TIERRA
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INC.

CIVIL AND SOILS
ENGINEERING
LAND SURVEYS AND
DEVELOPMENTS

GEOLOGIC AND SEISMOLOGIC INVESTIGATIONS OF THE FOLSOM, CALIFORNIA AREA

FINAL REPORT

PREPARED FOR:

U.S. ARMY ENGINEER DISTRICT
SACRAMENTO
650 CAPITAL MALL
SACRAMENTO, CA 95814

CONTRACT NO. DACW05-82-C-0042

632 PASEO DE PERALTA SANTA FE, NEW MEXICO 87501 505/982-2845

CIVIL AND SOILS ENGINEERING
LAND SURVEYS AND DEVELOPMENTS
TIERRA ENGINEERING CONSULTANTS, INC.
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SANTA FE, NEW MEXICO 87501
505/982-2845

18 July 1983

District Engineer
Department of the Army
Sacramento District, Corps of Engineers
650 Capitol Mall
Sacramento, California 95814

Attention: SPKED-F

Re: Fault Evaluations in the Vicinity of Folsom Dam and Lake
Contract No. DACW05-82-C-0042

Gentlemen:

We are pleased to submit the final report on the Geologic and Seismologic Investigations of the Folsom, California Area.

The report was completed on schedule and on budget. We would like to thank the Foundation and Materials Branch for the excellent cooperation in scheduling the field visits and expeditious review of the draft report. We also would like to thank the Real Estate Branch for the help in securing entry to the Russell Ranch.

We have enjoyed preparing this report, and look forward to other projects with the Sacramento District.

Very truly yours,

Richard B. Catanach
President

RBC:rk

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SECTION 1

1. EXECUTIVE SUMMARY

Folsom Reservoir is located in the Sierran foothills at the confluence of the North and South Forks of the American River, near Sacramento, California. In order to identify and evaluate the capability (Corps of Engineers criteria) of faults near the reservoir, the geology of a 12-mile-wide by 35-mile-long area centered on the reservoir was investigated. Elements of the investigation included aerial imagery analysis, ground reconnaissance, geologic mapping, and detailed fault capability assessments.

1.1 PROJECT GEOLOGY

The project area is underlain by metavolcanic rocks of Mesozoic age which are locally intruded by granitic and mafic plutons. These rocks are partly covered by Tertiary and Quaternary volcanics and sediments.

There are no major faults within the study area. Numerous lineaments identified within the study area were, however, investigated and five features were selected for more detailed study. These were:

1) The West Branch, Bear Mountains fault zone.
2) The Bass Lake fault.

3) The Linda Creek lineament.

4) The Mormon Island fault.

5) The Scott Road lineament.

Three of these features were eliminated from further study on the basis of data review, geologic mapping and/or imagery analysis. These were:

- The Bass Lake fault was found to be a band of serpentinite outcrops associated with the Pine Hill intrusive complex. The fault pre-dates or is contemporaneous with the Pine Hill complex, dated as approximately 168 million years old, and shows no evidence of movement in recent geologic time. The fault is not considered capable under Corps criteria.

- The Linda Creek lineament was shown to be unrelated to Quaternary faulting by previous studies made for the U.S. Bureau of Reclamation's (USBR) proposed Auburn dam. Based on the Auburn work, it was concluded that the Linda Creek lineament does not represent a capable fault under Corps criteria.

- The Scott Road lineament was assessed to have developed by differential erosion along an unfaulted geologic contact and is considered not to be a fault.

The remaining two faults, the West Branch, Bear Mountain fault zone and Mormon Island fault, required additional studies, including detailed lineament analysis, geomorphic analysis, geologic mapping, and trenching at selected locations. The results of these studies indicated that:

- The West Branch, Bear Mountains fault zone is not truncated by the Rocklin/Penryn pluton, but extends northward just east of the pluton. Based on undisplaced 60,000 to 70,000 year old soils overlying sheared bedrock exposed in trenches and the lack of geomorphic indications of Holocene faulting along the fault zone, it is concluded that the West Branch, Bear Mountains fault zone is not a capable fault under Corps criteria.

- The Mormon Island fault does not extend into the Rocklin/Penryn pluton, and the lineament zone associated with the fault dies out before reaching Mormon Island Dam. A review of the dam construction geology reports revealed no evidence of faulting of Quaternary alluvium in the ancient South Fork river channel. Undisplaced colluvium and weathering profiles dated as at least 65,000 to 70,000 years old overlie sheared bedrock exposed in a trench excavated across the fault. Based on those observations and the lack of geomorphic indicators of Holocene faulting along the fault zone, it is concluded that the Mormon Island fault is not a capable fault, nor does it pass through the foundation of Mormon Island Dam.

1.2 TECTONICS AND SEISMICITY

- The study area is located nearly at the center of the Sierran block. Much of the stress release associated with the tectonics of this block is taking place on the eastern and southern boundaries where intense seismicity is observed. Seismicity is, however, low along its western margin and very low within the block.

- Minor deformation has been occurring within the Sierran block as a result of westward tilting during the last 10 million years. Both down to the east and down to the west displacements have been observed within the western Sierran foothills. East-west extension is the inferred stress regime for both types of faulting.

- The extensional tectonic regime presently affecting the Sierran foothills is not conducive to major buildup and sudden release of stress causing major earthquakes.

- Instrumentally recorded rates of seismicity for the Sierran foothills are consistent with rates derived from pre-instrument newspaper accounts of earthquakes. Seismically active areas of California have a rate of seismicity greater than 30 times the rate of seismicity in the foothills.

- Changes in tectonics which might affect the style or locus of major faulting or rate of stress accumulation and release generally occur over a very long period of time. Hence, probability of a change in the seismotectonic regime of the study area in a manner as to affect the Folsom project during its useful life is considered nil.

1.3 RESERVOIR INDUCED SEISMICITY

- Although there have been a number of small earthquakes ($\geq M_L$ 4.0) within 30 miles of the site prior to construction of the dam, no macroseismic activity has been monitored or known to have been induced by the reservoir since it was filled 28 years ago.

- Monitoring in the vicinity of the Rocklin/Penryn plutons does not indicate any correlation between the occurrence of microseisms and reservoir elevation, or any increased macroseismicity in the area.

- Other worldwide microseismicity monitoring data at reservoirs do not indicate a direct correlation between increased microseismic activity and reservoir-induced macroseismicity.

- Microseismicity within the Rocklin/Penryn pluton does not appear to be reservoir induced based on available data. Evidence suggests the seismicity may be related to minor adjustments along igneous contacts within the pluton.

- On the basis of the above, it is concluded that it is unlikely that Folsom Lake can induce major macroseismicity.

1.4 MAXIMUM EARTHQUAKE AND GROUND SURFACE RUPTURE

- Faults investigated within the study area are judged to be non-capable by Corps of Engineers criteria.

- Displacements along existing non-capable fault zones within the study area are judged to be unlikely. Similarly, fault displacements in the foundations of Folsom Reservoir impoundment structures are judged to be highly unlikely, and represent a negligible hazard to the project.

o The nearest faults outside the study area that could be considered are located within the East Branch, Bear Mountains fault zone. The determination of capability was not made as a part of this study, but was made by others who judged the faults to be active using USBR activity criteria. In the Auburn Dam Earthquake evaluation, these faults were judged to be capable of generating a maximum credible earthquake of magnitude 6.0 to 6.5. The closest approach of the East Branch, Bear Mountains fault zone to major project structures is 8 miles to the Mormon Island Dam and 9.5 miles of the main dam. Thus, a hypothetical M_L 6.5 earthquake located 8 miles from project structures at a focal depth of 6 miles may be considered to be a conservatively high Maximum Earthquake. Such a hypothetical earthquake would likely cause stronger shaking at project structures than earthquakes originating from other known potential sources.

