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**Status report on the geology
of the Lawrence Livermore
National Laboratory site
and adjacent areas**
Volume I: Text and Appendices A-E

**D. W. Carpenter, K. P. Puchlik, A. L. Ramirez
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October 1980

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It must be emphasized that the above individuals and agencies should not be considered to have approved or otherwise endorsed the findings and conclusions contained in this report. The findings and conclusions reported herein are solely those of the authors, who are members of the Lawrence Livermore National Laboratory staff.

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Status report on the geology of the Lawrence Livermore National Laboratory site and adjacent areas

ABSTRACT

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

1. To obtain data for use in preparing a Final Environmental Impact Report for LLNL, pursuant to the National Environmental Policy Act.
2. To obtain data for use in improving the determination of a design basis earthquake for structural analysis of LLNL facilities.

The first phases of these investigations have been completed. Work completed to date includes a comprehensive literature review, analyses of three sets of aerial photographs, reconnaissance geophysical surveys, examination of existing LLNL site borehole data, and the logging of seven exploratory trenches, segments of two sewer trenches, a deep building foundation excavation, a road cut, and an enlarged creek bank exposure. One absolute age date has been obtained by the ^{14}C method and several dates of pedogenic carbonate formation have been obtained by the $^{230}\text{Th}/^{234}\text{U}$ method. A seismic monitoring network has been established, and planning for a site hydrologic monitoring program and strong motion instrument network has been completed. The seismologic and hydrologic investigations are beyond the scope of this report and will be discussed separately in future documents.

LLNL is located in the southeast 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 Diablo Range consists dominantly of metamorphic and igneous rocks of the Jurassic-Cretaceous Franciscan Assemblage. The Diablo Range is generally bounded to the west by the active San Andreas Fault system and to the east by the Coast Range Thrust Fault system. The San Andreas Fault system is a right lateral strike-slip fault system along which the Pacific Plate and the North American Plate are currently moving past one another. The Coast Range Thrust Fault system marks the location of an extinct subduction zone along which rocks of the Franciscan Assemblage and marine sedimentary rocks of late Mesozoic through late Tertiary age are juxtaposed.

Livermore Valley itself is underlain by up to 4,000 feet of predominately continental alluvial deposits of late Tertiary and Quaternary age. The active Calaveras and Greenville Fault zones bound the Valley on the west and east, respectively, while the active Las Positas Fault traverses at least a portion of the southern margin of the Valley. As discussed in this report, previous investigators have postulated thirteen other major and many minor faults within and near the Livermore Valley. Three of these, the Corral Hollow, Dougherty and Tesla Faults have been projected across LLNL by some previous investigators.

Within LLNL no evidence for the Corral Hollow or Doutherty Faults has been found in exploratory trenches and excavations made across their postulated locations. Undisturbed strata exposed in these trenches and excavations are of late Quaternary age, based upon soil profile development and dating of pedogenic carbonates by the $^{230}\text{Th}/^{234}\text{U}$ method.

Exploration within Sandia National Laboratory, Livermore (SNLL) property, which adjoins LLNL on the south, has confirmed late Quaternary and possibly Holocene activity along the Las Positas Fault zone. A ^{14}C age of $17\,400 \pm 250$ yr has been obtained for a wood sample preserved in the lower portion of an alluvial sequence displaced by the fault. Preserved slickensides dip at low angles, indicating predominately strike-slip movement along the Las Positas Fault.

An exploratory trench located south of the main strands of the Las Positas Fault zone produced no evidence for the second strand of the Tesla Fault zone as previously mapped. The second strand of the Tesla Fault is regarded by some investigators as potentially active. The exploratory trench penetrated late Quaternary terrace deposits and it exposed beds of the underlying Plio-Pleistocene Livermore Formation throughout most of its length.

Other faults of potential significance to LLNL have not as yet been investigated in detail. A $M = 5.9$ (U.S. Geological Survey) earthquake on the Marsh Creek Fault, a portion of the Greenville Fault zone, and numerous aftershocks provided unquestionable evidence for activity along that fault zone. Additional field studies are planned to better determine the extent of the Greenville Fault zone so that a refined assessment may be made of its maximum magnitude earthquake potential.

Investigations to obtain more data on the extent of the Las Positas Fault zone and its relationship to the postulated Livermore Fault zone are planned, as are studies of an area several kilometers south of LLNL where considerable microseismic activity has been detected.

Additional subsurface exploration within LLNL is being undertaken to assess the possibility of ground failure during a major earthquake; this work will be done concurrent with the planned hydrologic investigation. Appropriate geophysical and age determination studies will be performed in support of future field reconnaissance and exploration.

INTRODUCTION

OBJECTIVES AND SCOPE OF PROJECT STUDIES

In April 1979, a project consisting of comprehensive geologic, hydrologic, and seismologic investigations of the Lawrence Livermore National Laboratory (LLNL) site and nearby areas was begun by LLNL geoscience personnel. This study is being made at the request of LLNL management and is designed to provide an in-depth appraisal of aspects of site and regional geology that bear upon

safe operation of LLNL facilities. The area being studied includes the Livermore Valley, the western portion of the Altamont Hills, and the northern margin of the Diablo Range south of LLNL.

Particular emphasis is being placed upon identification and location of faults in the vicinity of the Laboratory and on the development and assessment of geologic and seismologic data bearing on fault activity and motion. Other geologic hazards such as slope stability and the potential for ground failure during a major earthquake are also being assessed.

Hydrologic studies will concentrate on the locations of aquifers, the transmissive characteristics of materials beneath the LLNL site, and the potential for ground water contamination in the event of a significant on-site spill of radionuclides or toxic chemicals.

The geologic, hydrologic, and seismologic data will serve as technical input to a Final Environmental Impact Report being prepared for LLNL, pursuant to the National Environmental Policy Act. The geologic and seismologic studies will also provide data for improving the design basis earthquake for LLNL. The improved design basis earthquake parameters will in turn be used by LLNL structural engineers as they reevaluate the adequacy of the seismic resistive designs of important Laboratory buildings.

OBJECTIVES AND SCOPE OF THIS REPORT

The first phase of the LLNL site study has been completed. Although additional major geoscience studies are planned for later 1980 and 1981, investigations to date have yielded significant geologic and geophysical data. Therefore, this report has been prepared in order that the geologic community and the public may be made aware of the results of these investigations and LLNL staff plans for future work.

The following studies have been completed and provide the basis for this status report:

- *Literature review and site visits.*

A thorough review and evaluation of existing geologic, geophysical, and seismic literature pertinent to the LLNL site and vicinity has been completed. A brief field reconnaissance was made of those areas south and east of LLNL where previous geologic studies differ significantly with respect to both data and interpretations.

- *Subsurface studies.*

All known subsurface data previously obtained for the LLNL site has been collected and evaluated. These data largely consist of exploratory borings made during foundation design studies for major buildings at LLNL.

- *Photographic studies.*

Three sets of black and white stereoscopic aerial photographs of the LLNL site and vicinity were examined for features potentially indicative of

faulting. Photo sets examined include flights in 1940 (scale 1:20,000) and flights in 1958 and 1972 (scale 1:12,000).

- *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 as a means of developing more detailed structural and stratigraphic data.

- *Geologic exploration.*

A major field investigation was conducted within and near the LLNL site to examine near-surface materials in areas where previous investigators have postulated faults or where geologic or geophysical studies have identified anomalies suggestive of faults. The field investigation consisted of the excavation and detailed geologic logging of seven exploratory trenches, improvement and mapping of an outcrop along the west bank of the Arroyo Seco within Sandia National Laboratory, Livermore (SNLL) property, and mapping of the Greenville Road cut north of the South Bay Aqueduct. 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.

- *Dating of soils.*

Samples of carbonaceous materials and caliche were obtained from exploratory trenches and exposures and were evaluated as to suitability for radiometric dating by established ^{14}C and experimental $^{230}\text{Th}/^{234}\text{U}$ dating method. Dating of suitable specimens has been completed. Geologic interpretations of the dates obtained are presented in this report.

OTHER PROJECT STUDIES

A seismic monitoring network, consisting of nine stations, has been established and is monitoring the microseismicity of the Livermore Valley and adjacent areas. At the beginning of the Livermore Valley earthquake sequence on January 24, 1980, four seismic monitoring stations were operative. A fifth station was put into operation on January 25, 1980. These stations provided valuable information

about the aftershock sequence that followed the January 24, 1980 earthquake. Details of the network operations and seismologic observations made will be discussed in separate project reports. A program for the installation of strong motion instruments in key buildings and at selected free-field sites at LLNL has been planned. Instruments are being procured and will be installed in early 1981.

LAWRENCE LIVERMORE NATIONAL LABORATORY SITE

LOCATION

The Lawrence Livermore National Laboratory is located in Sec. 12 (projected), T3S, R2E, Mt. Diablo Base and Meridian. The Laboratory site is in the southeastern portion of the Livermore Valley approximately 65 km (40 mi) east of San Francisco. The site and its environs are shown on 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 (6350 ft). Slopes on the site are relatively uniform and generally do not exceed three percent. Exceptions are the banks of the Arroyo Seco Creek channel and the side slopes of various open drainage ditches within LLNL. These slopes average about 50 percent. Site topographic features are shown on 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

Planning of the hydrologic investigation has been completed. Installation of monitoring wells and the obtaining of soil samples for determination of hydrologic parameters and nuclear chemistry studies are scheduled to be completed during the second half of 1980. The results of the hydrologic investigation will be presented in future project reports.

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 Arroyo Seco Creek.

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 (300 ft) at the drainage exit along the Arroyo de Laguna southwest of Pleasanton to an approximate elevation of 220 m (725 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 reach San Francisco Bay at Union City, by way of Alameda Creek.

FIG. 1. Location map of Lawrence Livermore National Laboratory (LLNL).

FIG. 2. Topographic setting of LLNL site (from USGS Altamont, CA Quadrangle, 1968 edition).

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 the 20th century, the lake was drained to permit agricultural develop-

ment, 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

REGIONAL GEOLOGY

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

This 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 and are related to local geology, there are three major fault systems that have been fundamental in the history of the province. These are: the San Andreas, the Sur-Nacimiento, and the Coast Range Thrust. These fault 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 eugeosynclinal rocks of the Franciscan assemblage. The third block consists of late Mesozoic through late Tertiary marine sedimentary rocks 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 Berkeley Hills west of Livermore Valley) remnants of this block are preserved within the core of the Coast Range province.

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 con-

tacts with the surrounding rocks. The Franciscan assemblage is a melange of graywacke, siltstone, shale, chert, limestone, and mafic volcanic rocks and in places has been so deformed as to resemble a megabreccia. However, abutting the Franciscan on the east is the contemporaneous miogeosynclinal Great Valley sequence (of late Mesozoic age) and overlying Tertiary rocks, which are ordered and conformable.

Both the Franciscan assemblage and the Great Valley sequence consist mainly of marine clastic rocks, but they differ in style of deformation and degree of metamorphism. The origin of the Franciscan assemblage and its tectonic relationship to the Great Valley sequence have long been subjects of controversy. Irwin (1957) and Bailey and others (1964) noted that faults generally separate the Franciscan from the Great Valley sequence, and they suggested that the Franciscan rocks and the Great Valley sequence are juxtaposed along a regional thrust fault, later named the Coast Range Thrust (Bailey and others, 1970).

Within the last decade, the concept of plate tectonics has revolutionized the interpretation of Coast Range geology. According to current theories, the Franciscan assemblage accumulated in a subduction zone, while the Great Valley strata accumulated farther east in a fore-arc basin (Hamilton, 1969; Blake and Jones, 1974). The ultramafic and mafic rocks that commonly separate these two sequences represent the oceanic crust and the upper mantle that now lie below the base of the westernmost 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 Fault located mainly along the eastern margin of the Coast Range Province is believed to mark the location of the subduction zone.

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

The Coast Range Thrust was active primarily between Jurassic and later Tertiary time. During that period, the fault was the most significant structural feature in California, marking the active subduction zone between the North American plate and various plates that existed to the west of the North American continent (Page, 1966). Thrust displacements across the fault were measured in many kilometers. During late Tertiary time, changes occurred in regional tectonics and the thrust fault surface was warped, folded, and sheared, consequently developing a complex *en echelon* fault system (Bailey and others, 1970). The Greenville, Tesla, and Orizaba Fault zones, located along the eastern margin of the Livermore Valley, are portions of this *en-echelon* fault system and are periodically active, as evidenced by the Livermore Valley earthquake sequence that began on January 24, 1980 (Cockerham and others, 1980).

Meanwhile, at great depth within the subduction zone, the Franciscan was successively metamorphosed and was then periodically returned to the surface (Ernst, 1971). This model accounts for the different deformation styles and metamorphic assemblages in the Franciscan Complex and Great Valley sequence.

In the Central California area, active subduction continued into Cenozoic time. The Pacific Ocean at that time extended inland to the foothills of the Sierra Nevada and a continental shelf that extended offshore included a large part of the present day Great Valley and some portions of the area where the Coast Ranges now stand. During most of the Cenozoic era, tectonic movements produced four cycles of marine deposition that are clearly recorded in the Paleocene to Miocene rocks of the Sacramento Valley region (Almgren, 1978). Rocks correlative with those in the Sacramento Valley region occur in the Altamont Hills east and southeast of LLNL. The Altamont Hills area has been highly disturbed by movements along faults that are descendants of the ancient Coast Range Thrust fault zone. The pattern of marine sedimentation is thought to have come to an end in Miocene time (roughly 15 million years ago) when right lateral plate boundary movement began along the San Andreas Fault system (Sullivan and Waters, 1980).

The San Andreas Fault and its associated branches are the best known geologic features of the

Coast Range Province. The fault system extends at least 1200 km (750 mi) from near the Mexican border north to Shelter Cove, California (Wesson and others, 1975). Based upon a paleogeographical 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.

Extensive Quaternary activity has led to the formation of a series of valleys along the entire length of the San Andreas Fault. Within these valleys, which vary in width from hundreds to thousands of feet, is a zone of brecciated rocks. The San Andreas Fault cannot be traced as a single strand through this zone; surface rupture usually occurs discontinuously across *en echelon* faults. Frequently, as a result of local stress concentrations or other factors, faults will branch off the main fault system and form subsidiary fault zones.

The geologic conditions in the region around Hollister are apparently conducive to branching: several significant branch faults diverge from the San Andreas in this area. Two of the most significant branches are the Hayward Fault zone and the Calaveras Fault zone (Fig. 4). Both of these faults are among the longest in the state. They disappear beneath the waters of San Francisco Bay and alluvial cover in the San Ramon Valley, respectively. During the 19th Century both faults generated large earthquakes, and both are presently readjusting to stress by creeping. Block faulting between the Hayward and Calaveras Faults gave rise to the impressive horse structure of Sunol Ridge west of the Livermore Valley.

Generally, the basement rocks between the San Andreas and the Coast Range Thrust Fault systems are Franciscan. In the region of Livermore, this area of Franciscan rocks is called the Diablo Antiform. The Diablo Antiform is a topographic and structural high that has been complexly folded and faulted. The Diablo Antiform is seismically active and monitoring by the U.S. Geological Survey during the period of 1969-1979 has defined several tight clusters of seismicity within the Antiform imbedded in a diffuse background of activity (Ellsworth and Marks, 1980).

As noted previously, the Livermore Valley itself is an exception to the general pattern of Coast Range geology. It is a structural and topographic

FIG. 4. Major fault zones of the San Francisco Bay area. The great San Andreas zone, lying to the west of the Bay, is one of the chief tectonic features of the earth. It is capable of very strong earthquakes—for example, the San Francisco earthquake of 1906, of magnitude 8.3. The Hayward and Calaveras zones, lying between the Livermore Valley and the Bay, are parts of the San Andreas system, branching off from the main fault some distance south of the Bay. These faults, too, are active and have produced strong earthquakes, probably up to magnitude 7.5. The Greenville, Tesla and Ortagalita Faults, located to the east of LLNL, may be remnants of the Coast Range Thrust Fault. The Livermore Valley earthquake sequence that began on January 24, 1980 gives evidence that these faults are periodically active. The Verona, Livermore, and Las Positas Faults are additional elements in Livermore Valley geology, although their tectonic significance is uncertain.

low area trending at nearly right angles to the regional grain. The Valley is filled with several thousand feet of young, largely continental, sedimentary deposits (CDWR, 1966) and includes northeast as well as northwest trending tectonic features (Herd, 1977).

GEOLOGY OF LIVERMORE VALLEY AND ADJACENT AREAS

Previous Studies

Early geologic work in the Livermore Valley and adjacent areas was performed by A. Huey (1948). Huey mapped the geology of the Tesla 15-minute quadrangle, and he traced and named a number of strands of the Tesla-Ortogonal Fault system in the hills east and southeast of LLNL. Geology as mapped by Huey is shown in Fig. 5.

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 ground water barriers that were believed to be the results of fault displacements. In 1974 CDWR made some revisions and extensions to their previous work. The Department's 1974 geologic map of the eastern Livermore Valley is shown in Fig. 6.

In 1971, John A. Blume and Associates (Blume) prepared a geotechnical investigation report concerning additions to the LLNL Plutonium Handling Facility, Bldg. 332. This study drew largely upon 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 Blume report (Blume, 1972), Huey provided background geologic information. Huey extrapolated several of his previously mapped faults from the hills into the Livermore Valley. These were the Greenville, Carnegie, Corral Hollow, and Tesla Faults.

Blume 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 was inspected for evidence of faulting.

On the basis of its investigations, Blume added strands 2 and 3 of the Tesla Fault, the Ramp Thrust Fault, and the Dougherty Fault to Valley geology. Blume concluded that west of Greenville Road and southeast of the Laboratory there was no geophysical evidence for the Corral Hollow Fault that had been previously projected across LLNL. Fault locations as postulated by Blume (1972) are shown in Fig. 7. Blume (1972) also produced geologic cross section A-A' (for location, see Fig. 7) based on interpretations of well data. This cross section is shown in Fig. 8.

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 study showed no strands of the Tesla Fault Zone as projected northwest by Huey (Blume, 1972). In contrast, Herd considered the Tesla to be a part of the Greenville Fault Zone and showed the two faults merging in the NE 1/4 Sec. 34, T3S, R3E. Herd's interpretation of the fault pattern near LLNL is shown in Fig. 9. He also reinterpreted the well data used by Blume (1972) and created a modified cross section as shown in Fig. 8.

In 1978, URS/Blume and Associates (URS/Blume) did a field study for SNLL. URS/Blume's general picture of the faulting changed little except that the Tesla 3 fault was removed and the Tesla 2 was moved slightly. 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. Faulting as interpreted in 1978 by URS/Blume is shown in Fig. 8 and Fig. 10.

