UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# GEOLOGIC MAP OF THE LAS POSITAS, GREENVILLE, AND VERONA FAULTS, EASTERN ALAMEDA COUNTY, CALIFORNIA

By

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Open-file report

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This report is preliminary
and has not been edited or
reviewed for conformity with
Geological Survey standards

## INTRODUCTION

Livermore Valley, a large east-trending valley in eastern Alameda County, California, approximately 50 km east of San Francisco, is unique in the central Coast Ranges, where all other major valleys trend northwest. Bounded on the west and east by two major right-lateral strike-slip fault zones--the Calaveras-Sunol and the Greenville, Livermore Valley was originally believed to be crossed by other northwest-trending faults, inferred from ground-water level differences and geophysical anomalies (California Dept. Water Resources, 1963, 1966, 1974; Wight, 1974).

Recent mapping in Livermore Valley and surrounding areas (Herd, 1975) has revealed the existence of the Las Positas fault zone, a high-angle, northeast-trending fault zone that forms the southern limit of the valley and extends from La Costa Valley, east of the Calaveras-Sunol fault zone, northeastward to the Greenville fault zone. The Las Positas fault zone is the first reported northeast-trending fault zone in the central Coast Ranges of California with a history of Quaternary movement.

### Purpose of map

This map depicts the geologic setting of the Las Positas and Greenville fault zones, which bound Livermore Valley on the south and east, and the Verona fault, which lies southwest of Livermore Valley. The map presents a new interpretation of the geology of Livermore Valley and adjoining areas, and contains new subdivisions of the Quaternary stratigraphy. The recency and recurrence of displacements along the three faults is assessed and an interpretation of the tectonic setting of Livermore Valley proposed.

## CONSTRUCTION OF MAP

This geologic map of eastern Livermore Valley and neighboring parts of the Diablo Mountains and the Altamont Hills was constructed by detailed interpretation of aerial photographs (Table 1) and field investigation. Some stratigraphic names of bedrock units previously mapped and identified in the Tesla quadrangle (Huey, 1948) and the Pleasanton quadrangle (Hall, 1958) have been used in this report, but the distribution, attitudes, and age classifications of several of the units have been changed. In particular, the Quaternary stratigraphy of Livermore Valley, recently studied by Helley and others (1972), has been completely revised, and a new series of Quaternary units identified.

## QUATERNARY STRATIGRAPHY

The Quaternary deposits in Livermore Valley have been subdivided into six stratigraphic units based on morphology, relative topographic position (as terraces above streams entering Livermore and La Costa Valleys), and soil-profile development on the deposits. This classification of Quaternary units differs from that of Helley and others (1972), derived from Soil Conservation Service mapping of soils in Livermore Valley (Welch and others, 1966).

Table 1.--Aerial photography of eastern Alameda County used in this report

| Area | Year | Scale | Agency | Availability |
| --- | --- | --- | --- | --- |
| lack and white | | | | |
| lameda County | 1940 | 1:20,000 | U.S. Dept. Agriculture | National Archives and Record Service, Washington, D. C. |
| an Francisco Bay region | 1970 | 1:80,000 | U.S. Geol. Survey | U.S. Geol. Survey, Menlo Park, CA. |
| olor | | | | |
| lameda County | 1973-1974 | 1:20,000 | U.S. Geol. Survey | Keith Cole Photograp Redwood City, CA. |

## Mapping of Quaternary deposits

The Quaternary stratigraphy for Alameda County devised by Helley and others (1972) was established using differences in texture, degree, and type of soil development as mapped by the Soil Conservation Service in 1966. Fluvial deposits were separated from interfluvial basin sediments and stream-channel gravels on the basis of the texture of the soil. Age designations of Pleistocene and Holocene were assigned to the units on the basis of the degree of development of the B horizon of the soil (E. J. Helley, oral commun., 1977). Soils reported by the Soil Conservation Service as having clay-rich (argillic) B horizons were considered to be of Pleistocene age; soils with no argillic B horizons were presumed to be of Holocene age.

During this investigation, it was discovered that the Soil Conservation Service mapping of soils in Alameda County cannot be generalized to construct a geologic map. Identical soil series are reported by Welch and others (1966) on alluvial terraces of substantially different age. The Positas soil series, for example, is mapped on the Livermore Gravels of Clark (1930), older alluvial units ($Qoa_4$ and $Qoa_3$), and gravelly outcrops of the Briones Sandstone. Although the soils developed on the Livermore Gravels and on alluvial units 4 and 3 are similar appearing in the uppermost 2 to 3 meters of their profiles (the soils are red and have well-developed argillic B horizons), the depth of soil development on the three units differs, the soils on the Livermore Gravels being more deeply developed. Because the Soil Conservation Service routinely examines only those parts of soil profiles within 2 meters of the surface, the differences in soil development of the three units were not mapped. Helley, Lajoie, and Burke (1972), in compiling their map of late Cenozoic deposits in Alameda County, assumed occurrences of Positas soils to represent areas of the Livermore Gravels (E. J. Helley, oral commun., 1977). As a result, their 1972 map shows deformed older sedimentary deposits (Livermore Gravels) where alluvial units 4 and 3 and some gravelly outcrops of Briones Sandstone occur.

Different soil series with dissimilar B-horizon development were mapped by the Soil Conservation Service on materials of the same age. Both Positas and Livermore soils, for example, are reported on parts of the terrace of alluvial unit 3 east of Arroyo Mocho. Properly, only soils of the Positas soil series should be mapped on that terrace as no Livermore series soils characteristically occur on unit 3. Because all occurrences of Livermore series were assumed by Helley and his associates (1972) to represent areas of Holocene alluvium, the terrace of alluvial unit 3 east of Arroyo Mocho is shown on their map as both Pleistocene and Holocene in age.

Certain soil series characteristically occur on alluvial deposits of a given age in Livermore Valley. Soils of the Positas series generally are found on the Livermore Gravels of Clark (1930) and on alluvial units 3 and 4. Pleasanton, San Ysidro, Shedd, and Rincon soils usually occur on alluvial unit 2. The Livermore series commonly occurs on alluvial unit 1. Yolo, Zamora, Sunnyvale, and Sycamore soils most generally are developed on recent flood-plain alluvium and associated stream gravel. These differences in soil development allow correlation of Quaternary units between valleys. But the distribution of these soils must be correctly determined before the soils can be used as a means of inferring time stratigraphy.

Tracing terrace levels down tributary stream valleys into Livermore and La Costa Valleys was found to be the best method of establishing alluvial stratigraphic successions. A flight of three terraces (made up of alluvial units 1, 2, and 3) occurs above the two principal streams that enter Livermore Valley from the south, Arroyo Mocho and Arroyo Valle, and above San Antonio Creek, which flows into La Costa Valley, in the southwest corner of the map area. Patches of alluvial unit 4 are preserved as isolated terrace remnants or as dissected alluvial fans. This unit may include several deposits of different age (because of their isolated occurrences, it is impossible to demonstrate that the deposits are coeval), but its deposits are all younger than the Livermore Gravels of Clark (1930). Southwest of Arroyo Mocho, unit 4 rests unconformably on deformed Livermore Gravels. Northeast of Arroyo Mocho, unit 4 is deposited against the base of a northwest-facing fault scarp in the Livermore Gravels.

By establishing the soil series characteristically associated with certain stratigraphic units, and by tracing terrace levels into the valleys, it was possible to establish a regional stratigraphy of Quaternary units.

### Age of Quaternary units

None of the alluvial deposits younger than the Livermore Gravels of Clark (1930) have been directly or absolutely dated. Only a relative age chronology of alluvial events has been established. However, judged by the degree of soil development on the deposits, all older alluvial units are assumed to be Pleistocene in age. All of the soils on older alluvial units have argillic B horizons. Birkeland (1974, p. 162-180) found that in California, some 40,000 years of soil formation appears to be required to form a minimal B horizon.

