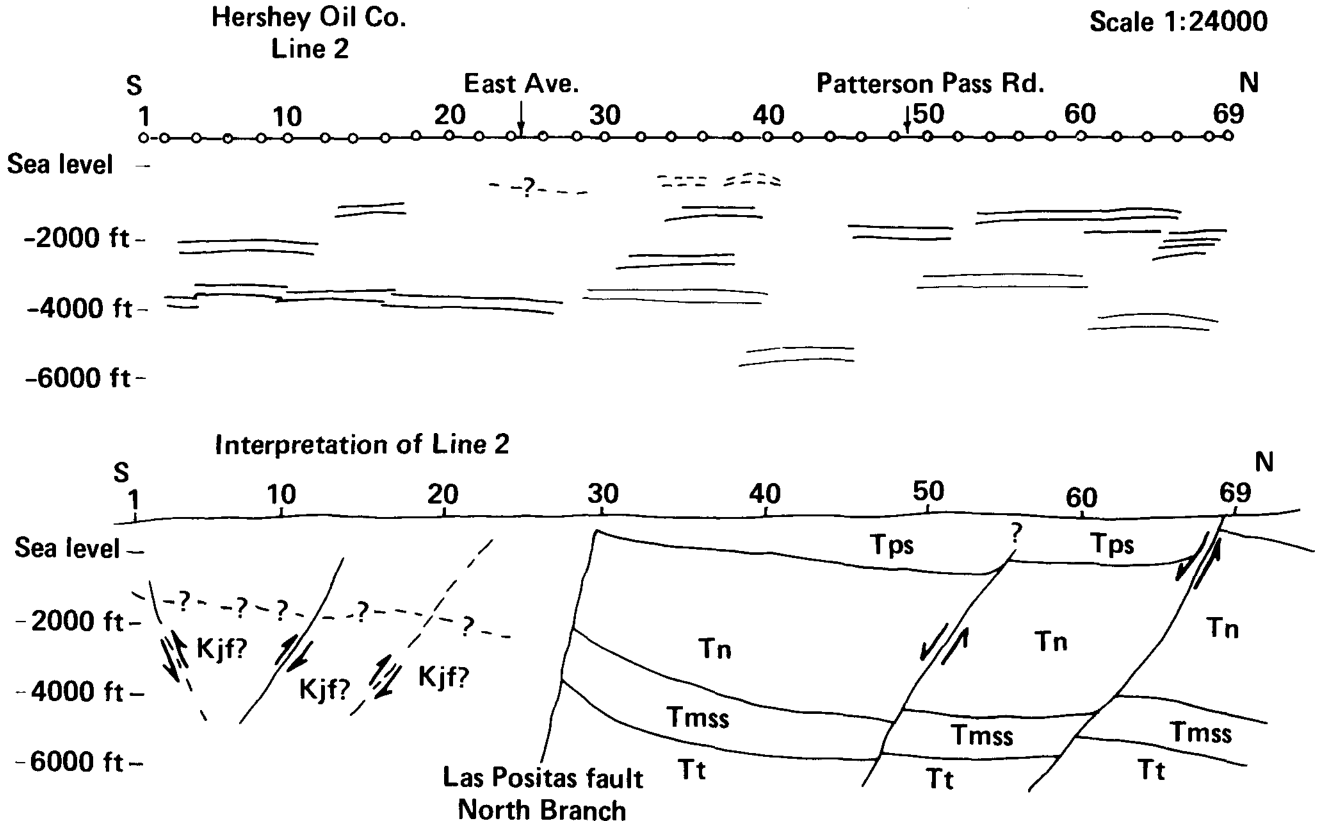


Fig. B-4. Apparent-depth seismic-reflection line 2 (top) with corresponding geologic section (bottom).

A cursory examination of the seismic sections reveals that there are numerous instances of truncated beds and apparent fault displacements. The Tertiary age sediments (Tc, Tmss, Tn, and Tps) are generally sandstones and siltstones with similar lithologic and physical properties, thus well-defined velocity discontinuities are not expected between units in the section or between the base of the Tertiary and the underlying shales and sandstone of the Great Valley Group (Kps). Therefore, reflectors seen in the seismic section cannot, in general, be correlated with the lithologic boundaries in the Tertiary rocks. The data have not been "migrated" (i.e., corrected to account for dipping reflectors), and some apparent offsets in the seismic sections could be due to rapid changes in the dip of the reflectors. Because of the poor quality of the seismic data and the difficulty in associating reflectors with known geologic conditions (for example, in the Livermore Oil Field) a direct geologic interpretation of the seismic data was determined to be impossible. As an alternative, geologic sections were prepared along each seismic line, based on extrapolation of known structures southeast of the area and on data concerning the ancestral Greenville Fault given above with modifications to emphasize some of the more obvious features of the seismic data. It is emphasized that there is no certain way to correlate separate reflectors and thus the association with specific geologic units is highly speculative. The geologic sections are shown in Figs. B-3, B-4, and B-5.

Line 1 shows a great number of reflectors in the central portion, between stations 30 and 40. Station 30 is near the Hershey-Rhodes borehole (HR of Fig. B-1) and station 54 is near the SPRR borehole. Both boreholes encountered Tertiary rocks and are, therefore, in strata equivalent to the folded sequences seen immediately to the north of Corral Hollow. Southwest of station 30 in line 1 there is a consistent reflector at a depth of 2400 to 2800 ft. This would correspond to the depth to Franciscan Assemblage basement seen in wells P1, H1, and HC1, as discussed in the body of the report. Therefore, locating the ancestral Greenville Fault just southwest of station 30, as shown in Fig. B-3, is consistent with both the borehole data and the seismic data. The large number of reflectors between stations 30 and 40 on line 1 are

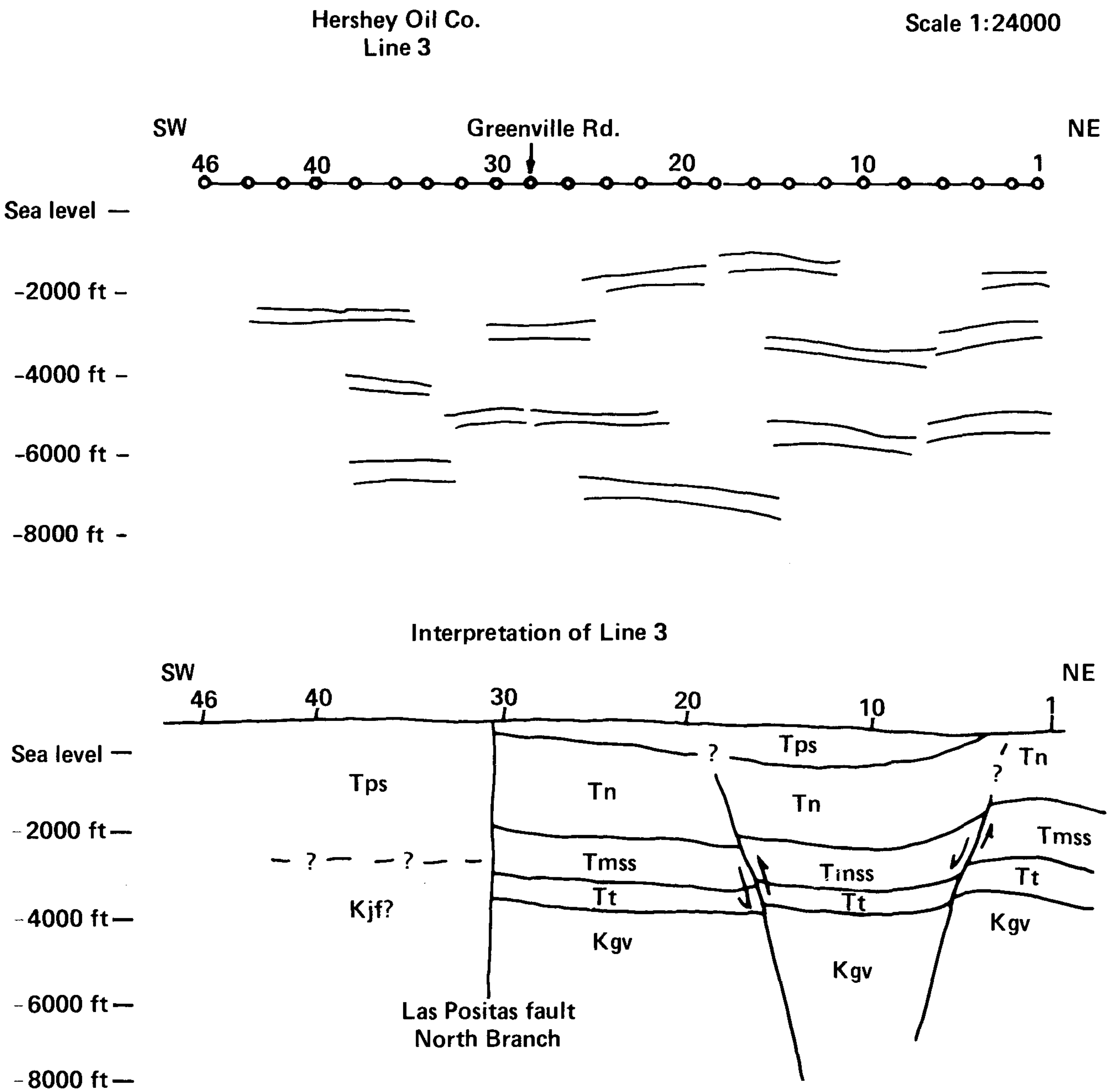


Fig. B-5. Apparent-depth seismic-reflection line 3 (top) with corresponding geologic section (bottom).

consistent with the presence of flat lying beds in the crest of an anticline, whereas the reflectors are lost northeast of station 40 because they are dipping to the northeast on the flank of the anticline.

On line 2 there is a clear break in the reflectors at the location of the Las Positas Fault, which is also the location on the line where the ancestral Greenville Fault crosses (Fig. 10, main text). Therefore, south of station 30 (the ancestral Greenville) Franciscan Assemblage basement would be expected, while the Tertiary sequence (with Great Valley Sequence at depth) would be seen to the north. This is to some extent supported by the seismic data. Reflectors south of station 30 are more sparse, with a reflector about 2200 ft down, corresponding to the approximate position of Franciscan basement. There is a hint of a possible anticline from the shallow reflector at stations 14 to 18 which corresponds to the anticline mapped between the north and south branches of the Las Positas Fault (see Fig. 10, main text). Reflectors north of station 30 suggest the possibility of faulting; faults in the geologic section were drawn to correlate with the seismic data, but there is no geologic data to confirm their presence. The fault depicted at station 69 may align with the fault shown in line 1 at station 58 and may be an extension of a fault inferred from drilling data seen in the Livermore Oil Field and the fault conjectured from field mapping to the southeast (see Fig. 10 and Fig. B-1).

Line 3 also crosses the intersection of the Las Positas and ancestral Greenville Faults near station 30. A reflector about 2400 ft south of station 30 could represent the top of the Franciscan basement. As was done for line 2, the faults drawn in the geologic section northeast of station 30 were included to correlate with the seismic data. The fault beneath station 20 may be the same as that at station 58 on line 2, but data is insufficient to confirm a connection. Similarly, the fault at station 3 of line 3 may be the same as that of station 69 of line 2. The trends of the above faults would parallel the present trace of the active Greenville Fault and pass northeast of LLNL. Continuing work by J. Springer, graduate student at San Jose State University, suggests the presence of several faults parallel to the Greenville Fault lying west of the present active trace. These faults were probably active in the past as the active trace of the Greenville Fault migrated eastward.

In conclusion, the seismic reflection data is extremely ambiguous and reflectors cannot be easily associated with definite stratigraphic boundaries. This is not surprising given the transitional nature of some of the lithologic boundaries (such as between Tn and Tmss) and the similarity in the physical properties of the rock units. Consequently, a unique interpretation of subsurface geology cannot be made from the seismic data. However, geologic sections drawn based on extrapolations from the area to the southeast and on borehole data are consistent with the seismic reflection data. The seismic lines lend further support to the existence of an ancestral Greenville Fault, which marks a major boundary between basement rocks of the Franciscan Assemblage and the Great Valley Sequence.

Appendix C
Geophysical Investigations

P. W. Kasameyer, N. R. Burkhard, J. J. Sweeney

Contents

Purpose and Scope of Geophysical Measurements

Geophysical data were collected as part of the effort to locate faults that might displace near-surface layers, and would therefore be considered active and contribute to the potential for ground rupture. Geophysical surveys were conducted to:

(1) evaluate the effectiveness of seismic refraction, resistivity, magnetics and SP data for detecting faults or extrapolating hidden faults away from trenches or outcrops,

(2) evaluate possible faults suggested by previous reports, and

(3) see if faulting could be detected in areas where there are no outcrops.

The geologic background and several location maps for this appendix are included in the main text. The methods used were chosen based on experience and practical considerations. Different geological materials from the area were known to have significantly different acoustic velocities and electrical resistivities, so seismic and electrical surveys were the principal methods employed. Previous studies employed electrical profiling methods that detect lateral variations only at a single depth. In order to reduce interpretation uncertainties, we combined profiling with soundings to produce two-dimensional geoelectric cross sections. Small-scale seismic studies were performed with a hammer source, and a Dinoseis source was used for larger-scale studies. Explosives were avoided to reduce hazards and environmental concerns, limiting our depth of investigation to about 200 ft.

Additional studies were performed with magnetic and self-potential (SP) methods. Magnetic methods had been used with considerable success over the outcrops southeast of the study area. However, smaller, hard to interpret, anomalies had been detected in the alluvial areas. We concluded that cultural effects dominated the magnetic data on the LLNL site and the Sandia property, and so we did not interpret the data we collected. SP data were collected along the Las Positas Fault on SNLL property. Similar studies had been successful along the Las Positas Fault west of the study area, presumably because the fault is a groundwater barrier with simple structure there. In the Sandia property, the SP data appeared highly variable, and we have concluded that any signals from the fault are overwhelmed by water infiltration from the Arroyo Seco and leakage from the canal. Therefore, this work is also not further considered here.

Several conclusions were drawn from the geophysical data. On the SNLL property, several features were found that match strands of the Las Positas Fault as inferred by other means, and nothing was detected to suggest that other faults are present. On the LLNL property, where the alluvial fill is deeper, small-scale refraction studies were uninformative, and larger-scale refraction studies were ambiguous. Locations where the seismic data raise questions were identified and evaluated using other geological and geophysical data.

The geophysical data described here have contributed very little to the geologic interpretations of possible near-surface faulting discussed in the main body of the report. The geophysical studies on the SNLL property successfully identified features which are interpreted to be caused by the Las Positas Fault. These measurements corroborate the extensive geological investigations there, but add little to the interpretation.

Geophysical studies in the areas covered with alluvial overburden produced ambiguous results about near-surface faulting, and the interpretations in the main body of the report are based primarily on results from trenching and borings. There are three reasons for the results being ambiguous:

1) Faults in alluvial deposits do not always produce recognizable geophysical anomalies. Geophysical methods measure physical properties, such as electrical conductivity or acoustic velocity. The young, dry alluvial deposits are very inhomogeneous and their physical properties vary irregularly both vertically and laterally. Relative displacement across a fault may (possibly) cause a detectable physical inhomogeneity, but that inhomogeneity will not be recognized as anomalous when compared to the characteristic inhomogeneity of the medium.

2) The water table was shown to be quite smooth in this area. In alluvial areas, faulting may produce a groundwater barrier causing the water table to slope steeply. Since seismic velocity and electrical conductivity generally increase with saturation, the water-table elevation is an attractive geophysical target. Within the area of observation, direct observations of the water table were made in more than 25 wells, with a typical spacing of about 1000 ft. These observations indicate that, to a much higher accuracy than is possible with geophysical measurements, the water table is quite smooth in the area studied. Consequently, the interpretation of the water-table surface was based on these observations, rather than on the geophysics.

3) The geophysical surveys did not produce convincing evidence for offsets of the "basement." The alluvial cover is underlain by more competent materials with contrasting physical properties. Irregularities in this boundary could be detected with geophysical surveys. These irregularities could either be older erosional features, or represent displacement along faults. Once again, direct geologic observations in wells and excavations were relied upon as the basis for determining whether the alluvium is offset by active faulting. These investigations were located to evaluate possible fault trends identified in part from earlier geophysical studies. The geophysical studies reported here did not produce convincing evidence of additional possible fault trends, and therefore did not influence the geologic investigations significantly.

Dipole-Dipole Resistivity Soundings

Dipole-dipole resistivity soundings were performed along six profiles in the field east and south of SNLL to evaluate the usefulness of this survey method and to search for features aligned parallel to either the Tesla or Las Positas Fault trends. Locations of the profiles are shown in Fig. C-1 and Fig. 21, main text. Data were collected by N. Chakakis, R. Egbert, and J. Sweeney. A Scintrex transmitter and IPR-8 receiver were used with steel rod electrodes at spacings of 100 and 200 ft. Apparent-resistivity pseudo depth sections, showing data obtained by the method described in Fig. C-2, are contained in the results as shown in Figs. C-3 to C-8.

Apparent-resistivity pseudo sections calculated for two-dimensional earth models have been compared to the 100-ft separation data (J. Sweeney, LLNL internal memo AG 80-20, revision). The primary features of the conclusions reached are discussed here.

First, the general features of the known geology are reflected in the interpreted resistivity cross sections. A thin (less than 10 ft), relatively conductive (20 ohm-m) weathering layer was observed in many places. The alluvium (Qal_1 and Hpal) in the flat areas was also conductive (15 to 30 ohm-m) and the outcrops of Livermore Formation (Tps and Qtl) that form hills were relatively resistive (50 to 60 ohm-m) to depths of 50 to 100 ft. This difference in resistivity could reflect the lower clay content of the Livermore Formation or a difference in elevation of the water table related to the topography. A prism of low resistivity is seen beneath the South Bay Aqueduct, perhaps indicating increased water content, clay, or

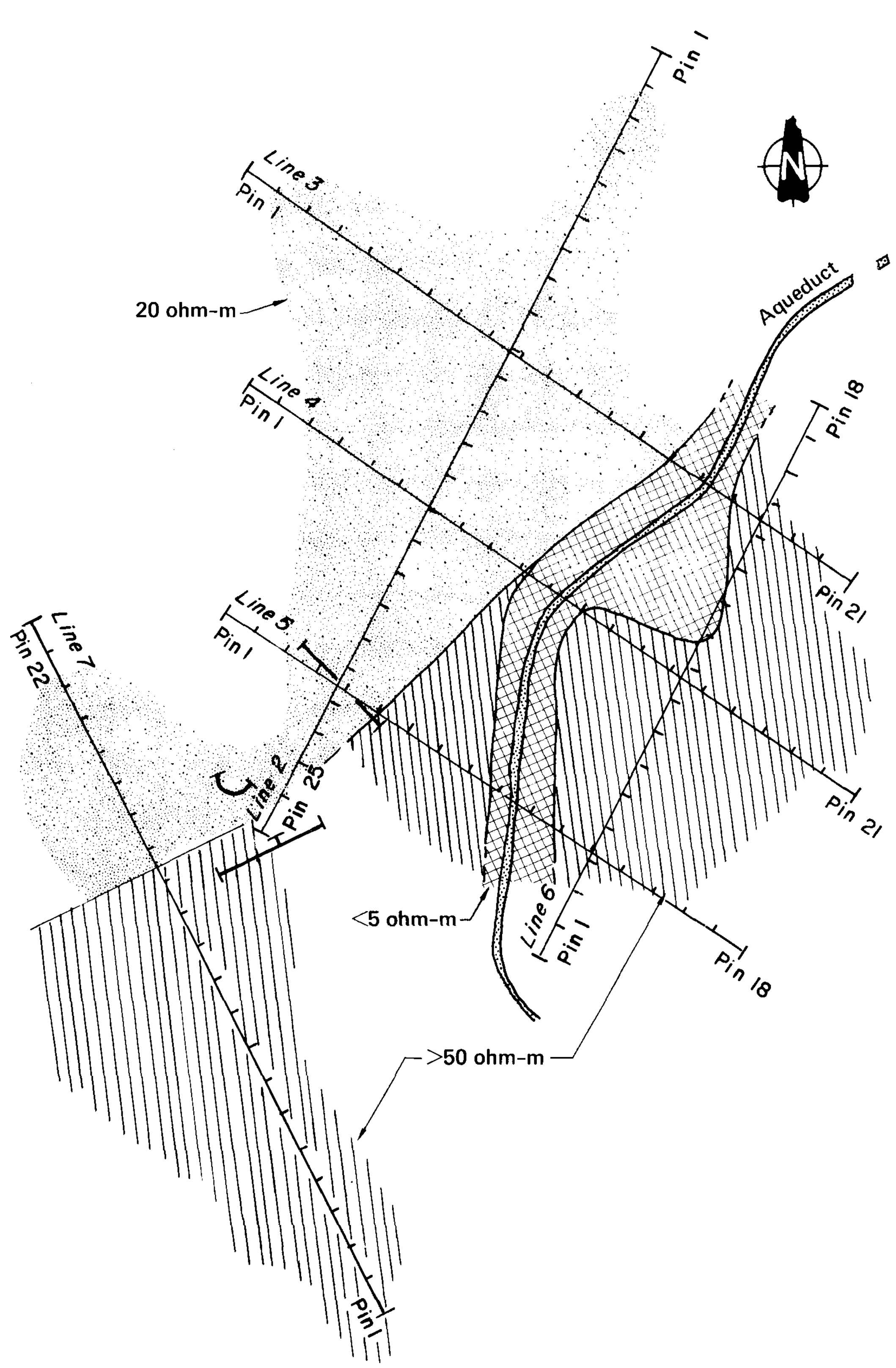


Fig. C-1. Map of survey lines for dipole-dipole resistivity in field southwest of SNLL. The tick marks on the profile lines represent locations of survey pins with 100-ft spacing. The pin numbers are also shown on the top of the pseudo depth sections in Figs. C-3 through C-7. The shading indicates the interpreted resistivity at 50-ft depth for lines 2 through 6, and at 150-ft depth for line 7. The heavily shaded areas are less than 5 ohm-m, the white areas about 20 ohm-m, and the lightly shaded areas are greater than 50 ohm-m.