SECTION 2

2. INTRODUCTION

2.1 PURPOSE

The purpose of this study was to assess the potential for earthquakes in the vicinity of Folsom Reservoir, develop data for estimating the magnitude of the earthquakes, and investigate the potential for ground rupture at the main dam, associated dikes and appurtenant structures.

Folsom Reservoir is located in east-central California, approximately 20 miles northeast of Sacramento. The location of the project is shown on Plate 2-1.

2.2 AUTHORIZATION

Authorization for the study was provided by letter from the Contracting Officer, Sacramento District, Corps of Engineers dated February 8, 1982. The letter authorized work in accordance with Tierra Engineering Consultants' proposal dated December 10, 1981 in response to RFP No. DACW05-81-R-0083.

2.3 SCOPE OF WORK

The comprehensive data accumulation and analysis involved in this study were accomplished by dividing the job into eight separate tasks, as originally outlined in the Proposal. The following is a brief description of the tasks in the order they were performed:

2.3.1 Data Compilation and Review

The initial task of this study consisted of compiling and reviewing the published literature relevant to the geology and seismicity of the area around Folsom. This compilation permitted the assessment of the level of information available on the study area, and identification of areas on which to concentrate further study. Previous work includes numerous general geologic and seismologic studies published through the years, beginning with the "Gold Folios" published by the U.S. Geological Survey in the 1890's. Other important sources of information included the engineering geologic investigations for New Melones Dam and proposed Marysville and Auburn dams, as well as studies performed for the Rancho Seco nuclear power plant. Unpublished student theses and county planning studies also contributed to the data base. A complete listing of the data collected and analyzed is included in Section 8 of this report.

2.3.2 Project Imagery Analysis

This task consisted of identifying, collecting and analyzing available aerial imagery of the project area. In addition, new low altitude, low-sun-angle (1:30,000) color photos were commissioned expressly for this project in May, 1982. A detailed lineament analysis was performed on the imagery by Photographic Interpretation Corporation of Hanover, New Hampshire. Lineaments were mapped on conventional low altitude photography at several scales, as well as Landsat, NASA U-2 color infrared and Skylab imagery. Detailed drainage nets were constructed using recent low altitude photography. These were used to aid in the indentification and interpretation of the lineaments found by independent analysis. A discussion of the procedures used in this phase are included in Appendix A.

2.3.3 Areal Geologic Investigation

Geologic mapping was undertaken within the field area in order to eliminate gaps in the geologic data base, to check existing mapping, and to resolve conflicts and inconsistencies between previous works. Field verification mapping was conducted in May, June and July, 1982 using USGS 7.5 minute topographic bases, scale 1:24,000. Strip mapping along fault zones and lineaments identified during the imagery analysis was conducted at a scale of 1:12,000 on enlarged USGS topographic bases. These ground efforts were supplemented by airphoto analysis and aerial observations made during a light plane flight in April, 1982. Map traverses included most main and secondary roads within the project area, and on private property where access could be arranged. Approximate flight lines and main road traverses are shown on Plate 2-2. The procedures used and areas covered in this phase are further outlined in paragraph 2.7.1 and in Section 5.

2.3.4 Investigation of Faults, Shears and Lineaments

The results of the third task of the study described above were used to select specific geologic features and areas for detailed investigation. These investigations consisted of detailed mapping at a scale of 1:24,000, geophysical profiling using a proton-precession magnetometer, soil stratigraphic mapping and exploratory trenching. These efforts were focused on the geologic structures judged to present the greatest potential seismic threat to the Folsom dam and its appurtenant structures. A more complete discussion of this work is found in paragraph 2.7.3 and Section 5.

2.3.5 Seismicity of the Rocklin Pluton

Seismic data from microearthquakes detected within the Rocklin/Penryn Pluton during the late 1970's and up to the present were cataloged and analyzed to determine the most probable cause of this activity, and to assess its relationship to mapped faults in the area. In addition to a general assessment of the seismicity in the Folsom area, a detailed evaluation was made of the Rocklin/Penryn Pluton microseismicity. These data were also used to aid in the development of the tectonic model of the region. Discussion of work methods, results and interpretations are found in Section 7 and in Appendix B.

2.3.6 Laboratory Age Determination

Relative age determinations of Quarternary stratigraphic units were made on the basis of detailed study of soil profile development as observed in test pits and trenches and during extensive reconnaissance of the area. Materials suitable for numerical/absolute dating methods were not encountered within the detailed study areas.

2.3.7 Data Evaluation and Tectonic Model Development

The final task in this study involved reviewing and synthesizing the information collected to develop conclusions regarding the likely sources and potential for damaging seismicity within the study area, and the development of a tectonic model. To complete this task, regional geodetic information, fault displacement vs. magnitude relations, strain rates, regional estimates of seismic moment and plate tectonic theory were integrated. The tectonic model is discussed in Section 6.

2.4 LIMITATIONS AND CONDITIONS

The analyses, conclusions and recommendations contained in this report are based on geologic, tectonic, seismic and physical conditions as they existed at the time of investigation, and on a review of existing data and reports prepared for other studies in the Folsom-Auburn area. The exploration and findings have been periodically reviewed by representatives of the Corps of Engineers and by a panel of Technical Advisors. The findings represent Tierra Engineering Consultants' and their subcontractors' best professional judgments and are presented, within the limits prescribed by the Corps, after being prepared in accordance with generally accepted professional geologic and engineering practice.

At the onset of the study a number of limitations and conditions were established by the Corps of Engineers and by the investigation team. The principal items established provided guidelines for: the area of detailed study; a maximum earthquake for the Foothills fault zone and a specific definition for capable faults. The following paragraphs describe the principal limitations and conditions.

2.4.1 Study Area Boundaries

The study area was specifically designated by the Corps of Engineers in the Request for Proposal. The area, which encompassed about 390 square miles, extended from approximately Coon Creek on the north to the Consumnes River on the south. The eastern boundary was delineated by a line passing through Pilot Hill and Pine Hill while the western boundary was set by a line 12 miles west and parallel to the eastern boundary. The study area boundaries are shown on Plate 2-3, along with pertinent USGS 7.5 and 15 minute quadrangles. All required knowledge and understanding of seismotectonic conditions outside of the study area boundaries was assimilated from a review of existing reports and data and from personal experience and knowledge. In conformance with the established area boundaries, all original work, i.e., geologic mapping, trenching, etc., was restricted to the study area.

2.4.2 Fault and Earthquake Definitions

The definition of a capable fault was specified by the Corps of Engineers as that definition given in ER 1110-2-1806, Earthquake Design and Analysis for Corps of Engineers Dams, dated April 30, 1977. As defined, a capable fault is one that is considered to have potential for generating an earthquake. The fault can be shown to exhibit one or more of the following characteristics.

1) movement at or near the ground surface at least once within the past 35,000 years;

2) macro-seismicity (3.5 magnitude or greater) instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault; and

3) a structural relationship to a capable fault such that movement on one fault could be reasonably expected to cause movement on the other.

Likewise, definitions for maximum earthquake and Operating Basis Earthquake are given as:

1) Maximum Earthquake. The maximum earthquake is defined as the most severe earthquake that is believed to be possible at the site on the basis of geological and seismological evidence. It is determined by regional and local studies which include a complete review of all historic earthquake data of events sufficiently nearby to influence the project, all faults in the area, and attenuations between causative faults and the site.