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. The 1979 CDWR study was based upon review of previous reports, field checking and reconnaissance mapping, reexamination of preconstruction exploration and construction records, and a limited trenching program.

SYMBOLS

Abbreviations: c-coal, cl-clay, Cr-chromite, f-foundry sand, h-hornstone, Mg-magnetite, Mn-manganese, r-rock used for roofing granules.

FIG. 6. Geologic map of southeastern Livermore Valley (CDWR, 1974).

FIG. 8. Section A-A', as shown in Blume (1972), in Blume (1978), and in Herd (1977). At a depth of about 2000 ft below sea level, between wells N-1 and N-2, the sections show a contact of the Franciscan and Panoche formations, which implies a relative displacement between the two of 5 000 to 10 000 ft. Such a displacement is usually interpreted as evidence of a fault. Blume (1972) identifies it as the Tesla Fault. The evidence from these same two wells, however, also shows that this contact is overlain by sands, gravels, and clays that have been undisturbed at least since the beginning of the Pleistocene epoch, more than a million years ago. Such a long period of dormancy suggests that the fault, if there is one, is inactive. Comparing Blume's 1972 and 1978 sections, one sees that Tesla Fault 2 has been introduced into the latter, and that the structure around well H-1 has been changed. Blume (1978) cites no new evidence, and an examination of the well logs by LLNL staff shows no reason for the change. Herd (1977) interprets the data near well H-1 essentially as originally interpreted by Blume (1972).

FIG. 9. Geology and faulting as mapped by Herd (1977). An essential difference from Huey and Blume is the replacing of the northwest-southeast trending strands of the Tesla system by southwest-northeast trending strands of the Las Positas zone in the region south of the LLNL site. Herd's interpretation of geologic cross section A-A' is shown in Fig. 8.

FIG. 10. Faulting as mapped in Blume (1978). Except for the deletion of Tesla Fault 3 and a slight relocation and questioning of Tesla Fault 2, this map is essentially the same as Fig. 7. Blume's 1978 interpretation of geologic cross section A-A' is shown on Fig. 8.

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 (that is, only the central portion of the fault zone shown in Fig. 9). 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. The 1979 CDWR interpretation of faulting near LLNL is shown in Fig. 11.

In view of the existing, often contradictory, geologic studies to date, a detailed reassessment of the geology in the vicinity of LLNL is required to provide adequate information for a Final Environmental Impact Statement and to permit improvement of the design basis earthquake for LLNL facilities.

Stratigraphy

General. Stratigraphic units exposed in the Livermore Valley and adjacent areas may be discussed in terms of three general groupings. These are:

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 previously under Regional Geology, rocks of the Franciscan assemblage and the earlier portions of the Cretaceous through later Tertiary sedimentary sequence are equivalent in age but were deposited in differing tectonic environments and appear to have been juxtaposed by movements along the Coast Range Thrust Fault system.

A generalized stratigraphic section for the Tesla 15-minute quadrangle was published by Huey (1948), and is reproduced in a modified form as Fig. 12. Brief descriptions of the formations described by Huey will be provided in following paragraphs. Additional subdivisions of Quaternary geology have been proposed by Helley and others

(1972) and Herd (1977); they will also be described below.

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 4000 ft of Plio-Pleistocene to Holocene alluvial deposits (CDWR, 1966). 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).

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 and forms irregular blocks in outcrop. In the vicinity of the Tesla Fault trace, as mapped by Huey (1948), the Franciscan assemblage is pervasively sheared. On the Fellingham Ranch in Sec. 28, T3S, R3E, the formation contains lenses of chert.

Cretaceous-Late Tertiary Marine Sedimentary Rocks. In fault contact with the Franciscan assemblage is the Lower Cretaceous Horsetown Formation, which was mapped by Huey in Sec. 27, T3S, R3E. Outcrops expose a greenish-brown to buff sandstone that is difficult to distinguish from the bordering Franciscan assemblage. The contact is thus uncertain.

The Horsetown Formation is overlain by the upper Cretaceous Panoche Formation (Huey, 1948). The Panoche Formation is widely exposed in the Livermore area and is referred to in more recent reports as the Great Valley sequence (Herd, 1977; CDWR, 1979). Regionally the Panoche Formation typically consists of variably cemented, brown, concretionary sandstone interbedded with dark gray shale and occasional conglomerate. However, in the area studied during this investigation (Sec. 27, T3S, R3E), the Panoche sandstone is greenish-gray and on first appearance resembles Horsetown sandstone. Only close examination reveals a different mineralogy. The presence of friable shale in the Panoche Formation also helps to differentiate between these two units. However, there is a

CENOZOIC	QUATERNARY	HOLOCENE	Qal	ALLUVIUM: UNCONSOLIDATED GRAVEL, SAND, SILT, AND CLAY.
		PLEISTOCENE	Qls	LANDSLIDE: ARROW INDICATES DIRECTION OF MOVEMENT
	TERTIARY	MIOCENE	QTI	LIVERMORE GRAVELS: POORLY CONSOLIDATED BUFF GRAVELS, GRAY SAND AND MINOR SANDY CLAYS. NONMARINE
			PLIO-PLEISTOCENE	
MESOZOIC	TERTIARY	MIOCENE	Tn	NEROLY SANDSTONE: BLUE SANDSTONE WITH MINOR CLAY SHALE, SILTSTONE, TUFF AND CONGLOMERATE. PREDOMINATELY MARINE
			Tc	CIERBO SANDSTONE: WHITE, YELLOW AND BUFF. MASSIVE TO CROSS BEDDED QUARTZOSE SANDSTONE WITH MINOR CONGLOMERATE AND CLAY SHALE. MARINE
			Kp	PANOCHÉ FORMATION: THINLY BEDDED TO MASSIVE, OCCASIONALLY CONCRETIONARY, SANDSTONE WITH INTERBEDDED CLAY SHALE AND SILTSTONE. MARINE
				UPPER CRETACEOUS

DEBORG C. L. HART

— 3 —

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BAY AQUEDUCT STATION AT+45 TO STATION
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MAP SCALE

FIG. 11. Geology of Patterson reservoir and vicinity (CDWR, 1979).

FIG. 12. Stratigraphic column for Livermore Valley (modified from Huey, 1948).

problem in differentiating the Horsetown and Panoche Formations in areas devoid of outcrop because of similar appearing float.

Huey (1948) mapped the late Cretaceous Moreno Grande Formation that overlies the Panoche Formation in a band extending southeast from Sec. 27, T3S, R3E to Sec. 33, T3S, R4E. The Moreno Grande Formation consists dominantly of dark siliceous, argillaceous, and 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 diggings provide excellent exposures. The unit is characterized by a white-to-buff quartz sand that lacks bedding. Attitudes in this formation are thus rare.

The Miocene Cierbo Formation unconformably overlies the Tesla Formation and is well exposed along Patterson Pass Road (Sec. 9, T2S, R3E). It consists of poorly consolidated white-to-buff sands with iron-oxide filled fractures. 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, and minor tuff and tuffaceous shale beds. The unit is easily mappable because of its distinctive purplish float and an abundance of bedding planes. The Neroly outcrops mainly along and north of Corral Hollow Road, 5 to 14 km (3 to 9 mi) southeast of LLNL, where it is preserved in a faulted syncline bordered to the north and south by the Cierbo Formation. Some new ranch roads in this area and to the northwest have exposed bedrock; these exposures reveal that the formation contacts are locally different from those shown by previous mappers.

Late Tertiary to Holocene Sediments. Livermore Valley is a topographic and structural depression filled with fluvial and lacustrine sediments of Plio-Pleistocene and Holocene age (CDWR, 1966; Blume, 1972). The total thickness of these deposits may locally exceed 4000 ft (CDWR, 1966). This thick sedimentary sequence has been subdivided

into the Plio-Pleistocene Livermore Formation and undifferentiated late Pleistocene to Holocene alluvium (ibid.). The subsurface boundary between the two units cannot be clearly established because of similarities of the two deposits, which consist of complex assemblages of gravel, sand, silt, and clay. More recently, other investigators have proposed further subdivisions, particularly for the late Pleistocene to Holocene alluvium (Helley and others, 1972; Herd, 1977).

The CDWR (1966) examined well drillers' logs 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 section are generally poorly cemented and are not preserved, at least in the coarser fractions.

The CDWR (1966) did not initially report any distinct areal variations in the composition of the Livermore Formation beneath the Livermore Valley. However, subsequent work (CDWR, 1974), recognized a clayey facies in exposures of the Livermore Formation along the eastern margin of the Valley. Herd (1977) mapped the same area but did not identify any subdivisions.

The CDWR (1966) analyzed logs of wells and noted 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 Mcho), 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) estimated that from a few feet up to 200 ft 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 ± 200 yr was obtained from a sample taken at a depth of about 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 sedimentation indicated by the age of the ^{14}C sample is representative of rates of sediment accumulation in the western Valley (about 3.5 ft per 1000 yr), then the indicated depth of Holocene alluvium (last 11 000 yr) in the area would be about 38 ft, roughly 20% of the maximum amount estimated by the CDWR.

Three other subdivisions have been made of near-surface materials within and adjacent to Livermore Valley. Huey (1948) separated the "Livermore Gravels" from the Quaternary terrace and alluvial deposits but did not further subdivide the Quaternary alluvium. Helley and others (1972) produced a map showing six subdivisions of the Quaternary alluvial sequence within Alameda County based upon soil types, stratigraphic position, and geomorphology. The portion of this map showing alluvial deposits near LLNL is shown as Fig. 13. Surficial deposits in the eastern Livermore Valley were largely mapped as Older Alluvial Fan Deposits (Qof) with some Younger Alluvial Fan Deposits (Qyf) near stream channels. Younger Alluvial Fan

Deposits predominate in the central and western portions of the Valley. The CDWR (1974) generally followed the alluvial classifications proposed by Helley and others.

Herd (1977) remapped the eastern two-thirds of the Livermore Valley and proposed a more detailed subdivision of the Older Alluvial Deposits than existed before. Herd recognized four subdivisions of the older alluvium based upon interpretations of soil series, degree and depth of soil profile development, and correlations of terrace surfaces (see Fig. 9). The four subdivisions were numbered Qoa₁ through Qoa₄, respectively, based upon increasing relative ages. Herd did not provide detailed descriptions of these units or specific criteria for their recognition.

None of the previous investigators of Livermore Valley geology were able to assign absolute ages to Quaternary alluvial units. Herd (1977) stated that all of the soils on older alluvial units have argillic (clay-enriched) B horizons and are therefore of Pleistocene age. He cited Birkeland (1974) as having established that in California, some 40 000 years of soil formation appear to be required to form a minimal B horizon. Herd regarded recent flood-plain alluvium and stream gravels as Holocene materials, a conclusion based on their deposition in the modern stream regimen.

A result of LLNL studies has been the determination of several age dates for alluvial deposits present in exploratory trenches within LLNL and neighboring SNLL sites. Materials dated include a wood fragment dated by the ^{14}C method and several specimens of pedogenic carbonate ("caliche") dated by the $^{230}\text{Th}/^{234}\text{U}$ method developed by Ku and others (1979). Sample locations and dating methodology are discussed in Appendix C of this volume and in Appendix F, found in Volume II of this report.

A comparison of the locations of dated materials with the late Quaternary stratigraphy proposed by Herd (1977) reveals the following:

- The ^{14}C date obtained from the wood fragment is 17400 ± 250 yr (Robinson, 1980). The material containing the wood fragment was mapped by Herd as Qoa₂. The sample site is in exploratory trench E-3, is located beneath a terrace or alluvial fan surface, and is about 75 ft northeast of Arroyo Seco Creek, within SNLL property (see Fig. 31).
- Two mature soil profiles were recognized in exploratory trenches excavated in the northeastern

DESCRIPTION OF UNITS

- Qyf** YOUNGER ALLUVIAL FAN DEPOSITS -- Includes colluvial fill in narrow canyons. Unconsolidated, moderately sorted, permeable fine sand and silt, with gravel becoming more abundant toward fan heads and within canyons. Forms well-drained levees which grade headward to stream deposits on terraces cut in Qof. Thickness varies from as much as 50 feet at fan heads and in canyons to about 20 feet where Qyf inter-fingers with Qyfo and Qb at the outer margins of fans. Locally contains aboriginal artifacts and skeletal remains.
- Qyfo** YOUNGER FLUVIAL DEPOSITS -- Unconsolidated deposits of fine, but variable grain size--mainly fine sand, silt, and silty clay; intermediate in character and lateral extent between Qb and Qyf. Forms levees and overbank deposits along the San Francisco Bay margin and in Livermore Valley, as well as valley fill in some open canyons. May be in part windblown in the southwestern part of the county. Generally less than 15 feet thick. Overbank deposits locally contain minor amounts of organic matter including fresh-water gastropods and pelecypods.
- Qb** INTERFLUVIAL BASIN DEPOSITS -- Plastic, poorly sorted, organic-rich clay and silty clay in poorly drained areas marginal to the bay and in Livermore Valley. Interfingers with Qyf, Qyfo, and recent mud of San Francisco Bay. Generally less than 10 feet thick. Locally contains fresh-water gastropods and pelecypods.
- Qof** OLDER ALLUVIAL FAN DEPOSITS -- Includes stream terrace deposits in some narrow canyons and on the margins of Livermore Valley. Weathered, weakly consolidated, poorly sorted silt sand and gravel (generally fine grained in northeastern Livermore Valley owing to derivation from friable sandstone bedrock). Less permeable and more poorly drained than younger alluvial fan deposits. Maximum thickness unknown but at least several hundred feet thick near bay margin. Headward portions overlapped by younger deposits on southern bay margin and incised by channels that are partially filled with younger deposits on northern bay margin and in Livermore Valley. Locally contains concentrations of continental vertebrate and invertebrate fossils. Includes the San Antonio Formation of Lawson (1914).
- QTs** DEFORMED OLDER SEDIMENTARY DEPOSITS -- Poorly consolidated to semiconsolidated alluvial deposits of gravel, sand, silt and clay with subordinate fine-grained lacustrine deposits; locally tuffaceous; locally contains abundant remains of continental vertebrate and invertebrate fossils. Maximum thickness unknown but over 5,000 feet in the hills south of Livermore Valley. Includes the Irvington Gravels of Savage (1957) in the Warm Springs and Mission San Jose districts of Fremont, the Livermore Gravels of Clark (1930) south of Livermore Valley, and the Tassajara Formation of Oesternrich (1955) north of Livermore Valley.

FIG. 13. Surface geology of the LLNL site and near vicinity (adapted from Helley and others, 1972).

FIG. 14. Locations of reported ground failures within Livermore Valley and nearby areas. The failures shown resulted from the great San Francisco earthquake, April 18, 1906 (location 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.

that an earthquake of magnitude 8.3, the largest historically experienced on the San Andreas Fault, could generate a peak bedrock acceleration of 0.4 g at LLNL.

Hayward Fault. The Hayward Fault is located generally along the eastern margin of the San Francisco Bay plain and passes about 32 km (20 mi) southwest of LLNL at its closest approach (Fig. 4). The known length of the Hayward Fault zone has been estimated as 72 km (45 mi) by Wesson and others (1975).

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

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, (Fig. 4) (Wesson and others, 1975). Ground failures as far away as San Francisco, were caused by the October, 1868 earthquake. However, none were reported from the Livermore Valley, which was then sparsely settled (Youd and Hoose, 1978).

Wesson and others (1975) indicate a maximum probable earthquake of magnitude 7.0 for the Hayward Fault zone, based on empirical length-magnitude relationships. The earthquake on October 22, 1868 is believed to have had a magnitude of 7 ± 0.5 (ibid) 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) could generate a peak bedrock acceleration of 0.35 g at LLNL.

Calaveras Fault. The Calaveras Fault zone branches from the San Andreas system near Hollister, (slightly south of the limits of Fig. 4) and trends northwest to the San Ramon Valley, a distance of about 115 km (72 mi) (Wesson and others, 1975). 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 (Fig. 4).

The Calaveras Fault zone has been historically active and a major earthquake in 1861 (estimated magnitude 6+) within the Livermore or San Ramon Valley has been attributed to the Calaveras Fault (Radbruch, 1968) (Fig. 15). 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). Ground failure appears to have occurred in the San Ramon area during the 1861 earthquake (location 168 on Fig. 14) (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. Right lateral tectonic creep has been measured along the segment of the Calaveras Fault zone south of Sunol (Wesson and others, 1975) and considerable microseismicity is associated with this portion of the Calaveras Fault zone (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 (ibid).

Wesson and others (1975) indicate a maximum probable earthquake of magnitude 7.3 for the Calaveras Fault zone, based on empirical length-magnitude relationships. Wight (1974) estimated that an earthquake on the Calaveras Fault of magnitude 7.5 at a distance of 17 km (11 mi) could generate a peak bedrock acceleration of 0.5 g at LLNL.

Faults in Livermore Valley and Adjacent Areas.

In addition to the Calaveras Fault, the CDWR (1966, 1974) mapped six other major faults and six minor faults within the Livermore Valley. Faults mapped in the Valley by the CDWR in 1966 and 1974 are shown on Figs. 6, 15 and 16. Fault locations were based largely on apparent groundwater flow barriers and variations in water quality, but CDWR studies also included air photo interpretation and limited geophysical investigations.

The six other major faults identified by the CDWR (1974) were the Carnegie, Corral Hollow, Tesla, Mocho, Livermore and Pleasanton Faults. The six minor faults included the Verona, Parks and four local, unnamed faults. The CDWR (1974) also

FIG. 15. Faults in western Livermore Valley (CDWR, 1974).

FIG. 16. Faults in central Livermore Valley (CDWR, 1974).

mapped the Williams and Valle Faults in the foothills south of Livermore Valley (see Fig. 34). In 1979, the CDWR provided additional data on the Livermore and Carnegie Fault zones.

Huey (1948) mapped the Greenville Fault as bounding the eastern margin of the Livermore Valley.* Huey mapped four additional faults in the hills southeast of Livermore Valley. From northeast to southwest these are the Patterson Pass Fault, the Carnegie Fault, the Corral Hollow Fault, and the Tesla Fault, respectively (see Fig. 5).

Huey showed the Greenville Fault crossing Quaternary alluvium in the vicinity of Frick Lake in the northeast corner of Livermore Valley. Huey did not show any of the other faults displacing Quaternary alluvial deposits although he showed these faults as locally separating the Livermore Formation from older units.

Blume (1971, 1972) mapped the Dougherty and Ramp Thrust Faults in eastern Livermore Valley (Fig. 7). However, subsequent investigators have not recognized these as Valley structures.