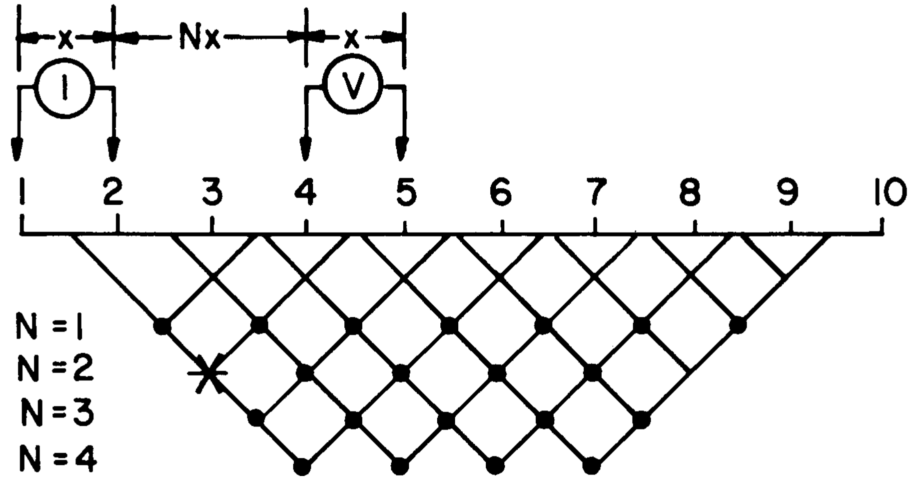


Fig. C-2. Method for plotting apparent-resistivity, pseudo depth sections. Current and voltage dipoles of fixed length x (100 or 200 ft) are placed along the line as shown. The apparent resistivity detected is a spacial average of the earth resistivity below the line. As the dipole spacing Nx is increased, the earth resistivity is averaged over a greater depth. To produce the pseudo depth section, the apparent resistivity is plotted on the line of the appropriate N value and midway between the dipoles. The star indicates the plotting position for the measurement geometry shown. The pseudo depth section is a convenient way to plot dipole-dipole data, but it does not represent an accurate map of the subsurface because each measurement averages over a large volume.

salinity in the materials beneath the aqueduct. The interpreted resistivity at 50-ft depth for lines 3, 4, and 5 and 150-ft depth for line 7 is indicated by the shading in Fig. C-1.

Second, two lines (2 and 6) cross the trace of the Tesla No. 1 Fault as postulated by John A. Blume and Associates (1972). These lines show no indication of lateral changes in resistivity due to rock type and are thus in agreement with URS/Blume and Associates (1978) in this area. Line 2 lies entirely in the alluvium and its pseudo section is quite featureless, indicating relatively uniform resistivity to depths of at least 100 ft. Line 6 lies in the Livermore Formation and is nearly parallel to the aqueduct. Along much of its length the profile was located close enough to the aqueduct to sense the low resistivity prism. Consequently, the pseudo section is complex and other features may be hidden. The zone of low resistivity under the aqueduct broadens near pin 12 of line 6; reasons for this broadening are not known.

Third, lines 3, 4, 5, and 7 cross the Las Positas Fault Zone. The boundary between high resistivity rocks (inferred to be Tps) and low resistivity rocks (inferred to be Qal_1 and Hpal) strikes approximately parallel to the trend of the Las Positas Fault. The location of that contact can best be determined on lines 5 and 7, since the boundary is obscured by the aqueduct anomaly on lines 3 and 4. On line 5, the boundary is seen to fall within ± 50 ft of pin 6.

On line 7, the boundary is 100 ft deeper than at line 5. This is consistent with a 4- to 5-degree west-southwest apparent dip of the strata, and is seen to fall between pins 14 and 15. This is the same location as the trace of the Las Positas Fault (see Figs. 10 and 21, main text) and is nearly on line with the trace of the fault identified in the outcrop along the southwestern bank of the Arroyo Seco.

In summary, the resistivity data detected a boundary which coincides with the Las Positas Fault as detected in trenches and outcrops. More modeling and measurements would be required to determine the nature of the boundary, i.e., whether it is abrupt or gradual, or whether similar beds appear on opposite sides at different depths.

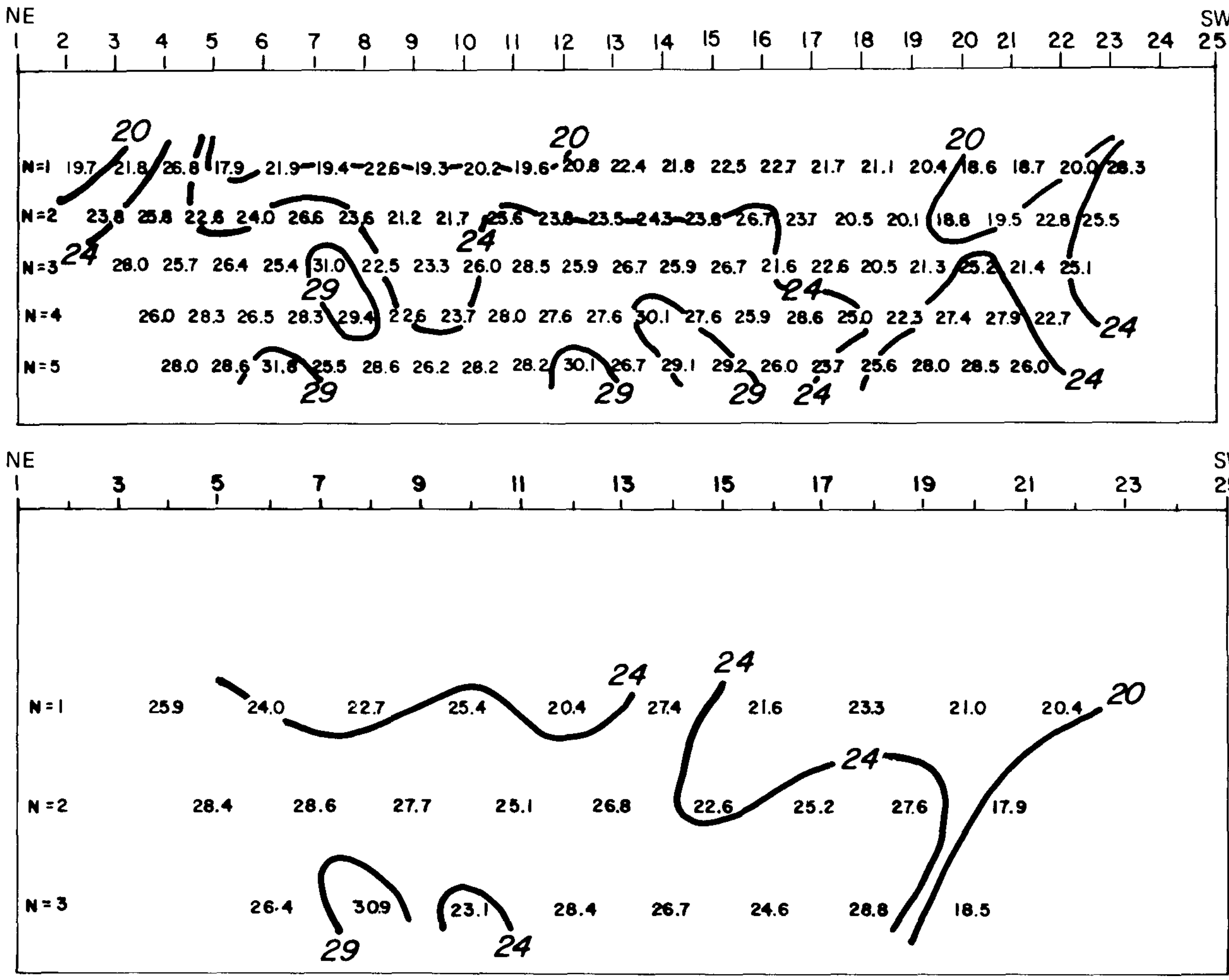
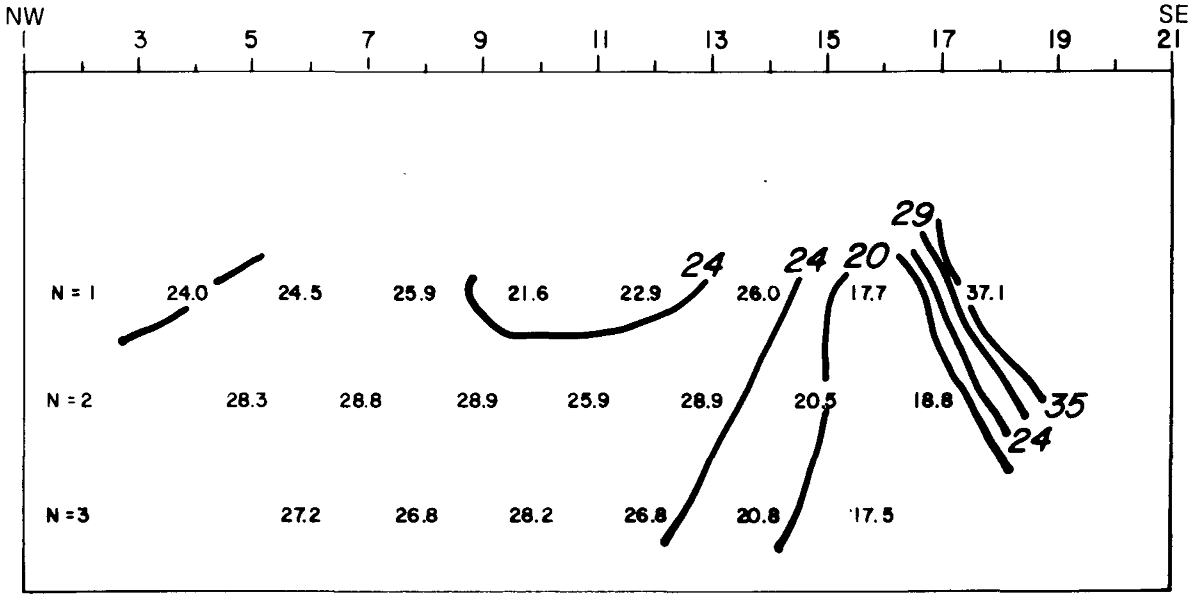


Fig. C-3. **Apparent-resistivity, pseudo depth sections along line 2. Run 1, the upper section, contains data taken with 100-ft dipoles. The lower section represents data taken with 200-ft dipoles. For these and all the following sections, each contour represents approximately a 20% increase in apparent resistivity.**

Small-Scale Seismic Refraction Surveys

Small-scale seismic refraction data were collected in three areas. Surveys on the SNLL property were collected to evaluate the usefulness of these data in the extrapolation of features seen in the trenches and outcrop of the Las Positas Fault. Hammer refraction lines were also run along the western boundary of LLNL and near the Visitor's Center to determine if shallow structures could be detected.

These measurements were reversed seismic refraction lines, and all data were taken on the Geometrics ES-1210F enhancement seismograph with 14 Hz vertical geophones. The source on these small-scale refraction lines was a 10 lb sledge hammer striking an aluminum plate 10 in. square by 1 in. thick. The geophone spacing was 13.5 ft on Survey 1 and 15 ft on the other lines. The ambient signal/noise ratio observed on the field monitor records varied greatly. On some survey lines, all data beyond 50 to 60 ms were dominated by noise (wind and/or other seismic noise). Field monitor records were taken on all survey lines along with 10 bit digital recording. Time picks were obtained from the digital tape using the SAC interactive computer picking capability (Tull, 1983) on the PRIME computer system, and then were verified by examination of multiple trace playbacks.



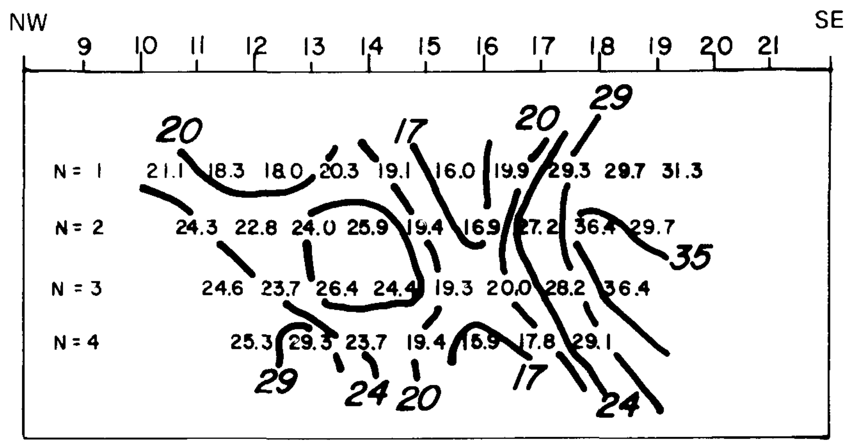


Fig. C-4. Apparent-resistivity, pseudo depth sections along line 3. Run 1, the upper section, represents data taken with 200-ft dipoles. Run 2, the lower section, represents data taken with 100-ft dipoles.

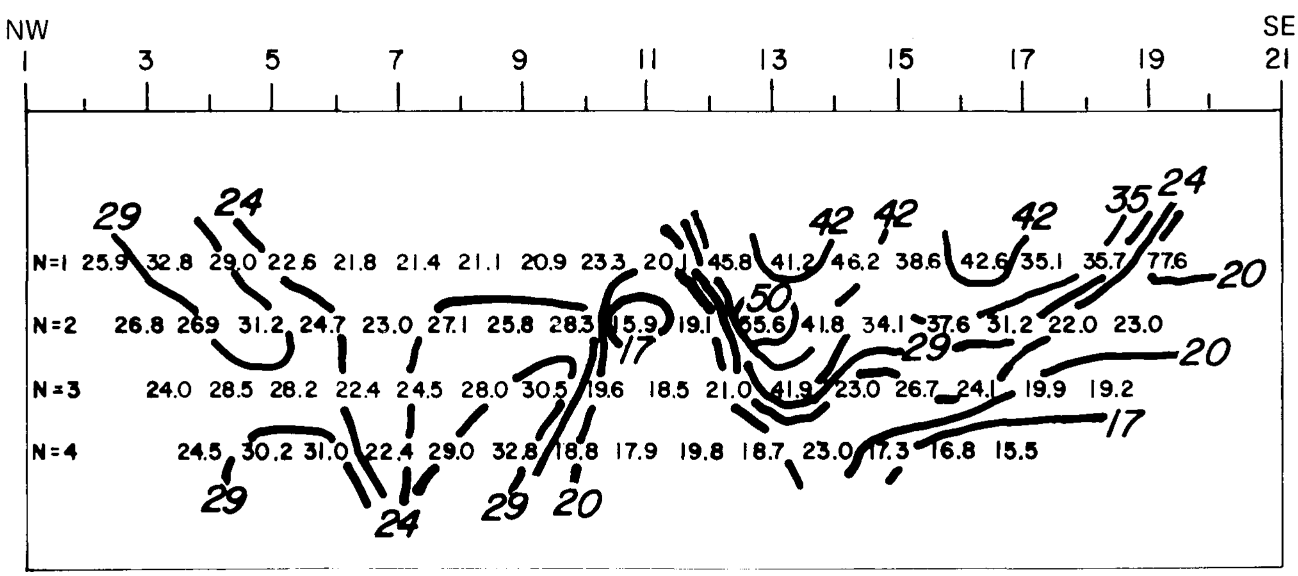


Fig. C-5. Apparent-resistivity, pseudo depth section along line 4, taken with 100-ft dipoles.

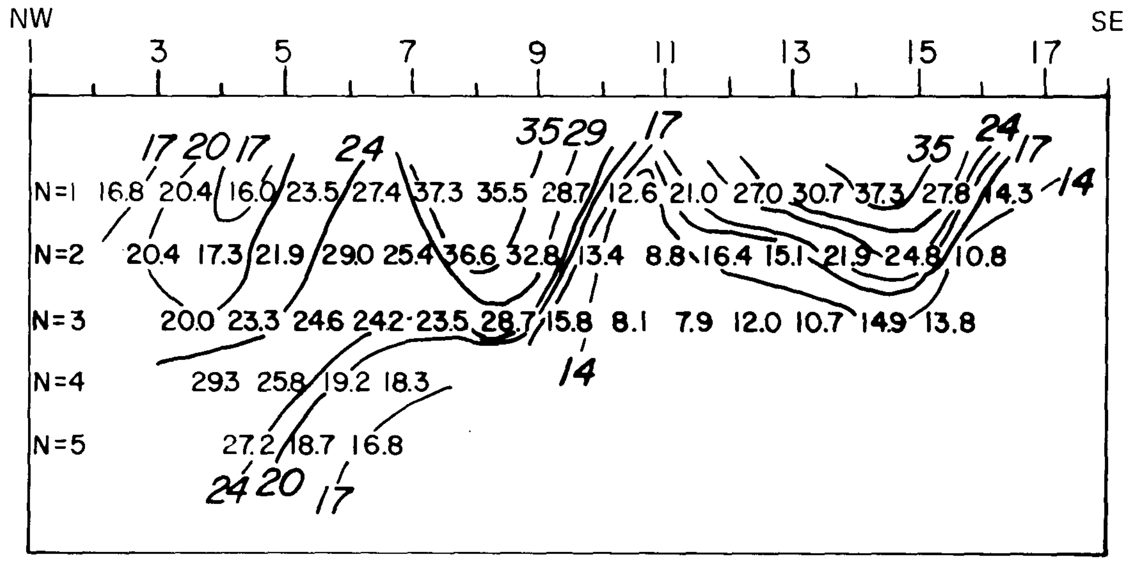


Fig. C-6. Apparent-resistivity, pseudo depth section along line 5, taken with 100-ft dipoles.

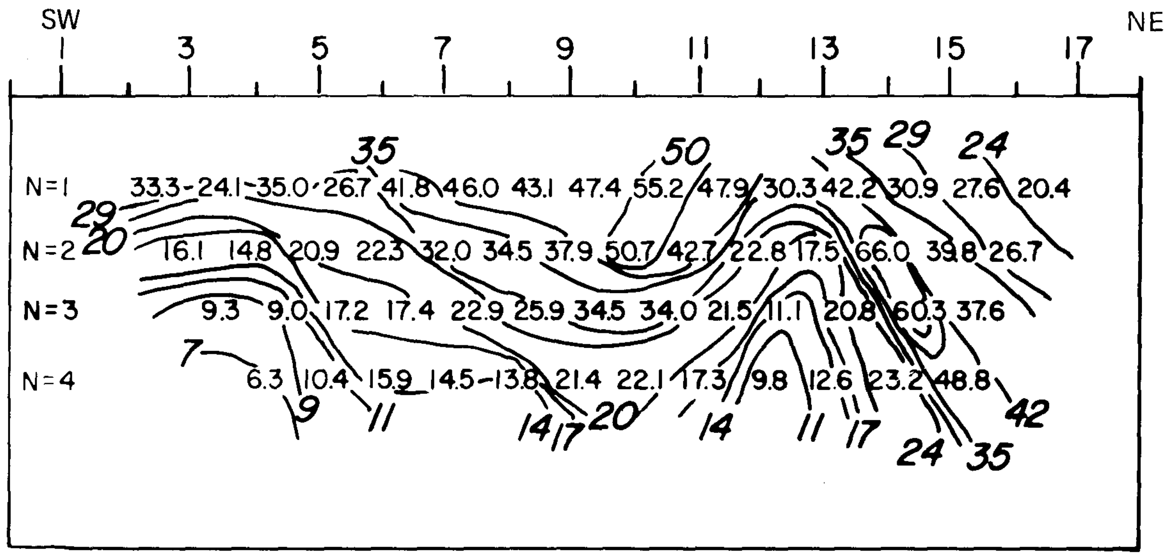


Fig. C-7. Apparent-resistivity, pseudo depth section along line 6, taken with 100-ft dipoles.

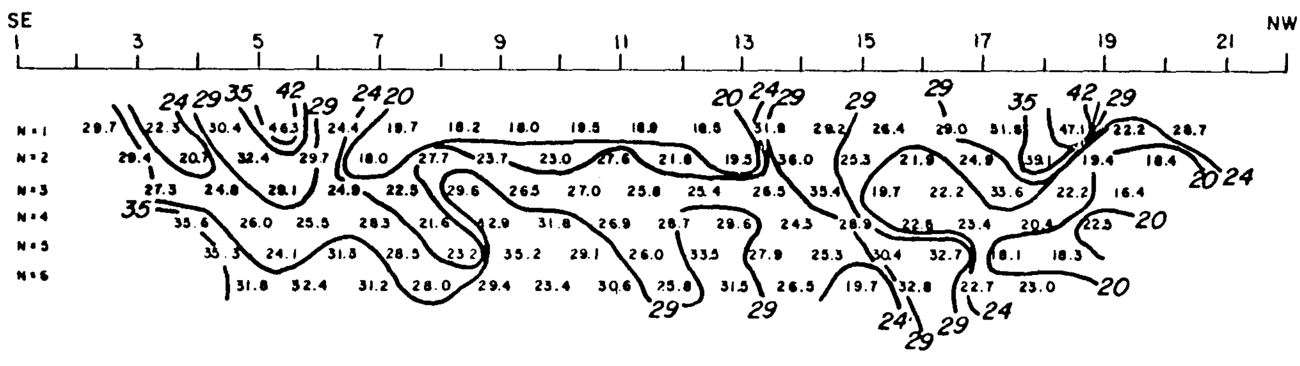


Fig. C-8. Apparent-resistivity, pseudo depth section along line 7, taken with 100-ft dipoles.

The surveys were interpreted following the approach of Moony (1980). Starting with the narrowest source separation (usually 60 to 82.5 ft), the pair of reversed travel-time curves were interpreted to determine a model with dipping layers over a half space. Obvious straight line segments were identified, and reciprocal times were used to constrain lines through ambiguous data sections. This procedure was repeated for greater source separations, if the data quality warranted an interpretation. In summary figures, these velocity boundaries are drawn over the approximate area where the refracted ray is on the refractor. Interpretation of areas where the dipping-layer model was inappropriate (such as at discontinuities) was included on the figures and is discussed below.

Surveys on Sandia Property

We conducted five surveys on Sandia property (labeled S-1, S-2, S-5, S-6-1, and S-6-2 (see Fig. C-9). Interpreted cross sections for these lines are shown in Figs. C-10 and C-11.

Earlier refraction lines (labeled B-1, B-2, B-3, and B-4 on Fig. C-9), taken in this area by two geophysical firms [reported in John A. Blume & Associates (1972)] produced radically different interpretations, leading John A. Blume and Associates (1972) to conclude that there could be detectable fault displacement between the two surveys. They attributed this displacement to a NW-trending strand of the Tesla Fault.

More recent geological observations indicate that the NE trending Las Positas Fault passes between these surveys, and could be the cause of this displacement. These seismic surveys, which explore no deeper than 75 ft, found discontinuities aligned with the Las Positas Fault locations in trenches and exposures (see Fig. C-9). This supports the conclusion that the Las Positas is the dominant fault in the Sandia area. Sloping refractors were detected along several lines, all consistent with a 20° NW dip mapped here. The surveys a few hundred feet apart showed significantly different velocity structures, making line-to-line correlations difficult. While longer lines might show better correlation, our main interest was in finding shallow offsets. Interpretations of the individual lines are discussed below.

A small-scale refraction survey (S-1) was run perpendicular to the trend of the Las Positas Fault, centered on the base of the hill front. Figure C-10a shows the general features detected by this survey. A significant discontinuity was observed at the hillfront, where a 30- to 40-ft-thick layer disappears to the southeast. The data do not constrain the higher velocity layer well, so many velocities and shapes are possible. However, all possible models have a considerable (greater than 30 ft) change in depth of that layer near the hillfront, and all models have much higher velocities at 40-ft depth than reported in Blume lines 3 and 4. The dip of the boundary is not well determined, but it is probably greater than 50° NW.