2) Operating Basis Earthquake. The "operational" earthquake is generally more moderate than the maximum earthquake and is selected on a probabilistic basis from regional and local geology and seismology studies as being likely to occur during the life of the project. It is generally as large as earthquakes that have occurred in the

seismotectonic province in which the site is located.

The required tasks in the Corps work statements specifically required establishment of the Maximum Earthquake, but did not require the Operating Basis Earthquake.

2.4.3 Earthquake Magnitudes - Previous Studies

An earthquake evaluation study conducted for the U.S. Bureau of Reclamation (USBR) in 1977-78 with reference to the Auburn Dam investigation was exhaustive. In particular, an extensive amount of work was done along a system of northwest trending lineaments which passes through the Auburn area. Individual lineaments were thoroughly studied and it was concluded that the system, for the most part, represented a series of anastomosing and branching faults, two of which were identified as active. The USBR defined an active fault as:

1) a fault which has experienced relative displacement during the last 100,000 years (USBR, Vol. 2, 1977).

As a result of the earthquake evaluation studies, the faults were judged to have a Maximum Credible Earthquake (MCE) magnitude 6.0 to 6.5. For further analytical design work on structures at the Auburn site the USBR adopted a M 6.5 earthquake, focal depth about 6 miles, located near the town of Auburn.

The seismotectonic studies completed by the USBR and its consultants were extensive in terms of time and money. The scope of work for this Folsom seismotectonic study did not include provisions for retracing any of the original work done by the USBR and its consultants. That zone of faulting passing through the Auburn area is identified as the East Branch of the Bear Mountains Fault in this study.

It is recognized that a detailed reevaluation of that fault system could conceivably show the system to be non-capable using the Corps of Engineers definition for a capable fault. Nonetheless, for purposes of this study, the faults are assumed to be a source of earthquakes and a hypothetical M_L 6.5 earthquake, located near Auburn at a focal depth of about 6 miles, may be considered as a Maximum Earthquake on the East Branch of the Bear Mountains fault. Tierra Engineering Consultants, their subcontractors, and technical advisors believe that if the fault system is, indeed active or capable, a M_L 6.5 earthquake is conservative on the high side considering the existing tectonic regime in the foothills at this time.

2.5 ACKNOWLEDGEMENTS

This investigation was conducted by Tierra Engineering Consultants, Inc. with Converse Consultants, Inc. acting as general subcontractor. Initial imagery analysis was performed by Photographic Interpretation Corporation of Hanover, New

Hampshire. Other consultants included Professor Bruce Bolt and Dr. Robert Uhrhammer in matters of seismicity and Dr. Roy J. Shlemon for soil stratigraphy and Quaternary geology and tectonics. A technical Board of Review consisting of Professor Bolt, Dr. Shlemon and Dr. N. D. Marachi provided guidance and review comments on the report. David K. Rogers provided technical advice and critically reviewed the report. The investigation and report preparation were under the technical direction of Alan L. O'Neill and Richard Catanach. George A. Ford served as Assistant Project Manager in charge of field studies and preparation of the report; he was assisted by Marci Pincus, Mike Perkins, Mark E. Shaffer and Steve Testa. The help and cooperation of Mssrs. John Crowe and Justin Moses of the Foundations and Materials Branch of the U.S. Army Corps of Engineers, Sacramento District was greatly appreciated. John Gewerth and Robert Treat of the Corps provided invaluable discussion and comments during all phases of fieldwork. Mssrs. George Wheeldon and Michael Vanderdussen of George A. Wheeldon & Associates provided helpful discussion and access to original records of their work. Ms. Thekla Pardun of the Corps and Bill Grangood of the USBR Folsom office helped greatly with access arrangements. Logan Teal and John Croslin facilitated trenching efforts and provided helpful advice. Finally, thanks must go to all of the property owners of the project area who so graciously permitted access to their land. Without their cooperation, the investigation could not have been completed.

2.6 PREVIOUS WORK

The area near Folsom Reservoir has been studied extensively in the past. General geological works began with the U.S. Geological Survey (USGS) "Gold Folios" published in the 1890's, and continued with Lindgren's Tertiary gravel study and the Mother Lode investigations of Knopf and Cloos. Modern interpretation of Foothills geology began with the work of Clark in the 1960's, and has continued through the present. Clark's initial work has been refined by Duffield and Sharp (1975) and Schweickart and Cowan (1975), who interpreted the geology based on a plate tectonic model. The U.S. Geological Survey has conducted extensive mapping of Cenozoic deposits throughout the northern Sacramento Valley and adjacent areas, and has published these results in a series of open-file maps that served as the source for much of the Quaternary geology used in this study. Published mapping and depositional models by Dr. Roy J. Shlemon also were used in the interpretation. Principal sources of mapping data for Cenozoic geology are shown on Plate 2-5 and Pre-Cenozoic geology on Plate 2-4.

Other studies located within the project area enhanced the level of geologic detail and proved quite useful in that respect. The original investigation for the Folsom Dam by Kiersch and Treasher (1952) was used in conjunction with Corps of Engineers dam construction documents. Area studies by Olmsted (1971), Taylor (1979), Livingston (1976) and doctoral theses by Springer (1971) and Behrman (1978) provided an excellent geologic base from which to work.

The 1975 Oroville earthquake spurred intensive investigations of the foothills where seismicity had been previously regarded as negligible. Engineering geologic studies which focused on faulting potential within the foothills include those for the Corps of Engineers' Marysville Lake Project, the U.S. Bureau of Reclamation's Auburn investigations, and Bechtel's Rancho Seco nuclear plant geological and seismological review. Other significant investigations in the foothills south of Folsom were conducted for the Corps of Engineers' New Melones Dam and Pacific Gas and Electric's proposed Stanislaus Nuclear Power Plant Project. These major studies contributed greatly to the understanding of geology and seismicity in the region, and helped form an extensive information base.

2.7 INVESTIGATION METHODS

Fieldwork was divided into three separate phases to facilitate efficient use of manpower and to insure that individual efforts could be closely supervised and coordinated. The field staff ranged in size from three to six geologists. Work was conducted continuously from June through December, 1982, and was coordinated through a field office maintained in Citrus Heights, California. The following paragraphs describe each phase of fieldwork.

2.7.1 Geologic Mapping

Mapping within the study area was conducted by several means in order to efficiently cover the most important aspects of the local geology. First, observations were made by two geologists during a light plane flight over the study area in April, 1982. Photographs were taken and notes recorded in order to develop a general picture of the region to aid in planning subsequent work. This flight also served to provide a "dry run" for low-sun-angle photography commissioned later, and permitted determination of the time span during which the sun-angle was optimal. The approximate flight path is shown in Plate 2.2.

Ground mapping efforts began with reconnaissance road traverses throughout the study area. The purpose of these traverses was to check existing geologic mapping and to work on resolving boundary inconsistencies between adjoining or overlapping maps by different authors. Traverse routes were mapped on USGS 7.5 minute topographic quadrangles, augmented with photographs and notes. In large areas with relatively few roads, such as in the ranchlands south of U.S. Highway 50, foot traverses were made across private land when access could be arranged.

During the initial data compilation and review, one region was identified that had not been mapped in reasonable detail since the publication of the USGS "Gold Folios" of the 1890's (see Plate 2-4). The region, a 90-square mile oblong belt along the southwest side of the study area, was the focus of special attention. Both reconnaissance traverses and areal and photogeologic mapping were performed using USGS 7.5 minute quads at a scale of 1:24,000 as base maps. The effort was directed toward developing a map of the general structure of these areas, and to bring the geologic detail up to a level more consistent with the rest of the area.