The recent flood-plain alluvium and recent stream gravel are Holocene, the sediments being deposited in the modern stream regimen.

## NONMARINE DEPOSITS OF PLIOCENE AND PLEISTOCENE AGE

### Green Valley and Tassajara Formations, Undivided, of Clark (1943)

The hills north of Livermore Valley are underlain by several hundred meters of nonmarine conglomerate, conglomeratic sandstone, sandstone, claystone, thinly bedded limestone and tuff. The rocks are folded into a series of northwestward-plunging and locally overturned anticlines and synclines.

These nonmarine deposits north of Livermore are referred to in this report as the Tassajara and Green Valley Formations, after Clark (1943).

The Tassajara and Green Valley Formations are lithologically inseparable except by the presence of the Lawlor Tuff and several other unnamed tuffs stratigraphically below the Lawlor (Oestreich, 1958). Because the Lawlor and associated unnamed tuffs are not exposed in the hills north of Livermore, it is impossible to distinguish between the two formations in the map area. As a result, the rocks are referred to in this report as the Tassajara and Green Valley Formations, Undivided.

Livermore Gravels of Clark (1930)

Massive nonmarine gravel, sand, and clay beds with abundant Franciscan assemblage clasts are exposed in the hills south of Livermore Valley. The gravel unconformably overlies the Neroly, Cierbo, and Briones Sandstones, the Great Valley sequence, and the Franciscan assemblage. South of Livermore, the gravel dips at a low angle to the north. Summits of interfluves in the gravel between Arroyo Mocho and Arroyo Valle define a northward-sloping surface that extends from the Franciscan core of the Diablo Range outward into Livermore Valley. The gravel has been faulted and folded, and in some areas is steeply dipping.

The gravel has been variously referred to as the Livermore Gravels (Vickery, 1924; Clark, 1930; and Hall, 1958), the Livermore Formation (Clark, 1930), and the San Antonio Gravels (Clark, 1930). No type section has been established for the gravel. However, the name Livermore Gravels is retained in this report to agree with the stratigraphic nomenclature of Clark (1930) and Hall (1958).

Age and correlation of the Tassajara and Green Valley Formations and the Livermore Gravels

The Lawlor Tuff of Pliocene age (K/Ar-dated at 3.96 ± 0.16, 4.0 ± 1.0, and 4.46 ± 0.45 m.y.), which occurs between the Tassajara and Green Valley Formations, is also intercalated within the Livermore Gravels south of Livermore beyond the area of this map (Sarna-Wojcicki, 1976). The Lawlor Tuff occurs near the base of the section, indicating that the lower part of the Livermore Gravels and the base of the Tassajara Formation are both Pliocene in age.

Savage (1951, p. 284) listed the occurrence of Pleistocene vertebrates--*Mammuthus*, *Mammut* cf. *M. americanum*, *Equus*, camelid, anatid (duck), and turtle--in gravels north of Livermore (locality V4901) which are ascribed in this report to the Livermore Gravels. The stratigraphic position of the vertebrate remains in the Livermore Gravels is not known, however, because the Livermore Gravels south of Livermore that contain the Lawlor Tuff are not stratigraphically continuous with the gravels north of Livermore from which Savage collected the Pleistocene vertebrates. Also, the Livermore Gravels southwest of Livermore Valley are stratigraphically and topographically isolated from the Livermore Gravels which contain the Lawlor Tuff and the fossil vertebrates. As a result, the age of most of the Livermore Gravels is not well established.

## LAS POSITAS FAULT ZONE

There is evidence for a northeast-trending fault zone along part of the south side of Livermore Valley. A prominent northwest-facing scarp in the Livermore Gravels south of Livermore is alined with northwest-facing scarps in terraces of alluvial units 2 and 3, a linear vegetation pattern northeast of Arroyo Mocho, and a fault contact between the Cierbo Sandstone and Livermore Gravels southwest of Arroyo Valle. This fault zone, named the Las Positas fault zone (Herd, 1975) for its exposure in the west bank of Arroyo Seco in Las Positas Valley south of Lawrence Livermore Laboratory, has a total mapped length of approximately 15 km. To the northeast the fault zone ends against the Greenville fault zone; to the southwest, it is covered with landslide debris and alluvial units of Pleistocene age.

The principal evidence for the fault zone is the south side of Livermore Valley, which is bounded by a northwest-facing scarp in the Livermore Gravels. The scarp extends discontinuously from the southeast corner of Livermore Valley southwest to Arroyo Valle and is locally nearly 60 m in height. More than 120 meters of section of gravel, sand, and clay that dips at angles of $5^{\circ}$ to $7^{\circ}$ to the north ends abruptly along the scarp. South of Lawrence Livermore Laboratory (identified on this map by its former name, Livermore Radiation Laboratory), along the frontal scarp in sec. 13, T. 3 S., R. 2 E., a terrace of alluvial unit 3 along Arroyo Seco is terminated in a northwest-facing scarp approximately 3 m high. Northeast of Arroyo Mocho, approximately 350 m north of the intersection of Las Positas Avenue and Tesla Road, terraces of alluvial units 3 and 2 similarly end abruptly in northwest-facing scarps on line with the prominent frontal scarp cutting the Livermore Gravels.

Immediately southwest of these terrace scarps in sec. 14, T. 3 S., R. 2 E., a northeast-trending linear vegetation pattern in alluvial unit 1 (fig. 1) is alined with the front of the scarps. Plant growth is apparently affected by impoundment of ground water south of a northeast-trending fault break. The vegetation south of the fault remains verdant throughout the year owing to near-surface ground water. Farther southwest, at Tesla Road, a small hill of the Livermore Gravels with a northwest-facing scarp occurs anomalously in the center of the flood plain of Arroyo Mocho.

Southwest of Arroyo Valle, the vertical to steeply northwest-dipping Cierbo Sandstone of Miocene age is faulted against gently northeast-dipping Livermore Gravels. This fault contact is along the southwestward projection of the scarp in the Livermore Gravels northeast of Arroyo Valle. More than 200 m of Livermore Gravels is preserved north of the Cierbo Sandstone, but only small isolated patches of Livermore Gravels are found on top of the Cierbo and adjacent Great Valley sequence. The summit of the Livermore Gravels north of the Las Positas fault zone is topographically higher than the erosional surface on the Cierbo Sandstone and the adjacent Great Valley sequence on which the Livermore Gravels is only locally preserved. However, much of the Livermore Gravels was presumably derived from the south (the gravel contains lithologies derived from the Franciscan assemblage) and must have once been continuous across the Cierbo Sandstone and the Great Valley sequence. As only a few isolated patches of the gravel are preserved on the crest of interfluves in the Cierbo Sandstone and the Great Valley sequence, the bulk of the Livermore Gravels south of the fault zone must have been stripped away by erosion accompanying uplift of the block south of the fault.