Herd (1977) mapped the Greenville and Las Positas Faults as major Valley structures. He also presented evidence for relocating the Verona Fault and suggested that it is more significant than previously believed. The CDWR (1979) noted the probable presence of the Las Positas Fault but regarded it as a local structure limited to the area from Arroyo Del Valle northeast to Arroyo Seco (Fig. 11).

Descriptions of all reported faults are given in the following subsections. Reported faults are discussed in alphabetical order.

Carnegie Fault. Huey (1948) (see Fig. 5) mapped the Carnegie Fault in the hills east of LLNL and found 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 the projected location of the fault and therefore mapped it as buried and dying out beneath alluvial cover.

*The CDWR (1966) mapped the Greenville Fault bounding the eastern margin of the Livermore Valley but did not discuss it further, possibly because it did not materially influence the Valley ground water system.

The CDWR (1974) (see Fig. 6) did not specifically identify a groundwater barrier along the Carnegie Fault as projected across the northeastern portion of the Livermore Valley. They did separate the Altamont subbasin from the Spring subbasin to the southwest along the projected fault trace (CDWR, 1974).

The Carnegie Fault has been located in the Livermore Oil Field approximately 1 km (0.6 mi) northeast of LLNL (Blume 1972). Fault movement is upward on the north side. South of the fault, steeply dipping Tertiary sediments form the north flank of the Livermore syncline (ibid).

During an investigation of private properties in the northern Livermore Valley, Cooper-Clark and Associates (1973) identified geophysical anomalies in the vicinity of the Carnegie Fault as projected by the CDWR. They also reported slickensides and overturned beds in the Tertiary Cierbo Formation along the trace of the Carnegie Fault north of Raymond Road. Evidence was cited for possible tectonic creep where the fault is projected to cross the South Bay Aqueduct. Based on their observations, they concluded that the Carnegie Fault was an active structure, although they gave no specific criteria for their judgement.

In their 1979 study (see Fig. 11), the CDWR showed the Carnegie Fault extending along the northeastern margin of the Livermore Valley. They reported that the Carnegie Fault is a high angle reverse fault. The Carnegie Fault is not well exposed in the area but the CDWR stated that it could be traced across the Livermore Oil Field by interpretation of well logs. Geomorphic features along the trace of the Carnegie Fault and its close relationship with the active Greenville Fault suggested to the CDWR that the Carnegie Fault is active.

The CDWR (1979) mapped a fault crossing the South Bay Aqueduct at Station 544+75 (see Fig. 11). The fault was observed in Plio-Pleistocene Livermore Gravels but was not seen in younger alluvium to the north. The fault was regarded as a possible branch of the Carnegie Fault zone.

Herd (1977) (Fig. 9) mapped the Carnegie Fault as being truncated by the Greenville Fault and considered the outcrop reported by Cooper-Clark and Associates (1973) to be an exposure of the Greenville Fault zone. Herd also included the main trace of the Carnegie Fault zone as shown by the CDWR (1979) as part of the Greenville Fault zone.

LLNL has investigated the Carnegie Fault in the hills southeast of the Laboratory. The Carnegie Fault is poorly exposed in the north end of Sec. 22, T3S, R3E, where it forms the contact between the Neroly and Cierbo Formations. Differences in location of the fault northwest of Sec. 22 that are shown by other investigators result from the heavy soil cover and uncertainty of the Cierbo-Neroly contact. Roads recently constructed in the area provide additional information that is presently being evaluated.

During LLNL field reconnaissance, it was found that northwest of Sec. 22 the Carnegie Fault could not be traced with any accuracy, although several springs and topographic depressions may mark its trace. No disruption of the soil cover was seen in stream or road cuts along its strike. People living along the trace felt only a minimum of motion during a June 1977 seismic event (see below for further discussion of this earthquake). Further to the southeast, Huey (1948) mapped the Carnegie Fault as merging with the Tesla Fault (Fig. 5).

Corral Hollow Fault. Huey (1948) (Fig. 5) mapped the Corral Hollow Fault as locally displacing the Livermore Formation but showed the fault as dying out before reaching the Valley. During its initial studies, the CDWR (1966, 1974) projected the Corral Hollow Fault northwest across the Livermore Valley as a subsurface feature (see Fig. 6) but in 1979, the CDWR mapped the Corral Hollow Fault essentially as it had been mapped by Huey (see Fig. 11).

The CDWR (1974) did not recognize the Corral Hollow Fault as a factor influencing Valley geohydrology. Evidently the CDWR could find no influence on groundwater movement or quality related to the Corral Hollow Fault. Blume (1972) did not observe any evidence for the Corral Hollow Fault in geophysical profiles performed within and immediately southeast of LLNL.

During LLNL field reconnaissance, surface evidence for the Corral Hollow Fault was sought starting in Sec. 35, T3S, R4E, where it branches from the Tesla Fault as mapped by Huey (1948). Huey has shown the fault crossing Corral Hollow road and truncating the upper part of the Tesla Formation in this area. The fault is not easily traced to the northwest and no evidence for it could be observed west of Sec. 21, T3S, R3E. At none of the locations where the Corral Hollow Fault was mapped by Huey could any geomorphic features be ob-

served that were suggestive of geologically youthful movements.

As part of a detailed exploratory program, LLNL geoscience personnel directed excavation of trenches in two areas shown on Fig. 17. As shown on Fig. 18, exploratory trench E-5 within LLNL was excavated across the trace of the Corral Hollow Fault as projected (see Fig. 6) by previous investigators (Blume 1971; CDWR, 1966, 1974). The trench was extended to cross vague linear tonal contrasts noted on aerial photographs. No evidence for faulting was observed in alluvial deposits exposed in trench E-5. A specimen of pedogenic carbonate was obtained from fractures (probably fossil desiccation cracks) within a silty clay bed present at a depth of 11 ft in Trench E-5. The age of the pedogenic carbonate determined by the $^{230}\text{Th}/^{234}\text{U}$ method is approximately 23 000 yr, indicating that the trench extended deeply enough to expose late Pleistocene materials. A detailed geologic log and summary description of trench E-5 are included in Appendix F (in Volume II) as Fig. F-6.

Doutherty Fault. Blume (1972) (see Fig. 7) identified and mapped the Doutherty Fault as crossing the northeastern portion of LLNL, based on their interpretation of geophysical data. Gravity data indicated that the northeast block appears displaced up and seismic refraction data suggested a groundwater barrier along the postulated fault (ibid).

The postulated Doutherty Fault has no physiographic expression either in the Valley alluvium or in the hills to the southeast. However, URS/Blume (1978) reported a night infrared (IR) photo lineament near the suspected fault trace (see Fig. 18).

During the summer of 1979, an approximately 20-to-24-ft deep basement excavation was made for the Nova addition to the Shiva laser facility at LLNL (Bldg. 391). The basement excavation is located across a trace of the Doutherty Fault as mapped by Blume (1972). Two 8-to-10-ft deep storm drain trenches excavated as part of the Bldg. 391 project also cross strands of the Doutherty Fault as mapped by Blume (1972) and the night IR lineament reported by URS/Blume (1978).

Geologists from LLNL and elsewhere inspected these excavations for evidence of faulting and found none. In order to document the geologic observations, detailed logs were prepared for segments of the two storm drain trenches and for the

FIG. 17. Key map locating areas of exploration that are shown in more detail in Figs. 18 and 31.

FIG. 18. LLNL site map showing locations of postulated faults, airphoto lineaments, excavations studied, and geophysical surveys made.

south and east faces of the Bldg. 391 excavation. Locations of logged exposures are shown in Fig. 18 and detailed logs and summary descriptions of the exposures are included in Appendix F (Volume II) as Figs. F-8 through F-11. The excavations exposed complexly interbedded and lensed sandy silts, sands, and fine to coarse gravel beds. Slight clay enrichment and local presence of caliche were noted in the alluvial deposits immediately below original ground surface, indicating moderate soil profile development characteristic of Pleistocene rather than Holocene alluvial deposits (Herd, 1977). Gravels backfilling an ancient stream channel were found in the general vicinity of the night IR lineament. Difference in soil moisture between the gravel deposits and adjacent finer sediments could create the observed lineament.

LLNL geoscience personnel directed excavation of exploratory trench E-2 in the eastern portion of LLNL, across the mapped fault trace. The trench site has been mapped by Herd as unit Qoa₂. The trench exposed older alluvial deposits with a well-developed soil profile. Several ancient stream channel deposits were found in the trench but no features suggestive of faulting were observed. The location of Trench E-2 is shown on Fig. 18. A detailed log and summary description of the trench are included in Appendix F (Volume II) as Fig. F-2. A sample of pedogenic carbonate obtained at a depth of 5.5 ft in trench E-2 was found to be unsuitable for dating by the ²³⁰Th/²³⁴U method (see Appendix C). A poor wood specimen was also obtained from trench E-2 but was judged unsuitable for dating (Robinson, 1980).

Greenville Fault. The Greenville or Greenville-Riggs Canyon Fault zone is a major structural feature of the Livermore Valley-Mt. Diablo area.

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 late Pleistocene unit (Qoa₃) 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.

Unquestionable evidence for activity along the Greenville Fault zone was provided at 11:00 a.m. PST on Thursday, January 24, 1980 when an earth-

quake of M=5.9 (USGS) occurred approximately 17 km (11 mi) north of Livermore, on the Marsh Creek Fault (see Fig. 19) (Cockerham and others, 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 and others (1971). Locations of surface faulting as compiled by the U.S. Geological Survey (Bonilla and others, 1980) are shown in Fig. 20. Descriptions of features at various locations shown on Fig. 20 are presented in Appendix E (data taken from Bonilla and others, 1980).

A single foreshock preceded the earthquake and over 600 aftershocks followed during the next 33 days (Cockerham and others, 1980). The largest aftershock occurred at 6:33 p.m. PST on Saturday, January 26, 1980. It had a magnitude of M=5.3 and occurred about 14 km (9 mi) southeast of the main shock (ibid) (see Fig. 19).

Field reconnaissance studies following the earthquake were made by geologists from LLNL, the USGS, various State and Local Governments, and private consulting firms. Most of the surface fault features shown on Fig. 20 were visible on Friday, January 25, 1980 following the main earthquake. However, additional surface faulting and fracturing occurred during the Saturday, January 26, 1980 event; numerous new cracks and enlargement of older ones were observed on Sunday, January 27, 1980. The new cracks were mostly concentrated near the southeasterly end of the zone of surface faulting, mainly in the vicinity of locations 18, 19, 20, and 22 shown in Fig. 20. Representative photographs of surface faults found by LLNL geologists after the earthquakes are shown in Figs. 21 through 28.

The area of discontinuous surface faulting along the Greenville Fault zone extends from the vicinity of the intersection of Greenville Road and Interstate Highway 580 northwest to Sec. 15, T2S, R2E, a distance of approximately 6.4 km (4 mi). The area affected by surface faulting ends about 2.6 km (1.6 mi) north of LLNL.

The area affected by discontinuous surface faulting is southeast of the main shock epicenter and separated from it by about 9 km (5.6 mi) (Cockerham and others, 1980). The extent of the separation and characteristics of the shallow aftershock pattern led Cockerham and others to

FIG. 19. Locations of main shock and principal aftershock of Livermore Valley earthquake series, January 24, 1980 and following (adapted from Cockerham and others, 1980).

FIG. 20. Locations of surface faulting, Livermore Valley earthquake series beginning January 24, 1980 (from Bonilla and others, 1980).

FIG. 21. Surface faulting during January 24, 1980 earthquake on Greenville Fault zone, shown as location 27 on Fig. 20. The amount of offset is about 2 cm horizontal and vertical. (Photo by A. Ramirez, LLNL).

FIG. 22. Surface faulting caused by January 24, 1980 earthquake. Fault crosses N. Vasco Road, shown as location 12 in Fig. 17. Alameda County road crew repaired the road on January 24, 1980 because pavement buckling was sufficient to interfere with traffic safety.(Photo by A. Ramirez, LLNL).

FIG. 23. Fractures in pavement at location 12 in Fig. 20, prior to repair. Lens cap is approximately 50 mm in diameter. (Photo by H. Ganow, LLNL).

FIG. 24. Zone of numerous fractures in pavement of Laughlin Road at location 17 in Fig. 20. Field reconnaissance on January 25 and January 27, 1980 demonstrated a considerable increase in frequency of fracturing in this area following the main aftershock on January 26, 1980. Subject shown in photo is pointing southeast along the strike of the Greenville Fault zone. (Photo by A. Ramirez, LLNL).

FIG. 25. Southeast striking fracture crossing Laughlin Road near the south limit of location 20 on Fig. 20. The fracture correlates closely with the strand of the Greenville Fault zone mapped by Herd (1977). (Photo by A. Ramirez, LLNL).

FIG. 26. Fracture crossing Laughlin Road at location 18 in Fig. 20. Trend of fractures in this area and at location 19 (behind photographer) is about N10°W in contrast to N40°W trend of the main zone. This change in trend suggests the presence of a subsidiary cross fault along which surface rupture transferred from the main trace to a more southwesterly trace (locations 20 and 22 in Fig. 20). (Photo by A. Ramirez, LLNL).

FIG. 27. En echelon left-stepping shears indicating right-lateral strike-slip movement linking repaired pavement buckles in N. Vasco Road, shown as location 12 in Fig. 20. (Photo by A. Ramirez, LLNL).

FIG. 28. Shears in pavement on the east side of Greenville Road at the intersection with Altamont Road, shown as location 22 in Fig. 20. Fractures at this location are right stepping and suggest apparent left lateral movement near the south end of the surface rupture zone. (Photo by A. Ramirez, LLNL).

speculate that the zone of surface displacement may not be continuously connected to the zone of rupture at depth but may be sympathetic in origin.

Preliminary strong motion data for the January 24 and January 26, 1980 earthquakes have been compiled and are presented in Table 1. No strong motion instruments were in operation at LLNL at the time of the earthquakes, but Tokarz and Shaw (1980) have estimated a peak ground motion of 0.2–0.3 g for the Laboratory Site.

Very strong ground motions were experienced by many residents of southern Contra Costa County during the January 24 and January 26, 1980 earthquakes. In a few instances, apparent ground motions caused by the January 26, 1980 earthquake exceeded those caused by the January 24 event. LLNL civil engineer Roger Lake coordinated efforts by members of the Tassajara Volunteer Fire Department in compiling relative intensity data for the area, based on the Modified Mercalli Scale (Richter, 1958). Results of their work are shown in Fig. 29.

On June 21, 1977 a moderate earthquake ($M=4.7$) was felt in Livermore Valley and nearby areas. Based upon refined crustal model data developed following the January 1980 earthquakes, Ellsworth and Marks (1980) relocated the epicenter for the 1977 event at $37^{\circ}38'N$ lat, $121^{\circ}40'W$ long, about 3 km (2 mi) SW of the southerly portion of the Greenville Fault zone as mapped by Herd (1977).

During field reconnaissance in the spring of 1979, local citizens told LLNL geologists of several unexplained physical events that occurred in the area near the southerly extension of the Greenville Fault zone. These included the experience of a property owner on Reuss Road who stated that large cracks had recently developed in the basement of his old house. Also, an alleged displacement of several hundredths of an inch in the power line alignment across Sec. 17, T3S, R3E, based on the results of a private survey, was reported. Residents in Sec. 20, T3S, R3E strongly felt the June 21, 1977 earthquake. They reported incidents of minor damage, sloughing of stream banks, and the coincident cessation of flow of Arroyo Seco Creek and several springs.

A good exposure 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.

Wight (1974) assumed a length of 42 km (26 mi) for the Greenville-Riggs Canyon Fault zone, based upon available regional data. He computed a maximum earthquake magnitude of 6.7 for the zone, based upon empirical fault length-rupture length-magnitude relationships developed by Albee and Smith (1966). Because of insufficient data, Wesson and others (1975) did not attempt to characterize the Greenville-Riggs Canyon Fault zone as to activity.

Las Positas Fault. The northeast-trending Las Positas fault was initially mapped by Herd (1977) (see Fig. 9) based on geomorphology, air photo interpretation, a ground water 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 feet north of the South Bay Aqueduct). The Las Positas Fault, as mapped by Herd, crosses the southern portion of the SNLL site and coincides with a break in slope separating the nearly-flat Valley floor to the north from an area of small terraces and hills to the south. Features that Herd used to establish the existence of the Las Positas Fault are concentrated in an area that extends roughly 2 km northeast and southwest from SNLL.

Approximately 3.2 km (2 mi) northeast of SNLL, the Las Positas Fault was mapped by Herd as ending abruptly at the Greenville Fault, in an area of obscure structure.

Herd (1977) 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. Herd's map shows the Las Positas Fault throughout this interval as being largely concealed by materials ranging in relative age from recent stream gravels to his oldest alluvial deposit (Unit Qoa₄). Herd's map does show a short segment of the Las Positas Fault zone displacing older alluvial unit Qoa₃ about 1 km northwest of the U.S. Veteran's Administration Hospital south of Livermore. Between about 1.8 km (1.2 mi) and 3.4 km (2.1 mi) southwest of the Veteran's Hospital, Herd mapped the Las Positas Fault as separating the Plio-Pleistocene Livermore Formation from the Miocene Cierbo sandstone.

URS/Blume (1978) excavated 10 trenches within SNLL across the postulated trace of the Las Positas Fault. Locations of these trenches are

TABLE 1. Preliminary strong motion data, pertaining to the Livermore Valley earthquakes of January 24 and January 26, 1980. (CDMG, 1980, SMIRS, 1980)

CDMG (1980) stations	Channels	24 Jan 1980		26 Jan 1980	
		Distance from epicenter (km)	Location	Distance from epicenter (km)	Location
1. Antioch	3	21	grnd	0.04	30 grnd
2. Briones Dam					
Left-Abutment	3	40		0.02	49
Left Crest	3			0.04	
Center Crest	3			0.06	
3. Capitola Fire Station	3	95	grnd	0.02	89 b
4. El Cerrito, Capwells	6	45	grnd	0.02	54 grnd
			roof	0.02	roof
5. Fremont, Mission San Jose	3	36	grnd	0.06	33 grnd
6. Halls Valley	3	55	grnd	0.04	45 b
7. Hayward, APEEL 3E	3	30	grnd	0.08	31 grnd
8. Hayward, Cal. State Univ.	3	30	grnd	0.04	31 grnd
	13		roof	0.15	roof
9. Lexington Dam-Abutment	3	73		b	66 b
Left Crest	3			0.02	b
Right Crest	3			0.02	b
10. Oakland, Calrus Bldg.	8	33	grnd	0.02	37 grnd
			roof	0.07	roof
11. Oakland, Title & Trust Bldg.	6	48		a	55 grnd
					roof
12. Pleasant Hill, Citizens Sav.	12	29	grnd	0.03	39 grnd
			roof	0.10	roof
13. Redwood City, Canada College	6	61	grnd	0.02	60 grnd
			roof	0.02	roof
14. San Jose, Great Western Sav.	13	55	grnd	0.02	49 grnd
			roof	0.05	roof
15. San Jose, Town Park Towers	13	55	grnd	0.02	49 grnd
			roof	0.07	roof
16. San Ramon, Eastman Kodak	6	16	grnd	0.15	21 grnd
			roof	0.24	roof
17. San Ramon, Fire Station	3	19	grnd	0.04	24 grnd
18. Saratoga, West Valley Coll.	11	68	grnd	0.02	61 grnd
			roof	0.06	roof
19. So. S. F., Kaiser Hospt.	11	59	grnd	0.02	63 grnd
			roof	0.13	roof
20. Tracy	3	33	grnd	0.09	26 a
21. Walnut Creek, Fidelity Sav.	3	26	grnd	0.03	36 grnd
	13		grnd	0.03	grnd
			roof	0.17	roof

^aNot operating.