The third sub-task in the geologic mapping involved focusing on specific features deemed to be important. These included previously mapped fault traces, structural and stratigraphic discontinuities, and zones of strong deformation that were identified during the data review and through the earlier reconnaissance mapping. These factors included two different versions of the Bear Mountains fault zone, as mapped on the old and new California Division of Mines and Geology (CDMG) 1:250,000 scale Geologic Map of the Sacramento Quadrangle (1954 and 1981), zones of deformation mapped by Olmsted (1971), and several lineaments south of Folsom Reservoir. This work was conducted by constructing strip maps along fault zones, structural corridors and lineaments, using

1:12,000 scale enlargements of USGS 7.5 minute quadrangles as a base.

2.7.2 Lineament Analysis

Lineament analysis comprised a substantial portion of the time spent in the field. This complicated task was necessary to reduce the very large number of lineaments mapped as part of the aerial imagery study to a manageable group of the most important features, which could then be investigated in detail. The analysis began with the construction of lineament maps on clear overlays to USGS 7.5 minute quads by a team of three professionals. The lineaments were mapped on aerial imagery of various types and scales (see Table 2.1 for a listing, Plate 2-6 shows the areas covered by each type of imagery). These maps were then combined at 1:24,000 scale and discussed by the three team members. Lineaments were weighted according to their strength of expression, on a strong-moderate-weak scale based upon the number of team members that has noticed them. The weighted lineament maps also were color-coded to indicate the type of imagery on which the lineament was observed. A more complete discussion of the lineament identification and mapping process is included in Appendix A.

TABLE 2-1

AERIAL IMAGERY SOURCES

Source	Type	Scale
(High Altitude)		
LANDSAT	Color IR	(various)
SEASAT	Radar	(various)
SKYLAB	Color	(various)
NASA U-2	Color IR	1:120,000 1:30,000
USGS Ortho-quad	BW	1: 80,000 1:24,000
SCS	BW	1: 63,000
(Low Altitude)	BW (1971)	1: 20,000
	BW (1952)	1: 20,000
	Low-Sun-Angle (color, 1982)	1: 36,000

The first field task in the lineament analysis was ground truthing of lineaments selected by imagery analysis. This work was conducted over several days by a member of the imagery analysis team and several field geologists already familiar with the area. Once this task was completed, a general review of the lineament mapping results was undertaken by the field geologists. Lineaments known to be man-made were eliminated directly, as were lineaments known to be not fault related on the basis of previous work. In a few cases, lineaments were added to the overlay maps based on imagery analysis performed by members of the field party, who had the benefit of extensive on-the-ground observations.

The subsequent stage of lineament analysis involved dividing the lineaments into high and low priority groups based upon consideration of:

- o proximity to the reservoir impoundment structures;
- o strength of expression and continuity of the lineament; and
- o the general level of knowledge regarding the local geology.

The low priority group of lineaments was removed from active consideration at this point. This group consisted of moderately to weakly expressed lineaments, generally less than a mile long, located at relatively large distances (greater than 5 miles) from the dams. The high priority grouping was composed of long, strongly expressed lineaments and lineament systems, long alignments of moderate to weakly expressed lineaments, and all lineaments of any size or strength of expression that were located within 5 miles of project structures. The high priority lineaments were then investigated individually by more field reconnaissance, strip mapping and photogeologic mapping. Through these efforts the large number of high priority lineaments were reduced to a small group of mapped faults and lineaments of uncertain nature that could be investigated by trenching, soil-stratigraphic studies and very large scale mapping.

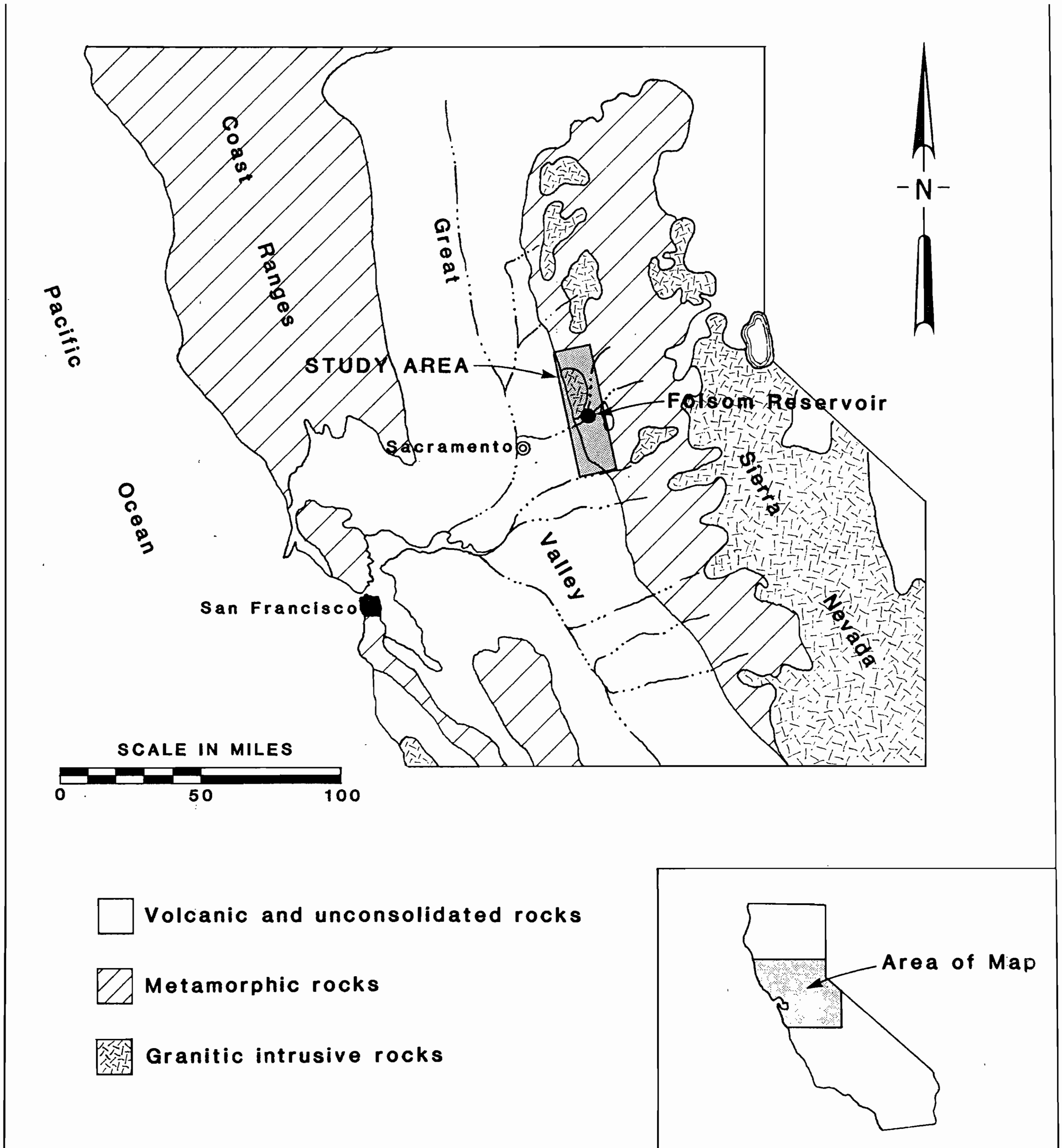
2.7.3 Detailed Site Examination and Trenching

The final stage of field work involved intensive investigation of small areas located on fault zones identified by the previous work, in order to determine if the faults were capable. Techniques for study of the small areas involved detailed geologic mapping at a scale of 1:24,000, magnetometer profiling and excavation of soil-stratigraphic test pits and exploratory trenches across the fault zones. Sites were selected for further study using one or more of the following criterion:

- observed or inferred presence of Quaternary or Tertiary deposits,
- soil profile development,
- proximity to the reservoir,
- narrowness and clarity of definition of the fault zone.