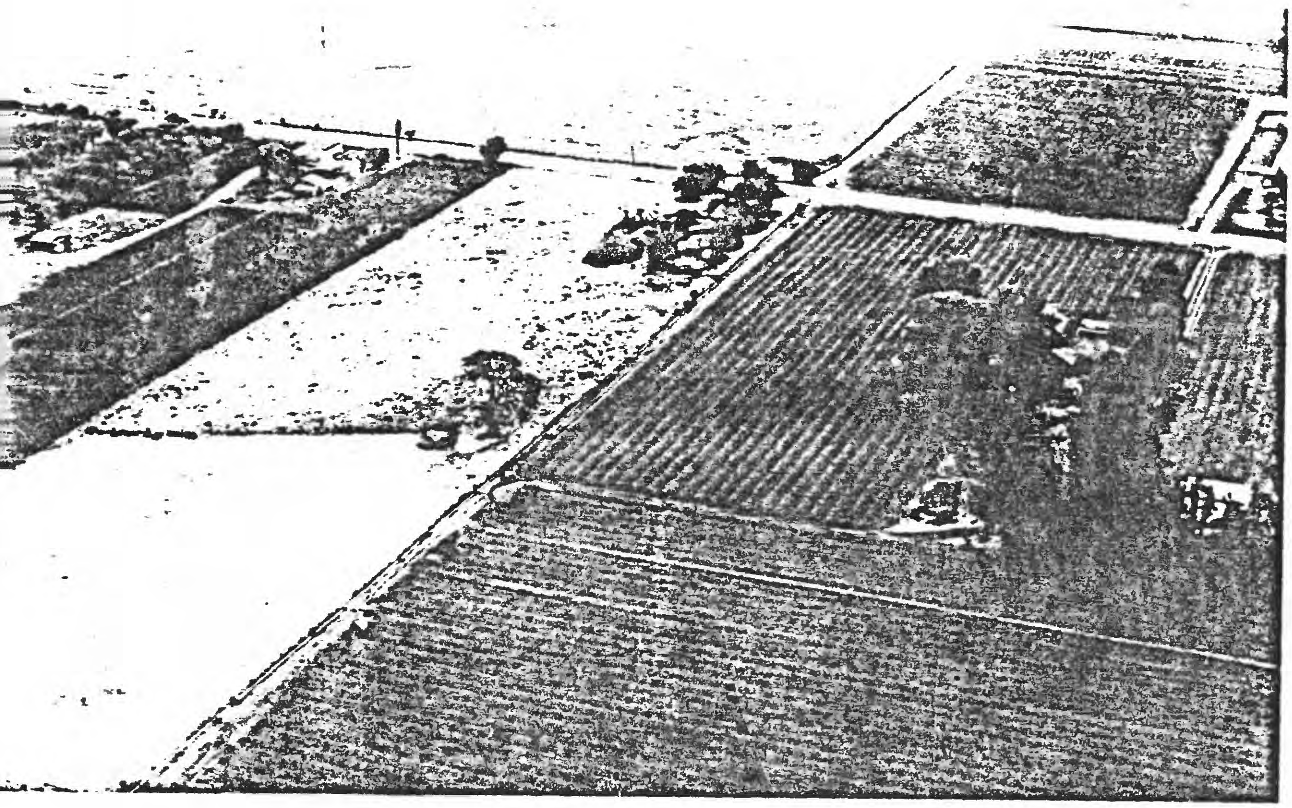


Figure 1.--Linear vegetation pattern created by impoundment of ground water in alluvium behind fault in Las Positas fault zone in sec. 14, T. 3 S., R. 2 E. East-west highway south of fault is Tesla Road. Aerial view looking southeast.

Exposures

The Las Positas fault zone is exposed in two localities in the southeast corner of Livermore Valley near Lawrence Livermore Laboratory. One fault in the Las Positas fault zone crops out in the south bank of Arroyo Seco, in sec. 13, T. 3 S., R. 2 E., where the stream cuts into the terrace of alluvial unit 3 terminated to the north in a northwest-facing scarp by the fault zone. The exposed fault (fig. 2) strikes S.40°W. and dips 85°SE. The Livermore Gravels and unconformably overlying unit 3(?) alluvium are downthrown to the south across the fault. A massive sand in the Livermore Gravels is juxtaposed against lenses of Livermore sand and gravel that dip 45°N.

A second exposure of the Las Positas fault zone is afforded by a road cut in the north-facing scarp in the Neroly Sandstone on the east side of Greenville Road, approximately 80 m south of the intersection with East Avenue. There, steeply northward-dipping (70-85°) siltstone in the south block is faulted against colluvium composed predominantly of Livermore Gravels. The fault strikes N.75°E. and dips 70°N.

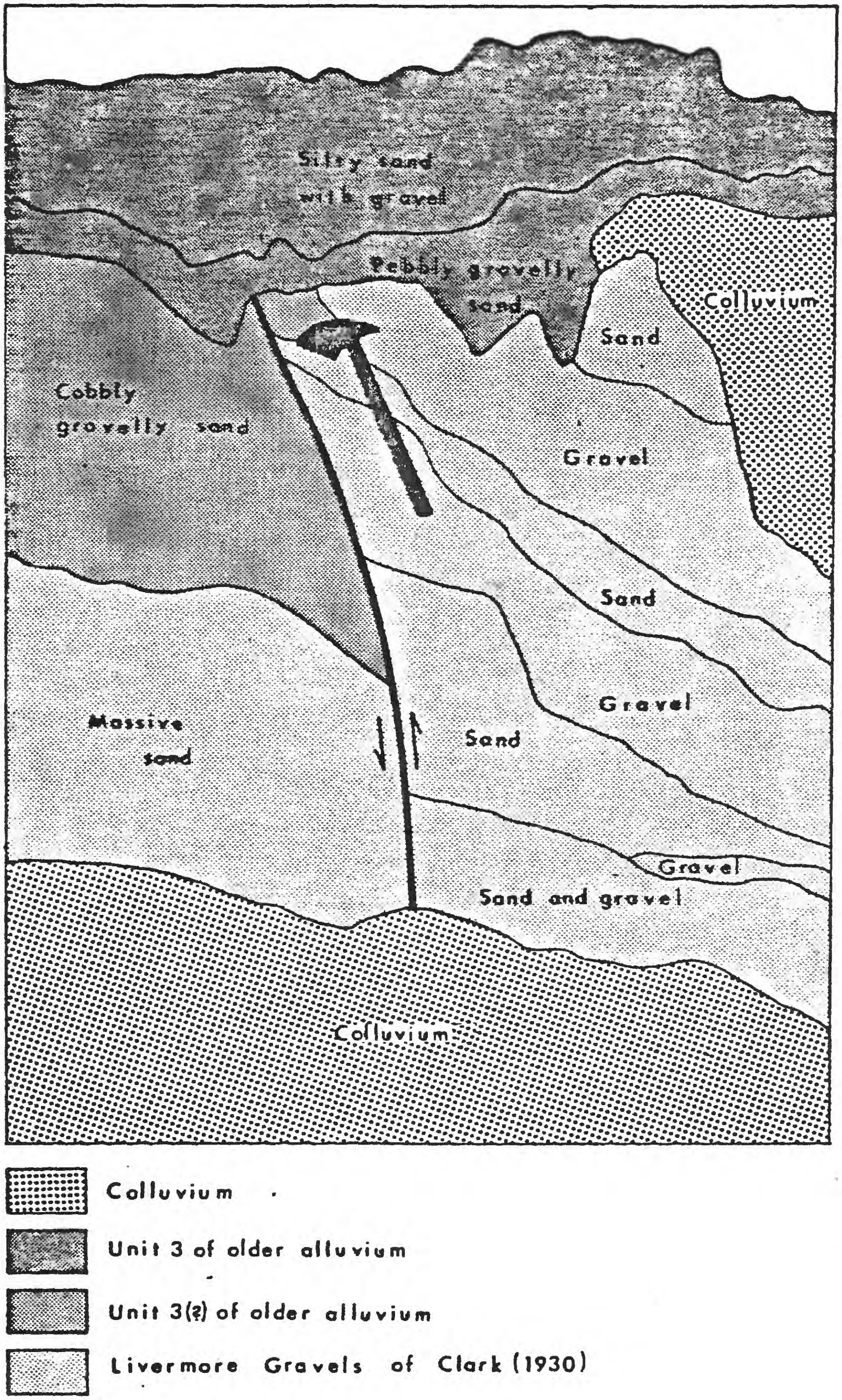
Recency of Faulting

At least three and possibly four episodes of movement along the Las Positas fault zone are recorded by offsets in the Livermore Gravels and younger alluvial deposits.