^bNot triggered.

TABLE 1. (Continued.)

CDMG (1980) stations	Channels	24 Jan 1980			26 Jan 1980		
		Distance from epicenter (km)	Location	Peak Ampl. (g)	Distance from epicenter (km)	Location	Peak Ampl. (g)
Temporary stations installed after January 24, 1980:							
1. Conta Loma	3				27	grnd	0.03
2. Fagundes Ranch	3				6	grnd	0.25
3. Morgan Territory Park	3				9	grnd	0.27
SMIRS (1980)							
1. Livermore VA Hospital	3	20	grnd	0.17			
2. Del Valle Dam	3	23	toe	0.26			
			crest	0.21			
3. General Electric Corp., Vallecitos	3	23	grnd	0.11			

^aNot operating.

^bNot triggered.

shown in Fig. 30. URS/Blume found evidence suggestive of faulting in some trenches but not in others. Geophysical and trenching investigations on property approximately one-half mile southwest of SNLL produced data that suggested faulting and provided evidence that strata tentatively correlated with the Livermore Formation had been displaced. (Judd Hull and Associates, 1977; Carpenter, 1977).

To obtain more data concerning the Las Positas Fault, LLNL geoscience personnel performed an extensive field study. Areas investigated are shown in Fig. 17. Locations of detailed exploration are shown on Figs. 18 and 31. Elements of the investigation were as follows: detailed mapping of the Greenville Road cut; removal of overburden and enlargement of the Arroyo Seco outcrop; and excavation of three exploratory trenches. Trenches E-1 and E-6 were dug in the southeast portion of LLNL where vague air photo lineaments trending subparallel to the mapped trace of the Las Positas Fault had been noted during preliminary phases of the LLNL investigation, and by others (Hull, 1977). Locations of trenches E-1 and E-6 are shown in

Fig. 18. Detailed logs and summary descriptions of the trenches are included in Appendix F (Volume II) as Figs. F-1 and F-7 respectively.

Exploratory Trench E-3 was excavated in alluvium northeast of Arroyo Seco creek and crossed the mapped trace of the Las Positas Fault. The trench location is shown on Fig. 31, and a detailed log and summary description are included in Appendix F (Volume II) as Fig. F-3.

Two faults were noted in the enlarged Arroyo Seco creek bank exposure (see Fig. F-12 in Volume II). These faults displace the contact between northwest-dipping beds of the Livermore Formation and an overlying terrace deposit (Qoa₃ of Herd, 1977). Along the northwesterly fault, younger terrace deposits (Qoa₂?) are juxtaposed against highly disturbed gravels derived from unit Qoa₃. However, as the contact between the two units is not visibly faulted, it is unclear whether the Qoa₂? unit formed by deposition against an erosional surface (including a fault scarp) or whether the unit has been displaced by faulting. The southerly fault has offset the erosion surface

FIG. 29. Map showing intensities in the epicentral region of the January 24, 1980 earthquake in the Livermore Valley. Letter-digit combinations (e.g. T4) that appear on the map are to be interpreted as follows. The letter T indicates the apparent intensity during the Thursday, January 24 earthquake and the letter S indicates the apparent intensity during the aftershock on Saturday, January 26. The associated digit indicates the modified Mercalli scale intensity experienced (Compiled by R. Lake).

FIG. 30. Site plan showing URS/Blume and Associates' exploratory trench locations on SNLL property (modified from URS/Blume and Associates, 1978).

FIG. 31. SNLL site map showing locations of postulated faults, airphoto lineaments, excavations studied, and geophysical surveys made.

developed across the dipping Livermore Formation beds by about one foot. Material overlying the erosion surface consists of remnants of alluvial unit Qoa₃ and colluvium; these materials appear at least in part to have been displaced as well.

Both faults strike northeast and dip near vertical. Faint slickensides preserved on the southerly fault plane plunge 25° northeast, indicating oblique but dominantly strike-slip movement.

The southerly fault was observed by Herd in 1977. The fault further to the northwest was not visible at the time of Herd's mapping. Both faults observed occur within an approximately 50 ft wide zone coincident with the slope break across the southern portion of the SNLL property.

Trench E-3, excavated about 75 ft northeast of Arroyo Seco Creek (Fig. 31), encountered an approximately 20 ft wide zone of faulting at the hill front near its southerly end. The faulting is believed to be associated with the Las Positas Fault zone. Displacement of alluvium (probably Qoa₂) against steeply dipping Livermore Formation beds was observed in trench E-3. A wood sample obtained at a depth of 11 ft in Trench E-3 has been dated by the ¹⁴C 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 exposed in Trench E-3. However, correlative and overlying alluvium traceable to the fault has been displaced, thus 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 roughly 120 ft north from the faulted section. However, a pocket of young appearing, unaltered alluvium abruptly terminates along a 6-in. step within the fault zone, suggesting minor late Pleistocene or Holocene movement. Colluvial soils overlying the fault zone are thickened but have not been displaced. Figure F-3 (Volume II) includes a detailed drawing of the fault zone seen in exploratory Trench E-3.

Ambiguities exist at the Greenville Road cut site (for location see Fig. 31). A number of small faults cut probable Livermore Formation beds. A one foot 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 seen by Blume (1972) and were regarded as evidence for the location of the Corral

Hollow or Ramp Thrust Fault zones. A detailed log of the Greenville Road cut is included in Appendix F (Volume II) as Fig. C-13.

A zone of highly fractured claystone containing pods of greenish clay strikes about N80°E in the Greenville roadcut (Sta. 1+10). Colluvial soils (Unit 15) are thicker north of the fracture zone than south of it, and a gravel horizon in the base of the colluvium north of the shear is terminated along a line that strikes N35°E across Greenville Road. The line of termination coincides with the fracture zone on the east side of Greenville Road but no evidence for faulting, such as slickensides or pebbles upturned relative to bedding planes, can be seen along it. The gravel bed could not be identified south of the fracture zone.

Two of the northwest-trending small faults terminate against the northeast-trending Greenville Road fracture zone. The others daylight in the face of the roadcut; their relationship to the northeast-trending fracture zone cannot be determined.

Abundant carbonate fills fractures in Livermore Formation mudstone and siltstone beds south of the probable Las Positas Fault exposure along Greenville Road (Fig. 31). Two samples were obtained from the carbonate and their ages determined independently. The average age of the fracture filling carbonate is 67 000 yr ± 10-20%. This is much younger than the minimum estimated age for the Livermore Formation (Herd and Brabb, 1980). Therefore, the carbonate is clearly secondary and fills fractures in the Livermore Formation that were created by movements along the Las Positas Fault. The most probable explanation for formation of the carbonate is the presence of a groundwater barrier along the fault. South of the fault the barrier forced groundwater to the surface, leading to carbonate precipitation.

Most of the carbonate-filled fractures show no evidence of movement subsequent to carbonate precipitation. However, some slickensided carbonate is present and there is local evidence of offset of colluvium that is demonstrably younger than the carbonate filled fractures. Therefore, some movement has doubtless occurred along the Las Positas Fault in the Greenville Road area since carbonate formation.

As shown in Fig. 18, several vague airphoto lineaments subparallel to the Las Positas Fault were identified as crossing the southeastern portion of

LLNL (Hull, 1977; this investigation). Exploratory trenches E-1 and E-6 were excavated across these vague lineaments.

As discussed earlier, exploratory trench E-1 exposed two well developed soil profiles within later Pleistocene alluvial deposits. The lower profile was dated at approximately 115 000 yr by the $^{230}\text{Th}/^{234}\text{U}$ method (see Appendix C). Note that the date obtained represents a minimum age for the material exposed in Trench E-1 because the alluvium in which the soil profile develops must be deposited and a period of geologic stability must exist before a closed system carbonate can form. No evidence of faulting was found in Trench E-1.

Exploratory trench E-6 was excavated in late Pleistocene alluvial deposits mapped by Herd (1977) as Qoa₂. The $^{230}\text{Th}/^{234}\text{U}$ age for the well-developed paleosol exposed in Trench E-6 is 17 000 yr. Remnants of an older paleosol were found in Trench E-6 but did not yield carbonate suitable for dating. No evidence of faulting was found in Trench E-6.

None of the aftershocks of the January 24, 1980 earthquake were near the main portion of the Las Positas Fault zone mapped by Herd (Cockerham and others, 1980). However, a number of aftershocks do plot near a subparallel fault mapped by Herd (1977) approximately 4 km (2.5 mi) to the southeast. Cockerham and others (1980) indicate that the focal mechanisms shown by these aftershocks are consistent with the left-lateral strike-slip displacement postulated by Herd as occurring along the Las Positas Fault zone.

During their studies following the January 24, 1980 earthquake, Bonilla and others noted concentrations of fractures across roads in the vicinity of the Las Positas Fault. Locations of observed fracture concentrations are shown in Fig. 32; descriptions of the sites are included in Appendix E.

The USGS regarded the fractures at locations 34 and 35 as evidence of sympathetic motion along approximately 1.1 km (0.7 mi) of the Las Positas Fault zone. Fractures at locations 33 and 36 were regarded as of non-tectonic origin.

LLNL geologists observed several fractures in an SNLL road at location X on Fig. 32. These fractures are located about 300 ft south of where the Las Positas Fault is mapped across the road; no fracturing was noted at the postulated fault crossing.

Fractures noted at locations 33 through 36 and at location X are similar to fractures in asphalt pavements at a number of locations in the eastern

Livermore Valley that experienced strong ground shaking during the January 24 and 26, 1980 earthquakes. Sites of such pavement fractures include the Springtown subdivision north of Livermore, segments of Raymond Road north of Springtown, and the northerly frontage road north of I-580—for at least 2000 ft southwest of its intersection with Greenville Rd. Similar cracks also cross Morgan Territory Road in southern Contra Costa County near the mapped intersection of the Greenville and Marsh Creek Faults; the USGS did not postulate surface faulting at this location.

Figure 33 shows the zone of fracturing along S. Vasco Road at location 35 identified in Fig. 32. Fracture E is of particular interest since it is the only fracture that crosses S. Vasco Road and since it consists of a series of en-echelon segments that may reflect shear. The pattern of fracture segments at fracture E has been interpreted as evidence for left-lateral strike-slip displacement of about 0.5 mm (Bonilla and others, 1980). However, the fractures shown at location E (Fig. 33) show a "left-stepping" pattern and therefore suggest apparent right-lateral motion rather than the left-lateral motion interpreted from them by the USGS.

Towse (1980) has questioned the interpretation that features observed along the hill front across SNLL are the result of tectonic faulting. He stated that other possible hypotheses must be seriously considered before the tectonic fault hypothesis can be accepted scientifically and listed five possible explanations for the geologic features visible along the hill front near SNLL. These are presented and discussed in the following paragraphs:

Alternative hypothesis 1: The apparent movement of the gravels is due to subjacent bedrock faulting.

Discussion. Essentially, this is the hypothesis best supported by existing evidence. Features seen along the hill front are most probably shears that have broken to the surface through relatively weak Quaternary materials as a result of repeated movements along a fault at depth. The location and sense of movement of the main fault at depth is presently unknown; evaluation of this hypothesis can be provided only by future geologic, geophysical and seismologic studies. An important element in these studies must be the establishment of precise epicentral locations and fault plane solutions for local

FIG. 33. Sketch map showing fractures in pavement of Vasco Road in relation to the centerline of Tesla Road and the approximate position of the north-facing scarp of the Las Positas fault (from Bonilla and others, 1980).

earthquakes. Several years of seismic-monitoring-network operations will be required before these data will be available.

Alternative hypothesis 2: The features are the result of faulting at some distance.

Discussion. Sympathetic movement along one fault as a result of a major earthquake on another has been documented (see Saul, 1975, for one example). Such movements are usually a small percentage of the movements observed on the active fault.

The Las Positas Fault zone strikes southwest toward the Calaveras Fault, a major active regional fault system. However, the area in which the Las Positas Fault is best expressed is separated from the Calaveras Fault by a distance of approximately 10 miles (16 km) and a connection between the two faults is not definitely established.

It would appear that if the two structures were linked, the largest and most frequent movements along the passive Las Positas Fault zone would be in the vicinity of the point of linkage and the fault zone would have a well-defined expression in that area.

Other faults in the region with which the Las Positas could be linked include the Greenville, Tesla, and Livermore systems. The relationship of the Las Positas fault to these other structures requires additional study. The USGS suggested that a very minor amount of sympathetic movement along the Las Positas Fault resulted from the January 24, 1980 earthquake on the Greenville Fault zone. However, it does not seem probable that the amount of movement that appears to have occurred along the Las Positas Fault zone can be attributed solely to sympathetic response to earthquakes on other regional faults.

Alternative hypothesis 3: The features are the result of gravity induced sliding concurrent with local episodic uplift or surface tilting.

Discussion. The pattern of shearing features along the hill front near SNLL is highly linear. Arcuate features characteristic of large landslide blocks have not been observed, and the existing scattered landslides in the area are minor superficial mudflows and slumps.

The area near SNLL presently has low to moderate relief. The pattern of Pleistocene terraces

capping and surrounding steeply dipping, older Livermore Formation beds implies a Quaternary history of erosion, deposition, and local uplift. There is no evidence to suggest that past relief was greater than presently existing relief. Evidence is lacking for a terrain compatible with large-scale landsliding or gravity block gliding. Also, as discussed above, neither the oblique slickensides preserved on some shears nor the linear en-echelon pattern of fault strands parallel to the hill front are compatible with landslide movements. In the present topographic setting, landsliding and gravity block movements should produce low angle, north-dipping shears; none have been observed.

Alternative hypothesis 4: The features are the result of slippage caused by stream erosion and bank collapse.

Discussion. Some of the features visible in the outcrop along the Arroyo Seco may be attributed to local slumping and ravelling rather than to fault displacements. This is particularly true for the zone of chaotic, reddish gravel exposed in the northern part of the outcrop, immediately south of a sequence of subhorizontally bedded gravels and silts (see Fig. F-12, Volume II). These gravels could have formed either as a result of periodic erosion and ravelling along a stream bank or as talus along a growing fault scarp. As noted previously, the contact between the chaotic gravel and the bedded sequence is not visibly faulted.

Parts of the stepped contact between the terrace deposits (Qoa₃ of Herd, 1977) could be attributed to slumping in response to stream erosion except that the associated shears persist at depth in the Livermore Formation. These shears cut the entire outcrop, which is approximately 6 m (20 ft) deep, with a near-vertical dip. As stated previously, a terrain of much greater relief than exists now, or is believed to have existed, would be required to cause the known shears through erosion effects.

Oblique slickensides preserved on the southerly fracture in the Arroyo Seco outcrop indicate lateral shearing movement along the plane. This is not compatible with stream erosion and slumping, which should have produced an unslickensided tension crack instead of a shear plane. Also, the steep-dipping, gouge-bearing contact between tilted Livermore Formation beds and nearly flat-lying,

bedded alluvial deposits exposed in Trench E-3 cannot be attributed to erosion, slumping, or sliding.

Alternative hypothesis 5: The features may be some combination of these.

Discussion. Multiple causes for the features observable along the hill front near SNLL cannot be ruled out. Some offsets may be the result of either aseismic slip (tectonic creep) or sympathetic motion along the Las Positas Fault in response to the stress field created by the regional San Andreas Fault system and its major branches, such as the Calaveras Fault. As noted previously, the chaotic gravel exposed in a portion of the Arroyo Seco outcrop may be a talus that developed along a fault scarp or a fault-controlled stream bank. However, all data point to active faulting as the principal cause of the observed features; other causes are at best secondary.

In addition to the alternative hypotheses outlined by Towse, the Las Positas Fault may have formed as a result of consolidation of Livermore Valley fill caused by groundwater withdrawal. Overdraft conditions have existed periodically in the Valley (Alameda County Planning Department, 1979), but principal movements are in evidence along the fault in materials much older than the historic era and are not present in potentially historic deposits, such as the colluvium exposed in Trench E-3. Also, oblique movement such as along the southerly shear in the Arroyo Seco outcrop is incompatible with faulting caused by groundwater withdrawal, which would result in steeply dipping, normal faults that are downthrown on the Valley side to the north.

In summary, the Las Positas Fault appears to be an active tectonic feature based upon generally accepted criteria. However, as noted previously, well-defined evidence for the Las Positas Fault is restricted to an area that extends roughly 2 km northeast and southwest from SNLL, although Herd has mapped the fault zone as extending approximately 9.6 km (6 mi) further southwest.

Livermore Fault. The CDWR (1966) identified the Livermore Fault based on a well-defined ground-water barrier between the Livermore and Santa Rita subbasins. They showed three strands of the fault passing through the western portion of Livermore (1974) (see Fig. 16). An outcrop of the easternmost strand was recognized in Oak Knoll, a

hill composed of the Livermore formation and located in 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 air photo 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 because it cuts geologically young sediments and appears associated with moderate seismic activity, the Livermore Fault should be considered active.

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 (Qoa₄). 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, which he mapped in the southwestern portion of the Livermore Valley area (see Figs. 15 and 16 and discussion below).

Note that a portion of the groundwater barrier detected by the CDWR within Livermore Valley may be the result of perturbation of the upper aquifer beneath Livermore Valley caused by draw-down of the water table around large gravel pits located north of the Arroyo Valle between Livermore and Pleasanton (Alameda County Planning Department, 1979).