A second line (S-2) was run behind the stream cut outcrop of the Las Positas Fault, to determine if the fault detected there could be traced by a shallow seismic survey. In this short survey, the geophone spacing was 15 ft. One interpretation of these results is shown in Fig. C-10b. A possibly continuous layer (with velocity of about 2700 ft/s) is overlain by two different materials. To the northwest the velocity is very low, about 1300 ft/s, typical of heavily weathered material, and similar to surface velocities seen in survey S-1. Between stations 4 and 5, the direct velocities increase to 2000 ft/s. The data suggest that a third layer exists, but do not define it. The velocity in this layer is much higher than those detected in Blume lines 3 and 4. Thus the fault observed in the outcrop can be interpreted as causing the discontinuity in the seismic section.

Line S-5 was collected southwest of and nearly parallel to line S-1, in a flat area where the Las Positas Fault trend was not reflected in the topography. The interpreted section is shown in Fig. C-10c. The near-surface layering is irregular, appearing to thicken to the northwest. At a depth of 7 to 20 ft, a refractor appears with a quite high velocity (6600 to 7300 ft/s). This corresponds in location to the refractor identified as the water table in the interpretation of the John A. Blume and Associates (1972) report but has a slightly higher velocity and is consistent with shallow groundwater encountered during excavation of exploratory trench E-3. This refractor is truncated (or possibly becomes too thin) about 100 ft from the NW end of the survey line, on the mapped trend of the Las Positas Fault. A higher velocity secondary arrival is seen on the SE end of the survey, indicating a bed with an apparent dip of 21° to the northwest. If this corresponds to the basement with a very shallow dip on the orthogonal line B-1-2, then the true dip is about 21° NW.

Line S-6-1 crosses trench E-4 which nearly parallels a detected strand of the Las Positas Fault. The interpreted section is in Fig. C-11a. The near-surface velocity is higher and the weathered layer thinner southeast of the trench than northwest indicating that the fault observed in the trench can be observed seismically. The transition is within 10 ft of the trench. A deeper horizon is seen dipping to the NW with

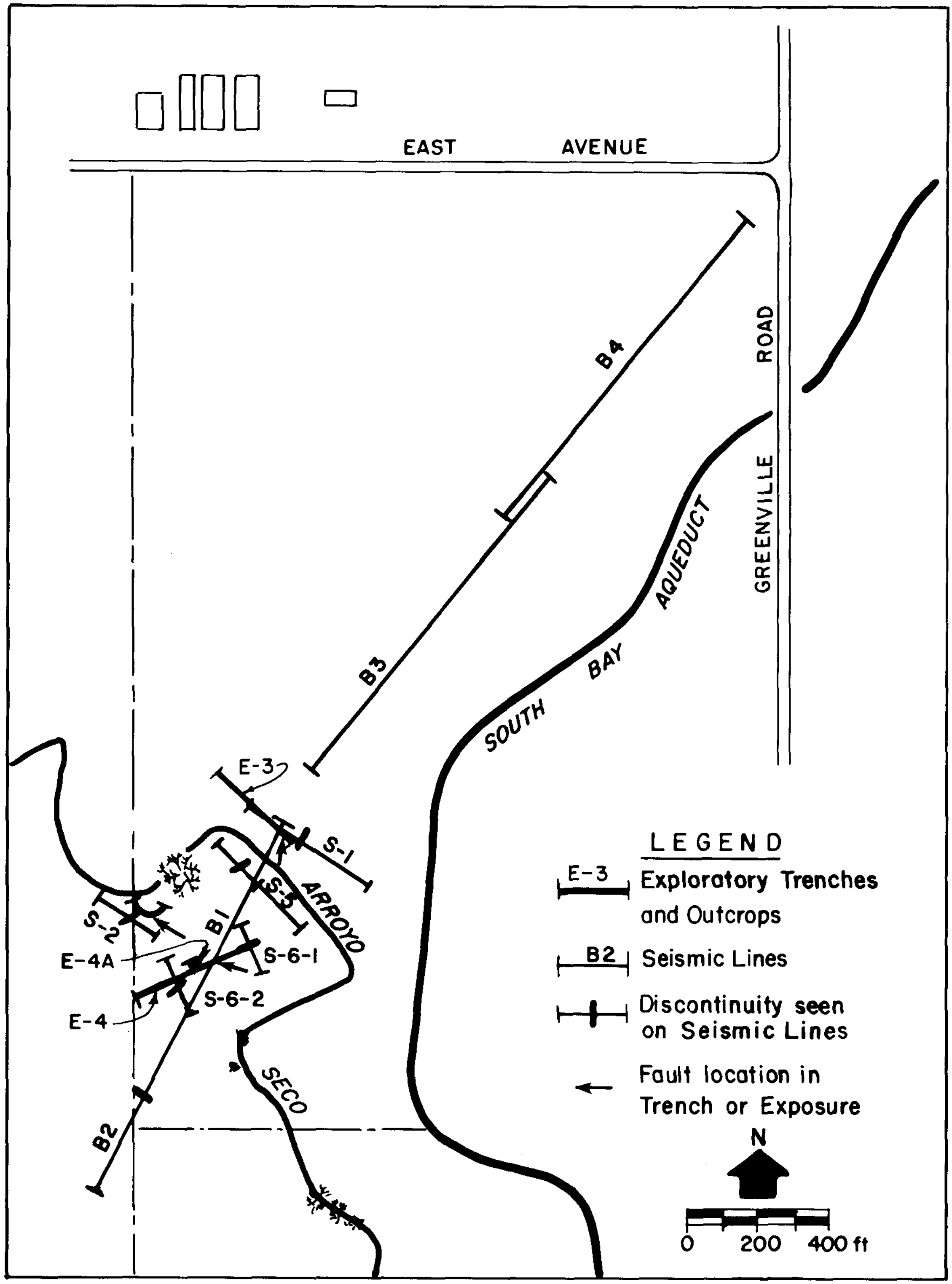


Fig. C-9. Map showing locations and survey lines on the SNLL property. Those labeled "S" are small-scale seismic lines surveyed during this study. Interpretations of lines labeled "B" were presented by Blume and Associates (1972). Interpreted discontinuities along seismic lines are indicated by bars, and fault locations, seen in trenches, are indicated by arrows.

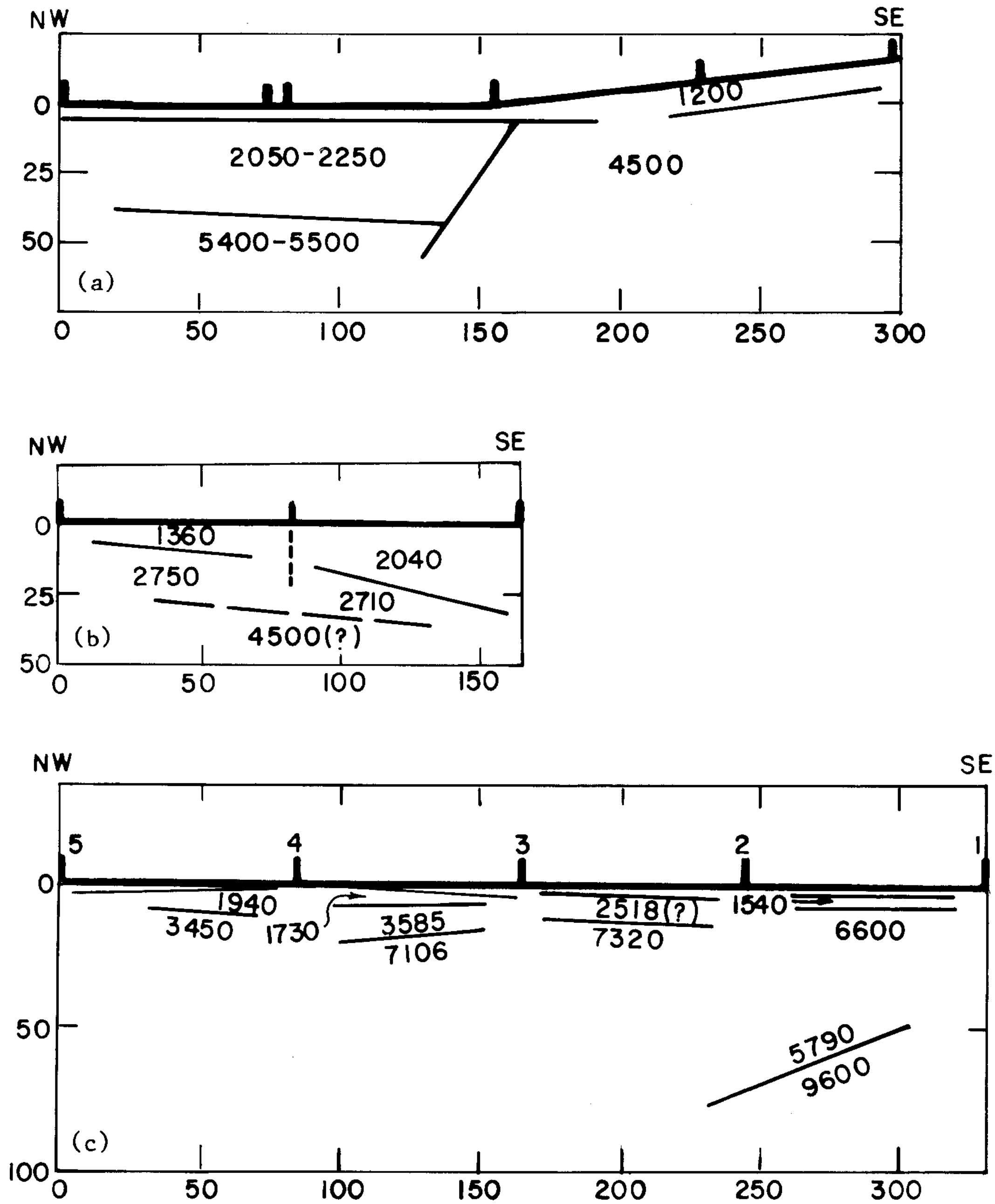


Fig. C-10. Interpreted cross sections for small-scale seismic lines S-1 (a), S-2 (b), and S-5 (c). No vertical exaggeration. See Fig. C-9 for locations. Depths and horizontal locations are shown in feet and layer velocities are given in ft/s. The approximate ground surface is indicated by the heavy line and the source locations by vertical tick marks.

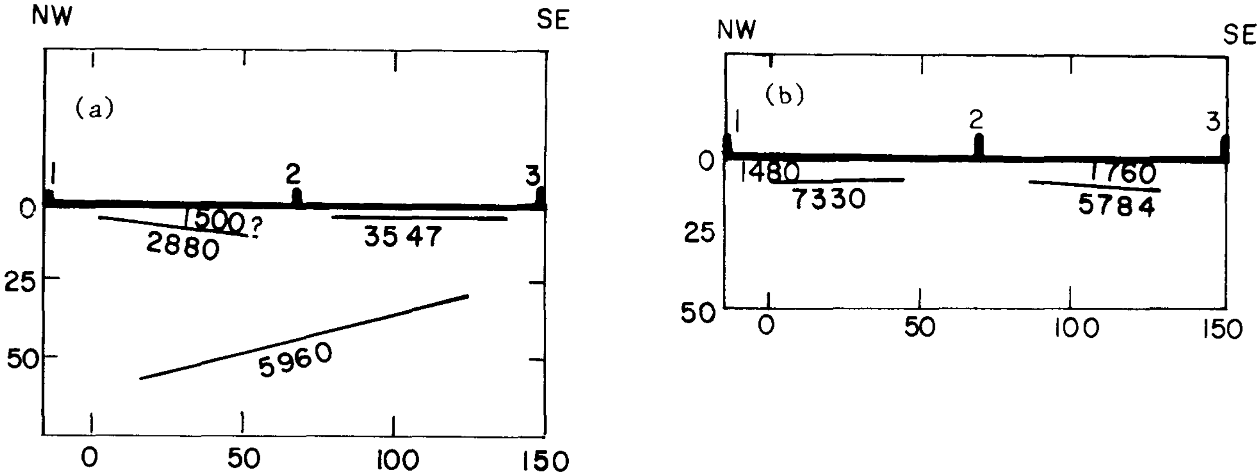


Fig. C-11. Interpreted cross sections for small-scale seismic lines S-6-1 (a) and S-6-2 (b). See Fig. C-9 for locations and description.

apparent dip of 15°. The data do not detect any offset of this horizon, although some curvature in the arrival is produced by the change in overburden velocity. These data are of good quality and indicate that the vertical displacement of this bed is less than 10 to 15 ft (3 to 4 m). Line S-6-2 is parallel to and about 200 ft NE of S-6-1, just off the end of the trench. Much higher velocities were observed, with a similar discontinuity in velocity near the trench, but the higher velocity is north of the trench (Fig. C-11b). This 7000-ft/s velocity layer was also seen on line S-5. If these discontinuities represent a continuous fault, then lines S-6-1 and S-6-2 indicate that the seismic character changes over short distances, even on one side of the detected fault.

Elevation of the Water Table

Seismic determinations of the water-table elevation can be compared to data from wells. In John A. Blume and Associates (1972), the water table is inferred to be the boundary where velocity increases from 2000 to 3000 ft/s to about 5000 ft/s or more. Rogers (1982) describes hydrologic determinations of the water table in this area. Northwest of the Las Positas Fault, the water table is a smooth surface 515 to 525 ft above sea level, with a slight depression near the corner of East Avenue and Greenville Road. Data are sparse south of the Las Positas Fault, with observed levels 610 to 666 ft above sea level. Rogers does not have enough data to determine if the water table is perturbed by either the Arroyo Seco or the canal in this area. Blume's lines 1 and 2 show water-table elevations of 640 to 670 ft. These elevations are consistent with values observed south of the Las Positas Fault by Rogers (1982).

Blume's lines 3 and 4 show an interpreted elevation for water-table velocities of about 430 ft, significantly below elevations observed in 1982 north of the Las Positas Fault. This discrepancy could indicate an increase in water-table elevation with time, or it could indicate that low velocity layers made the seismic depth determination inappropriately large. If the inferred water-table elevations are correct, then Blume's lines 1 and 2 lie to the SE of the water-table barrier associated with the Las Positas Fault. Our short-scale seismic surveys did not detect any consistent refractors which we could conclusively identify as the water table. Discontinuities observed in the seismic refraction surveys are consistent with those seen during resistivity surveys made in the same area (Fig. C-1) and with geologic observations.

Surveys Near the West Gate of LLNL

Survey S-3 was conducted along the western boundary of LLNL north of Mesquite Way. Geophones were located at 15-ft spacing along a 990-ft line and signals were recorded from 13 equally spaced hammer-blow sites (see Fig. C-12). Several factors contribute to produce picking uncertainties as large as 10 to 50 ms at times later than 50 ms:

(1) Noise levels, primarily caused by traffic and construction, were moderately high.

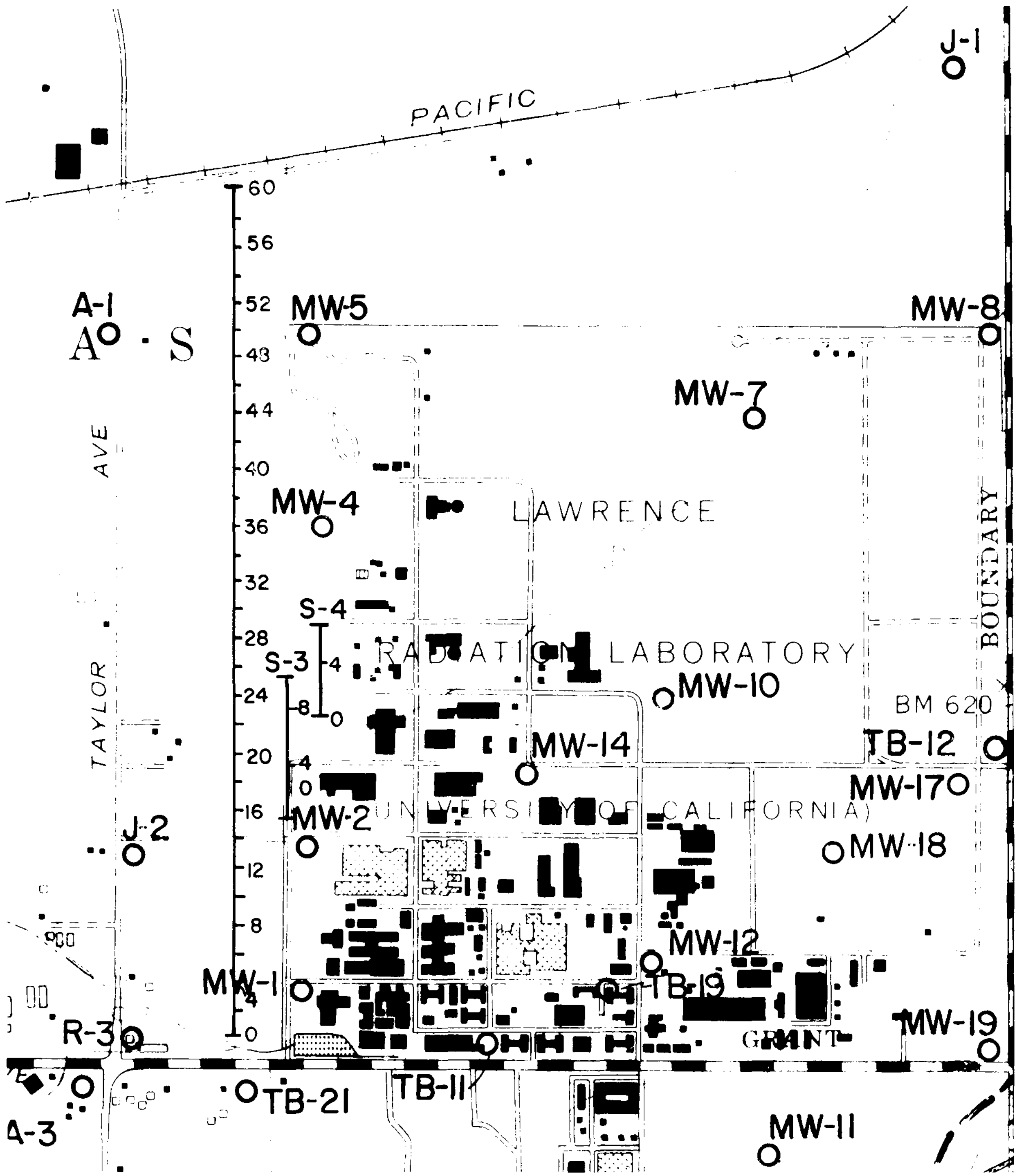


Fig. C-12. Locations of seismic reflection surveys near the west boundary of LLNL. Tick marks indicate the distance (in hundreds of feet) from the south end of the lines. Lines S-3 and S-4 are small-scale seismic lines using a sledge hammer as a source. A Dinoseis was used for the large-scale seismic line.

(2) The velocities detected were relatively low (less than 3000 ft/s) and there was no single strong refracted signal.

(3) In many cases, signals were attenuated rapidly with distance, possibly because propagation took place in thin or discontinuous layers. The resulting low signal level makes it easy to pick different cycles of the arrivals on successive geophones.

The time-vs-distance curves in this survey are very similar, showing near-surface velocities 1100 to 1300 ft/s (not much faster than the velocity in air) and apparent velocities increasing to 2200 to 2800 ft/s 30 to 80 ft from the source. Slightly higher velocities are suggested at greater source-receiver distances, where the signal-to-noise ratio produces large picking uncertainties.

Figure C-13 shows an interpreted seismic cross section based on the procedures suggested by Moony (1980). Reversed profiles from source points separated by 82.5 ft were interpreted by assuming the data for a single layer over a half-space with a dipping boundary. Between stations 3 and 5, a third velocity is seen, so for this 165-ft segment the model was two layers over a half space. The seismic cross section shows a thin low-velocity veneer of variable thickness (5 to 20 ft) lying on a low velocity (2300 to 2800 ft/s) "basement." Where the basement is deepest (stations 3 and 5) an intermediate velocity layer is also seen.

Several observations contribute to the interpretation of this seismic cross section.

1) The near-surface velocity is so slow that it probably represents dry, weathered material. The "basement" material is less weathered.

2) Except near stations 3 and 5, the offsets in depths to the unweathered materials (such as near station 8) are within the interpretation uncertainty and the depth to the unweathered materials is smooth but variable.

3) The intermediate (1700 ft/s) layer probably represents a change of materials type in the near surface. This layer could be present throughout the section, but only be detectable when the "basement" is deep enough. Wherever the intermediate velocity layer is presumed to exist, the "basement" depth could be increased by 20% over that shown in Fig. C-13.

4) If the section consists of interbedded stringers of different velocities (1100 and 1700 ft/s), then velocity inversions near stations 3 and 5 would cause the real "basement" depth to be as shallow as 55% of the depth indicated in Fig. C-13.

The results of survey S-3 say very little about the presence or absence of faulting in the subsurface. The cause of the thickening of the lower velocity layers near stations 3 and 5 is not known, but variations like this are common in alluvial environments. This survey suggests that unless a hard or saturated material is expected in the upper 20 to 30 ft, then hammer seismic studies are of little use in detecting faults in alluvial environments. Water table elevation observations and the Dinoseis seismic data described below are felt to be better methods in an area where the water table and hard rock are deep.

Survey Near Building 151

Survey S-4 was collected along a N-S profile west of Building 151. Geophones were located at a 15-ft spacing along a 660-ft line and signals were recorded from 9 equally spaced hammer-blow sites. (See Fig. C-12.) The signals and interpreted cross section (Fig. C-14) are very similar to those recorded on survey S-3, about 300 ft to the west. The near surface layer varies in thickness from 5 to 12 ft, and the lower layer interpreted velocity varies from 2200 to 3100 ft/s. This cross section looks very uniform, with the possible exception of the apparent velocity increase in the lower layer near stations 7 and 8. Arrivals from a third layer were seen near stations 1 and 2. These arrivals correspond to a velocity of 3700 ft/s at a depth of about 30 ft. This refractor is not seen on the rest of the section, presumably because of the limited signal strength of the hammer blows.

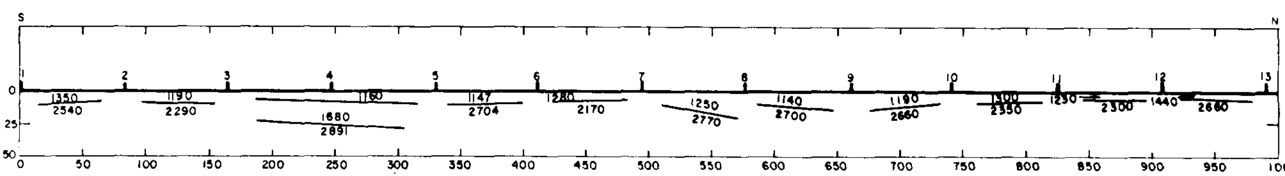


Fig. C-13. Interpreted cross section for the small-scale seismic line S-3 near the west boundary of LLNL. See Fig. C-12 for the location, and refer to the caption of Fig. C-9 for the description.