Movement along the Las Positas fault zone occurred after the Livermore Gravels was aggraded across Livermore Valley in a series of coalescing alluvial fans, and before fans of alluvial unit 4 were built. The summits of interfluves in the Livermore Gravels south of the Las Positas fault zone define an irregular northward-sloping surface that ends abruptly at the fault zone. The surface presumably continued to the north unbroken and may have been continuous with the top of the Livermore Gravels exposed north of Livermore. This surface was displaced and the Livermore Gravels immediately north of the fault zone downthrown and subsequently buried by alluvial unit 4 and younger alluvium. Southwest of Arroyo Mocho, alluvial unit 4 was deposited against the frontal scarp in Livermore Gravels but is not offset by the Las Positas fault zone.

A second episode of movement along the Las Positas fault zone followed the deposition of alluvial unit 2 in Livermore Valley but preceded the accumulation of alluvial unit 1. Terraces of alluvial unit 3 along Arroyo Seco (in sec., 13, T. 3 S., R. 2 E.) and Arroyo Mocho (just north of the intersection of Las Positas Avenue and Tesla Road) end in northwest-facing scarps along the Las Positas fault zone. At a site immediately west of Las Positas Avenue, north of Tesla Road, alluvial unit 3 north of the fault zone is downthrown more than 6 m. The adjacent next lower terrace, underlain by alluvial unit 2, is also offset in a northwest-facing scarp. The neighboring alluvial unit 1 is offset by the same fault (as evidenced by the linear northeast-trending ground-water barrier in sec. 14, T. 3 S., R. 2 E.), but no scarp is visible. The faulting event that created the scarps in the terraces of alluvial units 3 and 2 must have followed the deposition of unit 2, but preceded the accumulation of alluvial unit 1 since there is no scarp in the adjacent alluvial unit 1.

Figure 2.--Exposure of fault in Las Positas fault zone in west bank of Arroyo Seco, E½SW¼NE¼ sec. 13, T. 3 S., R. 2 E. Gravel and sand of the Livermore Gravels are faulted against unconformably overlying cobbly gravelly sand of unit 3(?) of older alluvium. The fault strikes S.40°W. and dips 85°SE. The north block (right side) has moved up relative to the south. Mantling layers of unit 3 alluvium are not displaced.


Silty sand
with gravel
Pebbly gravelly
sand
Colluvium
Sand
Cobbly
gravelly sand
Gravel
Sand
Gravel
Massive
sand
Sand
Gravel
Sand and gravel
Colluvium
Colluvium
Unit 3 of older alluvium
Unit 3(?) of older alluvium
Livermore Gravels of Clark (1930)

Alluvial unit 2 along Arroyo Seco south of Lawrence Livermore Laboratory is not similarly offset in a scarp. The absence of the scarp indicates that alluvial unit 2 is not offset along Arroyo Seco, or that there is a change in the amount of throw along the Las Positas fault zone. The unit is shown on this map as being faulted because of the similar freshness of scarps in the Livermore Gravels and the terrace of alluvial unit 3 adjacent to Arroyo Seco to those west of Las Positas Avenue. Arroyo Seco makes an abrupt southwestward turn in its course where it crosses the Las Positas fault zone. The change in course could reflect control of the direction of Arroyo Seco by a fault in unit 2.

Another episode of movement along the Las Positas fault zone occurred after the deposition of alluvial unit 1 but before the modern stream courses were established. The terrace of alluvial unit 1 northeast of Arroyo Mocho near Tesla Road is cut by a number of faults in the Las Positas fault zone. One of these faults creates the ground-water barrier shown in figure 1. Although no scarp is associated with that fault, the other faults are evidenced by low ($\geq$1 m high) northwest-facing scarps in unit 1. The scarps do not continue into the recent flood-plain alluvium of Arroyo Mocho. The post-unit 1 faulting event followed the development of the soil in alluvial unit 1 northeast of Arroyo Mocho; the vegetation change along the ground-water barrier in sec. 14, T. 3 S., R. 2 E. indicates that the soil is cut by a fault which extends to the surface.

The surface of the recent flood plain northeast of Arroyo Mocho is irregular, however, and has a small broad northwest-facing step along the southwestward projection of the northernmost fault in the Las Positas fault zone. The flood plain at this locality is deeply channeled; any scarp that might have been present would surely have been eroded. The irregularity in the surface of the recent flood-plain alluvium may indicate that the flood-plain alluvium has been offset or deformed by recent movement along the Las Positas fault zone, possibly during the faulting event responsible for the offsets in the terrace of unit 1 alluvium, or during another post-unit 1 faulting event.

Character of motion along the Las Positas fault zone

The northwest-facing scarps in Livermore Gravels and in terraces of alluvial units 3, 2, and 1 along the Las Positas fault zone and the relative absence of Livermore Gravels atop the Cierbo Sandstone southwest of Arroyo Valle indicate uplift of the block south of the fault zone. The fault-created ground-water barrier in sec. 14, T. 3 S., R. 2 E., may evidence some strike-slip component of movement on the Las Positas fault zone. There is no scarp at that site, yet enough offset has occurred either to juxtapose alluvial units of different stratigraphies with contrasting permeabilities, or to emplace clayey gouge along the fault to create an impermeable barrier. A small amount of strike-slip motion along the fault could place different alluvial units opposite each other and not form a scarp.

## GREENVILLE FAULT ZONE

Livermore Valley is bounded on the east by the Greenville fault zone, a northwest-trending right-lateral strike-slip fault zone. Named the Greenville fault by Huey (1948, p. 52), the fault zone was originally referred to as the Riggs Canyon fault by Vickery (1925) and by Clark (1935). The fault zone extends the entire length of the map area, from the north end of Livermore Valley southeastward to Crane Ridge and beyond. Mapped by Huey (1948) as a single fault, the Greenville fault is in reality a wide zone of en echelon fault breaks that essentially separates Livermore Valley from the Altamont Hills, which lie east of the valley.

In the map area, the fault zone is largely within the Cierbo Sandstone. Fault-bounded slices of Neroly Sandstone are juxtaposed against the Cierbo Sandstone in the fault zone just south of Interstate Highway 580. In the southeast corner of Livermore Valley, the Las Positas fault zone ends against the Greenville fault zone. Farther south, the Greenville fault zone truncates the west-trending Carnegie and Tesla faults and juxtaposes the Jurassic and Cretaceous Great Valley sequence against the Franciscan assemblage.

Nowhere well-exposed, the Greenville fault zone is traced principally by geomorphic evidence--linear northwest-trending valleys, scarps, and notches. Although buried by the Livermore Gravels and younger alluvium, the main Greenville fault can be followed southeast of Livermore Valley along the irregular southwest-facing scarp on the west side of the Altamont Hills. The scarp is alined with the continuation of the fault zone in Franciscan rocks south of Tesla Road.

### Recency of movement along the fault zone

North of the Las Positas fault zone, unit 2 alluvium is displaced by faults in the Greenville fault zone. The breaks form two prominent northeast- and southwest-facing scarps in the unit 2 alluvium north of Interstate Highway 580, but do not cut recent flood-plain alluvium. Frick Lake, an intermittent lake in sec. 25, T. 2 S., R. 2 E., lies in a graben bounded by two of the faults. South of the Las Positas fault zone, Neroly and older rocks are offset by the Greenville fault zone; the Livermore Gravels and younger alluvium are not.

### Evidence for right slip

In the map area, there is little direct evidence for right-lateral strike-slip motion along the Greenville fault zone except for horizontal slickensides in an outcrop of a fault in the Greenville fault zone along the tracks of the Western Pacific Railroad above Altamont Creek in the southeast corner of sec. 25, T. 2 S., R. 2 E. There, in the headwall of a landslide in the Cierbo Sandstone, polished horizontal slickensides on the surface of the block east of the fault have been exposed by the fall of the west block. The fault is nearly vertical and strikes N.40°W. Continuation of the fault to the northwest is unclear because it is within the Cierbo Sandstone and has not been mapped.