Mocho Fault. The CDWR (1966) postulated the existence of the Mocho Fault, based on geomorphic features southeast and north of the Valley, and mapped it (1974) (see Figs. 6 and 16) as extending northwestward from the Arroyo Mocho valley across central Livermore and into the Tassajara Hills north of Camp Parks. As mapped, the fault crosses the Mocho groundwater subbasin and is described as having some effect on groundwater levels beneath Livermore—but not further 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. Geophysical studies by Cooper-Clark and Associates (1973) were inconclusive regarding its presence. Cooper-Clark and Associates used magnetometer and electrical resistivity methods during their investigation. 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. Air photo 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.

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 northwestern Livermore Valley (see Figs. 15 and 16) 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 Quarternary alluvium in the subsurface and strongly influences groundwater movement near it.

The CDWR did not include the Parks Fault on its 1979 map.

Patterson Pass Fault. Huey (1948) (see Fig. 5) mapped the Patterson Pass Fault in the Altamont Hills northeast of LLNL. He showed it as a bedrock structure branching eastward from the Greenville Fault. Field reconnaissance by LLNL geologists indicates that this fault may merge with or be truncated by the Greenville Fault. It could also be a part of the Tesla Fault system because it appears to merge with this system in the SE 1/4 Sec. 29, T3S, R4E. The surface expression of this fault is postulated on the existence of springs along Patterson Pass Road in Sec. 10, T3S, R3E. Near a power line in the north half of the section, its location appears to be marked by a low, north-facing scarp. Huey (1948) mapped the Patterson Pass Fault northwestward from this location to a junction with the Greenville Fault in Sec. 5, T3S, R2E. However, during field reconnaissance, it was not possible to trace the fault on the ground northwest of Sec. 10.

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 (see Fig. 11). 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 seismic activity along its trace, the Patterson Pass Fault was regarded as active by the CDWR.

Pleasanton Fault. The Pleasanton Fault was mapped by the CDWR (1966, 1974) in the western Livermore Valley, based on a groundwater barrier and air photo interpretation. The postulated fault location is shown on Figs. 15 and 16. The fault was delineated north of I-580 on 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 Burkland and Associates (1975a) and Carpenter (1975) conducted extensive investigations in Holocene

materials and the Livermore Formation, respectively, without finding evidence for the Pleasanton Fault along its mapped trace. Other investigators had similar results. However, Judd Hull and Associates (1977b) reported evidence for a subsurface fault approximately one-fourth mile west of the previously mapped location.

At present the location and even the existence of the Pleasanton Fault is uncertain, especially since Haltenhoff (1979) stated that air photo evidence for the Pleasanton Fault in the hills north of the Livermore Valley can be correlated with strands of the recently discovered San Ramon Valley Fault zone. The San Ramon Valley Fault zone appears to be a local feature that does not project toward the LLNL. The relationship, if any, of the San Ramon Valley Fault zone to faults in western Livermore Valley is presently unknown.

Ramp Thrust Fault. Blume (1972) mapped the Ramp Thrust Fault as a local structure in the hills southeast of LLNL (see Fig. 7). Blume 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 (Fig. 31). This road-cut has subsequently been interpreted as an exposure of the Las Positas Fault zone (Herd, 1977; this investigation) (see Fig. F-13 in Volume II).

Herd (1977) mapped the area that included the Ramp Thrust Fault as defined by Blume (1972). Herd did not find evidence for the Ramp Thrust Fault, although the southeasterly portion of the fault as mapped by Blume is roughly coincident with one of the strands of the Las Positas Fault zone as mapped by Herd. The CDWR did not show the Ramp Thrust Fault on either its 1974 or 1979 maps.

Tesla Fault. This is the northernmost segment of the Tesla-Ortogonalita Fault zone. This zone is composed of many faults of varying ages and runs along the eastern flank of the Diablo Range from the Livermore Valley to Panoche Valley. The northernmost extent of the Tesla Fault is not presently known, although Herd (1977) showed the Tesla Fault truncated by the Greenville Fault in Sec. 34, T3S, R3E (see Fig. 9).

The Tesla-Ortogonalita Fault zone is probably a part 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 ancestral 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.

To the southeast in Sec. 27, the trace of the fault in the Franciscan bedrock is difficult to determine other than by stream channel orientation. This is because the Franciscan itself is often pervasively sheared and masks any fault disturbance. Thus the evidence for faulting is only weakly suggestive; 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 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 two miles 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 5 miles northwest of Livermore aligned with the projected fault trace and was cited as possible evidence for left-lateral offset along the Tesla Fault.

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.

Blume (1972) mapped three strands of the Tesla Fault system, based on geomorphic features and interpretation of geophysical data obtained by use of magnetometer, seismic refraction, and gravity methods (see Fig. 7). Blume (1972) stated that Strand 1 of the Tesla Fault zone had not undergone movement since deposition of the Livermore Formation (possibly 4 000 000 yr ago) and therefore was not considered a potential hazard.

Blume (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 also coincides with the mapped location of the Las Positas Fault. URS Blume (1978) excavated exploratory Trench T-1 in alluvium across the postulated location of Strand 2 of the Tesla Fault within SNLL and found no evidence of faulting. The location of Trench T-1 is shown in Fig. 30.

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 Las Positas Fault. The location of Trench E-4 is shown on Fig. 31. The detailed trench log and summary description of the trench are given in Appendix F (in Volume II) as Fig. F-4.

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 CDWR (1979) noted that the southernmost segments of the Tesla Fault zone are considered active but that no geomorphic evidence exists to suggest recent movement to the north. The CDWR noted that numerous earthquake epicenters plot near the Tesla Fault zone.

Strand 3 of the Tesla Fault system was mapped by Blume (1972) (see Fig. 7) 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 (see Fig. 10).

Verona Fault. The CDWR (1966) mapped the Verona Fault southwest of Pleasanton 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. The location of the Verona Fault as postulated by the CDWR is shown on Figs. 15 and 16.

Herd (1977) placed the Verona Fault southwest of the position shown by the CDWR. His mapping placed the fault close to the General Electric Corporation's Vallecitos Nuclear Center, a mapping that necessitated detailed studies of the Vallecitos area. The ensuing investigations located the Verona Fault essentially as mapped by Herd and also identified several other smaller faults in the area. The Verona Fault and other nearby faults were found to dip at low angles. A lengthy controversy has arisen as to whether these features are of tectonic origin or represent the surface traces of slip planes of large, degraded landslides that developed in the past along the southwest slope of the hills northeast of Vallecitos (see Rice and others, 1979). The CDWR did not include the Verona Fault on its 1979 map.

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,

FIG. 34. Map showing locations of the Williams, Valle, and Mocho faults as mapped by CDWR (1974).

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 but some could be compatible with right-lateral move-

ment 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 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.

Other 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.

Herd (1977) mapped several short east-west trending faults in the foothills south of the Livermore Valley. These showed evidence for displacement of the Livermore Formation. A southerly branch of the Las Positas Fault system was mapped along the south side of the low hills, which include the southern part of SNLL. A well-defined air photo lineament marks this fault, and small faults displace terrace deposits where the lineament crosses Greenville and Tesla roads. The CDWR (1979) also 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.

A considerable amount of microseismicity has been detected along the southern margin of the Livermore Valley, generally from the vicinity of Del Valle reservoir eastward (Ellsworth and Marks, 1980). Aftershocks of the January 24, 1980 Livermore Valley earthquake have also been recorded in this area (Cockerham and others, 1980). A number of these events plot in the vicinity of the short faults mapped in the area by Herd (1977).

Geodetic Measurements. Benchmark surveys and triangulation data for various areas within and near Livermore Valley have been reviewed and analysed by Gibson and Wollenberg (1968), Blume (1972), Alt (1979), and the CDWR (1979).

Gibson and Wollenberg (1968) detected horizontal and vertical movements across faults mapped in northwestern Livermore Valley (see Fig. 35). Blume (1972) noted similar vertical movements near the eastern margin of the Valley (Fig. 35).

Blume (1972) interpreted data developed during their study and that developed by Gibson and Wollenberg 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. It does not appear that vertical creep movements are taking place on the fault, but rather differential movements are taking place by elastic deformation in the vicinity of the fault. According to the theory of elastic rebound, these deformations and accumulated stresses would be relieved periodically by movement on the Calaveras Fault.

- At the east margin of Livermore Valley near the LLNL site, a change from ground subsidence to uplift also takes place. This change in direction of ground movements does not coincide precisely with the location of the Carnegie Fault, which is one of the boundary faults of the valley. Instead, the change appears to take place along a line parallel to and southwest of the Carnegie Fault. The line of change passes in a northwesterly direction through the northeast corner of LLNL. This line of change coincides with the postulated location of the Dougherty Fault, a fault hypothesized through various indirect lines of evidence. Although the direction of ground movement appears to change along this presumed fault line, the general topography of the region indicates that most differential vertical movement in the area has taken place on the Carnegie Fault.

Blume (1972) made a detailed analysis of benchmark leveling data from within and near LLNL. This data included surveys of Laboratory benchmarks as well as U.S. Coast and Geodetic Survey benchmarks as shown in Fig. 36. Movements shown for the Coast and Geodetic Survey stations are annual averages based on resurveying over a 20 year interval. Data for LLNL benchmarks were for a one year resurveying interval. Blume noted that resurveying of the LLNL benchmarks indicated higher apparent rates of movement than those calculated for the Coast and Geodetic Survey marks. No explanation for the apparent differences in movement rates could be established.

Blume (1972) noted that the area of maximum subsidence within and near LLNL appears to coincide approximately with the axis of the Livermore syncline while areas of minimal subsidence (or uplift) coincide more with the margins of the syncline. This was interpreted as evidence that the tectonic forces that initially produced the syncline are still active.

Blume (1972) noted that groundwater withdrawal could be a factor in subsidence of the Valley

LEGEND

- U.S. COAST & GEODETIC SURVEY MONUMENTS.
VERTICAL GROUND MOVEMENT SHOWN IN
THOUSANDTHS OF A FOOT PER YEAR.
- MAP NORTHWEST OF PLEASANTON
FROM GIBSON & WOLLENBERG (1968)
- MAPPING IN CENTRAL AND EASTERN VALLEY
BY BLUME AND ASSOCIATES, 1972.

FIG. 35. Geodetic information in Livermore Valley
(from Blume, 1972).

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NOTE: FROM BLUME & ASSOCIATES (1972)

FIG. 36. Map showing bench marks and vertical ground movement within LLNL (from Blume, 1972).

floor. They indicated that subsidence related to groundwater withdrawal would be superimposed on the tectonic subsidence and therefore would be difficult to estimate. They expressed the opinion that such subsidence would be uniform over large areas while the observed subsidence shows considerable variability in a way which could indicate a relationship to tectonic structures. However, with respect to this opinion, it should be noted that groundwater withdrawal is not uniform throughout the Valley (Alameda County Planning Department, 1979) and therefore the potential exists for additional uncertainties in the data. It should also 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.

Alt (1979) reviewed the results of periodic first-order geodetic leveling along the Southern Pacific Railroad line from the Niles district in Fremont to Altamont Pass east of Livermore Valley. The latest data available to him were obtained in 1965 and were therefore probably available to Blume in 1972.

Alt noted uplift of the Berkeley Hills west of Livermore Valley at a rate of 1.5 to 2 mm/yr relative to the San Francisco Bay Plain. He reported that the area of uplift is bounded on the east by the Calaveras Fault and that there is relative subsidence east of the fault within Livermore Valley. Differential subsidence has occurred within Livermore Valley and has had a maximum subsidence rate of about 7 mm/yr east of Pleasanton (ibid). Alt noted a gross correlation between locations of differential subsidence within Livermore Valley and reported groundwater barriers.

Alt (1979) stated that the Altamont Hills east of Livermore Valley are being uplifted relative to

the San Francisco Bay Plain at a rate of about 1.5 mm/yr, but he regarded this value as questionable because of a wide scatter in survey data. Alt stated that the boundary between subsidence of Livermore Valley and uplift of the Altamont Hills is at the approximate mapped location of the Carnegie Fault.

Alt (1979) noted that an analysis of second-order leveling data along lines extending south from Livermore Valley indicates a relatively uniform northward tilt.

The CDWR (1979) noted a strong correlation between subsidence in the area southwest of Patterson Reservoir and withdrawal of oil from the Livermore oil field. The CDWR data shown in Fig. 37 were based on (usually) annual resurveys of a benchmark array installed in 1969.

The CDWR (1979) detected a slight reversal in the trend of some benchmarks (2 mm maximum) during a 1977 resurvey. They suggested that the anomalous elevation changes may have been caused by the June 21, 1977 earthquake ($M=4.7$), which occurred about 3 km (2 mi) south of Patterson Reservoir. The CDWR stated that its 1978 resurvey showed that the original trend had resumed at all except a few benchmarks.

The cumulative contours drawn by the CDWR include the northeast corner of the LLNL site (see Fig. 37) and show the maximum amount of subsidence within LLNL as less than 10 mm. The area of subsidence mapped by the CDWR was also shown by Blume (1972) but was shown as an area of no change or slight uplift (see Fig. 36). Since both the CDWR and Blume were working during the same period in the early 1970's, reasons for their differing results are unclear.

LLNL SITE GEOLOGY

STRATIGRAPHY

LLNL is underlain by a thick sequence of late Tertiary and Quaternary alluvial deposits and by poorly lithified rocks of predominantly continental origin. Huey (in Blume, 1972) reported that hydrocarbon exploratory well P-1, located near the

southwest corner of LLNL, penetrated approximately 2420 ft of these materials before reaching "basement" rocks of the Franciscan assemblage.

Helley and others (1972) mapped most of the LLNL site and the northeastern portion of the adjacent SNLL property as being underlain by Older Alluvial Fan Deposits (Qof) (Fig. 13). These

FIG. 37. Areal subsidence in the vicinity of Patterson reservoir (from CDWR, 1979).

materials were described (on the map legend) as "weathered, weakly consolidated, poorly sorted silt, sand, and gravel (generally fine-grained in northeastern Livermore Valley owing to derivation from friable sandstone bedrock). Less permeable and more poorly drained than younger alluvial fan deposits... Headward portions... incised by channels that are partly filled with younger deposits on northern bay margin and in Livermore Valley. Locally contains concentrations of continental vertebrate and invertebrate fossils."

The southwestern corner of the LLNL site adjacent to the Arroyo Seco was mapped as Younger Alluvial Fan Deposits (Qyf). These were described (in the map legend) as

"unconsolidated, moderately sorted, permeable fine sand and silt, with gravel becoming more abundant toward fan heads and within canyons. Forms well-drained levees which grade headward to stream deposits on terraces cut in Qof."

Herd (1977) remapped the eastern two-thirds of the Livermore Valley. He mapped most of the LLNL site and the northerly portion of the SNLL site as an older alluvial deposit (Qoa₂). The central portion of SNLL was mapped as a slightly older alluvial deposit (Qoa₃). The western portion of LLNL and a small area in the northern part of the site were mapped as Recent Flood-Plain Alluvium (Qfa) while the hilly southern portion of SNLL was mapped as underlain by "The Livermore Gravels of Clark (1930)" (QT1). Herd's mapping of the LLNL and SNLL sites is shown in Fig. 9.

Herd did not provide lithologic descriptions of Recent Flood-Plain Alluvium or the Older Terrace Deposit sequences. Analysis of logs of 132 test borings made chiefly for building foundations on the LLNL site show that LLNL is underlain by alternating sequences of silts, clays, sands, and gravels. These exploratory borings are concentrated in developed portions of LLNL and range in depth from 4 ft to a maximum of 126 ft; most range from 25 to 65 ft in depth. The borehole logs are on file in the LLNL Plant Engineering Department offices. Drillers' logs of several deeper (300 ft and greater) cathodic protection wells and water wells also exist. Lithologic descriptions included in these logs are rather generalized and of uncertain quality.

During trenching studies in the eastern portion of LLNL, two moderately-well developed soil profiles were observed in the near-surface portion of the alluvial sequence underlying the Laboratory and nearby areas. As discussed previously, an average age of about 19 000 yr was obtained for a soil formed within alluvium mapped by Herd as Qoa₂. An age of approximately 115 000 yr was obtained for a deeper horizon.

No continuous, readily recognizable marker beds could be detected in the subsurface below LLNL. This is consistent with previous findings by the CDWR (1966). However, aggregate lithologic units consisting of predominately coarser materials, sands, and gravels, or predominately finer materials, silts, fine sands, and clays can be recognized locally.

STRUCTURE

As shown in Figs. 6, 7 and 10, various investigators have postulated faults traversing the LLNL site. Faults previously mapped as underlying LLNL are the Corral Hollow Fault (Blume, 1971; CDWR, 1974), the Doutherty Fault (Blume, 1972), and the Tesla Fault (Blume, 1972; CDWR, 1974). Air photo lineaments subparallel to the nearby Las Positas Fault zone cross the southeast portion of LLNL (Judd Hull and Associates, 1977; this investigation).

As discussed in a preceding section and in Appendix F (Volume II), exploratory trenches have been excavated across the mapped locations of the Corral Hollow and Doutherty Faults within LLNL and across the Tesla and Las Positas Faults on SNLL property. Two air photo lineaments possibly related to the Las Positas fault have also been trended within LLNL.

No direct geologic evidence has been found within LLNL to suggest that any of the postulated faults cut alluvial deposits that have been dated as late Pleistocene, based upon soil profile development and the ¹⁴C and ²³⁰Th/²³⁴U age dating methods. No evidence for the Tesla Fault, as mapped, was found in late Pleistocene or Pliocene materials from the trench on SNLL property. Several strands of the Las Positas Fault zone were encountered in exploratory trenches and in other excavations made on SNLL property. These fault strands displace late Pleistocene alluvial

deposits and beds of the Plio-Pleistocene Livermore Formation. No evidence for strands of the Las Positas Fault zone was found in late Pleistocene alluvial deposits exposed in exploratory trenches excavated in the southeastern portion of LLNL.

Blume (1972) mapped a local fold structure, the Livermore syncline across the northeastern portion of LLNL (Figs. 7 and 36). They presented evidence suggesting that the Livermore syncline is an area of active tectonic downwarping.

SUMMARY AND CONCLUSIONS

LLNL is underlain by a thick sequence of Quaternary alluvial deposits overlying a complex basement of Mesozoic metamorphic and late Mesozoic and Tertiary marine sedimentary rocks. The 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.

The Laboratory is located in a tectonically active region. Folding and faulting of Quaternary materials and periodic seismicity support this conclusion.

Limited geodetic data suggest active downwarping of alluvial deposits beneath LLNL. However, soil profiles developed in alluvial deposits exposed in excavations and exploratory trenches within the eastern portion of the LLNL site suggest that periods of relative stability (with little net erosion or deposition) have occurred during late Pleistocene time. Motions indicated by existing geodetic data suggest downwarping along the axis of the Livermore syncline (mapped as crossing the northeastern portion of LLNL). The indicated motions do not support the existence of the Doutherty Fault as a hinge line separating areas of subsidence within the Valley from areas of uplift in the Altamont Hills to the east.