Six sites along two lineament systems were given further study as a result of the selection process. From this work, four sites were selected for exploratory trenching.

Topography of each of these sites was mapped photogrammetrically and a map prepared at a scale of 1:2400 (1" = 200') with 5 foot contour interval. The sites were geologically mapped at the large scale, some crossed with several magnetometer lines, and trenched. Exploration trenches ranged in length from 70 to 540 feet and in depth from 2 to 16 feet. After shoring, one wall was completely cleaned and graphically logged at a scale of 1:24. Full descriptions of rock and soil units were taken at the site. Key units and horizons were marked with orange paint prior to the review of the trench by Corps personnel and Technical Advisors. The logged and marked trench walls were photographed in color to provide an alternative record of what was seen. Finally, each trench was backfilled, compacted and the ground surface reseeded to insure rapid return to original conditions.



(Modified from Clark, 1964)

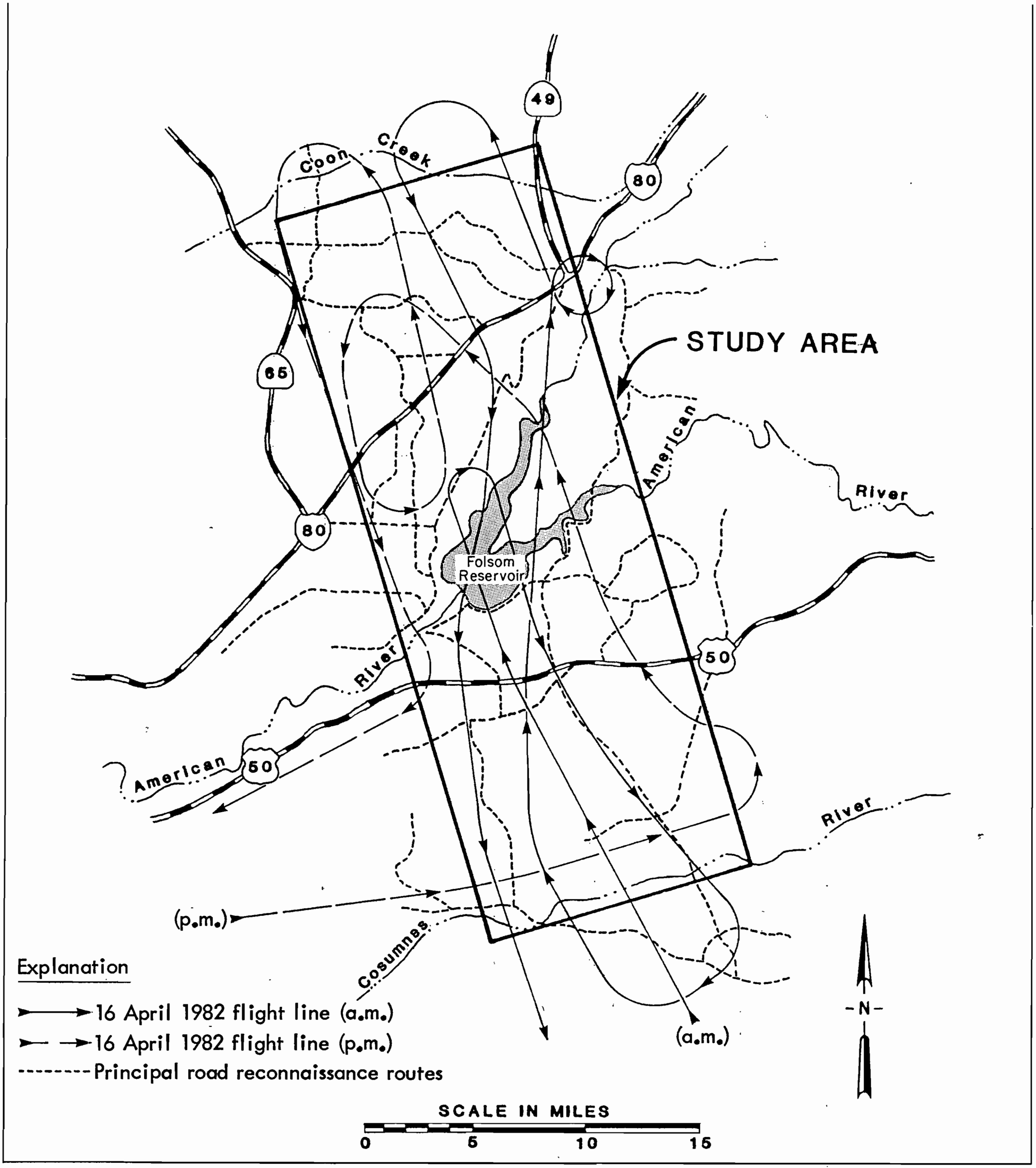
CALIFORNIA

TIERRA ENGINEERING CONSULTANTS

LOCATION MAP

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 2-1



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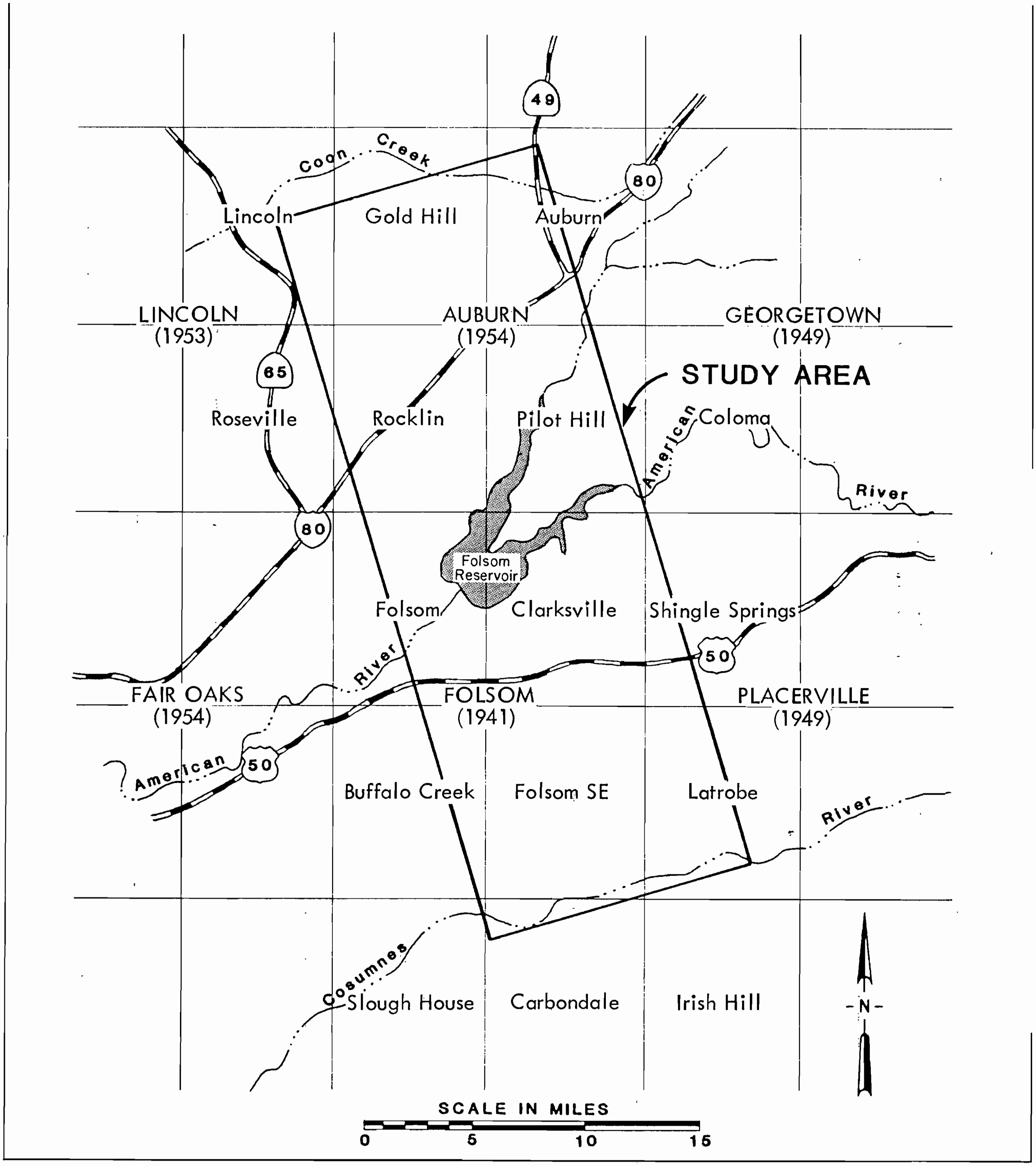
INDEX MAP: AERIAL AND GROUND RECONNAISSANCE