## VERONA FAULT

Livermore Valley is bound on the southwest by a northwest-trending ridge underlain by Livermore Gravels. These gravels, which dip to the northeast (15-30°), end abruptly to the southwest in an arcuate, scarp-like line of west-facing truncated spurs. More than 100 m of section of Livermore Gravels is represented from the base to the top of the escarpment. The height along the scarp diminishes to the northwest towards Pleasanton. Southwest of Vallecitos Valley, the scarp is covered by northward-dipping unit 4 alluvium that is deposited against the scarp. A discontinuous line of springs and seeps occurs along the base of the arcuate line of truncated spurs in the Livermore Gravels.

This change in elevation in Livermore Gravels across the west-facing escarpment on the ridge southwest of Livermore Valley was interpreted by Hall (1958, p. 42) as evidence of a northwest-trending fault zone that he named the Verona fault. This fault was shown by Hall as striking N.60°W., extending from Arroyo de la Laguna southeastward to Vallecitos Valley. The trace of the Verona fault was mapped by Hall oblique to the west-facing escarpment in Livermore Gravels, crossing the hills above Vallecitos Valley. Hall continued the fault to the southeast to end between the change in attitude in the northeast-dipping Livermore Gravels in the ridge southwest of Livermore Valley and the northward-dipping alluvial unit 4 gravels which Hall considered to be Livermore Gravels.

More likely, the Verona fault extends along the foot of the arcuate, scarp-like line of west-facing truncated spurs in Livermore Gravels at the west side of the ridge southwest of Livermore Valley. The change in elevation in Livermore Gravels in the ridge southwest of Livermore Valley and west of the ridge occurs at the escarpment, not oblique to it. The northeast-dipping Livermore Gravels in the ridge end abruptly at the escarpment, or are eroded back from the scarp by down-dip cutting of streams.

The escarpment in Livermore Gravels on the west side of the ridge cannot be explained by erosion of a large section of Livermore Gravels from atop the eastward-dipping Livermore Gravels which lie west of the escarpment. Erosion of Livermore sands, gravels, and clays would not result in a line of west-facing truncated spurs. Rather, erosion would cause an irregular, rilled west slope on the ridge.

### Recency of Faulting

Movement along the Verona fault occurred after the deposition of the Livermore Gravels which comprise the ridge southwest of Livermore Valley, but probably not after the deposition of alluvial unit 4 gravels which cover the extension of the fault scarp southwest of Vallecitos Valley. The unit 4 alluvium is not evidently offset in a scarp alined with the base of the ridge. However, the unit 4 gravels are deeply dissected; erosion could have obscured evidence of post-alluvial unit 4 faulting.

The uplifted Livermore Gravels northeast of the Verona fault, like all the Livermore Gravels, are inferred to be of Pliocene and Pleistocene age, but the gravels at this locality have not been directly dated. Similarly, no age control is available for the alluvial units 2, 3, and 4 which locally overlie the Verona fault. As a result, it is not possible to put limiting ages on the recency of movement on the fault. However, since more than 100 m of Livermore Gravels are upthrown northeast of the fault, it seems probable that repeated uplift along the Verona fault in the Pleistocene was required to elevate the gravels.

## NORTHEAST-TRENDING FAULTS SOUTH OF THE LAS POSITAS FAULT ZONE

The Las Positas fault zone is paralleled to the south by several other northeast-trending faults.

### Faults southwest of Arroyo Valle

Two northeast-trending faults occur in the mountains immediately southwest of the U.S. Veterans Administration Hospital. The more northerly of the two faults, entirely within the Cierbo Sandstone, strikes approximately N.40°E. The rocks north of the fault have been downthrown, creating a northwest-facing scarp along the fault. Although nowhere exposed, the fault is inferred to be nearly vertical or to dip steeply northward. The Miocene Cierbo Sandstone is juxtaposed against the Great Valley sequence along the southerly of the two northeast-trending faults. The fault strikes generally N.30°E. and is nearly vertical or dips steeply to the north (80°). Although the contact between the Cierbo Sandstone and the Great Valley sequence was not originally mapped as a fault (Hall, 1958), the two units must be in fault contact for several hundred meters of Tertiary rocks (the Paleocene and Eocene Tesla Formation and the Miocene Briones Sandstone) are missing along the contact. There could be an unconformity between the Cierbo and Great Valley sequence. If it is an unconformity, however, the Cierbo Sandstone has been deposited against a northwest-facing scarp in the Great Valley sequence; however, since both formations are similarly northward-dipping, this is extremely unlikely. Moreover, the contact is generally linear, which would be unexpected if it were an unconformity. The erosional surface atop the Cierbo and Great Valley sequence is not displaced by the fault. Movement along the fault must have preceded the erosional beveling of its wall rocks.

### Fault between Arroyo Valle and Arroyo Mocho

A northeast-trending fault was discovered in 1952 beneath the Livermore Gravels immediately west of sec. 27, T. 3 S., R. 2. E., during drilling of two oil wells (California Division of Oil and Gas, 1973). The exact strike of the fault is not known, but the fault is believed to be nearly vertical. The block north of the fault is downthrown.

### Faults northeast of Arroyo Mocho

1. <u>Fault crossing Tesla Road and Arroyo Seco.</u>--To the south approximately 0.5 km, the Las Positas fault zone is paralleled by an arcuate northeast- to east-trending fault. The fault bounds the south side of the line of hills south of Lawrence Livermore Laboratory. The fault is evidenced by a prominent south-facing scarp in the Livermore Gravels and Neroly Sandstone and an alined southeast-facing scarp in unit 3 alluvium. The fault is exposed in a road cut along Greenville Road approximately 0.5 km north of

Tesla Road. In the outcrop, two fault breaks trending N.65°E. and dipping 80°N. cut the Livermore Gravels which dip to the south at 55-70°. This gravel unconformably overlies older gravel and sand that is vertical or dips steeply to the south (approximately 80°).

The block south of the fault has been downthrown, and the north end of the block has been buried by alluvium. Summits of the hills underlain by the Livermore Gravels south of Lawrence Livermore Laboratory were presumably once continuous with the top of the Livermore Gravels on the north flank of Crane Ridge. However, the surface now defined by the crest of interfluves in Livermore Gravels on the north side of Crane Ridge projects below the top of the Livermore Gravels south of the laboratory.

At least two episodes of movement along the fault are evident. The first faulting event occurred after the deposition of the Livermore Gravels but before the fan of unit 4 south of Arroyo Seco was built. The unit 4 alluvium is graded to a level below the base of the south-facing scarp in Livermore Gravels and Neroly Sandstone north of Arroyo Seco. The block south of the fault must have been downthrown before the unit 4 alluvium was deposited. The second episode of displacement along the fault followed the deposition of alluvial unit 3 but preceded channeling of the unit 3 alluvium west of Arroyo Seco by streams that deposited unit 2 alluvium. In the northeast corner of sec. 23, T. 3 S., R. 2 E., alluvial unit 3 is offset in a southeast-facing scarp at the south end of the fault. The scarp is not continued to the south into the younger unit 2 alluvium.

2. Buried fault in S1/2 sec. 18, T. 3 S., R. 3 E.--A steeply southward-dipping fault separating the Franciscan assemblage from the Great Valley sequence was found during the drilling of several oil wells southeast of Lawrence Livermore Laboratory (cross section A-A′, Wight, 1974, p. 19). The fault is overlain by the Tassajara and Green Valley Formations(?) and Livermore Gravels that are not offset. The strike of the fault is unknown, but it is shown as east-trending because of its presumed similarity to the arcuate east-trending fault to the north.