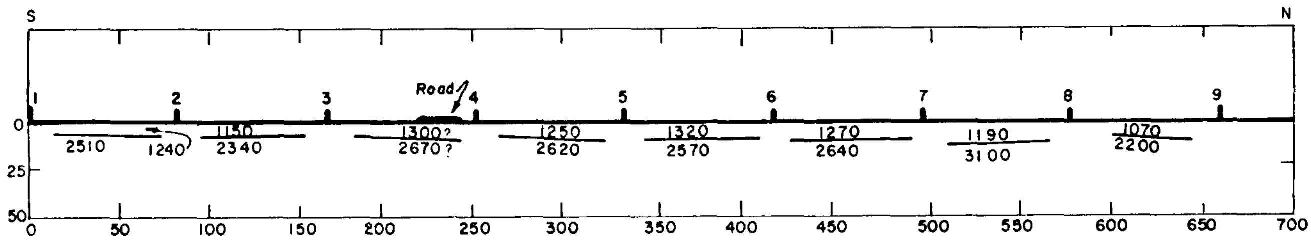


Fig. C-14. Interpreted cross section for the small-scale seismic line S-4 near Bldg. 151. See Fig. C-12 for the location, and refer to the caption of Fig. C-9 for the description.

Survey S-7 Near the Visitor's Center

Compacted sediments correlated with the lower member of the Livermore Formation (Tps) were found at about 25 ft in borehole TB-12 drilled near the Visitor's Center and at 70 ft in well MW 17-A slightly to the southwest (see Figs. 29 and 31, main text). A hammer seismic survey was performed to determine if this zone was detectable and whether it could be traced to greater depths by this method. Four lines were shot with 15-ft geophone spacing (Fig. C-15). Roads, parking lots, and picnic tables imbedded in cement limited the choices of survey line locations.

The interpreted sections are shown in Fig. C-16. All lines show a 3- to 10-ft-thick weathering layer. On line 1, near well TB-12, the weathering layer is directly underlain by 2380-ft/s material. The E-W survey (lines 2 and 4) all detected an intermediate velocity (1600 to 1850 ft/s) zone. There is a possible 1 to 2 ft change in thickness of the weathering layer in line 1 (indicated by the question mark). This could be related to the landscaping in the area of this survey. The lines 2 and 4 are nearly identical in structure. The 2380-ft/s material could be the Livermore Formation. However, none of these lines detected unusually high-velocity zones which would be expected from highly compacted material. Results of a larger scale line run in this vicinity follow.

Larger-Scale Seismic Refraction Surveys

Larger scale seismic surveys were performed with a more powerful seismic source, in order to attempt to penetrate the alluvial deposits more deeply. These surveys were conducted in two locations along the east and west boundaries of the site. The surveys were conducted with a 50-ft geophone spacing, and shot-points were located on approximately 275-ft intervals. All data were collected with a Geometrics ES-1210F signal enhancement seismograph with 14-Hz vertical geophones. The seismic source was a leased, pickup-truck-mounted Dinoseis Gas Gun with a 2- to 3-ft bell. Up to 30 shots were recorded from each shot-point. Each trace was turned off when its signal-to-noise ratio was adequate. Consequently, near phones may have recorded only 2 to 4 shots. The data were processed in the same manner as the small-scale seismic surveys.

The recording system was triggered by the signal from a vertical geophone placed 2 ft from the edge of the gas gun bell. This triggering method produced consistent triggering for repeated shots at each set-up, but caused the recorder to trigger 1 to 5 ms after the shot was fired. This delay was discovered by examination of the records after all the data had been collected. The size of this delay varies from shotpoint to shotpoint and cannot be recovered. Consequently, crossover distances were used to interpret the data.

The geologic sections studied here have several features which make interpretation of seismic refraction data ambiguous. The "overburden" generally consists of unconsolidated dry alluvial deposits (labeled Qal_1 and Hpal in this report). The geologic cross section A-A' in Fig. 29 (main text) is typical. The Qal is a "completely interbedded and interlensed" mixture of coarse (very low velocity?) and fine (slightly higher velocity?) facies. The thickness of any one zone varies considerably and many zones are discontinuous. The refraction signals received from this kind of overburden can be expected to have several properties (see Schmoller, 1983):

Fig. C-15. Locations of seismic refraction surveys near the east boundary of LLNL. Survey lines 1 through 4 are small-scale seismic lines using a sledge hammer as the source. A Dinoseis source was used for the large-scale seismic lines, VC-1 through VC-3.

1) The signals will be weak. Dry, unconsolidated material attenuates seismic energy severely and refracted waves in the thin beds are also rapidly attenuated.

2) The overburden will have masked layers, defined as ones that are not detectable by seismic refraction. Because the deposits vary so much with depth, there can be low velocity layers which produce no headwaves, and other layers whose signals are too late in the record to be seen. Because these layers are undetectable, they cause the overburden to be incorrectly characterized and lead to incorrect estimates of the depth to "basement." For velocities seen here, these estimated depths can be anywhere from a factor of 2 too deep to 20% too shallow. Consequently, some independent depth estimates are required to interpret these data with any certainty.

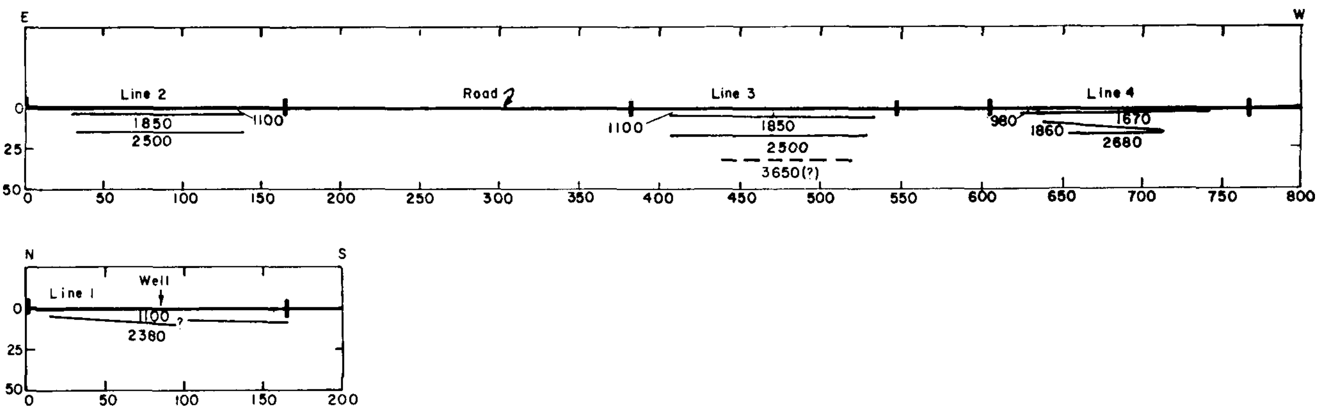


Fig. C-16. Interpreted cross section for the small-scale seismic survey, lines 1 through 4, near the LLNL Visitor's Center. See Fig. C-15 for the location, and refer to the caption of Fig. C-9 for the description.

3) The overburden may not produce a seismic indication of a fault. Since the alluvial depositional environment provides many mechanisms to truncate layers, or make them thinner, and produces highly variable sections, the seismic structure within that section provides little information about the absence or presence of faults.

Saturated alluvium, and older (Tertiary) sediments which are locally lithified (Tps) are found under the overburden by these seismic surveys. These deposits produce velocities 3500 to 7000 ft/s, and features on their upper surface could result from faulting and/or erosional processes. Unfortunately, the undetected nature of the overburden produces considerable depth uncertainty, and undetected lateral changes in the overburden can produce artificial features on the interpreted basement.

Survey West of LLNL (Location Shown in Fig. C-12)

a. *Description of Data.* Most of the shots on this survey line produced similar data. Most travel time curves can be fitted by two straight lines, but a few show indications of a shallower (weathering?) layer. Upper layer velocities are variable, ranging from 2000 to 2900 ft/s. A single refractor with apparent velocity of 5000 to 6000 ft/s is seen on nearly all records. The refracted signal is emergent, with apparent half period of 15 to 25 ms, limiting relative picking accuracy to plus or minus several ms. Two factors limit the detail of possible interpretation:

(1) The signal-to-noise ratio deteriorates beyond 500 to 600 ft so the uncertainty is greater at larger distances.

(2) For geophones within 10 ft of the source, the initial arrival was not recorded, due to the triggering delay discussed above. Because of these factors near-surface velocities cannot be accurately determined, and refracted arrivals from several shots cannot be "phantomed" to produce continuous reversed coverage of the refractor.

This survey provides strong indications that the horizontal and vertical variability of the overburden velocity structure produces considerable interpretation uncertainty. This is to be expected in the inhomogeneous alluvial sequence that underlies LLNL.

Horizontal variability is illustrated by data shot from location 11+00 into an array from 11+00 to 16+50 (Fig. C-17). Most shots produced upper-layer apparent velocities between 2000 and 2400 ft/s, reasonable values for dry, relatively unconsolidated materials. The arrivals at the first 5 stations in the figure have an apparent velocity of about 2900 ft/s. This higher velocity material is either truncated or becomes so thin that the refracted wave is attenuated near location 13+50. A similarly truncated zone is seen between locations 42+50 and 46+00. Smaller variations in upper layer velocities are seen throughout this survey line as was seen on small scale line S-3. The observed high velocity zones could be clay lenses. Vegetation in the vicinity of locations 11+00 to 13+50 stays green longer into the spring than in adjacent areas, suggesting the higher velocity there could be caused by greater water retention.

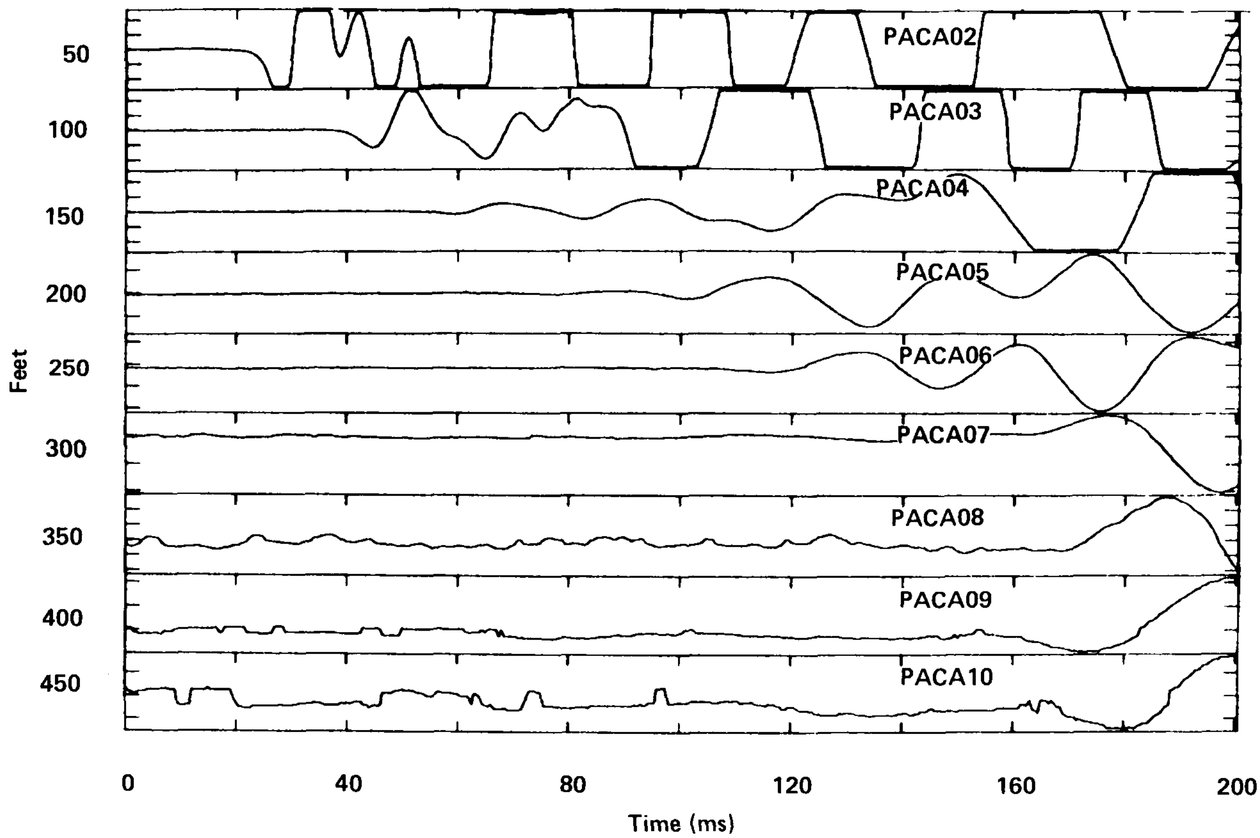


Fig. C-17. Data from the large-scale seismic line near the west boundary of LLNL. See Fig. C-12 for the location. The source was located at station 11+00, and the distance to each geophone (in ft) is shown in the figure. An early arrival disappears at a distance of about 200 to 250 ft.

The 5000 to 6000 ft/s refraction could come from the water table. Hidden low velocity layers cause the depth of this layer to be overestimated by as much as 50%. The shape of the refractor surface is evaluated by examining the distance from the shot at which the refracted arrival crosses the upper-layer arrival. This distance, x_c (called the cross-over distance), is not perturbed by the timing uncertainty discussed above. The cross-over distances are plotted on Fig. C-18. Dobrin (1976) shows that for a horizontal layer with V_0 over a horizontal refractor with velocity V_1, x_c is proportional to the depth, z, of the refractor.

$$z = \frac{1}{2}\left(\frac{V_1 V_0}{V_1 + V_0}\right)^{1/2} x_c \quad .$$

If the upper-layer velocity and refractor velocity could be determined, then Fig. C-18 could be translated into a cross section of depth to the refractor.

The observed values of x_c decrease nearly monotonically from south to north. The trend of the data is well represented by a straight line with a value of 380 at location 0+00 and a value of 170 at 60+00. The formula from Dobrin yields depth

$$z = 0.34\, x_c \quad ,$$

if $V_0 = 2200$ ft/s and $V_1 = 6000$ ft/s. Table C-1 shows the apparent elevation of this straight line fit to the data, based on this two-layer model.

Thus the refractor is more nearly horizontal than the ground surface, and probably is the water table. About three months after the seismic survey Rogers (1982) measured water levels in several wells near

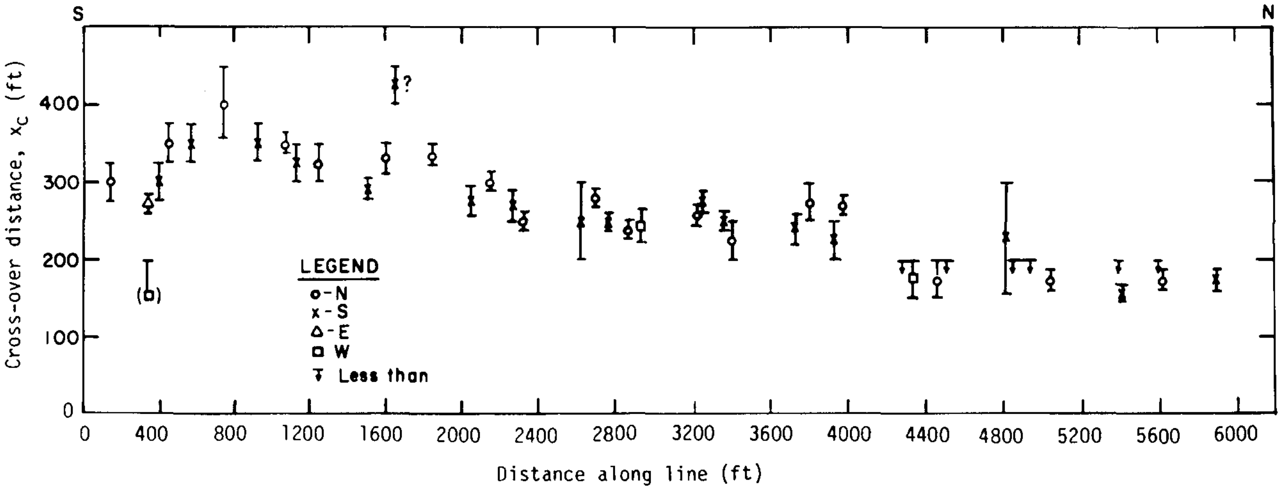


Fig. C-18. Cross-over distances, x_c (ft), determined from large-scale seismic line taken near the west boundary of LLNL. See Fig. C-12 for the location and the text for a definition of x_c. The values for x_c are measured from signals propagating in a variety of directions, as indicated in the legend. If the arrival from the overburden was not detected, then the largest possible cross-over distance is plotted.

LLNL. She concluded that near our survey line the water-table elevation was very flat at an elevation near 525 ft. A small rise in the water table was observed near Arroyo Seco, about 20 ft south of our Station 0+00.

As can be seen from Table C-2, by multiplying by a factor of 0.22, x_c can be converted to a flat surface at the elevation of the water table. This is a reasonable interpretation for this refractor. Unfortunately, the small factor (0.22) cannot be produced from a simple two-layer model, unless the upper layer velocity is assumed to be 2/3 of the refractor velocity. That assumption is inconsistent with the travel time curves. Schmoller's (1982) three-layer interpretation charts show that this depth discrepancy could be caused by a velocity inversion, with the low velocity 1500 ft/s or less.

The geologic sections in this area consist of relatively thin interbedded layers of different materials. If the upper layer does consist of such a section, then the "direct" wave would propagate with the highest velocity in the section, and the vertically traveling waves to and from the refractor would be delayed. This kind of geologic section will produce depth uncertainties similar to those produced by three-layer models. In such a situation, it is impossible to determine the characteristics of the upper layer, and the refractor depth must be determined from additional information.

Using the water-table data, we will then estimate the refractor depth by multiplying x_c by 0.22. Figure C-19 is the resulting section. The refractor lies at nearly constant elevation, but its interpreted depth shows short wavelength fluctuations which exceed the uncertainties based on measurement errors. On Fig. C-19 the amplitude of these fluctuations is indicated by a band of $\pm 12\%$ uncertainty (in depth) about the known water-table depth. These fluctuations could represent actual curvature of the water-table surface, or they could be caused by lateral changes in the velocity structures above and within the refractor. Table C-3 indicates a three-layer model that produces the correct water-table depth, and the parameter changes

Table C-1. Apparent elevation of straight-line fit to the date.

	Location	
	0 ± 00	60 ± 00
Straight line fit to x_c	380	170
Depth = 0.34 x_c	130	58
Surface elevation	610	562
Refractor elevation	490	505

Table C-2. Conversion of data in Table C-1 to match water-table surface.

	Location	
	0+00	60+00
Straight line fit to x_c	380	170
Surface elevation	610	562
d = elevation − 525 ft	85	37
d/x_c	0.223	0.217

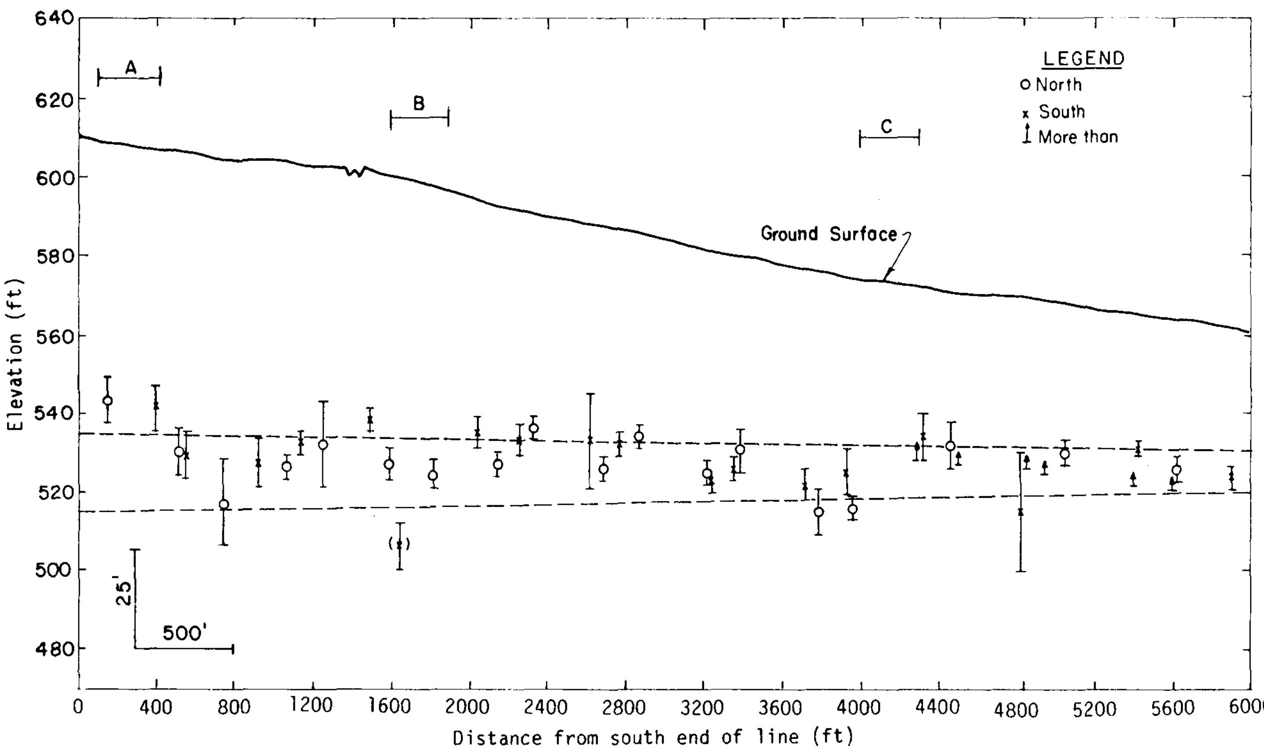


Fig. C-19. Interpreted cross section from the large-scale seismic line taken near the west boundary of LLNL. Water-table measurements were used to determine the "true" depth from the cross-over distances. Vertical exaggeration is 20:1. The dashed lines represent the interpreted water-table depth ±12%. Features of interest are labeled A, B, and C.

required to change the depth by 12%. The table shows that lateral variations in the fraction of high-velocity material in the unsaturated zone would cause large uncertainties in the refractor depth, and can easily account for the observed variability. Such variations are expected in alluvial deposits which consist of interbedded lenses of various materials. As discussed above, the seismic data showed evidence for lateral variations in the upper layer.

Three features of the interpreted refractor surface have been marked on Figs. C-19 and C-20. "A" indicates a mound (10 to 20 ft high) near Arroyo Seco. This feature could be an artifact caused by higher, upper-layer velocities near the Arroyo, or it could be a real increase in water-table elevation due to recharge. "B" indicates a local zone where the water table appears deeper. The point at 16+50 is plotted with parentheses because it comes from a shot which produced an unusual intermediate velocity arrival. Because of the complexity of this travel-time curve, the crossing distance method does not produce an appropriate depth here. The velocity structure in this anomalous area cannot be determined from the

Table C-3. Three-layer model producing the correct water-table depth, and parameter changes required to change the depth by 12%.