Within the Livermore Valley and adjacent areas, geologic and seismologic evidence demonstrate Holocene activity along the Calaveras and Greenville Fault zones that bound the Valley on the west and east, respectively.

Geologic features visible along the hill front near SNLL provide evidence for the presence of the Las Positas Fault, a strike-slip fault of tectonic origin. Southwesterly displacement of the Arroyo Seco channel and some minor drainages coupled with the "right-stepping" pattern of *en-echelon* fault

strands in the vicinity of the Arroyo Seco suggest left-lateral movement. Outcrop and trench data provide clear evidence for repeated late Pleistocene movement; Holocene movement may have occurred.

Displacements of late Pleistocene and Holocene materials have occurred along strands of the Verona Fault zone in the southwestern Livermore Valley. However, the nature of movements along this zone are unclear and controversial.

There is evidence for local displacement of Quaternary materials along the Carnegie, Livermore, Williams, and Valle Faults and possibly along the Patterson Pass Fault.

There is no direct geologic evidence regarding location and recency of activity along other faults projected beneath the Valley floor. However, indirect evidence such as probable groundwater barriers and geophysical data suggests that several faults are present as subsurface features. Little evidence supports the existence of the Mocho Fault, and direct examination has ruled out the Doutherty and Corral Hollow Faults as features affecting near-surface materials along their mapped projections. Indirect evidence for the existence of the Doutherty Fault at depth is very questionable. Trenching studies have failed to locate Strand 2 of the Tesla Fault as projected toward LLNL by previous investigators. However, Quaternary movements may have occurred on portions of the Tesla Fault zone several miles southeast of LLNL—although direct field evidence for such movements is lacking.

Because of deep soil cover and landslide deposits in the area southeast of LLNL, the location of contacts between formations can only be inferred. The need to infer the location of contacts explains why there are many differences in the maps of this area. Further, since some faults are postulated on the juxtaposition of the formations, the existence

of some fault traces is in doubt. Roads and stream channels are the best areas for examining deposits and locating contacts between formations. Recently excavated roadcuts and trenches have exposed bedrock profiles and locations that differ from those shown on previous maps.

Recent compilations by the USGS of regional seismicity show a close correspondence between

centers of seismic activity and portions of the Calaveras and Greenville Fault zones. Additional diffuse seismicity, noted in an area located east of Del Valle reservoir and several kilometers south of LLNL, cannot be presently related to any particular fault. Rather, it may reflect movements on several relatively small faults that have been mapped in the area.

PLANS FOR FURTHER STUDIES

The first phase of the geologic investigation of the LLNL site and its environs has been completed. The principal purposes of this first phase of the study were to thoroughly review previous pertinent geological studies and to search LLNL and nearby areas for faults that displace late Quaternary materials. These objectives have been accomplished.

However, before a comprehensive geologic hazards appraisal of LLNL can be completed, additional studies are required. These studies have been planned and are listed in the following paragraphs.

REGIONAL GEOLOGIC MAPPING

- *Studies of the Greenville-Carnegie Complex.*

Geologic evidence for a zone of young faults along the eastern margin of the Livermore Valley has been presented by the USGS and CDWR. Individual faults have been considered part of the Greenville or Carnegie Fault zones, seemingly based on author preference. The January 1980 earthquake series is at least in part associated with these faults. The extent and geologic evidence for Quaternary activity along the fault complex needs to be critically evaluated. Further, the relationships of these faults to the Tesla Fault, Las Positas Fault, and faults on strike with the system in Contra Costa County need to be determined.

- *Further Study of the Las Positas Fault Zone.* Strong evidence for the existence of the Las Positas Fault zone is presently confined to the portion of the hillfront extending about 2 km northeast and southwest from SNLL. However, the USGS

has mapped the fault over a much larger area. Air photo and field reconnaissance work is planned in order to assess the extent of the Las Positas Fault zone and its relationship to other regional faults such as the Greenville-Carnegie complex, the Livermore Fault, and possibly the Williams and Calaveras Faults.

- *Evaluation of Area East of Del Valle Reservoir.* A number of epicenters have been plotted in the area east of Del Valle reservoir and the CDWR has mapped the Williams and Valle Faults in this general area. A number of aftershocks of the January 1980 earthquake series occurred in this area and appear to relate to possible northeast trending faults mapped by Herd (1977). Airphoto studies and field reconnaissance are planned to provide a better understanding of observed seismicity.

- *Evaluation of the Livermore Fault.* The CDWR regards the Livermore Fault as a young, potentially active geologic structure; the USGS strongly disagrees. An independent assessment of the Livermore Fault is planned. Data obtained may also be important to the LLNL geohydrologic study since the CDWR regards the Livermore Fault as an important groundwater barrier.

Several months of field mapping at a scale of 1:24 000 and airphoto interpretation will be required in order to complete this work. Early operations of the seismic monitoring network may focus these studies, but an effort involving most of the Altamont 7-1/2 minute Quadrangles and portions of the Livermore, La Costa Valley, Mendenhall Springs, Midway, and Cedar Mountain Quadrangles is anticipated.

SUBSURFACE INVESTIGATIONS

In cooperation with the planned geohydrology effort, samples will be obtained during the drilling of wells to monitor groundwater and from other boreholes. These samples should permit identification and correlation of strata beneath LLNL based on consistent criteria. It is presently not possible to determine the extent to which variations among existing test borings represent geologic changes and the extent to which they reflect variations in logging resulting from work by different geotechnical groups using differing technical standards.

In addition to the observation wells planned for the geohydrologic study, borings will be located to permit construction of one or two northeast-southwest oriented cross sections. The planned observation wells and test borings will permit evaluation of deeper horizons and groundwater levels normal to the projected Tesla, Doutherty, and Corral Hollow Fault trends. About 31 holes roughly 30 m (100 ft) in depth are planned. The locations of the planned exploratory holes and observation wells are shown on Fig. B-1 in Appendix B.

No further trenching studies are scheduled at this time. However, field mapping studies should identify locations where exploratory trenches will provide important data concerning fault locations, associations, and activity. Most of these locations

will be on private property and, therefore, permission of owners will have to be obtained.

AGE DATING

The application of the $^{230}\text{Th}/^{234}\text{U}$ age dating method to caliche samples has already provided some significant results. Dating will continue and be supplemented by additional samples, if these can be collected at geologically significant locations. Attempts will be made to use caliche recovered from core samples for the dating of stratigraphic horizons at depth beneath LLNL.

Additional samples of carbonaceous materials suitable for dating by the ^{14}C method will be sought during field mapping studies and future exploratory programs. If suitable samples are found, additional ^{14}C dates will be obtained.

The feasibility of performing paleomagnetic studies on fine-grained sediments obtained from outcrops and future exploratory trenches is being investigated. This method of age dating will be applied if found pertinent.

Relative ages may be obtained by further examination of soil profile development in the LLNL area. This will be further explored as part of the planned Quaternary mapping study.

APPENDIX A

AIR PHOTO INTERPRETATION

by A. L. Ramirez and D. W. Carpenter

Three sets of black and white air photographs were studied during the preliminary stages of the 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 and 1972. Two detailed monoscopic and stereoscopic analyses were made of each of the three photo sets. Each of the investigators worked independently of the others so that the results of one study would not influence the other's interpretations.

Tonal variations and linear patterns have been observed in photographs of areas within and adjacent to the LLNL site. Such tonal variations and linear patterns may indicate surface expressions of faults, or they may indicate other geologic features such as former stream channels. These 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. 18 and 31.

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 coincide with the location of the Las Positas Fault as mapped by Herd (1977). Air photos taken in 1940, 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 air photos. These faint lineations strike subparallel to the Las Positas Fault of Herd (1977).

The 1940 aerial photographs show a stream channel in the area where faint lineaments and tone variations, attributed to the Dougherty Fault (Blume, 1972), can be seen on later photographs. Discontinuous lineaments and faint tone patterns were observed in the area where Strands 1 and 2 of the Tesla Fault zone have been projected (Blume, 1972).

Faint and discontinuous tonal variations that cut across the entire LLNL site were observed by one investigator. The southeastern segment of these tonal variations is indistinct in places but roughly coincides with the projected position of the Corral Hollow Fault trace (Blume, 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 observed to intersect the northeastern corner of the Laboratory's perimeter and will be evaluated further during regional geologic studies.

APPENDIX B

ANALYSIS OF EXISTING SUBSURFACE DATA

by A. L. Ramirez and D. W. Carpenter

As part of the preliminary investigations for the seismic safety assessment program, copies of the geotechnical investigation reports for foundation designs of many of the buildings in the Laboratory were compiled and examined. This information is in the files of the LLNL Plant Engineering Department. Table B-1 summarizes important characteristics of all known exploratory borings that were drilled during the foundation investigations. Figure B-1 shows the locations of these borings.

A total of 132 test borings are known to have been drilled during the foundation investigations. Many borings are shallow (10-30 ft in depth), but some extend to depths of as much as 126 ft. Drillers' logs of two water wells and five cathodic protection wells also exist. The two water wells were located along the western boundary of LLNL and were drilled to a depth of 702 ft each. The cathodic protection wells average about 300 ft in depth.

Logs of all known borings were examined and some rough plots were made to aid planning of future site geologic studies. Data from existing test borings and from future LLNL exploratory drilling will be used in the preparation of the final geologic report.

Logs of test borings on the LLNL site were prepared by the consultants' personnel at various times and in accordance with a variety of logging standards, thereby complicating analysis and interpretation. However, most holes drilled during the past 10 to 15 years appear to have been logged in accordance with the Unified Soils Classification system, a generally accepted standard in geotechnical professions.

Accuracy of the test boring logs cannot be independently judged; none of the borings are known to have been observed by LLNL geoscience personnel. In general, it may be assumed that the most accurate logs are of borings in which frequent soil samples were obtained or that were drilled with a bucket auger, a rig that returns all materials to the surface for inspection. Logs of holes drilled by wash boring techniques or of deep borings drilled by screw-type augers must be regarded as of limited value in establishing subsurface conditions, unless frequent soil samples were recovered.

No geophysical logs, which could have been of assistance in establishing lithologies between sampling points, have been found. It is doubtful that any exist since geophysical logs are not usually obtained during foundation studies for buildings.

Groundwater at a depth of 74 ft was reported in test boring 391-1, drilled at the site of additions to Bldg. 391. Groundwater was not reported as having been encountered in other test borings at LLNL except for a shallow seep observed in boring 435-1. Notes on logs of many test borings indicate that groundwater was either not encountered or that where water was added during drilling (wash borings) the water levels were declining at the completion of drilling.

No test borings are known to have been completed to permit long-term groundwater level observations.

TABLE B-1. Summary of test boring data.

Bldg.	Hole #	Elevation ft	Depth ft	Method	Date	Consultant	Remarks
111	111-1	617	80	bucket auger	Mar/1966	Dames & Moore	
	111-2	617	67				
	111-3	616	57				
	111-4	620	60				
	111-5	617	58				

TABLE B-1. (Continued.)

Bldg.	Hole #	Elevation ft	Depth ft	Method	Date	Consultant	Remarks
113	113-1	624.7	40	N/A	N/A	Dames & Moore	
	113-2	624.5	40				
	113-3	624.5	40				
	113-4	622.9	40				
	113-5	623.5	40				
	113-6	621.2	40				
	113-7	621.7	20				
	113-8	620.8	20				
	113-9	620.3	65				
	113-10	623.3	65				
121	121-1	616.5	25.5	bucket auger	May/1956	Dames & Moore	
	121-2	617.3	10.5				
	121-3	617.6	21.5				
	121-4	618.2	25.0				
131	131-1	608.7	32.5	bucket auger	Sept/1957	Dames & Moore	
	131-2	611.3	27.5				
	131-3	610.5	21.5				
	131-4	611.1	24.0				
	131-5	612.6	26.5				
131	131-1A	606.7	34.5	bucket auger	Jan/1963	Dames & Moore	Borings drilled for additions to the building.
	131-2A	610.0	31.0				
	131-3A	609.7	35.5				
	131-4A	610.5	30.5				
	131-5A	613.2	36.0				
166	166-1	595.3	20	bucket auger	Sept/1961	Dames & Moore	Hole previously referred to as hole #3 of Bldg. 166; data included in report for Bldg. 261.
239	239-1	618.3	60	bucket auger	June/1967	Cooper-Clark & Assoc.	
	239-2	615.3	58				
241	241-1	609.2	25	N/A	July/1958	Woodward, Clyde, Borings map shows a building shaped Sherard & Assoc. differently from Bldg. 241.	
	241-2	610.8	15				
	241-3	608.8	20				
251	251-1	603.2	40	rotary wash and auger	Oct/1966	Harding Miller Lawson & Assoc.	
	251-2	603.1	50				
	251-3	603.4	46				
	251-4	603.2	80				
	251-5	603.3	4				
	251-6	603.3	4				
253	253-1	600	25	screw-type auger	Mar/1964	Robert S. Cooper & Assoc.	
	253-2	602	28				
	253-3	602	25				
261	261-1	597	30	power auger	Feb/1958	Woodward, Clyde, Sherard & Assoc.	
	261-2	596	25				

TABLE B-1. (Continued.)

Bldg.	Hole #	Elevation ft	Depth ft	Method	Date	Consultant	Remarks
261	261-1A	594.8	20	bucket auger	Sept/1961	Dames & Moore	Location of these borings obtained from LRL Test Borings Plans, by process of elimination.
	261-2A	595.7	20				
261	261-1B	595.7	21	continuous flight	Dec/1970	Woodward-Clyde & Assoc.	Borings drilled for building additions.
	261-2B	596.0	21				
	261-3B	597.1	21				
	261-4B	597.4	21				
Pipe- line	P-2	589.5	31.5	continuous flight	May/1973	Woodward-Lundgren & Assoc.	
	P-2	591.5	32.0				
291	291-1	587.5	31.5	auger	Apr/1970	Woodward-Lundgren & Assoc.	
	291-2	587	16				
311	311-1	628.7	38	bucket auger	July/1964	Dames & Moore	
	311-2	632	40				
321	321-1	622.6	19.5	bucket auger	Feb/1958	Dames & Moore	
	321-2	623.1	33.0				
	321-3	624.7	19.5				
	321-4	625.2	29.0				
327	327-1	621	40	power auger	Feh/1958	Woodward, Clyde, Sherard & Assoc.	Title of report indicates that this hole was drilled for Bldg. 321; however, coordinate positions suggest it was drilled for Bldg. 327, and was included in report for Bldg. 261.
332	332-1	N/A	31	bucket auger	Feh/1958	Soil Testing Services	
	332-2	620.0	31				
	332-3	616.0	31				
	332-4	619.0	31				
	332-5	615.5	31				
	332-6	615.5	31				
332	332-1A	617.4	100	bucket auger	Oct/1972	Shannon & Wilson	Holes drilled in support of exploration for additions to Bldg. 332; a trench was also excavated for this investigation (for location see Fig. B-1).
	332-2A	N/A	50				
	332-3A	617.5	80				
	332-4A	620.3	51.5				
	332-5A	617.3	51.5				
	332-6A	616.9	49.5				
341	341-1	613.8	18.5		Oct/1962	Woodward, Clyde, Sherard & Assoc.	
	341-2	614.8	24.0				
	341-3	614.5	23.0				
361	361-1	604.0	25	bucket auger	Nov/1965	Robert S. Cooper & Assoc.	Holes 361-5, 361-6 are referred to respectively as holes 9 & 10 in the soils report.
	361-2	606.0	25				
	361-3	603.0	25				
	361-4	603.0	25				
	361-5	602.5	25				
	361-6	603.5	25				

TABLE B-1. (Continued.)

Bldg.	Hole #	Elevation ft	Depth ft	Method	Date	Consultant	Remarks
364	364-1	600.0	25	bucket auger	Nov/1965	Robert S. Cooper & Assoc.	Holes 364-1,2,3,4, are referred to as holes 5,6,7,8 in the soils report.
	364-2	601.0	25				
	364-3	600.5	25				
	364-4	600.5	25				
391	391-1	593.0	126	rotary wash	Mar/1978	Dames & Moore	Stabilized water level at 74 ft in boring 391-1.
	391-2	593.0	50				
	391-3	594.0	50				
	391-4	595.0	52				
431	431-1	619.7	124.5	bucket auger & cable tool	June/1950	Dames & Moore	Cable tool used on 431-2 from 65 ft to 125.5 depth.
	431-2	621.7	125.5				
431	431-1A	622.2	48.5		Mar/1964	Woodward, Clyde, Sherard & Assoc.	Holes were drilled in support of ex- ploration for Astron Tunnel (addition to Bldg. 431).
	431-2A	623.7	53.5				
	431-3A	624.5	46.0				
	431-4A	626.1	51.5				
431	431-1B	N/A	86	continuous flight auger	Dec/1977	Bechtel, Inc.	Borings done in support of MFTF con- version.
	431-2B	N/A	82				
435	435-1	620.5	30	power auger	May/1958	Woodward, Clyde, Sherard & Assoc.	Hole 435-1 encountered free water at time of drilling.
	435-2	622.2	25				
	435-3	621.1	30				
	435-4	619.7	29				
	435-5	621.1	27.5				
441	441-1	623	29.0	auger	Aug/1978	Woodward-Clyde Consultants	Holes 441-1,2,3,4,5,6 are referred to as holes 7,8,9,10,11,12 of Bldg. 441 in the soils report.
	441-2	624.5	19.5				
	441-3	625	20.0				
	441-4	626	39				
	441-5	626	20				
	441-6	624.5	16.5				
451	451-1	613	24.5	auger	Aug/1977	Woodward-Clyde Consultants	
	451-2	614	21.5				
	451-3	614	23.5				
	451-4	613	41.0				
	451-5	612	24.5				
	451-6	612	24.5				
	451-7	613	16.5				
481	481-1	595.5	41	rotary wash	Apr/1979	Dames & Moore	Holes are referred to respectively as E. F. G in the soils report.
	481-2	600	41				
	481-3	600	41				
511	511-1	642.5	20	screw-type auger	Mar/1964	Robert S. Cooper & Assoc.	Holes 511-1 and 511-2 are referred to as holes 4 & 5 in the soils report. They were drilled for an addition to the struc- ture as part of the same exploratory program as Bldg. 253.
	511-2	639.8	20				

TABLE B-1. (Continued.)