3. Faults on Crane Ridge.--Three northeast-trending faults cross Crane Ridge east of Arroyo Mocho. The northernmost of the three cuts the Livermore Gravels, displacing the surface of the gravel down to the south. The eroded southeast-facing scarp along the fault strikes approximately N.60°E. and is antithetic to the slope. Movement along the fault followed the deposition of the Livermore Gravels but preceded the aggradation of the fan of unit 4 alluvium south of Arroyo Seco. The terrace of alluvial unit 4 at the head of the fan is not cut by the fault.

The easternmost of the three faults on Crane Ridge is in secs. 32 and 33, T. 3 S., R. 3 E. The fault is not exposed but is inferred from the linear course of the unnamed northeast-trending stream, which is nearly perpendicular to the strike of the surrounding Franciscan assemblage.

The southernmost of the three faults follows the linear course of an unnamed stream that strikes generally N.50°E. This fault is inferred from: (a) the linear trend of the channel; (b) the presence of more than 60 m of the Livermore Gravels north of the channel and the absence of any gravel south of the channel; and (c) the nearly coincident southern limit of the Livermore Gravels with the course of the stream. The block north of the fault is presumed to be downthrown.

Livermore oil field

In 1958 a small producing oil field was discovered (California Division Oil and Gas, 1973) in the southeast corner of Livermore Valley. During drilling of the oil field, the Las Positas and Greenville fault zones were found to intersect there, and the precise location of the Greenville-Las Positas fault intersection was established. A number of northeast-trending faults that lie between the Las Positas and Greenville faults were discovered. The blocks north of the northeast-trending faults are predominantly downthrown.

## SEISMICITY

Epicenters and magnitudes of eastern Alameda County earthquakes from 1942 through 1968 (fig. 3) were recorded by the University of California, Berkeley Seismographic Station. Since 1969, the area has been monitored by the U.S. Geological Survey seismic network. Microseismicity in eastern Alameda County from 1969 through 1971 recorded during the first 3 years of operation of the Geological Survey seismic network is shown in figure 4. Very few of the earthquakes have been located instrumentally on either the Las Positas, Greenville, or Verona faults. Epicenters occur near the faults, and several at least are astride the faults. Some earthquakes may be associated with the faults, but are yet mislocated as a result of the number and distribution of seismograph stations and the constraints on our ability to correct for the complexities of wave propagation in the earth's crust.

A sequence of earthquakes (five with magnitudes 4.0 or greater) that occurred in Livermore Valley between March 27, 1943, and June 28, 1943 (table 2) may, however, have been generated by movement along the Las Positas fault zone. The sequence was initiated by an earthquake of magnitude 2.8 that occurred shortly before 10 p.m. on the evening of March 27, approximately 3.1 km south of Pleasanton. The earthquake was followed 2 days later by one of the two strongest recorded earthquakes in Livermore Valley (both magnitude 4.2), located at the site of the earthquake of March 27. During the next 3 months, 18 additional earthquakes ranging in magnitude from 2.2 to 4.2 were recorded in Livermore Valley. Although these earthquakes are not well located (the epicenters were determined to within only the nearest minute of latitude and longitude), the epicenters form a northeast-trending band parallel to and about 5 km north of the Las Positas fault zone (fig. 5). The epicenters extend from south of Pleasanton northeastward to the east end of Livermore Valley, roughly approximating the entire length of the Las Positas fault zone. The epicenters could reflect sympathetic motion on a series of unmapped parallel northwest-trending faults in Livermore Valley, but an epicenter pattern wider than the narrow one recorded would have been expected. The areal grouping of the earthquakes and their occurrence in sequence suggests that the quakes were caused by movement along a northeast-trending fault zone like the Las Positas.

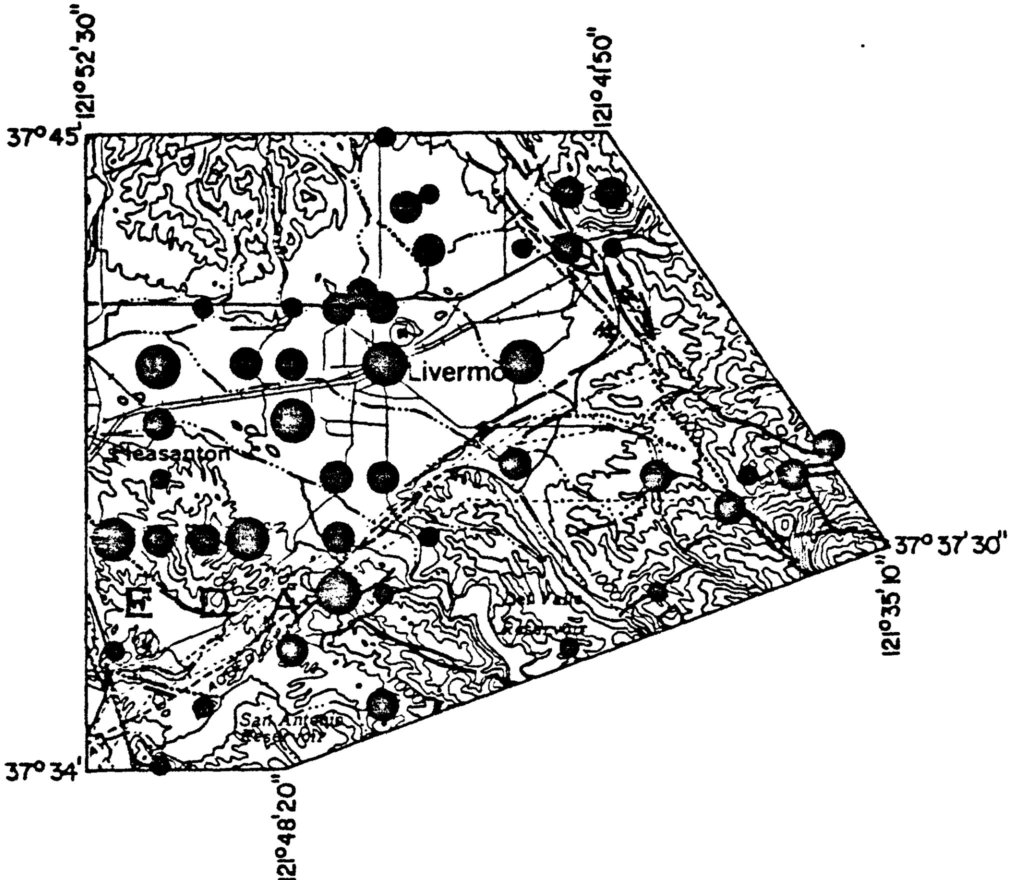



Figure 3.--Epicenters of earthquakes in Livermore Valley, 1942-68 (compiled from University of California, Berkeley, Bulletin of the Seismographic Stations, v. 12, no. 1, 1950--v. 38, no. 2, 1970)

- Magnitude 3.5 and greater
- Magnitude 2.5 to 3.5
- Magnitude 1.5 to 2.5

First or largest shock at any specific locality is shown.

All faults in map area are shown.