Parameter	Interpreted depth	Value for: 12% shallower	Value for: 12% deeper
Ratio of upper layer high and low velocities V_1/V_2	0.50 (V_2 = 1100)	0.40 (V_2 = 880)	0.58 (V_2 + 1276)
Fraction of high velocity material in upper layer D_1/D_2	0.50	0.44	0.55
Refractor velocity	6000	4611	8408
Upper layer high velocity	2200	2870	1570

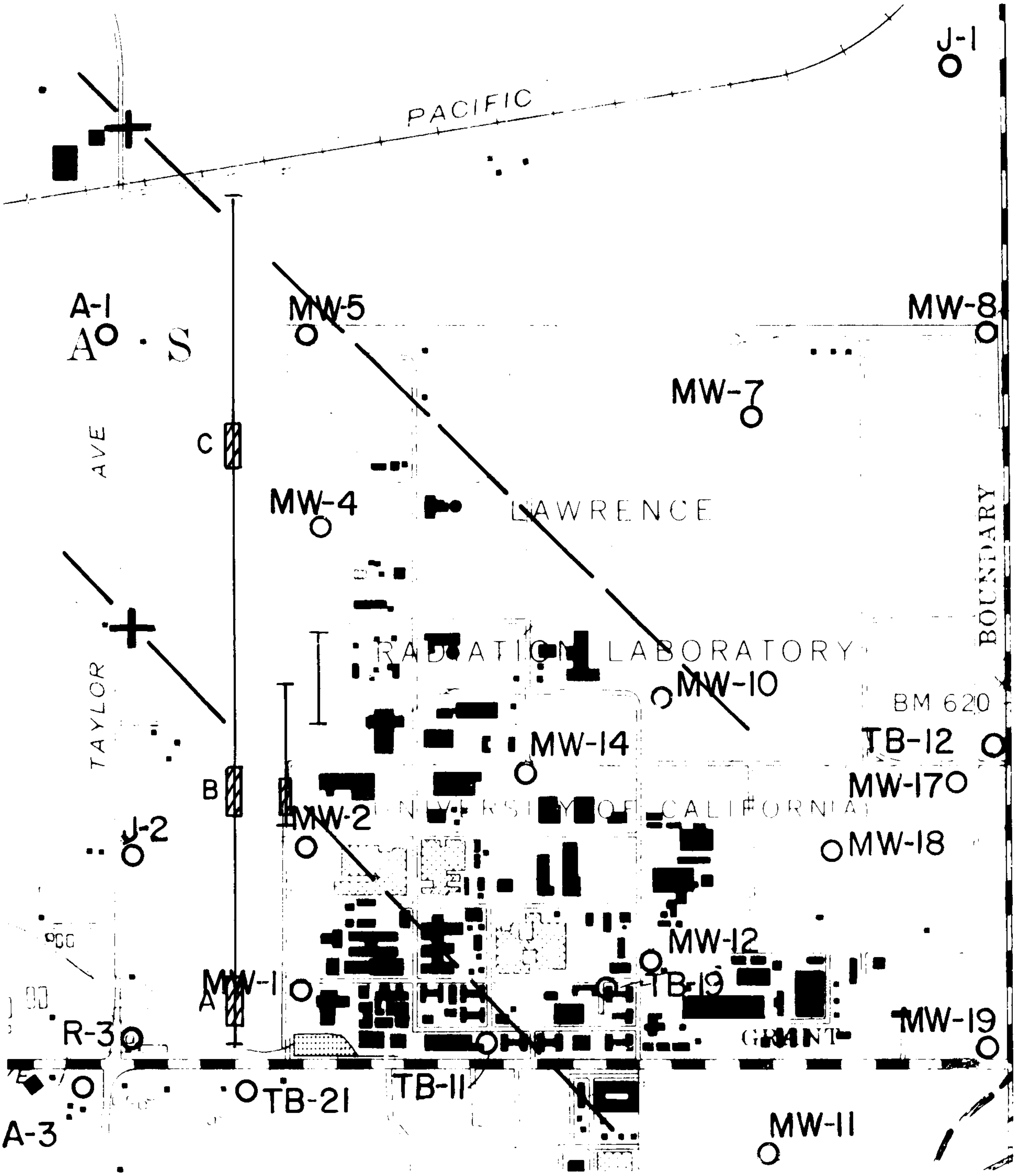


Fig. C-20. Locations of features detected near the west boundary of LLNL. Shaded areas indicate features described in the text. "+" indicates earlier reported features and inferred fault traces from a CDWR (1966) study.

present data. The apparent deepening could be caused by unusually slow near-surface material, or could represent a depression of the water table. "C" indicates a region where the apparent refractor depth appears offset by about 10 ft. This feature could be an artifact caused by the observed lateral velocity variations in the area or it could represent an actual feature of the water-table surface. The feature could be related to the nearly flat topographic zone between stations 46 and 50, which might indicate a change in near-surface materials. Several wells intersect the water table in this area, and the observed water table is horizontal to within ±1 foot (Rogers 1982). These observations suggest that the observed 10-ft offset is indeed an artifact of changes in near-surface velocities.

b. *Conclusions Based on Survey West of the Lab.* The interpreted section shows at least 100 ft of poorly consolidated, laterally and vertically inhomogeneous sediments. The only observable velocity contrast occurs at the water table. Two aspects of this section can be studied with seismic refraction surveys: the velocity variations above the water table and the shape of the water table itself. Better knowledge of the first aspect provides little geologic insight, because considerable inhomogeneity is expected in an alluvial environment. The possibility of velocity inversions and lateral variability in the unsaturated zone makes quantitative estimation of the water-table depth from seismic data difficult, and depth estimates must be tied to independent observations. The seismic data here show that the water table is generally horizontal but could have fluctuations as large as 10 to 20 ft in amplitude. Since well observations constrain the surface to ±1 ft, these fluctuations are either artifacts of our seismic interpretation, or extend over very short distances away from the survey line. Locations of these fluctuations have been identified.

Earlier seismic studies for CDWR, reported by John A. Blume & Associates (1971), concluded that "seismically detected faults" were seen at two locations shown in Fig. C-20. The nature of these anomalies is not known. The CDWR and the original seismic contractor were contacted and they do not have either the data or time-distance plots for these refraction surveys. Figure C-20 also shows the fault trends inferred from these seismic surveys, as summarized by John A. Blume & Associates (1971). The zone of thick intermediate velocity on small-scale line S-3 falls along one of these trends. However, no indication of faulting was seen on the large-scale seismic line along the trends indicated.

Surveys Near the LLNL Visitor's Center

Three survey lines were run south of the LLNL Visitor's Center using the pickup-truck-mounted Dinoseis source. The locations of these surveys are shown in Fig. C-15. The method employed was the same as described for the larger scale survey run west of LLNL. The triggering uncertainty for these surveys appears to be up to 10 ms.

These three surveys (like small-scale survey S-5) were run for the purpose of determining the shape of geologic boundaries detected in wells TB-12, MW-17, and MW-19. The discussion below indicates that the geologic boundaries do not produce corresponding seismic arrivals, and that the water-table geometry can be interpolated between these observations. Cultural features limited the locations available for these surveys. The near-surface layering seen in survey S-5 is very similar to the layering detected here.

Survey VC-1 was run along the western edge of Greenville Road (Fig. 15). Geophones were placed at 50-ft intervals along a 1650-ft line. Nine shot points were located at 275-ft intervals. Strong signals were recorded out to source-receiver distances up to 825 ft. The travel time curves can generally be fit with two or three straight line segments. The apparent velocity changes only by 30 to 40% between adjacent line segments indicating that there are not significant differences in velocities between successive layers.

The timing uncertainty and gradual increase in velocity leads to ambiguity in the choice of line segments to fit the data. One interpretation, based on one set of line segments, is shown in Fig. C-21A. Five distinct zones are seen, with velocities of approximately 2000, 2600, 3200 to 3600, 4000, and 5000 ft/s. Solutions for adjacent reversed shots are in close agreement, indicating that the thicknesses of the zones vary continuously through the cross section. Three locations are marked where the travel time curves indicate a possible zone of offset.

Location 1. The arrival from the 2600-ft/s layer appears to be offset by 3 to 4 ms here. This could correspond to a layer offset of less than 4 ft (up to the north) or a change in the near surface layers which are not sampled by this survey. No offset was detected in the deeper layers at this location suggesting that the anomaly is not fault-related.

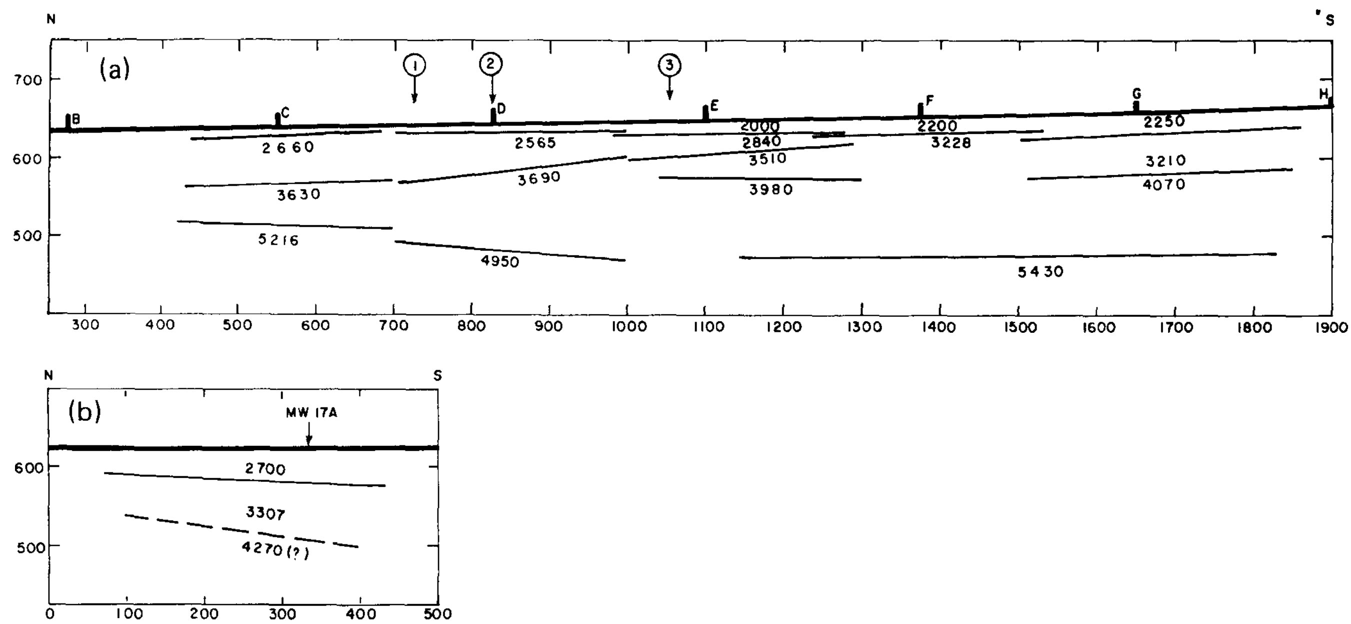


Fig. C-21. Interpreted cross section for the large-scale seismic surveys VC-1 (a) and VC-3 (b) near the the LLNL Visitor's Center. Elevations (in ft) are indicated along the left-hand edge of the cross sections. See Fig. C-15 for the location and refer to the caption of Fig. C-9 for the description.

Location 2. The arrivals from the 3200-to-3600-ft/s layer appear to be offset by about 7 ms here. This offset occurs at the boundary between two geophone line setups and is probably caused by the timing errors discussed above.

Location 3. The 3980-ft/s arrival disappears to the north of this location. This may be due to the lenticular nature of these alluvial sediments.

The 5000-ft/s layer probably represents the water table. Water was detected at about 525 ft elevation at well TB-12 (near shot point A) and at 513 ft in MW-19, about 300 ft south of shot point H. The seismic data show a slightly greater apparent elevation change on the water table (about 40 ft) and indicate that most of it takes place between shot points C and E.

The other arrivals do not correlate with geologic boundaries determined in the wells. For example, sediments corresponding to the lower member of the Livermore Formation are very shallow on the north end of the line (elev. 605 ft) and deeper to the south (elev. 555 ft). None of the seismic layers coincide with the lower member of the Livermore Formation. The 3000-ft/s layer does rise as the hills to the south are approached.

Survey VC-2 was run E-W about 175 ft south of MW-17. Geophones were placed at 50-ft intervals along a 1100-ft line and 6 shot points were occupied at 275-ft intervals. The resulting interpretation is shown in Fig. C-22. Each boundary shown was determined from reversed shots by the method described above, with the exception of the dipping 5364-ft/s segment on the east end of the line. At the location marked number 4, the slope of the arrival changes abruptly. Since we did not shoot off the east end of the line, we had only one directional coverage of this zone. The slope change is assumed to indicate a change in dip of the refractor. The dip in the interpreted section was determined by fixing the velocity to match that between II and III. Three layers are detected, with velocities about 2400, 3300 and 5500 ft/s. The middle layer becomes hidden in the middle of the section, but probably continues through, as indicated by the dashed lines. This hidden layer contributes about a 10% uncertainty to the depth below it.

Seismic line VC-2 ties into VC-1 near point C. The 2400-ft/s layer dips slightly to the west, and the water table appears to rise about 20 ft in the center of this survey, and then fall again to the west.

Survey VC-3 runs north from line VC-2 past well MW-17. Landscaping and roads limited the length of this line to 500 ft, and only three shots produced useable data. As seen in Fig. C-21B, the first two layers

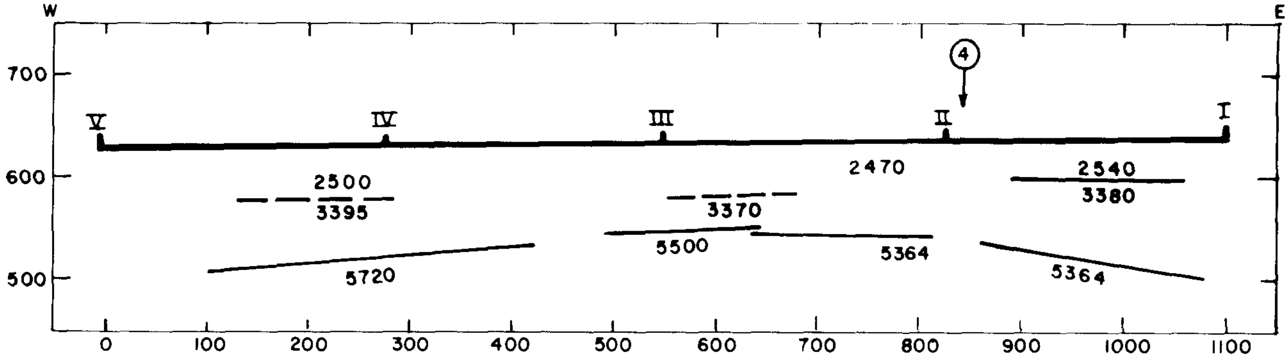


Fig. C-22. Interpreted cross section for the large-scale seismic survey VC-3 near the LLNL Visitor's Center. Elevations (in ft) are indicated along the left-hand edge of the cross section. See Fig. C-15 for the location and refer to the caption of Fig. C-9 for the description.

were detected, but the source-receiver distance was not adequate to receive arrivals from the water table. The dashed line indicates an interpretation based on data from the two most distant geophones. The uncertainty in velocity for these points is high enough that they could be the first arrivals from the water table.

Seismic Reflection Data

Gasch and Associates, Inc., ran two small-scale, high-resolution seismic reflection profiles on the LLNL site (Fig. C-15). They were not given information about previous seismic refraction data taken on the site, and were not asked to interpret their results. These data were collected for the purposes of:

1. Providing a means of evaluating the quality of data collected by a contractor.
2. Determining whether reflectors at moderate depths (200 to 500 ft) could be detected by the seismic reflection technique.

Descriptions of data collection and processing, as well as common-depth-point stacked sections, are contained in their report (Gasch and Associates, Inc., Project #GA79042, 1979).

From our examination of these results and unprocessed data we conclude that:

1. Critically refracted energy corresponding to a layer 75 to 150 ft deep with an apparent seismic velocity of about 6000 ft/s is seen on the unstacked records. This energy, probably from the water table, contaminates the stacked sections, which are constructed assuming all energy is from reflections.
2. Strong, easily identifiable reflections are not seen in the raw data, nor do they appear in the processed data. The processed sections do show some short scale coherence, but cannot be interpreted. The lack of strong continuous reflections may be caused by discontinuous layering, by inadequate recording, or by inappropriate processing because of lack of knowledge about the velocity structure.

We did not choose to perform additional reflection surveys to study moderate depth reflectors. We felt that (1) the water-table elevations were adequately understood, (2) the possibility of surface rupture was adequately addressed by the geologic studies, and (3) regional geological studies provided adequate evidence so that the understanding of the ground shaking hazard would not be improved by information from such a survey. Deep reflection data collected by oil companies on nearby parcels is discussed in Appendix B. These data were used to evaluate the hazard from ground shaking.

Magnetic Data

Total field surveys have been made on the LLNL site and east of SNLL (see Figs. 20 and 21 main text). Measurements made in these surveys and the measurements published in the John A. Blume and Associates (1972) and URS/Blume and Associates (1978) reports reflect effects of man-made features such as pipes and fences. These cultural effects mask any possible fault indications from these data.

Self-Potential Data

Self-potential measurements were made near the resistivity survey of the Las Positas Fault. The purpose was to see if possible strands of that fault could be located by self-potential methods. The data were highly variable, and showed no linear features. It was concluded that this approach is not useful at this site.

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Appendix D
Uranium-Series Dating of Pedogenic Carbonates from the LLNL Site and Nearby Areas

K. Knauss

Contents

As a part of the comprehensive geologic studies of the LLNL site, many trenches, boreholes, outcrops, and building excavations have been mapped and sampled. Within these exposures a variety of pedogenic carbonates were encountered, including finely disseminated caliche from near-surface sandy layers, caliche-filled desiccation cracks (in some cases up to 1/2 in. thick) at the base of argillic (clay-enriched) B-soil horizons within buried paleosols, root casts, massive nodular caliche, and caliche cements from clayey gouge zones along faults. Age dates for these materials may:

(1) provide a time stratigraphy for the alluvial units mapped,
(2) provide some limits (minimum age) for last fault movement, and
(3) establish the degree of tectonic stability.

Recently, several variations of the same uranium-series disequilibrium technique have been used to provide absolute dates for terrestrial carbonates (Ku *et al.*, 1979; Szabo *et al.*, 1981; Knauss, 1981). The results presented here are an attempt to extend the uranium-series method to the dating of semiarid-region pedogenic carbonates from the Livermore Valley. A total of 15 carbonate samples have been dated. The results for nine trench and outcrop samples have been previously reported (Knauss, 1981) and a detailed description of the method is provided in the work cited. An additional six borehole caliche samples are reported here. Table D-1 includes a brief description of each sample. The interpretation of the results is included in the main text.

Age Calculations

The procedure includes a weak acid leaching of the carbonate followed by isotopic analyses of both the leachate and residue. The analytical results are presented in Table D-2. The errors quoted are standard deviation (1σ) derived from counting statistics. Most of these analyses result in an uncertainty in the $^{230}Th/^{234}U$ activity ratio of $\pm 5\%$ or less. Hence, for a value of this ratio of 0.95 ± 0.05, and with a uranium isotopic activity ratio ($^{234}U/^{238}U$) of 1.10, the age is 281×10^3 yr, but can range from infinite age to 230×10^3 yr within 1σ. Counting samples for a very long time to improve counting statistics is not justified, because the reproducibility as estimated from coeval trench samples is on the order of $\pm 10\%$. The net result with respect to the core caliche samples is that dates greater than or equal to about 250×10^3 yr can not be adequately distinguished from infinitely old material.

As a first approximation, the leach analytical data can be used to represent data for the carbonate phase. Ages of the samples as calculated from the leach data are listed in Table D-3 as "uncorrected." These ages should be amenable to refinement, as shown below.

Most terrestrial carbonates are actually a mixture of detrital silicates and authigenic carbonates. The soluble weight fraction listed in Table D-2 gives an indication of the relative amount of authigenic carbonate. To deal with possible problems caused by the presence of detrital material, two schemes have been derived. One is numerical (Ku *et al.*, 1979) and one is graphic (Szabo *et al.*, 1981). Ages calculated from corrected analytical data, i.e., the estimated isotopic composition of the authigenic carbonate phase, are listed in Table D-3 as either "numerical" or "isochron plot."

Table D-1. Sample descriptions.

Identification[a]	Type
(Dated samples)	
	Carbonates from trenches and outcrops
E-1 C1a	Caliche filling vertical shrinkage fractures up to 8 in. long and 1/2 in. thick. Taken from argillic B horizon in soil profile (unit 9) approximately 11 ft below present surface at station 1+67.
E-1 C2a	Caliche taken in position stratigraphically equivalent to E-1 C1a at station 1+72.
Greenville Rd. (No. 1)	Gray-white mudstone (unit 9) containing abundant disseminated caliche. Unit associated with Las Positas Fault Zone and present only south of the zone.
Greenville Rd. (No. 2)	Sample taken on revisit to Greenville Rd. cut, equivalent to Greenville Rd. No. 1.
E-5 (No. 1)	Caliche filling vertical shrinkage fractures in clayey members of unit 5 approximately 10 ft below present surface at station 234.
E-6 (No. 3)	Caliche filling vertical fractures in silty clay (unit 5) approximately 10 ft below present surface at station 1+40 on west wall of trench.
	Carbonates from boreholes
B-1 20	Relatively thick (0.1-in.) caliche veinlets filling vertical fractures in a silty sand. The sand was light-brown and the sample was damp. Depth is 20 ft.
B-1 30	Identical to sample above. Depth is 30 ft.
B-1 141	Silty clay containing hard, white, nodular caliche. The clay was brown. Depth is 141 ft.
MW-7 33	Large (1-in.) caliche nodules taken from a damp clay. The clay was brown in color. Depth is 33 ft.
TB-15 51[b]	Caliche veinlets filling fractures in a sandy silt. The silt was light brown in color and damp. Depth is 51 ft.
TB-15 121[b]	Caliche nodules contained in a damp clay. The clay was gray-brown in color. Depth is 121 ft.
	Wood
E-3	Wood fragment in unit 46 north of Las Positas Fault Zone approximately 11-1/2 ft below present surface at station 2+32.
(Undated samples)	
	Carbonates from trenches and outcrops
E-2 (No. 2)	Caliche filling vertical fractures in silty clay (unit 3a) approximately 5-1/2 ft below present surface at station 2+15.
E-6 (No. 1)	Composite sample taken from caliche filling vertical fractures in silty clay (unit 2) approximately 5 ft below present surface between stations 0−5 and 0−15.
Nova (No. 2)	Traces of caliche filling narrow fractures coated with reddish-brown clay in large lens of sandy silt (unit 3) approximately 8 ft below the present surface at station 1+56.

[a] For locations of sampling points, see Figs. 20 and 21 in main text.
[b] Hole renumbered MW-19.

Table D-2. Results of radiochemical analyses of leach and residue fractions.