Bldg.	Hole #	Elevation ft	Depth ft	Method	Date	Consultant	Remarks
551	551-1	614.5	29	continuous	Aug/1978	Woodward-Clyde Consultants	
	551-2	616.5	14.5	flight auger			
	551-3	618.5	19				
	551-4	619.5	39				
	551-5	618	29				
	551-6	616	19.5				
Substation							
230/	SS-1	631.3	20	continuous	Jan/1979	Peter Kaldveer	
13.8	SS-2	631.0	20	flight auger			
KV	SS-3	630.5	20				

N/A = not available.

APPENDIX C

URANIUM-SERIES DATING OF PEDOGENIC CARBONATES FROM THE LIVERMORE VALLEY

by Kevin Knauss

INTRODUCTION

As part of the Site Investigation being undertaken by DOE at LLNL and SNLL, seven exploratory trenches, two storm sewer trenches, an outcrop, a roadcut, and a basement excavation have been mapped. 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 "B" soil horizons within buried paleosols, root casts, massive nodular caliche presumably from the Plio-Pleistocene Livermore gravels, and caliche cements from clayey gouge zones along faults. Age dates for these materials may provide a time stratigraphy for the alluvial units mapped, and hence may provide some limits (minimum age) for last-fault movement and establish the degree of tectonic stability.

Recently, a technique was developed to age date pedogenic carbonates in gravelly desert soils (Ku et al., 1979) using uranium-series methods. The results presented in this appendix are an attempt to extend the uranium series method to the dating of semi-arid region pedogenic carbonates from the Livermore Valley. The nine samples from the Livermore Valley studied thus far include six specimens taken from argillic "B" horizons. The "B" horizon within a paleosol is generally thought of as a zone of accumulation or illuviation, and in alkaline environments the "B" horizon has been considered a "chemically closed system" (Hunt, 1972). However, during pluvial periods within the Pleistocene this concept of the "B" horizon may not have been correct. The age dating implications of an "open system" will be discussed later. In addition, one of three wood fragment samples collected from the trenches contained enough material to be age dated by the ^{14}C method. A brief description of the samples is provided in Table C-1.

TABLE C-1. Descriptions of samples.

List A: Samples giving reliable age dates

Carbonate samples	
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) approx 11 ft below present surface at Sta. 1+67.
E-1 C2a	Caliche taken in position stratigraphically equivalent to E-1 C1a at Sta. 1+72.
Greenville Rd. #1	Grey-white mudstone (unit 9) containing abundant disseminated caliche. Unit associated with Las Positas Fault zone and present only south of the zone.
Greenville Rd. #2	Sample taken on revisit to Greenville Rd. cut; equivalent to Greenville Rd. #1.
E-5 #1	Caliche filling vertical shrinkage fractures in clayey members of unit 5 approx 10 ft below present surface at Sta. 2+34.
E-5 #3	Caliche filling vertical fractures in silty clay (unit 5) approx 10 ft below present surface at Sta. 1+40 on west wall of trench.
Wood samples	
E-3	Wood fragment in unit 46 north of Las Positas Fault zone approx 11-1/2 ft below present surface at Sta. 2+32.

TABLE C-1. (Continued.)

List B: Samples giving unreliable age dates

E-2 #2	Caliche filling vertical fractures in silty clay (unit 3a) approx 5-1/2 ft below present surface at Sta. 2+15.
E-6 #1	Composite sample taken from caliche filling vertical fractures in silty clay (unit 2) approx 5 ft below present surface between Sta. 0-5 and 0-15.
Bldg 391	Traces of caliche filling narrow fractures coated with reddish brown clay in large lens of sandy silt (unit 3) approx 8 ft below present surface at Sta. 1+56.

AGE CALCULATIONS

The caliche samples were analyzed using a modification of the procedure of Ku and Joshi (1980) and Ku et al. (1979). The procedure includes a weak acid leaching of the carbonate followed by isotopic analyses of both the leachate and residue. As a first approximation, the leach analytical data can be used to represent data for the carbonate. Ages of the samples as calculated from leach data are listed in Table C-2 as Age¹. These ages should be amenable to refinement, as shown below.

An upper limit may be estimated for the age of the carbonate using the assumption that the carbonate phase was initially free of ²³⁰Th (Ku and Joshi, 1980). Calculated ages using this correction scheme are listed as Age² in Table C-2. Alternatively, one may make assumptions about the nature of the detrital phase and calculate a slightly different corrected age (Ku et al., 1979). These corrected ages are listed as Age³ in Table C-2. For a derivation of the model age equations, see the references mentioned above. Table C-2 contains the analytical data and modeled data for the nine caliche samples analyzed. The term F_L refers to the leach fraction, i.e., that fraction of the sample that was soluble in dilute acid. Figure C-1 presents the ages in a graphical format. The best estimate is taken as the mean of Age¹ and Age³. These best estimates for the age dates that are considered reliable are summarized in Table C-3.

The wood fragment from Trench E-3 was dated by Dr. Steve Robinson of the USGS, Menlo Park. Standard ¹⁴C dating techniques and age calculations were employed. The fragment's age is also presented in Table C-3.

TABLE C-2. Sample data.

		Analytical Data				Concentration		Activity Ratio				Dating Result
Sample		²³² Th	²³⁸ U	²³⁴ U	²³⁰ Th	U	Th	²³⁴ U/ ²³⁸ U	²³⁰ Th/ ²³² Th	²³⁰ Th/ ²³⁴ U	F _L	(× 10 ³ yr)
		(dpm/g)				(ppm)						
E-1 C1a	Leach	0.236	1.343	1.486	0.879	1.799	0.974	1.107	3.717	0.591	0.712	Age ¹ = 100
		±0.011	±0.032	±0.034	±0.024	±0.042	±0.046	±0.030	±0.189	±0.021		
	Residue	1.054	1.343	1.212	1.814	1.799	4.347	0.903	1.720	1.496		
		±0.042	±0.031	±0.029	±0.057	±0.041	±0.172	±0.028	±0.078	±0.059		
	Carbonate	N/A	1.343	1.433	1.070	N/A	N/A	1.067	N/A	0.747	N/A	Age ² = 145
	Carbonate	N/A	0.746	0.836	0.473	N/A	N/A	1.121	N/A	0.566	N/A	Age ³ = 95
E-1 C2a	Leach	0.168	1.745	1.961	1.385	2.338	0.695	1.124	8.210	0.706	0.663	Age ¹ = 135
		±0.006	±0.045	±0.049	±0.020	±0.060	±0.024	±0.031	±0.298	±0.021		

TABLE C-2. (Continued.)

Sample		Analytical Data				Concentration		Activity Ratio			F _L	Dating Result ($\times 10^3$ yr)
		²³² Th	²³⁸ U	²³⁴ U	²³⁰ Th	U	Th	²³⁴ U/ ²³⁸ U	²³⁰ Th/ ²³² Th	²³⁰ Th/ ²³⁴ U		
		(dpm/g)				(ppm)						
Greenville Road Cut #1	Residue	0.640 ±0.023	1.599 ±0.034	1.639 ±0.034	1.982 ±0.046	2.143 ±0.045	2.636 ±0.096	1.024 ±0.027	3.100 ±0.123	1.209 ±0.038		
	Carbonate	N/A	1.745	1.981	1.579	N/A	N/A	1.135	N/A	0.797	N/A	Age ² = 160
	Carbonate	N/A	1.030	1.266	0.864	N/A	N/A	1.230	N/A	0.683	N/A	Age ³ = 125
	Leach	0.123 ±0.006	0.669 ±0.029	0.897 ±0.029	0.440 ±0.011	0.897 ±0.038	0.508 ±0.023	1.339 ±0.058	3.572 ±0.184	0.491 ±0.020	0.666	Age ¹ = 70
	Residue	1.295 ±0.045	1.373 ±0.040	1.162 ±0.046	1.526 ±0.049	1.840 ±0.054	5.337 ±0.184	0.846 ±0.033	1.178 ±0.049	1.313 ±0.059		
	Carbonate	N/A	0.669	0.791	0.517	N/A	N/A	1.182	N/A	0.654	N/A	Age ² = 110
Greenville Road Cut #2	Carbonate	N/A	0.447	0.569	0.295	N/A	N/A	1.273	N/A	0.518	N/A	Age ³ = 77
	Leach	0.117 ±0.007	0.768 ±0.026	0.951 ±0.030	0.410 ±0.014	1.029 ±0.034	0.481 ±0.029	1.239 ±0.049	3.511 ±0.237	0.431 ±0.020	0.760	Age ¹ = 63
	Residue	1.393 ±0.034	1.332 ±0.035	1.208 ±0.033	1.654 ±0.039	1.785 ±0.047	5.741 ±0.144	0.907 ±0.032	1.187 ±0.037	1.368 ±0.049		
	Carbonate	N/A	0.768	0.911	0.512	N/A	N/A	1.186	N/A	0.562	N/A	Age ² = 88
	Carbonate	N/A	0.527	0.671	0.271	N/A	N/A	1.273	N/A	0.404	N/A	Age ³ = 58
	E-2 #2	Leach	0.223 ±0.011	1.235 ±0.055	1.359 ±0.058	0.273 ±0.013	1.654 ±0.073	0.921 ±0.046	1.101 ±0.058	1.211 ±0.080	0.201 ±0.013	0.541
E-5 #1	Residue	1.397 ±0.054	1.278 ±0.040	1.194 ±0.039	1.589 ±0.059	1.713 ±0.054	5.759 ±0.223	0.934 ±0.037	1.137 ±0.049	1.331 ±0.066		
	Carbonate	N/A	1.235	1.388	0.536	N/A	N/A	1.043	N/A	0.416	N/A	Age ² = 55
	Carbonate	N/A	0.717	0.770	0.019	N/A	N/A	1.074	N/A	0.025	N/A	Age ³ = 3
	Leach	0.171 ±0.009	2.016 ±0.047	2.331 ±0.052	0.527 ±0.017	2.702 ±0.063	0.703 ±0.038	1.156 ±0.028	3.089 ±0.186	0.226 ±0.009	0.604	Age ¹ = 28
	Residue	1.211 ±0.037	1.406 ±0.048	1.390 ±0.048	1.816 ±0.048	1.884 ±0.064	4.992 ±0.151	0.998 ±0.041	1.499 ±0.050	1.307 ±0.056		
	Carbonate	N/A	2.016	2.321	0.795	N/A	N/A	1.151	N/A	0.343	N/A	Age ² = 45
E-6 #1	Carbonate	N/A	1.491	1.795	0.271	N/A	N/A	1.204	N/A	0.151	N/A	Age ³ = 18
	Leach	0.198 ±0.011	1.262 ±0.037	1.458 ±0.041	0.265 ±0.013	1.691 ±0.051	0.816 ±0.045	1.155 ±0.043	1.338 ±0.097	0.182 ±0.010	0.421	Age ¹ = 21
	Residue	1.533 ±0.056	1.214 ±0.038	1.150 ±0.037	1.914 ±0.065	1.628 ±0.051	6.318 ±0.233	0.947 ±0.038	1.248 ±0.053	1.664 ±0.078		
	Carbonate	N/A	1.262	1.370	1.227	N/A	N/A	1.086	N/A	0.895	N/A	Age ² = 240
	Carbonate	N/A	0.530	0.161	0.018	N/A	N/A	3.038	N/A	0.112	N/A	Age ³ = 13
	E-6 #3	Leach	0.378 ±0.017	2.259 ±0.055	2.272 ±0.064	0.557 ±0.021	3.027 ±0.074	1.561 ±0.070	1.207 ±0.031	1.470 ±0.081	0.204 ±0.009	0.586

TABLE C-2. (Continued.)

Sample	Analytical Data				Concentration		Activity Ratio			F _L	Dating Result (× 10 ³ yr)
	²³² Th	²³⁸ U	²³⁴ U	²³⁰ Th	U	Th	²³⁴ U/ ²³⁸ U	²³⁰ Th/ ²³² Th	²³⁰ Th/ ²³⁴ U		
	(dpm/g)				(ppm)						
Residue	1.899 ±0.082	1.364 ±0.037	1.325 ±0.037	2.239 ±0.092	1.829 ±0.050	7.825 ±0.339	0.971 ±0.033	1.179 ±0.054	1.689 ±0.084		
Carbonate	N/A	2.259	2.700	1.174	N/A	N/A	1.194	N/A	0.434	N/A	Age ² = 59
Carbonate	N/A	1.196	1.636	0.113	N/A	N/A	1.368	N/A	0.068	N/A	Age ³ = 9
Bldg. 391 Leach	0.540 ±0.024	1.359 ±0.045	1.510 ±0.048	0.592 ±0.026	1.821 ±0.059	2.225 ±0.101	1.111 ±0.045	1.097 ±0.066	0.392 ±0.021	0.286	Age ¹ = 53
Residue	1.681 ±0.072	1.479 ±0.031	1.409 ±0.029	1.607 ±0.071	1.982 ±0.041	6.929 ±0.296	0.953 ±0.023	0.956 ±0.041	1.140 ±0.056		
Carbonate	N/A	1.359	1.335	0.911	N/A	N/A	0.983 ^b	N/A	0.682	N/A	Age ² = 120
Carbonate	N/A	0.523	0.500	0.076	N/A	N/A	0.955 ^b	N/A	0.152	N/A	Age ³ = 19

^aN/A = Not applicable to dating method.

^bThe corrected carbonate ²³⁴U/²³⁸U must be assumed approximately 1.0 to even attempt to calculate model ages.

TABLE C-3. Best estimates of age of samples that were dated.

Sample	Type	Best estimate of age (× 10 ³ y)
E-1 C1a	carbonate	98
E-1 C2a	carbonate	132
Greenville Rd. #1	carbonate	73
Greenville Rd. #2	carbonate	60
E-3	wood	17
E-5 #1	carbonate	23
E-6 #3	carbonate	17

DISCUSSION OF AGE DATE RELIABILITY

Most of the samples dated thus far consist of relatively thick caliche filled desiccation cracks in argillized "B" soil horizons. These samples are in contrast to the relatively massive, impermeable pebble coatings dated by Ku et al. (1979), although they are similar to the carbonate cementations of an arid-zone fanglomerate deposit dated by Ku and Joshi (1980). There are intuitive concerns dealing with the "closed system" nature of the Livermore Valley pedogenic carbonates. Although the "B" soil horizon is generally considered to be a zone of accumulation in alkaline environments, conceivably during wetter periods it may have been subject to leaching and material transport. Directly confirmation of the "closed system" nature of these pedogenic carbonates would require concordia between these ²³⁰Th/²³⁴U dates and ages obtained from other radiometric dating methods. Such methods are not available in this instance; therefore, evaluations will have

FIG. C-1. Summary of age determinations for one wood and six pedogenic carbonates in samples taken from trenches and roadcuts in the Livermore Valley.

to be made on the internal consistency of our 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 precludes 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.

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 C1a to E-1 C2a and Greenville Rd. #1 to Greenville Rd. #2. The data have been summarized in Table C-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 C-2, the uranium and thorium concentrations in the residues are in the range 1 to 8 ppm, with an average Th/U weight ratio of 3:1. These values are generally expected from an average shale. The $^{234}\text{U}/^{238}\text{U}$ activity ratios are near the secular equilibrium value (average 0.94). Ku et al. (1979) have determined that criteria can be specified by which large deviations from these norms can be used to identify samples unsuitable for dating by these methods.

Analyses of several of the samples did not give reliable age estimates. 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 $^{230}\text{Th}/^{232}\text{Th}$ 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 #2, E-6 #1, and Bldg. 391 excavation) are not included in the interpretive discussion in the text.

TABLE C-4. Age estimates of coeval pedogenic carbonates.

Sample	Age ¹ ($\times 10^3$ y)	Mean ¹	Age ²	Mean ²	Age ³	Mean ³
E-1 C1a	100		145		95	
		118 $\pm$ 24		153 $\pm$ 12		113 $\pm$ 24
E-1 C2a	135		162		130	
Greenville Rd. #1	70		110		77	
		67 $\pm$ 5		99 $\pm$ 15		68 $\pm$ 13
Greenville Rd. #2	63		88		58	

CONCLUSIONS

Although Trench E-3 contained no caliche, which would provide a direct concordancy check with the wood fragment acquired, concordancy can be indirectly inferred. The wood fragment in Trench E-3 was taken from Qoa₂ material. Two carbonate samples from other trenches, also taken from Qoa₂ material, corroborate the date. Preliminary results indicate that the method of Ku et al. (1979) may be extended to semi-arid region pedogenic carbonate as well as to other non-pedogenic carbonate cementations resulting from the actions of ground and surface waters. Secondary carbonates may provide useful information about stratigraphic relationships between various alluvial units within the Livermore Valley. Under appropriate conditions, absolute ages may be obtainable with better than $\pm 20\%$ precision. This is a tolerable level of precision when one considers that no other absolute dating techniques are available. In appropriate situations, relationships between disturbed and undisturbed units allow one to deduce a minimum age for fault movement or to potentially bracket ages.

Paleoseismicity in the Livermore area may possibly be determined by examining the depositional record contained in Frick Lake. Slumping or other disturbances would reflect the various seismic events. It may also be possible to age date sediment horizons beneath this playa lake by age dating the marls resulting from desiccation or other freshwater carbonates—such as pelecypods, gastropods, or tufa—using uranium-series age dating techniques. This work would complement any paleomagnetic determinations made on the playa sediments.

APPENDIX D GEOPHYSICAL EXPLORATION

by Paul Kasameyer

DIPOLE-DIPOLE RESISTIVITY SOUNDINGS

Dipole-dipole resistivity soundings were performed along five 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 Figs. D-1 and 31. 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. Results are shown in Figs. D-3 to D-7, which contain apparent resistivity pseudo-depth sections showing data obtained by the method described in Fig. D-2.

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 ($20 \Omega \cdot m$) weathering layer was observed in many places. The alluvium (Qal) in the flat areas was also conductive ($20-30 \Omega \cdot m$) and the outcrops of Livermore Gravels (QTI) that form hills were relatively resistive ($50-60 \Omega \cdot m$) to depths of 50-100 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 salinity in the rock beneath the aqueduct. The interpreted resistivity at 50 ft depth is indicated by the shading in Fig. D-1.

Second, two lines (2 and 6) cross the trace of the Tesla #1 fault. They show no indication of lateral changes in resistivity due to rock type and are thus in agreement with the 1978 URS/Blume report 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 and 5 cross the trend of the Las Positas Fault. The boundary between high resistivity rocks (inferred to be QTI) and low resistivity rocks (inferred to be Qal) strikes approximately parallel to the trend of the Las Positas Fault. The location of that contact can best be determined on line 5, 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. This boundary does not align with faults identified in the Sandia outcrop. An extension of the boundary to the southwest would pass through the east end of trench E-3 and pass to the northwest of trench E-4.