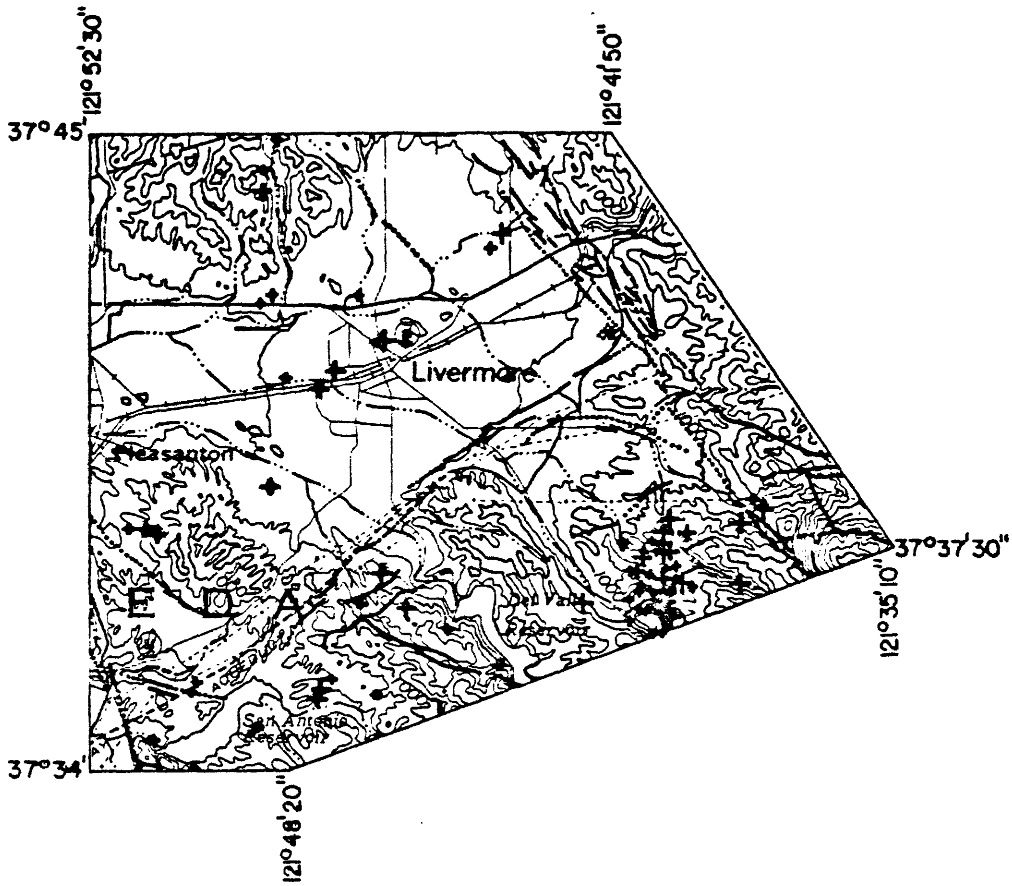



Figure 4.--Epicenters of earthquakes in Livermore Valley, 1969-71 (U.S. Geol. Survey, 1972)

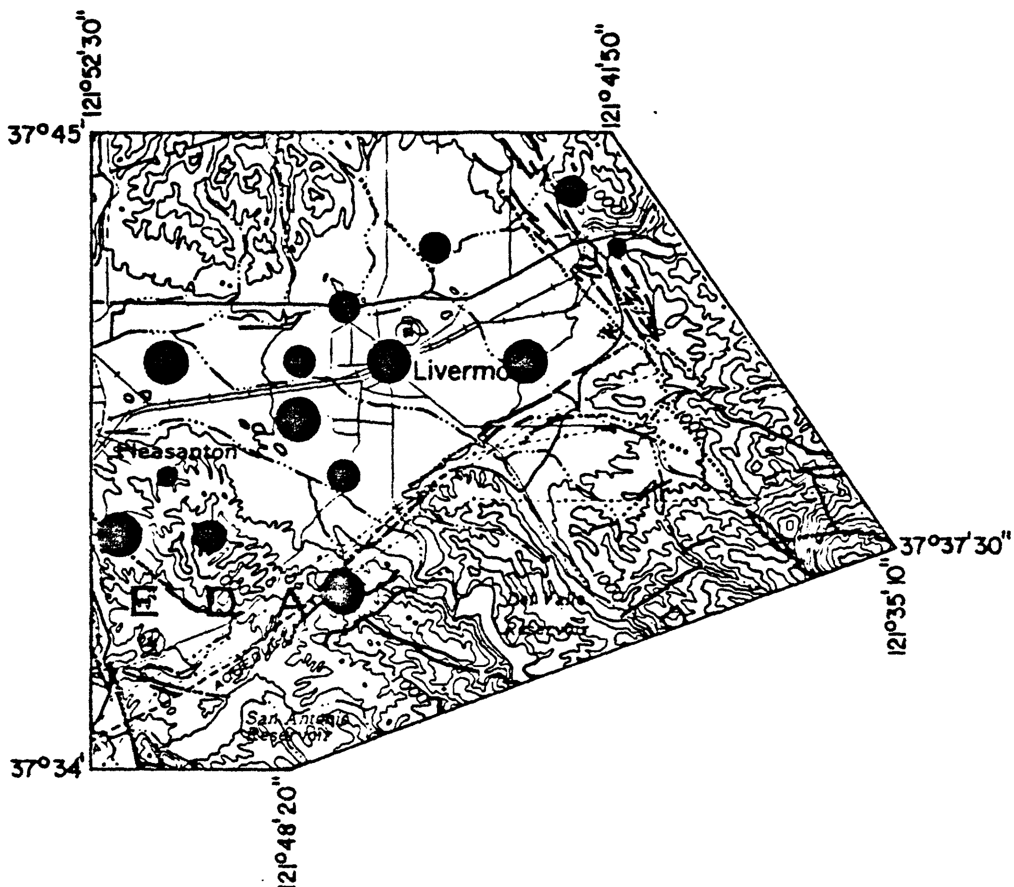
- X Magnitude 3.5 and greater — All shocks shown.
- X Magnitude 2.5 to 3.5
- + Magnitude 1.5 to 2.5
- + Magnitude 0.5 to 1.5

All faults in map area are shown.

TABLE 2.--Livermore Earthquake Sequence

| 1943 | HR | MN | SEC | LAT N | LONG W. | MAG |
|---|---|---|---|---|---|---|
| March 27 | 21 | 52 | 45 | 37° 38′ | 121° 52′ | 2.8 |
| 29 | 3 | 45 | 55 | 37° 38′ | 121° 52′ | 4.2 |
| 30 | 23 | 6 | 9 | 37° 41′ | 121° 51′ | 3.6 |
| April 4 | 22 | 24 | 48 | 37° 43′ | 121° 41′ | 2.2 |
| 6 | 16 | 15 | 1 | 37° 39′ | 121° 47′ | 3.4 |
| 7 | 16 | 13 | 4 | 37° 41′ | 121° 48′ | 3.0 |
| 10 | 18 | 16 | 29 | 37° 42′ | 121° 47′ | 2.5 |
| 12 | 13 | 20 | 42 | 37° 41′ | 121° 46′ | 2.9 |
| 15 | 4 | 28 | 11 | 37° 41′ | 121° 46′ | 3.2 |
| 15 | 7 | 23 | 4 | 37° 41′ | 121° 46′ | 4.0 |
| 15 | 7 | 31 | 2 | 37° 41′ | 121° 46′ | 4.1 |
| 19 | 18 | 0 | 19 | 37° 39′ | 121° 51′ | 2.2 |
| 21 | 15 | 39 | 44 | 37° 41′ | 121° 43′ | 4.2 |
| 26 | 3 | 54 | 0 | 37° 47′ | 121° 47′ | 4.1 |
| May 8 | 4 | 29 | 39 | 37° 44′ | 121° 42′ | 3.4 |
| 26 | 22 | 10 | 1 | 37° 43 | 121° 45′ | 2.8 |
| 28 | 20 | 57 | 5 | 37° 40′ | 121° 48′ | 2.7 |
| 29 | 17 | 4 | 9 | 37° 40′ | 121° 48′ | 3.7 |
| June 9 | 21 | 55 | 27 | 37° 38′ | 121° 50′ | 2.5 |
| 28 | 20 | 54 | 23 | 37° 44′ | 121° 42′ | 3.4 |

(From Bulletin of the Seismographic Stations, v. 13, no. 1, p. 5, 1950; v. 13, no. 2, p.37-38, 1950)




igure 5.--Epicenters of earthquakes of Livermore earthquake sequence, March 27, 1943-June 28, 1943 (compiled from University of California, Berkeley, Bulletin of the Seismographic Stations, v. 13, no. 1, p. 5, 1950; v. 13, no. 2, p. 37-38, 1950) (table 2).

| | |
|---|---|
| ● Magnitude 3.5 and greater | First or largest shock at |
| ● Magnitude 2.5 to 3.5 | any specific locality |
| ● Magnitude 1.5 to 2.5 | shown. |

All faults in map area are shown.