Sample		Activity (dpm/g)				Concentration (ppm)		Activity ratio			Wt fraction soluble in
		^{232}Th	^{238}U	^{234}U	^{230}Th	U	Th	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	0.2 *N* HCl/HNO_3
E-1 Cla	Leach	0.24 ±0.01	1.34 ±0.03	1.49 ±0.03	0.88 ±0.02	1.80 ±0.04	0.97 ±0.05	1.11 ±0.03	3.72 ±0.19	0.59 ±0.02	0.71
	Residue	1.05 ±0.04	1.34 ±0.03	1.21 ±0.03	1.81 ±0.06	1.80 ±0.04	4.35 ±0.17	0.90 ±0.03	1.72 ±0.08	1.50 ±0.06	
E-1 C2a	Leach	0.17 ±0.01	1.75 ±0.05	1.96 ±0.05	1.39 ±0.02	2.34 ±0.06	0.70 ±0.02	1.12 ±0.03	8.21 ±0.30	0.71 ±0.02	0.66
	Residue	0.64 ±0.02	1.60 ±0.03	1.64 ±0.04	1.98 ±0.05	2.14 ±0.05	2.64 ±0.10	1.02 ±0.03	3.10 ±0.12	1.21 ±0.04	
Greenville Rd. No. 1	Leach	0.12 ±0.01	0.67 ±0.03	0.90 ±0.03	0.44 ±0.01	0.90 ±0.04	0.51 ±0.02	1.34 ±0.06	3.57 ±0.18	0.49 ±0.02	0.67
	Residue	1.30 ±0.05	1.37 ±0.04	1.16 ±0.03	1.53 ±0.05	1.84 ±0.05	5.34 ±0.18	0.85 ±0.03	1.18 ±0.05	1.31 ±0.06	
Greenville Rd. No. 2	Leach	0.12 ±0.01	0.77 ±0.03	0.95 ±0.03	0.41 ±0.01	1.03 ±0.03	0.48 ±0.03	1.24 ±0.05	3.51 ±0.24	0.43 ±0.02	0.76
	Residue	1.39 ±0.03	1.33 ±0.04	1.21 ±0.03	1.65 ±0.04	1.79 ±0.05	5.74 ±0.14	0.91 ±0.03	1.19 ±0.04	1.37 ±0.05	
E-2 No. 2	Leach	0.22 ±0.01	1.24 ±0.06	1.36 ±0.06	0.27 ±0.01	1.65 ±0.07	0.92 ±0.05	1.10 ±0.06	1.21 ±0.08	0.20 ±0.01	0.54
	Residue	1.40 ±0.05	1.28 ±0.04	1.19 ±0.04	1.59 ±0.06	1.71 ±0.05	5.76 ±0.22	0.93 ±0.04	1.14 ±0.05	1.33 ±0.07	
E-5 No. 1	Leach	0.17 ±0.01	2.02 ±0.05	2.33 ±0.05	0.53 ±0.02	2.70 ±0.06	0.70 ±0.04	1.16 ±0.03	3.09 ±0.19	0.23 ±0.01	0.60
	Residue	1.21 ±0.04	1.41 ±0.05	1.39 ±0.05	1.82 ±0.05	1.88 ±0.06	4.99 ±0.15	1.00 ±0.04	1.50 ±0.05	1.31 ±0.06	
E-6 No. 1	Leach	0.20 ±0.01	1.26 ±0.04	1.46 ±0.04	0.27 ±0.01	1.69 ±0.05	0.82 ±0.05	1.16 ±0.04	1.34 ±0.10	0.18 ±0.01	0.42
	Residue	1.53 ±0.06	1.21 ±0.04	1.15 ±0.04	1.91 ±0.07	1.63 ±0.05	6.32 ±0.23	0.95 ±0.04	1.25 ±0.05	1.66 ±0.08	
E-6 No. 3	Leach	0.38 ±0.02	2.26 ±0.06	2.73 ±0.06	0.56 ±0.02	3.03 ±0.07	1.56 ±0.07	1.21 ±0.03	1.47 ±0.08	0.20 ±0.01	0.59
	Residue	1.90 ±0.08	1.36 ±0.04	1.33 ±0.04	2.24 ±0.09	1.83 ±0.05	7.83 ±0.34	0.97 ±0.03	1.18 ±0.05	1.69 ±0.08	
Nova No. 2	Leach	0.54 ±0.02	1.36 ±0.05	1.51 ±0.05	0.59 ±0.03	1.82 ±0.06	2.23 ±0.10	1.11 ±0.05	1.10 ±0.07	0.39 ±0.02	0.29
	Residue	1.68 ±0.07	1.48 ±0.03	1.41 ±0.03	1.61 ±0.07	1.98 ±0.04	6.93 ±0.30	0.95 ±0.02	0.96 ±0.04	1.14 ±0.06	
B-1 20	Leach	0.36 ±0.01	2.65 ±0.06	2.97 ±0.07	1.35 ±0.03	3.55 ±0.08	1.50 ±0.05	1.12 ±0.02	3.70 ±0.12	0.45 ±0.01	0.62
	Residue	1.09 ±0.03	2.65 ±0.06	2.85 ±0.06	1.84 ±0.05	3.55 ±0.08	4.49 ±0.14	1.08 ±0.02	1.69 ±0.05	0.64 ±0.02	
B-1 30	Leach	0.58 ±0.03	1.61 ±0.05	1.68 ±0.05	1.75 ±0.06	2.15 ±0.07	2.40 ±0.13	1.04 ±0.04	2.99 ±0.18	1.04 ±0.05	0.59
	Residue	0.89 ±0.03	0.84 ±0.03	0.78 ±0.03	0.75 ±0.03	1.13 ±0.04	3.66 ±0.11	0.93 ±0.05	0.85 ±0.04	0.96 ±0.05	
B-1 141	Leach	0.48 ±0.02	1.19 ±0.03	1.44 ±0.04	1.38 ±0.04	1.59 ±0.04	1.97 ±0.08	1.21 ±0.04	2.88 ±0.13	0.96 ±0.04	0.58
	Residue	0.97 ±0.03	1.20 ±0.03	1.28 ±0.03	1.35 ±0.04	1.61 ±0.04	4.00 ±0.12	1.06 ±0.03	1.39 ±0.05	1.06 ±0.04	
MW-7 33	Leach	0.44 ±0.02	1.39 ±0.04	1.57 ±0.04	1.02 ±0.03	1.86 ±0.05	1.82 ±0.07	1.13 ±0.03	2.30 ±0.09	0.65 ±0.03	0.71
	Residue	1.41 ±0.04	1.94 ±0.05	2.07 ±0.05	1.70 ±0.04	2.59 ±0.07	5.81 ±0.16	1.07 ±0.03	1.20 ±0.04	0.82 ±0.03	
TB-15 51	Leach	0.35 ±0.01	3.77 ±0.09	4.07 ±0.09	4.24 ±0.08	5.05 ±0.11	1.45 ±0.06	1.08 ±0.02	12.02 ±0.51	1.04 ±0.03	0.68
	Residue	0.86 ±0.03	2.79 ±0.10	3.00 ±0.10	3.59 ±0.08	3.74 ±0.13	3.54 ±0.14	1.07 ±0.04	4.17 ±0.17	1.19 ±0.05	
TB-15 121	Leach	0.31 ±0.02	0.92 ±0.03	1.12 ±0.03	0.99 ±0.03	1.23 ±0.04	1.29 ±0.07	1.22 ±0.04	3.16 ±0.19	0.89 ±0.04	0.72
	Residue	1.53 ±0.05	1.62 ±0.06	1.72 ±0.06	2.12 ±0.06	2.17 ±0.08	6.29 ±0.21	1.06 ±0.05	1.39 ±0.05	1.23 ±0.06	

Table D-3. Sample ages.

Sample	Type	Age (10^3 years)		
		Uncorrected	Numerical	Isochron plot
E-1 C1a	Caliche	96	89	57
E-1 C2a	Caliche	128	119	88
Greenville Rd. (No. 1)	Caliche	71	77	52
Greenville Rd. (No. 2)	Caliche	60	55	42
E-3	Wood	17	–	–
E-5 (No. 1)	Caliche	28	18	16
E-6 (No. 3)	Caliche	26	8	7
B-1 20	Caliche	64	58	48
B-1 30	Caliche	–	–	–
B-1 141	Caliche	265	240	193
MW-7 33	Caliche	110	56	79
TB-15 51	Caliche	–	–	–
TB-15 121	Caliche	206	–	130

The reader is encouraged to refer to the referenced texts for derivation of the age-dating equations and detailed discussions of the methodology.

Age Date Reliability

Many of the samples dated thus far consist of relatively thick caliche-filled desiccation cracks in argillized B-soil horizons. The samples are in contrast to the relatively massive, impermeable pebble coatings dated by Ku *et al.* (1979), although they are similar to carbonate cementations of an arid-zone pediment gravel dated by Szabo *et al.* (1981). There are intuitive concerns dealing with the "closed system" nature of the Livermore Valley pedogenic carbonates. Although the B-soil horizon is generally considered a zone of accumulation in alkaline environments, conceivably during wetter periods it may have been subject to leaching and material transport. Directly confirming the "closed system" nature of these pedogenic carbonates would require concordia between these $^{230}Th/^{234}U$ dates and ages obtained from other radiometric dating methods. Such methods are not available in this instance. Therefore, evaluations will have to be made on the internal consistency of the data as well as their conformity with any relative age estimates of the alluvial units based on geomorphic evidence. The combinations of young and old potential C-sources for these pedogenic carbonates preclude the use of ^{14}C methods. In addition, this technique is limited to approximately a 40,000-yr range whereas many of the buried paleosols encountered are clearly older than that, as estimated from geomorphic evidence and soil-stratigraphic considerations (Shlemon, Appendix E).

The individual caliche dates represent average ages of the entire thickness of carbonate included in each analysis. The time elapsed in accreting this carbonate is unknown. In addition, the rates of accretion may have been more rapid during pluvial times in the Pleistocene.

The reliability (precision) of the ages may be inferred by a consideration of the two pairs of coeval samples analyzed: E-1 Cla + E-1 C2a and Greenville Rd. No. 1 + Greenville Rd. No. 2. The data have been summarized in Table D-4 and include the mean and standard deviation in the various model ages. The precision of approximately ± 10 to 20% is comparable to that observed in analyses of presumed coeval pedogenic carbonates by Ku *et al.* (1979). Because of the difficulty in assessing the initial ^{230}Th activities, dating impure carbonates by these methods will probably have inherent uncertainties of this magnitude. Nevertheless, as there are no other absolute dating tools for these deposits, limitations of precision of such magnitude can certainly be tolerated at this time.

In this preliminary effort it is important to consider the radiochemical nature of the noncarbonate detrital minerals because they are important to the assumptions used in correcting the leachate data. Some knowledge can be gathered by inference from the data on residues. As seen from Table D-2, the uranium

Table D-4. Age of coeval pedogenic carbonates.

	Age (10^3 years)					
Sample	Uncorrected age	Mean	Numerical age	Mean	Isochron plot age	Mean
E-1 C1a	96	112 ± 23	89	104 ± 21	57	73 ± 22
E-1 C2a	128		119		88	
Greenville Rd. No. 1	71	66 ± 8	77	66 ± 15	52	47 ± 7
Greenville Rd. No. 2	60		55		42	

and thorium concentrations in the residues are in the range 1 to 8 ppm, with an average Th/U weight ratio of 2.7 ± 1.0. These values are generally expected from an average shale. The $^{234}U/^{238}U$ activity ratios are near the secular equilibrium value (avg 0.98 ± 0.07). Ku *et al.* (1979) have determined that criteria can be specified by which large deviations from these norms can be used to identify samples that are unsuitable for dating by these methods.

Analyses of three of the samples did not give reliable age estimates. These three samples all had carbonate contents less than 60% by weight, whereas more reliably dated samples are above this amount. Furthermore, these three samples all had low leachate $^{230}Th/^{232}Th$ ratios compared to other samples, indicating that they contain a significant detrital or common thorium component in the leachate (carbonate) fraction. Because of the uncertainty in initial ^{230}Th content of the carbonate, the ages were less reliable and ranged widely. Ages for these samples (E-2 No. 2, E-6 No. 1, and Nova No. 2) were not included in the text.

Discussion

These age dates have been used in conjunction with detailed mapping, seismic, and other investigations to derive a stratigraphy for the Quaternary alluvial deposits at or near the LLNL site and to constrain time of last possible motion on several postulated faults. These interpretations are contained in the text of this report.

It must be stressed that development of these carbonates postdates formation of the alluvial deposits in which they occur. In the case of a strongly developed calcic horizon (C horizon) enough time is involved in its formation that reasonable antiquity is to be expected. However, several samples dated here are from argillic (B) horizons and the caliche occurs as relatively thin stringers of carbonate that apparently fill vertical desiccation/shrinkage fractures. This material may postdate the age of the alluvial deposit by a considerable length of time. The carbonate may be deposited by a more recent incursion of groundwater or may develop within root tubules.

Two of the borehole caliche samples were collected from below or near the present water table. These samples both have apparent ages that are barely finite, and hence slightly younger than samples collected above them. These are probably slightly open systems and, for all practical purposes, both samples must be considered as coming from material infinitely old ($\geq 250 \times 10^3$ yr).

References

Knauss, K. G. (1981), *Uranium-Series Dating of Pedogenic Carbonates from the Livermore Valley, California,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53095.

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Szabo, B. J., W. J. Carr, and W. C. Gottschall (1981), *Uranium-Thorium Dating of Quaternary Carbonate Accumulations in the Nevada Test Site Region, Southern Nevada,* U.S. Geological Survey, Menlo Park, CA, Open-File Report 81-119.

Appendix E
Soil-Stratigraphy and Relative Age Data

This appendix consists of two reports prepared by Dr. Roy J. Shlemon of Roy J. Shlemon and Associates. Dr. Shlemon provided consulting services to the LLNL geoscience staff with respect to the detailed characteristics of soil profile development within the alluvial deposits underlying LLNL and nearby areas. Dr. Shlemon also provided relative ages of alluvial deposits and opinions regarding times of movements along strands of the Las Positas Fault Zone (see "Letter Report").

Dr. Shlemon's reports are reprinted here in their entirety. Detailed logs of test pits TP-1 through TP-4 referred to in Dr. Shlemon's report of February 11, 1982, are presented in the Geologic Data Report, Lawrence Livermore National Laboratory Site (Carpenter *et al.*, 1982) prepared as a companion to the main text. Locations of the test pits and other exposures studied by Dr. Shlemon are shown in Figs. 10, 20, and 21 in the main text.

Late Quaternary Soil-Stratigraphy Lawrence and Sandia National Laboratories, Livermore, California

R. J. Shlemon

Contents

Introduction

Purpose

This report is one of several concerned with seismic safety within and adjacent to the Lawrence Livermore National Laboratory (LLNL) and the Sandia National Laboratory, Livermore (SNLL) in Alameda County, California (see location maps, geological setting, and investigative procedures in Carpenter *et al.*, 1980a). The main purpose of this report is to summarize field data and conclusions regarding the age of sediments at and near the LLNL and SNLL sites, particularly as assessed by geomorphic and soil-stratigraphic techniques. This information is requisite for determining the timing and recurrence of fault displacement in the study area.

Specific objectives (tasks) of the study were:

1. To review and critique existing geological data for the sites as collected by the LLNL geoscience staff through trenching, drilling, and radiometric dating techniques;
2. To undertake field reconnaissance of the eastern Livermore Valley with the LLNL staff, and to review the geomorphology and soil-stratigraphy as exposed in roadcuts, stream banks, and trenches; and
3. To inspect, describe, and measure soil (pedogenic) profiles at trenches excavated by LLNL which exposed buried paleosols and other Quaternary stratigraphic markers.

Tasks 1 and 2 were carried out during the Fall of 1981 by field inspection of existing exposures in the Livermore and Sandia sites, and by regional reconnaissance with the LLNL staff. Following these, task 3 was implemented by excavating four new trenches on the LLNL and SNLL sites, designated as soil trenches (test pits) 1, 2, 3, and 4 (see accompanying LLNL map for locations, dimensions, and geological logs).

Investigative Procedures

Test pits 1 and 2 were excavated on the LLNL in order to determine the age of undisplaced sediments and soils overlying inferred traces of the Corral Hollow and Las Positas Faults (Carpenter *et al.*, 1980a; Carpenter *et al.*, 1980b). Test pits 3 and 4 were sited on the SNLL near the Las Positas Fault in order to assess late Quaternary activity in this area.

Detailed soil profile measurements and descriptions for each of the respective trenches are given in Tables E-1 through E-4, accompanying this report. The notation follows that of the U.S. Soil Conservation Service (Soil Survey Staff, 1951, 1975). Soil-stratigraphic units in the various trenches, depicted by horizon and depth markers, have been documented photographically by the LLNL staff. The discussion following briefly reviews the major geologic and pedologic units in these trenches; summarizes soil-stratigraphic dating methods applicable to the LLNL and SNLL area; and presents an interpretation of age based primarily on comparison with similar stratigraphy dated elsewhere in the Livermore Valley and in the Central Valley of California by radiometric techniques and by association with the Quaternary, marine oxygen-isotope stage chronology (Marchand, 1977; Shackleton and Opdyke, 1973, 1976; Shlemon, 1979; Shlemon and Verosub, 1980; Steele, 1980).

Acknowledgments

This study was commissioned by LLNL under Contract Order No. 5179101. Gratefully acknowledged is the commentary and logistical support provided by the LLNL geoscience staff. Particularly appreciated is the assistance of D. Carpenter, D. Emerson, and R. Clark.

Soil-Stratigraphic Dating Techniques

Application of Soil-Stratigraphy to the LLNL and SNLL Area

Soil-stratigraphic techniques are increasingly being applied to engineering-geological investigations in order to date Quaternary sediments, and hence the age of any faults that may be encountered (e.g., Machette, 1978; Page and Walsh, 1974; Shlemon, 1975). In this regard, particularly useful are "strongly-developed" soils; that is pedological profiles characterized by distinctive structural development, color, illuvial clay morphology and other horizonation features (Soil Survey Staff, 1951; 1975). Many of these soils, especially relict and buried paleosols (Ruhe, 1965) owe their origin to regional changes in Pleistocene climate, vegetation, and sedimentation. In general, mid-latitude epochs of landscape (geomorphic) instability gave rise to regional piedmont fan deposition generally equated to major glacial (pluvial) events; whereas epochs of landscape stability resulted in soil formation usually associated with interglacial or interstadial events (Morrison, 1967 and 1968; Shlemon, 1972).

The Marine Isotope Chronology

Some soil-stratigraphic sequences can be dated directly by radiometric (usually radiocarbon and uranium-series) or paleomagnetic techniques. Unfortunately, materials useful for such dating are seldom found. However, many soils can be dated, at least relatively, by correlation with Pleistocene, climatically-controlled fluctuations of sea level. A marine, oxygen-isotope stage chronology, based on the relative timing of glacioeustatic high and low stands of sea level, and of changing ice volumes, has been well

(Continued on p. 141)

Table E-1. Soil profile description and measurement, LLNL Test Pit 1, north wall, Sta. 0+09, Corral Hollow Fault.[a]

Horizon	Depth (ft)	Description
An	0.0-1.1	Anthropic Horizon (artificial fill): Dark grayish brown (10YR 4/2) dry; ~20% gravels; pipe fragments; local relief to 1.5 ft, increasing to 3.0 ft near east end of trench; abrupt smooth boundary.
A	1.1-1.8	Grayish brown (10YR 5/2) to very dark-grayish brown (10YR 3/2) when moist, silty loam; massive-to-weak, fine-to-medium, subangular blocky structure; hard, firm, slightly sticky and slightly plastic; few medium-vertical roots; common, very fine constricted pores increasing to many fine and continuous pores near base; abrupt wavy boundary.
Ae-B	1.8-2.2	Dark, grayish brown (10YR 4/2) to very dark, grayish brown (10YR 3/2) when moist, pebbly silty clay loam; moderate-medium subangular blocky structure; hard to very hard, firm, sticky and plastic; few very fine vertical roots; many medium-to-coarse random pores; few very fine clay films in interstitial pores and bridging mineral grains and in tubular pores and root channels (degraded B horizon), ~10% subrounded clasts near base (weak stoneline); eluvial horizon (Ae) "perched" on underlying IIB horizon; geological unconformity; abrupt-smooth to abrupt-wavy boundary.
IIB_{21b}	2.2-3.4	Buried Paleosol: Dark brown (7.5YR 4/4-3/2) dry and moist, clay; strong very coarse-to-blocky prismatic structure; extemely hard, extremely firm, very sticky, and very plastic; few fine-to-medium vertical roots along ped faces; very fine, thin clay films on ped faces; strong pressure faces (primary clay); random slickensides; common, fine irregular lime concretions near base of horizon; strongly effervescent; gradual wavy boundary.
$IIIB_{22bca}$	3.4-4.2	Reddish yellow (7.5YR 6/6) to brown (7.5YR 4/6) when moist, light silty clay increasing to fine sand near base; moderate medium subangular to angular blocky structure; hard, very firm, slightly sticky and slightly plastic, few thin clay films on ped faces and in interstitial pores; strongly effervescent; common fine-to-medium lime concretions increasing in frequency near base; gradual wavy boundary.
IVB_{3bca}	4.2-5.4	Strong brown (7.5YR 5/6) to yellowish brown (10YR 5/4) when moist, gravelly silty clay loam; moderate-medium, angular, blocky structure; very hard, very firm, slightly sticky and slightly plastic; common thin, yellowish red (5YR 4/6) clay films on ped faces and in root channels; strongly effervescent; common, medium lime concretions; ~20% subrounded gravels near base; unit lenticular; lenses to 5 ft wide in trench; base of fining upward sequence; abrupt wavy boundary.
VC_{cab}	5.4-6.2	Yellow (10YR 7/6) to brownish yellow (10YR 6/6) when moist, silty clay; moderate medium platy to angular blocky structure; hard, firm, sticky, and slightly plastic; few thin clay films on ped faces and in interstitial pores, and bridging mineral grains; violently effervescent; many large lime concretions, soft masses near base; base of geological unit 2; unconformity; abrupt irregular boundary.
VIB_b	6.2-6.6	Buried Paleosol: Yellowish brown (10YR 5/4) dry and moist, pebbly clay loam; massive-to-weak subangular blocky structure; hard, firm, slightly sticky and slightly plastic; few thin clay films in interstitial pores bridging mineral grains and filling root tubules; ~20% very angular quartzitic clasts near base of horizon; weak buried paleosol; strongly effervescent; few to common, soft lime masses and disseminated lime from overlying units; geological unconformity; abrupt irregular boundary.
$VIIB_{cab}$	6.6-7.5	Dark, yellowish brown (10YR 4/4) to yellowish brown (10YR 5/4) when moist, silty clay; strong coarse to very coarse angular blocky to prismatic structure (primary clay); common, reddish-brown (5YR 4/4) thin to moderately thick patchy clay-filling dendritic root channels; violently effervescent; thick, continuous Mn staining on ped faces; common, disseminated and soft lime masses derived from V_{cab} horizon; sample collected for possible U-series assay; gradual irregular boundary.
$VIIIC_{1b}$	7.5-8.8	Yellowish-brown (10YR 5/4) dry and moist, fine, silty sand grading to pebbly coarse sand near base; massive to moderate medium subangular blocky structure; few, thin, reddish brown (5YR 4/4) patch clay films in interstitial pores and bridging mineral grains; violently effervescent; common medium irregular and soft masses near top of horizon; ~15% rounded pebbles near base; gradual wavy boundary.
IXC_{2b}	8.8-9.4	Pale-brown (10YR 6/3) to yellowish-brown (10YR 5/4) pebbly sand; massive structure; slightly hard, firm, slightly sticky and nonplastic; effervescent; ~40% subrounded to 1-in. diam, lenticular channel fill deposit; base of fining upward sequence; geological unconformity; abrupt wavy to abrupt irregular boundary.