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. One possible interpretation is that the relatively resistive rocks on the northwest side of the boundary are 50 ft deeper than on the southeast side.

SEISMIC REFLECTION DATA

Gasch and Associates, Inc. ran two small-scale, high resolution seismic reflection profiles on the LLNL site (Fig. 18). 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 (200-500 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. Electronic problems caused data to be of poor quality and led to uncertainty in determining shot time.
2. Critically refracted energy corresponding to a layer 100-150 ft deep with an apparent seismic velocity of about 6000 ft/s is seen on the unstacked records. This energy contaminates the stacked sections, which are constructed assuming all energy is from reflections.
3. 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.

Before more reflection work is considered, we will perform small scale seismic refraction work on several areas.

MAGNETIC DATA

Total magnetic field surveys have been made on the LLNL site and east of SNLL (see Figs. 18 and 31). Measurements made in these surveys and the measurements published in the Blume (1972) and URS/Blume (1978) reports reflect effects of man-made features such as pipes and fences. All available data are being plotted and examined for indications of faults.

SELF POTENTIAL

Self potential measurements are being made in the vicinity of the Las Positas Fault to see if possible strands of that fault can be located by self potential methods.

FIG. D-1. Map of survey lines for dipole-dipole resistivity in field southeast 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 sections in Figs. D-3 to D-7. The resistivities interpreted to be at a depth of 50 ft are indicated by shading.

FIG. D-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 detected apparent resistivity is a spatial 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 does not represent an accurate map of the subsurface because each measurement averages over a large volume.

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

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

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

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

APPENDIX E

FIELD OBSERVATIONS OF SURFACE FAULTING

Livermore Valley earthquake series, January 24, 1980 and following

The source of the following observations is Bonilla and others, 1980. Location numbers shown appear on Figs. 20 or 32. Locations 1-32, 37, 38 appear on Fig. 20 and locations 33-36 on Fig. 32.

Location	Observations
1	Zone 100 m long, trends N.47°W.; individual open fractures in soil trend N.25°W.-35°W., have left-stepping en echelon relation to the zone. At one point, right lateral displacement of 11 mm parallel to zone and extension of 20 mm perpendicular to zone (1 Feb.). Local minor left-lateral component, probably from downslope gravity movement.
2	Zone trends N.30°W., consists of at least 7 fractures in soil, on most of which right lateral separation could be seen. Site of survey quadrilateral installed by P. W. Harsh. Zone may extend 40 m farther NW where a pair of left-stepping fractures could be followed for 15 m; extends at least 20 m to SE. Includes small graben with maximum depth of 70 mm.
3	Zone trend N.30°W. consists of discontinuous fractures that trend N.30°-35°W. A taut root and match of pebble with its mold provided calculated right lateral displacements of 18 mm parallel to zone and extension of 47 mm perpendicular to zone.
4	Zone trend N.38°W. individual cracks generally show relative uplift (max. 50 mm) of northeast side and as much as 30 mm extension; a "bridge" of sod attached to both walls indicated a right lateral component.
5	Two isolated en echelon left-stepping fractures in dirt road indicate right-lateral displacement but unable to measure amount. Northeast of line joining locations 4 and 5 are some short fractures that are probably related to downslope gravity movements, although one showed 6 mm of right-lateral separation combined with 27 mm extension. Between locations 5 and 6 and on both sides of a line joining them is an area of extensive landsliding.
6	Prominent fracture in soil, at least 30 m long; trends N.36°W.; strong suggestion of right-lateral component based on differences in crack width and probable match of points across break; relative vertical displacement mostly down on downhill side but not consistent. Survey alinement array installed by P. W. Harsh on 26 January crosses this fracture.
7	A pair of fractures, in soil, that intersect an E.-W. fence on the half-section line. West fracture trends N.27°-32°W. shows mostly downhill extension (maximum vertical 90 mm, 6 Feb) but may have a right lateral component. Extends south of fence where it becomes part of a landslide studied by R. V. Sharp. About 2.4 m to 9.8 m east is another fracture, somewhat concave upslope in plan, with a general trend of about N.28°W. This fracture is in compression with thrusting of downhill side over uphill side; maximum vertical component 70 mm. The one place where lateral component could be inferred (6 Feb) indicates left lateral, but very uncertain. The origin of these fractures is not clear.

- 8 Fracture zone in soil, trend N.27°W., consists of left-stepping fractures, extends SE from N-S fence that is on the quarter-section line. Right-lateral displacement parallel to zone at two points (28 Jan) ranged from 10 mm to 25 mm. Farther to NW are other fractures with the same trend but they may not be of tectonic origin.
- 9 Fracture zone in soil, trend N.27°W–30°W., traced 52 m. Unable to match edges of fracture to measure right-lateral displacement but could be a few centimeters.
- 10 Single fracture in soil, trend N.30°W., right-lateral strike slip 8 mm, calculated parallel to average zone trend of N.44°W. Between locations 10 and 11 the fault trace was visible at several places; although evidence of right-lateral displacement was seen, we could not measure it.
- 11 Left-stepping fractures in soil; measured 22 mm of right-lateral strike slip 1 February which had increased about 1 mm when remeasured 6 February. Unable to find fault traces between localities 11 and 12.
- 12 At Vasco Road. Pressure ridges and fractures formed in the pavement which is built on artificial fill. At time of our detailed examination (28 January) the pressure ridges had been removed and many of the edges of the fractures had been modified by truck traffic, but right-lateral strike-slip displacement was estimated at about 2 cm parallel to the zone trend of N.30°W. Fault traces were not visible within 0.5 km SE of Vasco Road.
- 13 Road to East Alameda County Dump. Seven hairline fractures extending perpendicularly across this paved road were visible 31 January; at least four cracks were present 25 January. Most of the cracks lie near the projection of the main break, have a NE trend, and may represent incipient faulting.
- 14 A short fracture zone, trend N.40°W., was found in soil at the base of a scarp-like rock outcrop. Individual fractures trend about N.18°W. Right-lateral strike slip was 8 mm parallel to zone and extension was 4 mm perpendicular to zone on 30 January.
- 15 Zone of fractures in soil; individual fractures trend N-S; probable right-lateral strike-slip.
- 16 Fracture zone trending about N.30°W. crosses Laughlin Road; first observed by us on 25 January. Individual fractures trend N-S, step to left. Difficult to confidently match points across the fractures but strike slip parallel to zone may be as much as 6 mm on a single break (29 February) including afterslip. Fractures could be traced NW into cultivated field but we did not see them to the SE of the pavement. Between locations 16 and 17 several hairline cracks with no displacement cross the pavement approximately perpendicular to the road.
- 17 A fracture trending N.19°W. showing about 3 mm of right lateral displacement (measured parallel to crack; 28 Jan) in dirt NE of pavement.
- 18 Group of northeast-trending fractures in pavement. The most conspicuous one trends N.7°E. Slip vectors measured at two places on this fracture 29 February were 13 mm in N.20°W. direction and 15 mm in N.25°W. direction. Resolved parallel to trend of zone (between localities 18 and 19) the right lateral strike slip was about 14 to 15 mm; right lateral displacement resolved parallel to the fracture ranged from 12 to 13 mm, of which as much as 6 mm occurred after a white line was painted across the fracture by Woodward-Clyde consultants on 25 January.

- On 29 February extension perpendicular to the fracture was as much as 8 mm, and vertical separation near center of road was as much as 2 mm (down to SE) but was not detectable at edges of road. Only one hairline fracture was observed at this locality on 25 January. The fracture had widened and moved 2 mm right-laterally by 13 February; many more fractures were present on 13 February than on 25 January, indicating that they were related to the 26 January event or subsequent movement.
- 19 Fracture zone in shoulder of road crossed low cut at SW edge of right-of-way and extended into field. On 28 January right-lateral displacements were 7 mm resolved parallel to fracture zone and 6 mm resolved parallel to the direction between locations 18 and 19. Site of alignment array installed by P. W. Harsh 30 January.
- 20 More than 20 hairline fractures in the pavement of Laughlin Road. Spacing between fractures (29 January) ranged from 1 m to 20 m and trends ranged from about N.40°W. to about N.60°W., diagonal to the road. The number of fractures increased thru time—only two fractures were visible on 25 January.
- 21 Fractures between locations 21 and 22 cross frontage road N of Interstate 580 perpendicularly. Some, perhaps all, are old fractures in the pavement that apparently opened wider during the earthquakes.
- 22 Intersection of Greenville Road and frontage road. Several fractures, some old (possibly associated with previous seismic events) and some apparently new. Nearly all confined to asphalt pavement and not breaking concrete curbs; orientation about N-S. One conspicuous crack on N-S part of Greenville Road showed (29 January) extension of 6 mm, no lateral displacement, did not break the concrete divider and died out to south within 11 m.
- 23 Between locations 22 and 23 are at least 17 fractures, most if not all old, but with additional extension presumably at the time of the earthquakes. Spacing between fractures ranges from about 3 to 73 m with concentrations of fractures in certain areas. The fractures show only extension except for one at location 23; there a fracture trending about N.40°W. showed about 1 mm of right-lateral displacement (29 January) and 2 mm of extension. The right lateral component had increased to about 2 mm on 29 February and to 3 mm on 1 April. The fracture was best developed in the north part of the road. It did not reach the south edge of the pavement on 29 January, but did by 1 April. It could not be seen in the dirt north or south of the pavement. This location is directly on the projection of a fault shown by Herd (1977) within the Greenville fault zone.
- 24 South frontage road of I-580, west of Greenville Road. Examined in reconnaissance fashion 29 February. At least 21 fractures, perpendicular to the road, show only extension except for one about 160 m west of the centerline of Greenville Road which has a suggestion of less than 1 mm of right lateral displacement. Close to Greenville Road are several fractures most if not all of which are old; apparent right lateral displacement (1 mm or less) on two of them seems to be the result of vertical movement of the inclined face of the concrete curb. Fractures on Greenville Road are mostly perpendicular to that road and at right angles to the fractures on the frontage road.
- 25 On Vasco Road about 2 km north of the County line. Several right-stepping fractures in the pavement. One zone trends about N.70°E., crosses entire pavement and showed 1 to 2 mm of left lateral and up to 3 mm vertical displacement (side up not consistent) on 6 February; a subparallel zone a few meters away shows

only extension (maximum 5 mm), doesn't reach northeast side of pavement but visible in dirt on southwest side of pavement. Unable to find fractures beyond shoulder of road. Roadbed probably on bedrock (sandstone and shale dipping $30^{\circ}\text{S.}50^{\circ}\text{W.}$) but thin fill could be under pavement.

- 26 Fracture zone in soil, trend $\text{N.}38^{\circ}\text{W.}$, could be traced about 30 m by very careful search, including pulling of grass. Zone at least 5 m wide, consists of three or more fractures up to 5 mm wide, about parallel to zone. Except for a left-stepping pattern in places, no evidence of lateral movement was found. Other fractures to the east, on a northeast-facing slope probably result from downslope movement of the soil.
- 27 Fracture zone in soil, trend $\text{N.}55^{\circ}\text{N.}$ (sic), was traced 43 m. It consists of prominent discontinuous left-stepping fractures. Near south end, differences in widths of fracture indicate a left-lateral component, but 15 m to the northwest had 15 mm of right-lateral strike slip measured parallel to trend of zone; southwest side generally downdropped, the vertical component being as much as 20 mm locally.
- 28 Fracture zone in soil, trend $\text{N.}48^{\circ}\text{W.}$, traced about 45 m. Near middle of zone, left-lateral strike slip 10 ± 5 mm, extension about 30 mm, and vertical component (down to SW) about 30 mm. About half way between locations 22 and 28 is a fracture zone locally trending $\text{N.}58^{\circ}\text{W.}$. At one point on it both the extension and the vertical component (down on SW) about 20 mm and the right-lateral strike-slip component was 11 mm and 7 mm resolved parallel to the local zone trend and general zone trend respectively.
- 29 At Vasco Road breaks in the pavement had been repaired at time of our visit except near centerline of road, where there were three principal cracks that formed a zone about 1 m wide, and a vertical component (down on SW) was visible. About 3:30 pm on 24 January, just before the repairs were made, R. C. Wilson and D. K. Keefer measured and photographed the break at the southeast side of the road where it was a single fracture. At the white line there they measured 20 mm of right lateral displacement, 40 mm of extension, and 30 mm of vertical displacement, down on southwest. Because the white line is perpendicular to the fault, its lateral displacement represents right slip. Later visits showed that additional displacement represents right slip. Later visits showed that additional displacements have cracked the asphalt that was placed 24 January. This fracture zone could be followed continuously (25 January) as open cracks in the soil for at least 100 m northwest of Vasco Road and about 30 m southeast. About 40 m northwest from the road on 5 February the fracture showed 20 ± 10 mm of left lateral displacement measured parallel to the fracture (locally $\text{N.}26^{\circ}\text{W.}$) and some vertical displacement (down on SW, the downhill side).
- 30 Fracture zone in soil, general trend about $\text{N.}45^{\circ}\text{W.}$, was traced for 45 m. At one point right-lateral strike slip parallel to zone was 13 mm and the extension was 24 mm, with no vertical component. This site is on top of a flat spur with a slight inclination to the southeast. Southeastward from this fracture zone others were found in the next 50 m; these were open, generally had no vertical component and in places showed a left-stepping pattern.
- 31 Fracture zone in soil, general trend $\text{N.}45^{\circ}\text{W.}$, could be followed for 27 m. At one point extension was about 25 mm, vertical component 27 mm (down to SW), and

right-lateral strike slip was 8 mm; downslope movement alone would have given a left-lateral component. No other fractures were found to the southeast along the trend of this fault zone.

32 West of Vasco Road in W. 1/2 sec. 23, T. 25, R. 2 E. Fracture trending N.30°W. extends discontinuously for at least 0.3 km, extending over a hilltop, across a valley and up another hillside where access problems prevented a further search. Fracture shows mostly extension but at several places a right-lateral component was found. The maximum measured right-lateral strike slip was 5 mm combined with 6 mm of extension, both resolved with respect to the map trend of N.33°W.

33 At Mines Road eight sets of fractures designated 33A-33H were observed on 7 February. The fractures are located 210 to 250 m south of the centerline of Tesla Road. Azimuths of segments of the fractures range from 76° to 109° but trend approximately perpendicular to Mines Road; the fractures are largely confined to the northbound lane. Only 33A was noted to extend across the centerline on 7 February. Prior to 7 February, other investigators used orange spray paint to mark fractures 33A, 33B and 33C; fractures 33D-33H had not been painted. On 7 February, no measurable vertical or lateral displacements were associated with the fractures 33A-33H. No apparent post-paint propagation or extension of fractures 33A-C was observed.

On 29 February location 33 was reinspected. Blue paint had been applied to fractures 33D-33H. Fracture 33G now crossed the centerline of Mines Road, but had not grown since application of the blue paint. No displacements or apparent propagation of fractures other than 33G was observed.

The fractures exhibited dusty, weathered surfaces and did not expose freshly broken, black asphalt as did other fractures caused by tectonic displacement or by non-tectonic ground failure. Although fractures 33A-33C apparently coincide most closely with the trace of the Las Positas Fault (Herd, 1977), the absence of measurable displacement and the rather aged appearance of the fractures and their geometry (perpendicular to Mines Road) suggests a non-tectonic origin. The extension of fracture 33G across the centerline of Mines Road observed on 29 February followed a period of heavy rain. The extension of this feature if tectonic in origin, is the apparent southwestern limit of effects related to postulated surface rupture on the Las Positas Fault.

34 Tesla Road (inspected 7 February) nine fractures comprise three right-stepping en echelon sets of fractures. Fractures 34A, 34B, and 34F-34I coincide with mapped traces or lie on the projections of mapped traces of the Las Positas Fault zone. Fracture 34C displays about 1.5 mm left-lateral strike slip displacement. Post-earthquake propagation of fractures C, E, and F apparently occurred; the cracks extended through and beyond spots of blue spray paint which reportedly marked the ends of the cracks at the time the paint was applied. Surfaces of all fractures at location 34 exposed fresh, black asphalt. Commonly, pebbles had been "popped" from their position adjacent to the fracture edge.

The observed left-lateral strike-slip displacements, the right-stepping en echelon distribution of fractures associated with mapped traces of the Las Positas Fault, the unquestioned recency of the fractures and their growth or extension following the earthquakes of 24 and 26 January indicate that the fractures on Tesla Road are probably tectonic in origin.

- 35 Vasco Road, examined 7 and 29 February, five fresh fractures were mapped near the Las Positas Fault intersection at Vasco Road [called "Las Positas Ave" on Fig. 32]. Positions of fractures were measured, using a tape, north from the centerline of Tesla Road. Fracture E, [Fig. 33] a prominent break near the crest of the scarp of the Las Positas Fault, exhibited left-lateral strike slip displacement of about 0.5 mm. Fractures A-D [Fig. 33] did not exhibit displacements. Fractures A-C occurred only in the southbound lane; only D extended across the centerline of Vasco Road. Fractures A-D trend generally perpendicular to Vasco Road, and have merely opened with slip vectors oriented downslope and perpendicular to fracture trend; these features are interpreted as non-tectonic ground failure.
- 36 The small amount of left-lateral strike-slip measured at E coincident with the trace of the Las Positas Fault indicates that surface rupture of the Las Positas Fault extended at least 1.1 km from Tesla Road to Vasco Road. This interpretation is strongly supported by data from an alinement array which showed about 6 mm of left-lateral displacement across the fractures at location 35 between 21 February and 26 March (P. W. Harsh, personal communication), even though fracture E showed no obvious change between 7 February and 1 April 1980.
- 37 Greenville Road, four fresh fractures without measurable lateral displacement were noted. Three fractures trend perpendicular to Greenville Road and one is diagonal to it. As mapped on 7 February these features are shown relative to the northeast abutment of the Greenville Road bridge where it crosses the South Bay aqueduct. No extension or growth of fractures was observed on 29 February. The orientation perpendicular to Greenville Road and the absence of growth or a history of propagation indicate a probably non-tectonic origin for these fractures.
- 38 Five cracks trending N.35°E. in dirt road and embankments, observed by Brabb on 25 January. Northeast of this location at least 20 cracks trending about N.40°E. were visible in the pavement of Vasco Road. Some cracks step to the right and others step to the left; no lateral or vertical displacement was visible on them on 1 April.
- 38 Two cracks in Vasco Road, observed by Brabb on 25 January. One crack trends N.76°E., and crosses the pavement; the other trends N.81°E. and extends across the west lane only. No lateral or vertical displacement visible on 1 April.
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