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 2-2



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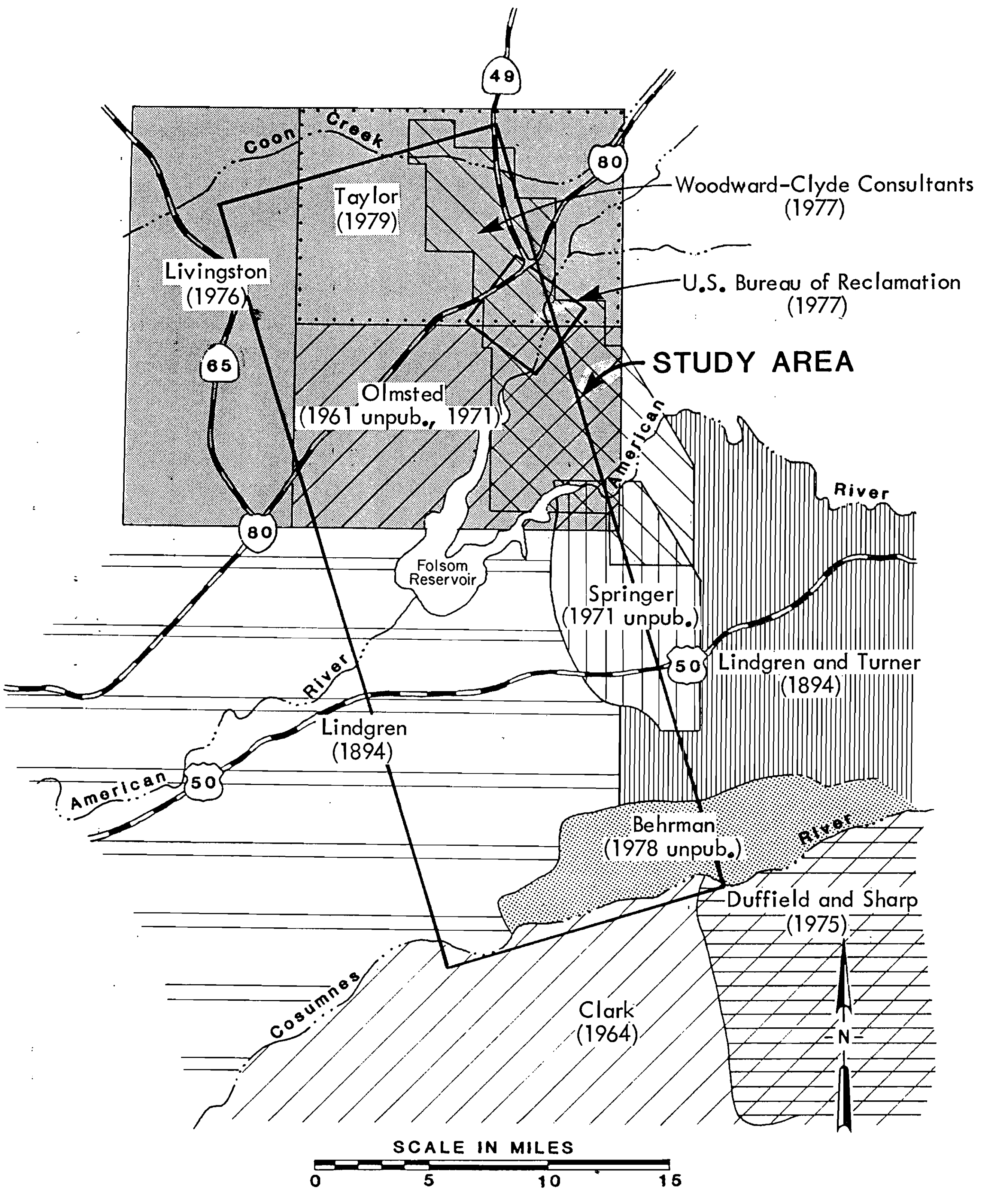
INDEX MAP: USGS 7.5' AND 15' TOPOGRAPHIC MAPS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 2-3