Table E-1. (Continued.)

Horizon	Depth (ft)	Description
IXC_{3b}	9.4-10.6	Light, yellowish brown (10YR 6/4) to yellowish brown (10YR 5/4) when moist, coarse sand to silty, fine sand; massive structure; slightly hard, firm, nonsticky and nonplastic; effervescent to strongly effervescent; few, fine to medium lime concretions near middle of horizon; ~10% rounded pebbles to 0.5-in. diam near base; gradual wavy boundary.
XB_{cab}	10.6-12.0	Buried Paleosol: Very pale brown (10YR 7/4) to yellowish brown (10YR 5/4) when moist, loam to silty loam; massive to weak fine subangular blocky structure; firm, friable, slightly sticky, and slightly plastic; common, fine, random pores; few fine clay films in interstitial pores and bridging mineral grains; strongly effervescent; few fine lime concretions filling root tubules to 1/4-in. diam near base; abrupt wavy boundary.
XC_{cab}	12.0-12.6	Pale brown (10YR 6/3) to yellowish brown (10YR 5/4) silty loam; weak to moderate medium-subangular blocky structure; firm, friable, sticky and slightly plastic; common fine pores; few thin colloidal clay films in old root tubules and bridging mineral grains; violently effervescent; common to many large lime concretions to 0.5-in. diam (stage III) and filling vertical root tubules to 0.5-in. diam; sample for possible U-series assay; base of geological unit; unconformity; abrupt irregular boundary.
XIC_{1b}	12.6-13.5	Very pale brown (10YR 7/4) to yellowish brown (10YR 5/4) when moist, fine sandy loam; massive structure; loose, friable, nonsticky, and slightly plastic; cross-bedded channel sand; effervescent near top of horizon; gradual wavy boundary.
XIC_{2b}	13.5-14.2	Very pale brown (10YR 7/4) to yellowish brown (10YR 5/4) when moist, fine sandy loam; massive structure; loose, friable, nonsticky, and nonplastic; effervescent; common, fine lime concretions near base; gradual wavy boundary.
XIC_{3cag}	14.2-14.8	Pale brown (10YR 6/3) to light, yellowish brown (10YR 6/4) when moist, heavy, fine sandy clay; massive to weak, medium subangular blocky structure; firm, friable, nonsticky, and slightly plastic; violently effervescent; common, medium-lime concretions in vertical roots to 1/4-in. diam (stage II carbonates); groundwater carbonates perched on underlying unit; gradual wavy to gradual irregular boundary.
XIC_{4b}	14.8-15.8	Pale brown (10YR 6/3) to yellowish brown (10YR 5/4) when moist, sand; massive structure; loose, friable, nonsticky, and nonplastic; violently effervescent; disseminated lime throughout horizon; abrupt wavy boundary.
$XIIC_{5cab}$ [b]	15.8-16.5+	Pale brown (10YR 6/3) to yellowish brown (10YR 5/4) when moist, fine sand; massive-to-moderate weak, subangular blocky structure; hard, firm, slightly sticky, and slightly plastic; violently effervescent; many large lime concretions in vertical root tubules to 0.5-in. diam; common, medium lime concretions, rounded, throughout horizon; probable groundwater carbonate; sample collected for possible U-series assay; base of trench.

[a] Soil measured and described by R. J. Shlemon, 30 September 1981. Seven geological units identified in trench at station where measured. Buried paleosol between 2.2 and 6.2 ft is slightly to moderately developed; interpreted to be isotope stage 3 in age, approximately 35,000 to 40,000 yr old. Calcic horizons between 6.6 and 12.6 ft are both pedogenic and groundwater in origin; probable stage 5 age, approx. 80,000 to 125,000 yr old.

[b] Carbonate sampled for U-series assay from horizon $XIIC_{5cab}$ at base of trench is of groundwater origin and, if datable, may yield young age not associated with argillic horizon.

Table E-2. Soil profile description and measurement, LLNL Test Pit 2, north wall, Sta. 0+25, Corral Hollow Fault.[a]

Horizon	Depth (ft)	Description
A_{11}	0.0-0.4	Light-brownish gray (10YR 6/2 to dark-grayish brown (10YR 4/2) when moist, silty loam; weak coarse angular blocky structure; very hard, very firm, slightly sticky, and plastic; common very fine vertical roots; common to many very fine random pores; abrupt smooth boundary.
A_{12}-B	0.4-1.2	Grayish brown (2.5YR 5/2) to very dark grayish brown (10YR 3/2) when moist, silty loam; massive to very coarse blocky structure; very hard, very firm, nonsticky, and slightly plastic; common very fine vertical roots; few thin colloidal films in interstitial pores and bridging mineral grains; and few thin, clay films on ped faces near base of horizon; gradual smooth boundary.
Ae-B	1.2-1.6	Light-brownish gray (2.5YR 6/2) and light gray (10YR 7/2) to brown-to-dark brown (10YR 4/3) when moist, light silty clay loam; moderate-medium platy structure; very hard, very firm, slightly sticky and slightly plastic; common to many medium, random pores; few to common, thin colloidal clay films in interstitial pores and bridging mineral grains; few, thin, light-yellowish brown (10YR 6/4) clay films on ped faces; eluvial horizon superimposed on cambic; base of geological unit 1; unconformity; abrupt wavy boundary.
IIB_{22b}	1.6-2.5	Buried Paleosol: Reddish yellow (7.5YR 6/6) to pinkish gray (7.5YR 6/2) when moist, silty clay; strong, very coarse angular blocky structure; very hard, very firm, sticky, and slightly plastic; few, very fine vertical roots; common thin, dark reddish-brown (5YR 3/3) clay films on ped faces; gradual smooth boundary.
IIB_{23b}	2.5-3.2	Dark brown (7.5YR 4/4) to dark brown (7.5YR 4/2) when moist, silty loam; strong-moderate, angular, blocky structure; very hard, very firm, sticky, and plastic; few fine to very fine vertical roots; common thin, reddish-brown (5YR 3/3) clay films on ped faces; common continuous films near base of horizon; disseminated lime throughout horizon; gradual smooth boundary.
IIB_{31b}	3.2-3.8	Strong brown to dark brown (7.5YR 5/6-4/4) to dark brown (7.5YR 4/2) when moist, heavy-silty clay; moderate to strong-medium, angular, blocky structure; few fine vertical roots; common, thin, reddish-brown (5YR 3/3) clay films on ped faces; effervescent near top of horizon; disseminated to few, fine, soft lime masses; gradual smooth boundary.
IIB_{32b}	3.8-5.0	Strong brown (7.5YR 5/6) to brown (7.5YR 5/4) when moist, silty clay loam; weak fine angular blocky structure; hard, very firm, slightly sticky, and slightly plastic; few very fine random roots; common, thin, reddish-brown (5YR 3/3) clay films on ped faces; gradual smooth boundary.
$IIIC_b$	5.0-7.2	Brown (7.5YR 5/4) to dark-yellowish brown (10YR 4/6) when moist, gravelly very coarse sand; massive to single-grained structure; loose to firm, friable, nonsticky and nonplastic; ~30% angular clasts to 2-in. diam, locally to 5 in. long, unit is laterally traceable stratigraphic marker in trench; base of geological unit 2; unconformity; gradual wavy to gradual irregular boundary.
IVB_{31b}	7.2-8.6	Buried Paleosol: Reddish yellow (7.5YR 8/6) to brown (10YR 5/3) when moist, pebbly sandy loam; massive-to-moderate subangular blocky structure; very hard, firm, slightly sticky and nonplastic; common, thin, reddish brown (5YR 3/3) clay films filling old dendritic root channels; gradual irregular boundary.
IVB_{32b}	8.6-10.5	Reddish yellow (7.5YR 7/6) to yellowish brown (10YR 5/4) when moist, silty loam; massive to weak, fine subangular blocky structure; hard, firm, slightly sticky and slightly plastic; very few, thin, reddish brown (5YR 3/3) clay films in old root channels; gradual irregular boundary.
IVB_{33cab}	10.5-11.6	Strong brown (7.5YR 5/6), dry and moist, silty clay; moderate to strong, very coarse blocky structure; hard, firm, sticky and slightly plastic; common, thin reddish brown (5YR 3/3) clay films in root tubules; violently effervescent near top of horizon; common, medium segregated lime concretions and accumulation in vertical fractures; gradual irregular boundary.
IVB_{34b}	11.6-13.0+	Strong brown (7.5YR 5/6) to dark brown (7.5YR 4/4) silty clay loam; weak medium-angular blocky structure; very hard, firm, slightly sticky and slightly plastic; few, thin, reddish-brown (5YR 3/3) clay films in root tubules in upper part of horizon; base of soil profile description at station 0+29.

[a] Soil profile measured and described by R. J. Shlemon, 1 October 1981.

[b] Three geological units identified at station 0+29: 1) est. post-15,000 to 20,000-yr-old sediments from surface to 1.6 ft with eluvial horizon superimposed on Cambic B; 2) geological unit, between 1.6 and 7.2 ft is cumulic soil profile; color, clay film morphology and development indicate moderate relative development; est. isotope stage 3 in age (35,000 to 40,000 yr); 3) geological unit 3, between 7.2 ft and base of trench, has moderately to strongly developed buried paleosol; is also cumulic profile, interpreted to be stage 5 in age (80,000 to 125,000 yr); parent material is older and judged stage 6 in age (~125,000 to 195,000 yr BP).

Table E-3. Soil profile description and measurement, LLNL Test Pit 3 (Sandia Area), North Wall, Sta. 0+16, Las Positas Fault.[a]

Horizon	Depth (ft)	Description
A_{11}	0.0-0.2	Very dark-grayish brown (10YR 3/2) to very dark-brown (10YR 3/2) when moist; pebbly loam; massive structure; soft, very friable, nonsticky, and nonplastic; common, fine random roots; ~15% subrounded clasts to 0.5-in. diam, gradual smooth boundary.
A_{12}	0.2-0.6	Dark yellowish brown (10YR 3/4) to very dark-grayish brown (10YR 3/2) when moist, sandy clay loam; massive to weak fine-angular blocky structure; soft, friable, nonsticky and slightly plastic; many fine random roots; common fine pores; ~5% angular clasts to 2-in. diam, gradual smooth to gradual wavy boundary.
A_{13}	0.6-0.9	Very dark-grayish brown (10YR 3/2) when moist, pebbly sandy loam; massive structure; soft, friable, nonsticky and slightly plastic; common to many medium vertical roots; 5-10% subangular clasts to 2- to 3-in. diam, weak imbricate structure; gradual wavy boundary.
A_{14}	0.9-1.6	Very dark-grayish brown (10YR 3/2) when moist, loam; massive structure; soft, very friable, nonsticky, and nonplastic; few medium vertical roots; ~5% subrounded clasts to 0.8-in. diam, gradual wavy boundary.
A_{15}	1.6-2.8	Dark-grayish brown (10YR 4/2) when moist, loam; massive structure; soft, friable, nonsticky and nonplastic; few fine roots; ~10% pebbles and 5% subrounded cobbles to 1- to 2-in. diam, abrupt wavy to abrupt irregular boundary; unconformity; base of geological unit 1; mainly colluvial slopewash derived from adjacent older terrace deposits to west; see LLNL geological log.
IIC	2.8-4.5	Strong brown (7.5YR 5/6) to dark-yellowish brown and dark brown (10YR 4/4-7.5YR 4/4) when moist, gravelly loamy sand; single-grained; soft, friable, nonsticky, and slightly plastic; few fine roots near upper part of horizon; ~60% subangular clasts to 4-in. diam, abrupt wavy boundary; horizon equivalent to geological unit 2; fluvial channel gravels, est. 15,000 to 20,000 yr old (isotope stage 2).
$IIIB_{31b}$	4.5-6.2	Buried Soil: Dark brown (7.5YR 4/4) to reddish brown (5YR 4/4) when moist; gravelly clay loam; single-grained; hard, friable to firm; sticky, and slightly plastic; few to common, thin, discontinuous yellowish-red clay films coating pebble faces near top of horizon; common, thin clay films in interstitial pores and bridging mineral grains and filling root channels in matrix; ~70% subrounded clasts to 1.5-in. diam,imbricate structure; fluvial gravel; upper horizon (B_{2t} ?) eroded; unit is stratigraphic marker; gradual wavy boundary.
$IIIB_{32}$-Cb	6.2+	Reddish brown (5YR 4/4) to yellowish red (5YR 4/6) when moist; gravelly clay loam; single-grained structure; hard, firm, slightly sticky, and slightly plastic; few, thin, yellowish-red clay films in interstitial pores and coating mineral grains; gravels similar in structure and texture to horizon above but decreasing to gravelly coarse sand near base of horizon; buried soil is moderately-developed; ~35,000 to 40,000 yr old (isotope stage 3).

[a] Soil measured and described by R. J. Shlemon (19 Nov. 1981). Test Pit (TP) 3 sited on lower geomorphic surface; upper 7.0+ ft exposed three distinct geological units: 1) organic (A) horizons to 2.8 ft, Holocene in age; 2) horizon IIC is channel gravel fill ~15,000 to 20,000 yr old, probably correlative to gravel in LLNL Trench E-3 as 17,400 C-14 age; 3) buried soil on gravels below 4.5 ft ~35,000 to 40,000 yr old (stage 3) forming on stage 4 (?) gravels inferred 60,000 to 70,000 yr old.

Table E-4. Soil profile description and measurement, LLNL Test Pit 4 (Sandia Area), North Wall, Sta. 0+15.5, Las Positas Fault.[a]

Horizon	Depth (ft)	Description
A_{11}	0.0-0.2	Very dark-grayish brown (10YR 3/2) to dark-yellowish brown (10YR 3/4) when moist, silty clay loam; massive to weak very fine subangular structure; soft, very friable, nonsticky, and slightly plastic; many medium roots (duff); abrupt smooth boundary.
A_{12}	0.2-0.4	Dark brown (10YR 3/3) dry and moist, silty clay; weak fine-to-medium subangular blocky structure; slightly hard, friable to firm, sticky, and slightly plastic; common fine vertical roots, ~5% pebbles to 0.3-in. diam, abrupt smooth boundary.
A_{13}	0.4-0.6	Dark yellowish brown (10YR 3/4) to dark brown (7.5YR 3/2) dry and moist, heavy silty clay; weak medium subangular blocky structure; slightly hard, firm, sticky, and plastic; few fine vertical roots; gradual smooth boundary.
A_{14}	0.6-0.9	Dark yellowish brown (10YR 3/4) to dark brown (7.5 YR 4/4) when moist; silty clay loam; weak medium subangular blocky structure; slightly hard, friable to firm, nonsticky, and slightly plastic; few fine vertical roots; gradual smooth boundary.
B	0.9-1.4	Dark yellowish brown (10YR 3/4) to dark brown (7.5YR 4/4) when moist, heavy silty clay; weak medium subangular blocky structure; slightly hard, firm, sticky, and plastic; few very fine roots, common fine pores; very few, thin, dark brown (7.5YR 3/2) clay films in root channels and in interstitial pores (cambic horizon); base of geological unit 1; unconformity, gradual smooth boundary.
B_{1b}	1.4-1.7	Buried Soil: Brown (7.5YR 5/4) to dark brown (7.5YR 4/2) when moist, silty clay loam; moderate fine to medium angular blocky structure; hard, firm, slightly sticky, and slightly plastic; few very fine pores; few, thin clay films in interstitial pores and bridging mineral grains; ~5% subrounded pebbles to 0.5 in. in diam, colluvial unit reworked from underlying parent material; lenticular, abrupt wavy boundary.
B_{2b}	1.7-2.0	Dark brown (7.5YR 4/2) to dark brown (7.5YR 3/2) when moist, gravelly fine sandy clay loam; moderate medium to coarse-angular blocky structure; very hard, very firm, slightly sticky, and slightly plastic; few, very fine pores; few, thin clay films in interstitial pores and bridging mineral grains, and few thin, dark brown (7.5YR 3/2) clay films on ped faces and coating clasts; few, fine disseminated lime zones; weakly effervescent; 5-10% subrounded clasts to 2-in. diam throughout horizon; basal stoneline and colluvial unit; unconformity; base of geological unit 2; moderately developed soil (isotope stage 3 ?); abrupt smooth boundary.
IIB_{2b}	2.0-2.8	Buried Soil: Reddish brown (5YR 4/4) to reddish brown (5YR 4/3) when moist, silty clay; strong coarse angular blocky to strong coarse prismatic structure near base; few, very fine random roots; common to many, moderately-thick and continuous reddish brown (5YR 3/2) clay films on ped faces and in interstitial pores; abrupt wavy boundary.
$IIIB_{3b}$	2.8-5.5+	Reddish brown (5YR 5/4) to reddish brown (5YR 4/4) when moist, gravelly coarse sandy loam; single-grained structure; common, thin clay films on pebble faces, locally common, moderately-thick clay films on ped faces and in interstitial pores and bridging mineral grains; ~50% subangular to subrounded clasts (fluvial channel and colluvial unit); few clayballs to 4-in. diam, horizon grades to dark brown (7.5YR 4/4) near base; horizon measured to 5.5+ ft.

[a] Soil profile description and measurement by R. J. Shlemon, 19 Nov. 1981. Three geological units to 5.5+ ft: 1) upper unit to depth of 1.4 ft is only slightly developed with Cambic horizon, est. less than 15,000 yr in age; 2) geological unit 2 from 1.4 to 2.0 ft bears moderately developed colluvium, est. 35,000 to 40,000 yr; 3) geological unit 3 bears very strongly developed buried soil with reddish brown color and thick, continuous clay films indicative of probable stage 5 age (80,000 to 125,000 yr); gravelly parent material est. to be stage 6 in age (125,000 to 195,000 yr). Basal units in trench appear to be source of reddish-brown colluvial gravels exposed in Sandia cut (Las Positas Fault exposure). Test Pit (TP) 4 sited on upper geomorphic surface; surface slope less than 3°; stable.

established for over 20 yr (Emiliani, 1955; 1966). However, the age of some of the various stages comprising this chronology are continually revised in accordance with newly-obtained radiometric and paleomagnetic data from throughout the world (Broecker and van Donk, 1970; Gartner and Emiliani, 1976; Hays, 1979; Hutson, 1980; Ruddiman *et al.*, 1979).

Particularly applicable to soil stratigraphy is the general isotope stage chronology depicted by Shackleton and Opdyke (1973, 1976). These workers, summarizing all data then available, identified stage boundaries as the mid-points of lines connecting major high and low stands of sea level (mainly climatically controlled), and dated these by extrapolation of applicable radiocarbon and uranium-series dates, and assumed, deep-sea sedimentation rates. Recent work shows, however, that the age of various isotope stages should be somewhat changed; and that many substages can be identified, reflecting intra-stage, short-lived fluctuations of sea level. This is well exemplified by isotope stage 5 (last major interglacial/late Sangamon), about 80,000 to 125,000 yr ago, which was punctuated by at least two deep low stands of sea level, each approximately 10,000 yr long, and apparently almost of full glacial intensity (Ruddiman, 1979; Ruddiman *et al.* 1979; Steinen *et al.*, 1973). Despite these complications, the well-known stage chronology of Shackleton and Opdyke (1973, 1976) remains valid, and provides an approximate age for terrestrial sediments and soils that likewise responded to world-wide changes of climate.

Correlation of Marine and Terrestrial Sequences

The marine isotope stage chronology has now been successfully applied to terrestrial sequences throughout the world (e.g., Fink and Kukla, 1977; Kukla, 1979; Morrison, 1978; Pierce *et al.*, 1976; Woillard and Mook, 1982). Correlation of marine and terrestrial sediments has likewise been made in California, particularly in the Central Valley (e.g., Marchand, 1977; Shlemon, 1980; Steele, 1980), and in the Livermore Valley (Shlemon, 1979; Shlemon *et al.*, 1980).

Because the age of the isotope stage boundaries is as yet inexact, and because of the yet unknown "time lag" between fluctuations of sea level and changes in terrestrial sedimentation, only approximate age ranges are assigned to soil-stratigraphic units in the LLNL and SNLL area. Thus, in this report, the ages of isotope stage "peaks" are used to date key soils and sediments. For example, Shackleton and Opdyke (1973, 1976) designate isotope stage 2 as spanning the range of about 13,000 to 32,000 yr ago, with the last maximum low stand occurring some 17,000 to 20,000 yr BP. In contrast, for the same stage, Bloom *et al.* (1974, p. 203) identify the major low stand of sea level (late Wisconsin) to have taken place some 15,000 to 20,000 yr ago. Likewise, the "peak" of isotope stage 3 (mid-Wisconsin) is deduced to be in the order of 35,000 to 40,000 or 45,000 yr BP, depending on assumptions about local sedimentation rates and tectonism. Thus there may often be several thousand years difference in the reported age of some isotope stage boundaries. Accordingly, in this report, the ages of several stage boundaries may not correspond directly with those of Shackleton and Opdyke (1973, 1976), but—where independent of radiometric control—are put forth as reasonable and conservative dates for late Quaternary soils and sediments in the LLNL and SNLL areas.

Corral Hollow Fault

Several traces of the Corral Hollow Fault have been projected across LLNL, based mainly on the presence of aerial-photographic lineaments (reviewed by Carpenter *et al.*, 1980a). These traces were trenched and logged by LLNL geoscience staff, who found no displacement of at least the upper 10 to 12 ft of Quaternary sediments (Carpenter *et al.*, 1980a; 1980b). Based on the presence of multiple buried paleosols and on U-series dating of pedogenic carbonates, these undisplaced sediments were interpreted to be over 100,000 yr old (Knauss, 1981, p. 17). Trenches 1 and 2 (TP 1 and 2) were thus sited adjacent to trenches across inferred traces of the Corral Hollow and Las Positas Faults, previously logged by the LLNL staff. A soil-stratigraphic chronology independent of the U-series dates was then established.

LLNL Trench (Test Pit) 1

Trench 1, approximately 45 ft long and 16 ft deep, was emplaced near Trench E-1 in the southeastern part of the LLNL (see locations in Carpenter *et al.*, 1980a). The stratigraphy was described on 30 September 1981 from the north wall at station 0+09. Several depositional units were identified, indicated by Roman numeral prefix (Table 1). These, in turn, are capped by three buried paleosols and a modern solum.

The uppermost depositional unit, about 2.2 ft thick, bears only a weak pedogenic profile typified by a cambic (B) and a superimposed eluvial (Ae) horizon. The surface at this locality has been disturbed; and up to 3 ft of fill (anthropic horizon) was observed (Table 1). The basal contact is characterized by a weak stoneline and an abrupt smooth to an abrupt wavy boundary marking an unconformity with the underlying buried paleosol (top of second geological unit). From these pedogenic characteristics, the uppermost depositional unit is judged to be no more than about 15,000 to 20,000 yr old. The unit is also morphologically comparable to soil-stratigraphic units elsewhere in the Livermore Valley assigned this age based on radiocarbon dating (Knauss, 1981), and on association to the isotope stage chronology (Shlemon, 1979).