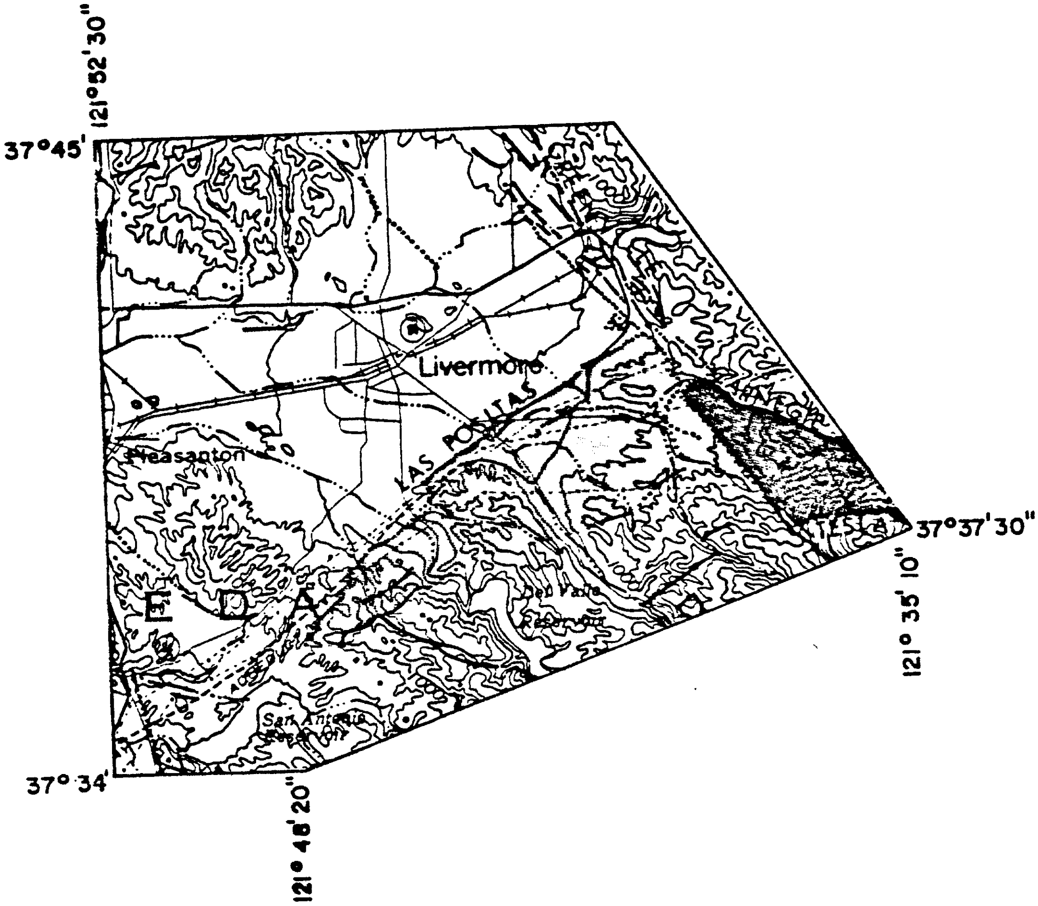
## TECTONIC INTERPRETATION

### Relation of the Las Positas fault zone and other northeast-trending fault zones west of the Greenville fault zone to the Carnegie and Tesla faults

The Carnegie and Tesla faults and the Las Positas fault zone and other northeast-trending faults to the south are structurally similar. All of the faults are high angle and basically dip-slip in character. The faults bound wedge-shaped blocks north of the exposed Franciscan core of the Diablo Range south of Livermore Valley (fig. 6). The Carnegie and Tesla faults border a northwest-elongate block composed of northwest-trending outcrops of the Neroly, Cierbo and Tesla Formations and the Great Valley sequence. West of the Greenville fault zone, a similar but southwest-elongate wedge appears to be defined by the Las Positas fault zone on the north and by the fault between the Cierbo and Great Valley sequence southwest of Arroyo Valle. The fault separating the Cierbo Sandstone and the Great Valley sequence is alined with the northeast-trending fault in the Livermore Gravels on the north side of Crane Ridge, east of Arroyo Valle. Although there is no evidence that the two faults are connected (the intervening ridge of Livermore Gravels between Arroyo Mocho and Arroyo Valle is not displaced), both faults have essentially the same strike. And the north block along both faults has been downthrown (the block north of the fault on Crane Ridge has been tilted to the north). Although the Livermore Gravels covers most of the "wedge" west of the Greenville fault zone, the Neroly and Cierbo do crop out. Drilling within the wedge (cross sections A-A′ and B-B′) penetrated the Cierbo and Great Valley sequence rocks in the fault-bounded block at depth east and south of Lawrence Livermore Laboratory.

The Las Positas fault zone could be the western continuation of the Carnegie fault. The alined northeast-trending faults south of the Las Positas might be the western equivalent of the Tesla fault. These faults could have been separated right-laterally by slip along the Greenville fault zone. If they were, then the wedges they bound were once connected. The distance between the Carnegie and Tesla faults at their point of intersection with the Greenville fault zone is less than that between the intersection of the Las Positas fault zone and the Greenville fault zone and the projected intersection of the northeast-trending fault on Crane Ridge with the Greenville fault zone. The Carnegie and Tesla faults are 4.4 km apart at the Greenville fault zone; the Las Positas fault zone and the northeast-trending fault zone to the south are separated by 5.1 km. The difference can be accounted for by the uplift and erosion of the block east of the Greenville fault zone. The Altamont Hills east of the Greenville fault zone are high standing; the main Greenville fault is delineated by a southwest-facing scarp along the west side of the hills. If the Tesla fault has a slight southeastward dip or a slight northeastward dip, or both, erosion of the block east of the Greenville fault zone would result in the apparent convergence of the two faults.

If this interpretation is correct, then the offset between the Carnegie and Las Positas faults and the Tesla fault and its unnamed western equivalent records a maximum right slip along the Greenville fault zone of 3.5 km. This movement must have occurred in the late Miocene or Pliocene for the Miocene Neroly Sandstone and older rocks are offset by the Greenville fault zone whereas the Livermore Gravels is not.




gure 6.—Fault-bounded wedges of rocks offset by right-lateral slip along the Greenville fault zone.

Structural geology of Livermore Valley

Livermore Valley appears to be a large northwest-trending syncline, bounded on the south by the northeast-dipping Livermore Gravels and on the north by nearly vertical or steeply southward-dipping Tassajara and Green Valley Formations. The syncline ends to the south against the Las Positas fault zone. Folding of the Livermore Gravels and the Tassajara and Green Valley Formations into the northwest-trending syncline apparently occasioned uplift of the Livermore Gravels along the Verona fault. Uplift of the mountains south of Livermore Valley along the Las Positas fault zone and the Altamont Hills east of the Greenville fault zone has enlarged and modified the shape of the valley. Uplift has continued along the Las Positas fault zone into the Holocene.

Although there is no evidence for any motion on the Greenville fault zone south of the Las Positas fault zone since the deposition of the Livermore Gravels, there is evidence of at least late Pleistocene movement along the Greenville fault zone north of the Las Positas fault zone. Scarps in unit 2 alluvium near Frick Lake may reflect the continued uplift of the Altamont Hills east of the fault zone.

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