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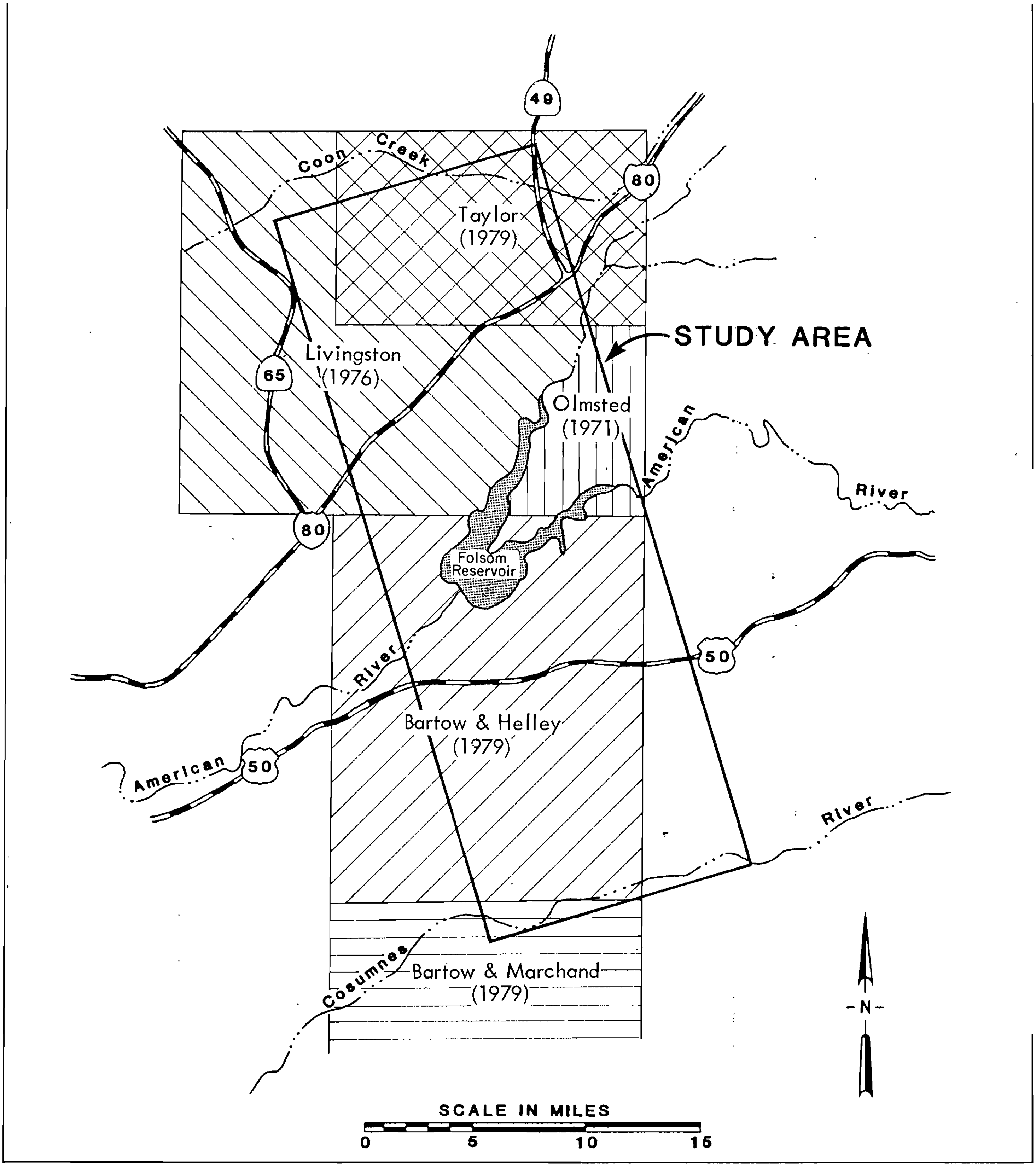
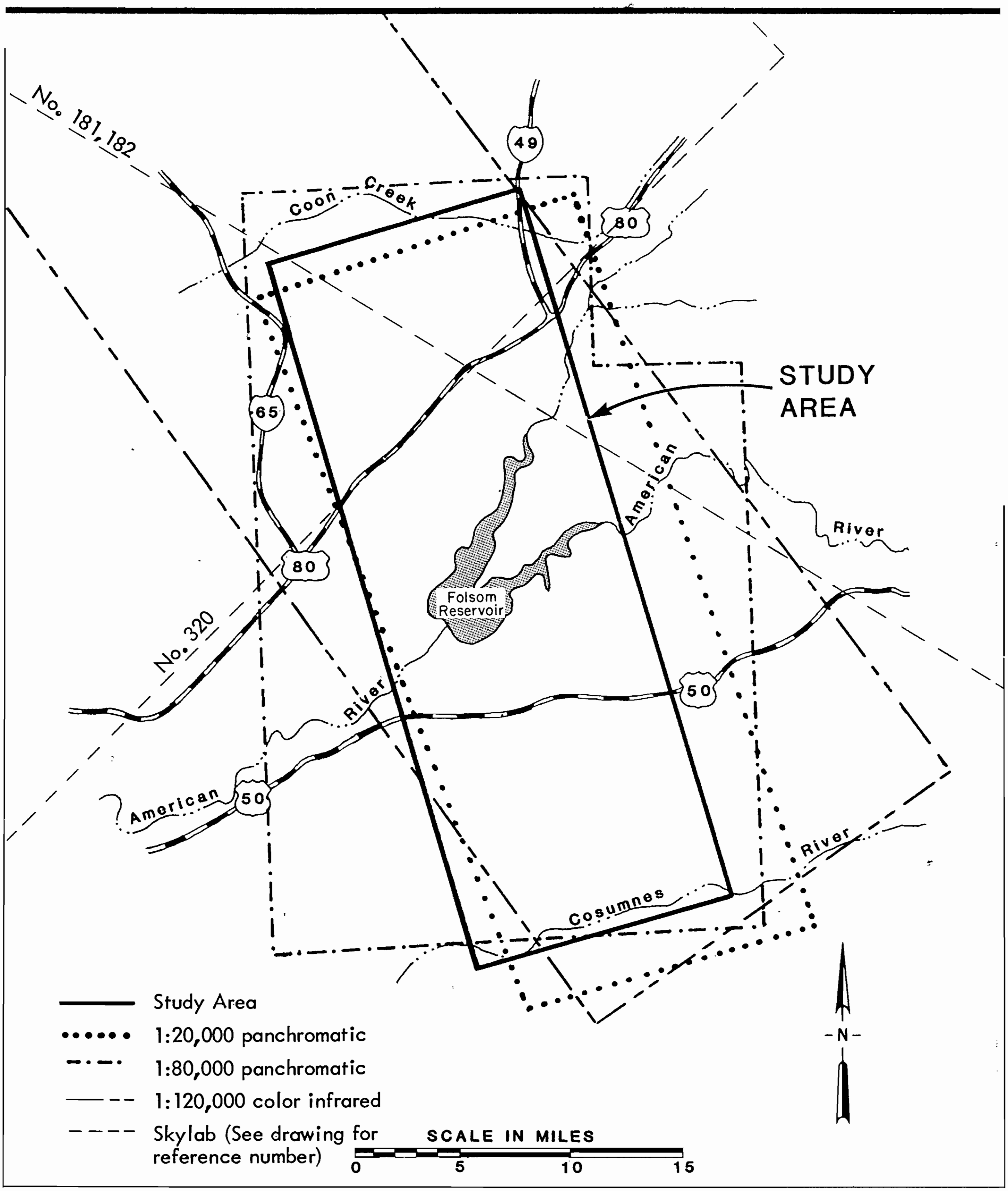
GEOLOGIC SOURCE DATA: PRE-CENOZOIC ROCKS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 2-4



TIERRA ENGINEERING CONSULTANTS	GEOLOGIC SOURCE DATA: CENOZOIC DEPOSITS
	GEOLOGIC AND SEISMOLOGIC INVESTIGATION FOLSOM, CALIFORNIA AREA for U.S. Army Corps of Engineers Sacramento District
	Plate No. 2-5