A moderately-developed buried paleosol is superimposed on four geological units at depths between about 2.2 and 6.2 ft (Table E-1). This soil is dark brown (7.5YR 4/4) to reddish-yellow (7.5YR 6/6) in color, is strong angular-blocky to prismatic in structure, and has few, thin, clay films on ped faces and in tubular and interstitial pores. Two calcic horizons are also present: the younger superimposed on the argillic (III_{2cab}) and the older at the base of the paleosols (VCcab). These multiple calcic horizons indicate changes of soil-climate in the past. These horizons and other pedogenic and stratigraphic relations also suggest that the buried paleosol probably formed about 35,000 to 40,000 yr ago (isotope stage 3). The sediments on which the soil developed (parent material) must be older; and, accordingly, are interpreted as laid down about 60,000 or 70,000 yr ago (isotope stage 4; Shackleton and Opdyke, 1973, 1976).

A second buried soil at 6.2 ft is truncated and only remnants of an argillic (VIBb) horizon remain (Table E-1). The soil is reddish-brown (10YR 4/4) and lighter than the first paleosol, owing to an influx of disseminated lime. But remnants of reddish-brown (5YR 4/4), moderately-thick clay films are preserved in dendritic root channels (horizon VIIIBcab) attesting to moderate relative soil development. The paleosol also has multiple carbonate zones. Some carbonates are pedogenic, whereas others appear to be of groundwater origin. The thickness, argillic horizon morphology, and carbonate accumulation of this paleosol suggest it likely formed during the latter part of stage 5 (substage 5a), about 80,000 yr ago.

The lowermost buried soil, encountered at 10.6 ft, is likewise truncated (Table E-1). Only a remnant argillic horizon (XBcab) is present. The probable age of the soil is afforded by the presence of a distinct calcic horizon (VCab) typified by lime concretions to 0.5-in. diameter (stage III development of Gile *et al.*, 1966). This strong development suggests soil formation throughout much of isotope stage 5; that is, between 80,000 and 125,000 yr ago (Shlemon, 1979). Carbonate samples from the same depth in nearby LLNL Trench E-1 yielded U-series dates averaging about 100,000 yr (Knauss, 1981, p. 18). If these soil-stratigraphic ages and the U-series dates are correct, then the underlying sediments in Trench 1 are obviously older. Inferentially, they were laid down during a preceding epoch of regional alluviation (Shlemon, 1979), namely, stage 6 of Shackleton and Opdyke (1973), from 125,000 to 195,000 yr ago.

LLNL Trench (Test Pit) 2

Trench 2, about 13 ft deep, was excavated adjacent to Trenches E-5 and E-6 across a projected trace of the Corral Hollow Fault in the southeastern part of the LLNL. A detailed soil-stratigraphy was measured and described from the north wall at station 0+25 (Table E-2).

The late Quaternary stratigraphy of this trench is comparable to that of Trench 1. In general, three geologic (depositional) units were observed: the upper bearing the modern solum; and the lower two capped by remnants of buried paleosols.

The upper depositional unit, a 1.6-ft-thick section of poorly-sorted alluvium and local colluvium, gives rise to a weakly developed surface soil with cambic and superimposed eluvial (B-Ae) horizons (Table E-2). The presence of these horizons, their color, horizon topography, and abruptness suggest that soil is forming on sediments less than 15,000 to 20,000 yr old (isotope stage 2).

Geological unit 2, from 1.6 to 7.2 ft, is a moderately developed buried paleosol, characterized by an argillic horizon (IIB_{22tb}) with common, dark reddish-brown (5YR 3/3) illuvial clay films on ped faces (Table E-2). Disseminated lime and a few soft carbonate masses also occur in the subsoil, but of insufficient quantity to designate the horizon as calcic. The almost 4-ft thickness of the paleosol B horizon, and the highly stratified parent material suggest that the paleosol is a cumulic profile (i.e., pedogenesis kept pace with slow deposition). Except for its above-average thickness, this paleosol is morphologically similar to the uppermost buried soil in Trench 1. In its relative development and stratigraphic position, the paleosol is similar to others in the Livermore Valley because it was formed mainly during isotope stage 3, or about 35,000 to 40,000 yr ago (Shlemon, 1979).

The basal geologic unit, from 7.2 ft to base of the trench, bears remnants of a moderately- to strongly-developed paleosol. This soil is also cumulic (Table E-2). Present are argillic horizons (IVB_{31b}) with reddish-brown (5YR 3/3) clay films in root channels, and a calcic horizon with common, segregated lime concretions (carbonate stage III). These pedogenic characteristics indicate that the paleosol probably formed during isotope stage 5 (from 80,000 to 125,000 yr ago). The parent material, laid down during a preceding stage of regional landscape instability, is tentatively assigned an isotope stage 6 age (from 125,000 to 195,000 yr ago).

In contrast to Trench 1, the Trench 2 soil-stratigraphy is not in accord with U-series dates derived from nearby LLNL trenches E-5 and E-6 (Carpenter *et al.*, 1980a). Carbonates from E-5 and E-6, at a depth of about 10 ft and in geologic units similar to unit 3 in TP-2 (Table E-2), yielded several U-series dates, ranging in age from 7,000 and 28,000 yr BP (Knauss, 1981, p. 16). From a regional soil-stratigraphic standpoint, these carbonates should be about 100,000 yr old, similar to comparable calcic horizons in Trench 1 dated by the same U-series technique. The cause of this disparity is not readily apparent, although Knauss points out that the dated samples were collected from "vertical shrinkage fractures" (1981, p. 10). It is thus possible that the samples were contaminated by younger carbonates filling root tubules, a feature characteristic of the buried calcic horizon in Trench 2 (horizon IVB_{33cab}; Table E-2).

Las Positas Fault

In addition to the Corral Hollow Fault, two trenches were excavated on the adjacent Sandia National Laboratory, Livermore (SNLL) to assess the displacement history of the Las Positas Fault (Herd, 1977). Two other trenches in this area had been previously logged by LLNL geoscience personnel, one of which (E-3) exposed the Las Positas Fault and yielded wood fragments dated by radiocarbon (Carpenter *et al.*, 1980a). Of further interest is the Quaternary soil stratigraphy of the Sandia area and whether this can be relatively dated by soil profile development and by association with the marine isotope stage chronology, and in turn correlated with geological units identified in LLNL trenches E-3 and E-4 (location maps and logs in Carpenter *et al.*, 1980a; 1980b). Soil test pits were emplaced on a geomorphic surface slightly above the modern floodplain of Arroyo Seco (Trench 3), and on an adjacent higher geomorphic surface displaced by the Las Positas Fault (Trench 4). Detailed soil profiles were measured and described at each of the test pits, and the stratigraphy dated mainly by geomorphic and stratigraphic position and by relative soil profile development.

SNLL Trench (Test Pit) 3

The soil-stratigraphy of Trench 3 was described on 19 November 1981 from the north wall at station 0+16. Three depositional units were identified: an upper colluvial/alluvial cover, 2.8 ft thick bearing an undeveloped soil (A-C); an underlying gravel-filled channel deposit about 2 ft thick at the measured locality; and a basal, fluvial gravel capped by remnants of a moderately developed, buried paleosol (Table E-3).

The upper depositional unit is a pebbly colluvium derived mainly from the adjacent, higher geomorphic surface. Only stratified organic horizons (A_{11} through A_{15}) are present; this lack of profile development indicating a probable Holocene age.

The middle geological unit, designated IIC (Table E-3), is a fluvial, gravelly sand. No distinct buried soil horizons are present. However, from its dark yellowish brown color (7.5YR 5/6) and the presence of fine roots and casts in the upper part, the gravelly sand was likely subject to incipient pedogenesis. The stratigraphic position of the gravels, their extent as determined from previous trenching, and their slight weathering characteristics, all suggest deposition during a more "humid" environment, here judged to be isotope stage 2, about 15,000 to 20,000 yr ago. Similar fluvial gravels in the same stratigraphic position also occur in nearby LLNL Trenches E-3 and E-4. And these gravels exposed in Trench E-3 yielded wood fragments dated by radio-carbon as 17,400 yr old (Carpenter *et al.*, 1980a, p. 22), supportive of the soil-stratigraphic estimate.

The lowermost geological unit in this trench, from about 4.5 ft to the base of the trench, is also of fluvial origin. However, it bears a moderately developed paleosol, one truncated but still preserving part of the subsoil (horizons $IIIB_{31b}$ and $IIIB_{32}$-Cb; Table E-3). The buried paleosol is a reddish-brown to yellowish-red (5YR 4/4–4/6), gravelly clay loam. Discontinuous clay films coat pebble faces, fill interstitial pores, and bridge mineral grains (Table E-3). The soil is thus comparable in morphology and stratigraphic position to others in the Livermore Valley assigned at 35,000 to 40,000 yr ago (Shlemon, 1979). Accordingly, the parent material (geologic unit 3) is inferred to have been laid down during a previous epoch of regional landscape instability (namely, isotope stage 4, or from 60,000 to 70,000 yr ago).

SNLL Trench (Test Pit) 4

Trench 4 was sited on a regionally extensive, "higher" geomorphic surface near an outcrop on Arroyo Seco that exposes the Las Positas Fault (locations in Carpenter *et al.*, 1980a). The northern escarpment forming the edge of the geomorphic surface is coincident with the Las Positas Fault, but other hypotheses for its origin have also been postulated (summarized in Carpenter *et al.*, 1980a). Of particular interest is the age of sediments and soils underlying this geomorphic surface, for this provides useful information concerning the late Quaternary displacement history of the Las Positas Fault. Trench 4 was therefore sited on the most stable part of the higher geomorphic surface, where the slope was less than about 3°. A detailed soil-stratigraphy was measured and described on 19 November 1981 from the north wall at station 0+15.5 (Table E-4).

Three depositional units were exposed in the 5.5-ft-deep trench: an upper colluvium (slopewash); an intermediate pebbly colluvium; and a basal, mixed fluvial channel and colluvial deposit. These units are separated by buried paleosols (Table E-4).

The upper colluvium (to 1.4 ft) consists mainly of thinly bedded slopewash. This deposit was apparently laid down under an environment more conducive to colluviation than the present, for the surface is now stable and a weak B horizon (cambic) has formed (Table E-4). The modern solum on this colluvium is at best slightly developed and—given its stratigraphic and geomorphic position—it is no more than about 15,000 yr old.

The intermediate colluvium (between 1.4 and 2.8 ft) is morphologically similar to the upper unit. However, it gives rise to a moderately developed, buried paleosol (horizons B_{1b} and B_{2b}) typified by coarse angular-blocky structure and dark brown (7.5YR 3/2) clay films on ped faces and on clasts (Table E-4). This paleosol development and stratigraphic position suggest that most soil formation took place about 35,000 to 40,000 yr ago (stage 3). The parent material is therefore estimated to have been laid down during a previous epoch of landscape instability some 60,000 to 70,000 yr BP (stage 4).

The basal depositional unit is a gravelly coarse sand, mostly fluvial in origin, but containing admixtures of locally derived colluvium. This unit is capped by a strongly developed paleosol, one characterized by strong, coarse, angular-blocky-to-prismatic structure, and reddish-brown (5YR 4/4), moderately thick and continuous clay films on ped faces and in interstitial pores (Table E-4). The paleosol is similar in development to the soil in LLNL Trench 1 dated as 100,000 yr by U-series assay. The paleosol is also comparable in morphology to soils elsewhere in the Livermore Valley judged to have formed between about 80,000 and 125,000 yr ago during isotope stage 5 (Shlemon *et al.*, 1980). If these age estimates are correct, then the gravels of unit 3 were probably deposited during stage 6, about 125,000 to 195,000 yr ago (Shackleton and Opdyke, 1973).

Summary and Conclusions

Soil-stratigraphic and geomorphic reconnaissance were conducted within and adjacent to the LLNL and SNLL areas in the eastern Livermore Valley as part of investigations to determine the presence, extent, and displacement history of the Corral Hollow and Las Positas Faults. Site-specifically, two trenches (soil test pits) were excavated over inferred traces of the Corral Hollow and Las Positas Faults in the southwestern part of the LLNL in order to determine the age of late Quaternary sediments by soil stratigraphy, a method independent of U-series assays. Both trenches exposed fluvial and colluvial units separated by moderately and strongly developed, buried paleosols. The paleosols contained calcic horizons, some of pedogenic and some of probable groundwater origin.

Soil-stratigraphic age assessments, based mainly on relative profile development and association with the marine isotope stage chronology, indicate that the deeper, strongly developed soils in each trench probably formed between 80,000 and 125,000 yr ago (stage 5). The underlying parent material (depositional units) are judged to be stage 6 in age, laid down about 125,000 to 195,000 yr ago. In one case, these age estimates are supported by U-series assay of pedogenic carbonates previously collected from an adjacent LLNL trench; these yielding average ages of about 100,000 yr. In another case, however, U-series dates from the stage 5 paleosol ranged between 7,000 and 28,000 yr. The cause of this disparity is unknown; although contamination by younger carbonates within root tubules, abundant in these horizons, is a distinct possibility.

Two soil-stratigraphic trenches were sited in the SNLL area to assess the age of deposits displaced by the Las Positas Fault. Underlying a geomorphic surface slightly above the Arroyo Seco floodplain are three depositional units: Holocene colluvium, and intermediate and lower gravels separated by buried paleosols. Soil development and stratigraphic position indicated that the intermediate gravel was deposited during isotope stage 2, between 15,000 and 20,000 yr ago. This estimate is borne out by a radiocarbon date of 17,400 yr for similar gravels in a nearby SNLL trench.

The higher SNLL geomorphic surface is also underlain by three depositional units: a latest Pleistocene-Holocene colluvium, an intermediate colluvium, and basal fluvial gravels. These units are likewise separated by buried paleosols. Based on pedological development and stratigraphic position, the intermediate colluvium is probably 60,000 to 70,000 yr old, and the underlying gravels are inferred to be more than about 125,000 yr old. These deposits, and their associated weathering profiles, can be traced to a nearby geomorphic escarpment coincident with the Las Positas Fault. At this locality, with the possible exception of recent slopewash, all geologic and soil-stratigraphic units underlying the "high" geomorphic surface have been displaced.

The soil-stratigraphic age assessments for the LLNL and the SNLL provide a means to date late Quaternary sediments independent of radiometric assays. Combined with detailed logging, borehole data, and radiometric dates presently available, this soil-stratigraphy sets forth a chronology within which to date late Quaternary displacements of the Corral Hollow and Las Positas Faults.

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Geological and Environmental Consultants
24 February 1982

Letter Report

Age of Displacement, Las Positas Fault
Eastern Livermore Valley, California

Introduction

This report summarizes field observations and conclusions regarding the amount and age of displacements for two branches of the Las Positas Fault near the Lawrence Livermore National Laboratory (LLNL) in the eastern Livermore Valley, Alameda County, California. The study is part of soil-stratigraphic investigations to determine the presence and age of faults in this area, and is commissioned under LLNL Contract Order No. 5179101. Soil-stratigraphic measurements and descriptions are given in an accompanying report "Late Quaternary Soil Stratigraphy, Lawrence and Sandia National Laboratories, Livermore, California" (February 1982). The conclusions stated in this Letter Report were reviewed with LLNL Geoscience personnel on 19 February 1982. Geologic logs, location maps and related supporting documentation are on file with the LLNL.

From regional mapping and aerial photographic interpretation, two branches of the Las Positas Fault are recognized near the LLNL: a Northern Branch cropping out in a cut of Arroyo Seco on the Sandia National Laboratory, Livermore (SNLL); and a Southern Branch exposed in a cut along Greenville Road. Both branches clearly displace the Tertiary/Quaternary Livermore Gravels, and in most cases cut overlying late Quaternary alluvial and colluvial units. The approximate amount and sense of displacements noted in this report are vertical; the extent of possible horizontal offset is unknown.

Las Positas Fault, North Branch

Northerly Splay

Detailed logging by the LLNL Geoscience Group shows that two and possibly three splays comprise the North Branch of the Las Positas Fault where exposed along Arroyo Seco. Vertical displacement along one, designated the "northerly splay," is down-to-the-north. The slip surface offsets the Livermore Gravels, an overlying, reddish-brown colluvial gravel, and extends upward into the organic-rich surficial colluvium. No materials suitable for radiometric assay have been observed in the displaced sediments; however, approximate ages can be postulated based on soil-stratigraphic evidence and geomorphic expression.

The base of the reddish-brown (older) colluvial gravels is displaced some 2.5 to 3 ft. Field exposures suggest that a scarp of this height once formed, across which spread additional gravels in the form of a local talus cone. The older colluvial gravels thus appear as a wedge, thickening substantially on the downthrown (north) side of the northerly splay.

These older, reddish-brown gravels are judged colluvial in origin owing to their crudely imbricate structure, which somewhat parallels the escarpment marking the trace of the Las Positas Fault. Additionally, the gravels bear no structural development or consistently-oriented clay films indicative of pedogenesis on a once stable geomorphic surface. Stratigraphic position as well as clast size and the reddish-brown color also suggest that the gravels were derived from adjacent fluvial deposits laid down in the order of 125,000 to 200,000 years ago (marine isotope stage 6) which were then subject to weathering (pedogenesis) about 80,000 to 125,000 years ago (stage 5). Accordingly, from these age assessments and from local stratigraphic and geomorphic relationships, the older gravels in the Arroyo Seco streamcut are judged to be younger than about 80,000 years. Whether displacement along the 2.5 to 3 ft "scarp" represents one or several events is not discernible from the present exposures. It is possible, however, that very detailed examination of the contact between the Livermore Gravels and the older colluvium might reveal the presence of a displaced imbrication pattern or other subtle evidence for multiple movement in late Quaternary time.

The northerly splay slip-surface also extends upward for at least three inches into the base of modern slopewash. This uppermost colluvial wash is a silty gravelly loam laid down across the regional escarpment coincident with the Las Positas Fault in this area. Where exposed in the Arroyo Seco cut, the colluvium is active, moving across a 15- to 18-degree slope. This movement is also reflected in the lack of surface soil development, essentially an A-C profile.

The slip surface is traced to within six inches of the modern surface, and may in fact extend higher. However, root zone bioturbation and active slope movement preclude recognition in this stratigraphic interval. Nevertheless, within a confidence level range of about 50 to 60%, it appears that the slip-surface passes through all of the uppermost colluvium. The last displacement, probably a few inches or less, is thus judged late Holocene in age, occurring possibly not much more than 500 or 1,000 years ago.

Southerly Splay

Another slip-surface of the Las Positas Fault, also exposed in the Arroyo Seco stream cut, is informally called the "southerly splay." It clearly displaces the base of the older colluvium about two feet, in a north-side-up sense of movement.

From a wedge-like bioturbation zone at the base of the older colluvium, a slip surface can be traced almost to the upper part of the unit. The slip-surface, however, apparently does not extend into or displace the upper colluvial slopewash. Differences in thickness of the older colluvium, at its base and top, suggest that about two feet were removed before deposition of the surficial deposits. If these observations are correct, then last displacement (vertical) on the southerly splay predates that on the northerly splay, at least in this area of the Las Positas North Branch. Last movements, a cumulative two feet or so, apparently took place on the southerly splay after about 80,000 years ago and, judged from lack of soil profile development, before an estimated 3,000 or 4,000 years ago.

Las Positas Fault, South Branch

The South Branch of the Las Positas Fault is well exposed in a cut along Greenville Road (south) north of the Arroyo Seco Bridge (location and geologic logs in LLNL Geoscience files). Examination of the west cut shows the presence of several, closely-spaced shears displacing the Livermore Gravels and overlying, post-Livermore channel deposits. At least one splay extends through the post-Livermore deposits, across a capping stoneline, and essentially to the surface.

Reconnaissance shows that the post-Livermore deposits contain remnants of several buried paleosols. These soils all have dark reddish-brown colors (5YR) and strongly-developed argillic (Bt) horizons indicative of formation before about 80,000 years ago. These deposits and interbedded paleosols are clearly displaced.

The capping stoneline is weakly developed, but discernible where crossing various splays of the South Branch. It slopes about 18 to 20 degrees, somewhat more than the modern surface which it essentially parallels. The stoneline is offset about 6 to 8 in., with a north-side-up sense of displacement. Its absolute age is unknown, but is judged to be no older than about 15,000 to 20,000 years (isotope stage 2) formed during a time of "accelerated" regional colluviation.

The uppermost colluvial unit, with the stoneline at its base, is essentially latest Pleistocene and Holocene in age. Except for a thin veneer of wash, the surface at this locality appears to be in equilibrium; that is, no distinct sediment loss or accretion is readily discernible. The modern solum here is also very young, essentially an undeveloped (A-C) profile.

From slight differences in grain size, at least one splay is traceable through this uppermost colluvium. In fact, it extends to the base of this year's annual grasses! A vertical offset of an inch or less would not likely produce a discernible "scarp" on slopes in the immediate area; and indeed none was observed.

However, the upward extent of the slip-surface through the youngest slope wash to the modern surface suggests that at least one movement (tectonic ?) occurred within historic time.

In sum, from the Greenville Road exposure, the South Branch of the Las Positas Fault has had multiple offsets in late Quaternary time. A stoneline, no older than 15,000 to 20,000 years, is displaced vertically 6 to 8 inches; and at least one shear extends to the present surface. The last movement, possibly an inch or less, seemingly occurred during historic time and, conceivably—from the local stratigraphic evidence—may have taken place within the last several years!

Roy J. Shlemon, Ph.D

RJS:bp

Appendix F
Contents and Repositories for Geologic Data Report (UCID-19666)

D. W. Carpenter

A considerable volume of detailed geologic data was collected during the LLNL Site Seismic Safety assessment program. Much of this data was in the form of detailed logs of exploratory boreholes, monitoring wells, trenches, test pits, and other excavations. Because of the volume of data collected and the expense of publication, this material is not included as a direct portion of this report but rather has been printed in limited quantity in the following report:

> Carpenter, D. W., R. J. Clark, D. W. Peifer, B. J. Qualheim, A. L. Ramirez, L. L. Rogers, J. J. Sweeney, and J. L. Wagoner (1982), *Geologic Data Report, Lawrence Livermore National Laboratory Site,* Lawrence Livermore National Laboratory, Livermore, CA, UCID-19666.

A copy of this report has been placed in the LLNL Visitor's Center, where it may be studied by interested parties. The report is filed with other data pertinent to the Final Environmental Impact Statement prepared by DOE for LLNL and SNLL operations.

Copies of this report have also been furnished to the local government and State of California agencies listed below. Interested parties may contact these agencies regarding the availability of the reports for public inspection and, if available, at what times and under what conditions such inspections may be made.

Alameda County Public Works Agency
399 Elmhurst St.
Hayward, CA 94544
ATTN. Edward A. Danehy, Alameda County Engineering Geologist

Alameda County Flood Control and Water Conservation
District, Zone 7
1404 Concannon Blvd.
Livermore, CA 94550
ATTN. Fred Moss

California Division of Mines and Geology
Ferry Building
San Francisco, CA 94111
ATTN. Earl W. Hart, Senior Geologist

City of Livermore, California
1052 South Livermore Ave.
Livermore, CA 94550
ATTN. Howard W. Nies, Director of Planning

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