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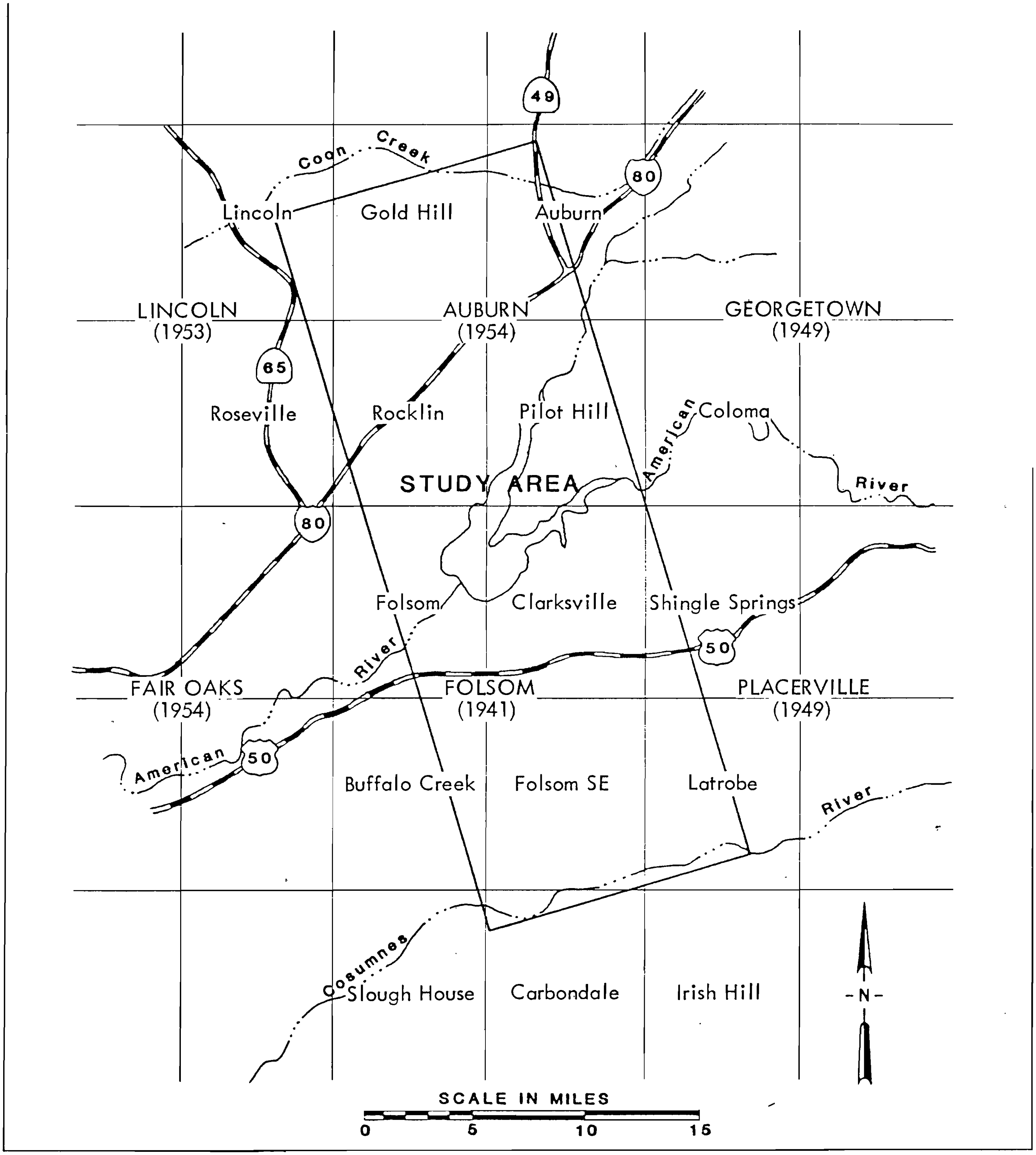
INDEX MAP FOLSOM AERIAL IMAGERY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 2-6



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INDEX MAP: USGS 7.5' AND 15' TOPOGRAPHIC MAPS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Figure No.

SECTION 3

3. REGIONAL GEOLOGY AND TECTONIC SETTING

Folsom Reservoir is located in east-central California between the Great Valley and Sierra Nevada geologic/tectonic provinces. This area is located on the eastern edge of the Great Valley geomorphic province, adjacent to the Sierra Nevada. The topography of the region is characterized by steep river canyons eroded into a gently westward sloping metamorphic bedrock surface. The rivers originate in the higher terrain of the Sierra, and debouch onto the relatively flat alluviated surface of the Great Valley to the west. This topography is the result of erosion of the uplifted and westward tilted mountain block, acting in combination with Tertiary volcanism and sedimentary deposition.

The following paragraphs provide an overview of the geology of these provinces to aid in the understanding of the regional tectonics.

3.1 FOOTHILLS METAMORPHIC BELT

The 250-mile-long band of deformed metamorphic rocks that parallels the western side of the Sierra was originally named the Western Metamorphic Belt by Clark (1960), who also named the Foothills fault system contained within it. In this report, Clark's Western Metamorphic Belt will be referred to as the Foothills Belt, in order to avoid confusion with other terminology. The Foothills fault system includes the Melones and Bear Mountains fault zones. This band of rocks ranges in width from 30 to 50 miles, and extends from the Mariposa area northwestward to the Sierra Nevada-Cascade/Modoc province junction. This complexly faulted and deformed region has been the subject of intense scrutiny and reinterpretation using plate tectonic concepts. Most recent geologic work and reanalysis has been based on the original work on the province by Clark (1960, 1964, 1976). Clark divided the foothills rocks into several sub-belts separated, in part, by various branches of the Foothills fault system. Schweickart and Cowan's 1975 major reinterpretation of previously mapped geology holds that the Paleozoic metamorphic rocks in the Foothills Belt originated in the collision of two volcanic arc-subduction zone complexes in earliest Cenozoic time. A new east-dipping subduction zone located to the west of the colliding arcs formed the Franciscan-Sierran arc-trench complex and gave rise to the magmas that became the middle and late Mesozoic Sierran plutons. The deformed rocks and Foothills fault system within the Foothills Belt represent the suture zone between the old arc-subduction zones during the early Cenozoic collision.

Schweickart and Cowan divided the complex assemblage of metamorphic rocks into western, central and eastern belts. The western and eastern belts consist chiefly of Mesozoic rocks, while the central belt contains older Paleozoic rocks. The eastern belt consists mainly of Mesozoic metamorphosed arc-trench volcanic and clastic rocks unconformably overlying the Palezoic central belt units. The structure and lithology of the central and western belts is significantly more complex, due in part to their greater extent. Generally, the central belt is composed of metavolcanics, discontinuous ophiolites and a thick series of steeply eastward-dipping metasedimentary rocks, including the Shoo Fly and Calaveras Formations. These belts are depicted on Plate 3-3. The western belt contains Jurassic metavolcanic and metaclastic rocks derived from island arcs, as well as blocks of tectonic melange probably derived from the country rocks. The western belt is separated from the central belt along part of its length by the Melones fault zone. The Melones is separated from the Bear Mountains zone by a melange belt along part of its length and forms the contact between the melange belt and other island-arc metavolcanics.

Special attention must be focused on the characteristics by which the members of the Foothills fault system were identified, in that they are not similar to most other faults in California. These faults were identified by Clark and subsequent workers on the basis of:

1) zones of pronounced structural and stratigraphic discontinuity,

2) deformed and sheared margins of elongated serpentinite bodies,

3) zones of strong schistosity, cataclasis or crumpling.

Generally, the Melones fault zone is better defined and more easily recognized as a fault. Previous workers (Sharp and Duffield, 1975) have noted that recognition of both zones is complicated by lithologic units that parallel the fault zones rather than intersect them. The Bear Mountains zone does not have the strong contrasts in lithology, age of rock units or degree of deformation across the structure that are common along the Melones zone (Sharp and Duffield, 1975, Parkison, 1976, USBR, 1977a). Sharp and Duffield were unable to demonstrate the existence of the Bear Mountains fault zone except as an "ancient zone related to subduction" (Bechtel, 1982).

3.2 SIERRA NEVADA BATHOLITH

The Sierra Nevada form an important part of the western tectonic boundary of North America. The range is an elongated north-northwest-trending body of granitic plutons, extending 400 miles in a 50 to 80-mile-wide band. Elevations range from 400 to over 14,000 feet, the highest peaks being concentrated along the southeastern edge. The eastern side of the range is a relatively steep escarpment, where Sierran intrusives are in fault contact with the rocks of the Basin and Range. In central California, the granitics are bounded on the west by the Foothills Belt, composed of Paleozoic and metamorphic rocks in a long north-south band, partly in fault contact with the intrusives.

Most of the Sierra batholith is composed of numerous plutons of granodioritic composition that were emplaced between middle Triassic and middle Cretaceous times. These plutons intruded older Paleozoic marine sedimentary strata and ophiolites which had developed along an ancient plate boundary. A long period of erosion resulted in the beveling of the marine and plutonic rocks to a relatively flat surface by the late Cretaceous. Beginning in the Late Cretaceous these basement rocks were gradually buried by a series of volcanic and sedimentary deposits, a process which continued well into Cenozoic time.

Uplift and westward tilting of the Sierras began in early Pliocene time, resulting in the development of the eastern Sierra Nevada frontal fault system and the steep escarpment bounding the range. The evolution of present day topography is largely due to this regional uplift and erosion of the batholith and Tertiary rocks overlying it, in combination with Quaternary alpine glaciation.

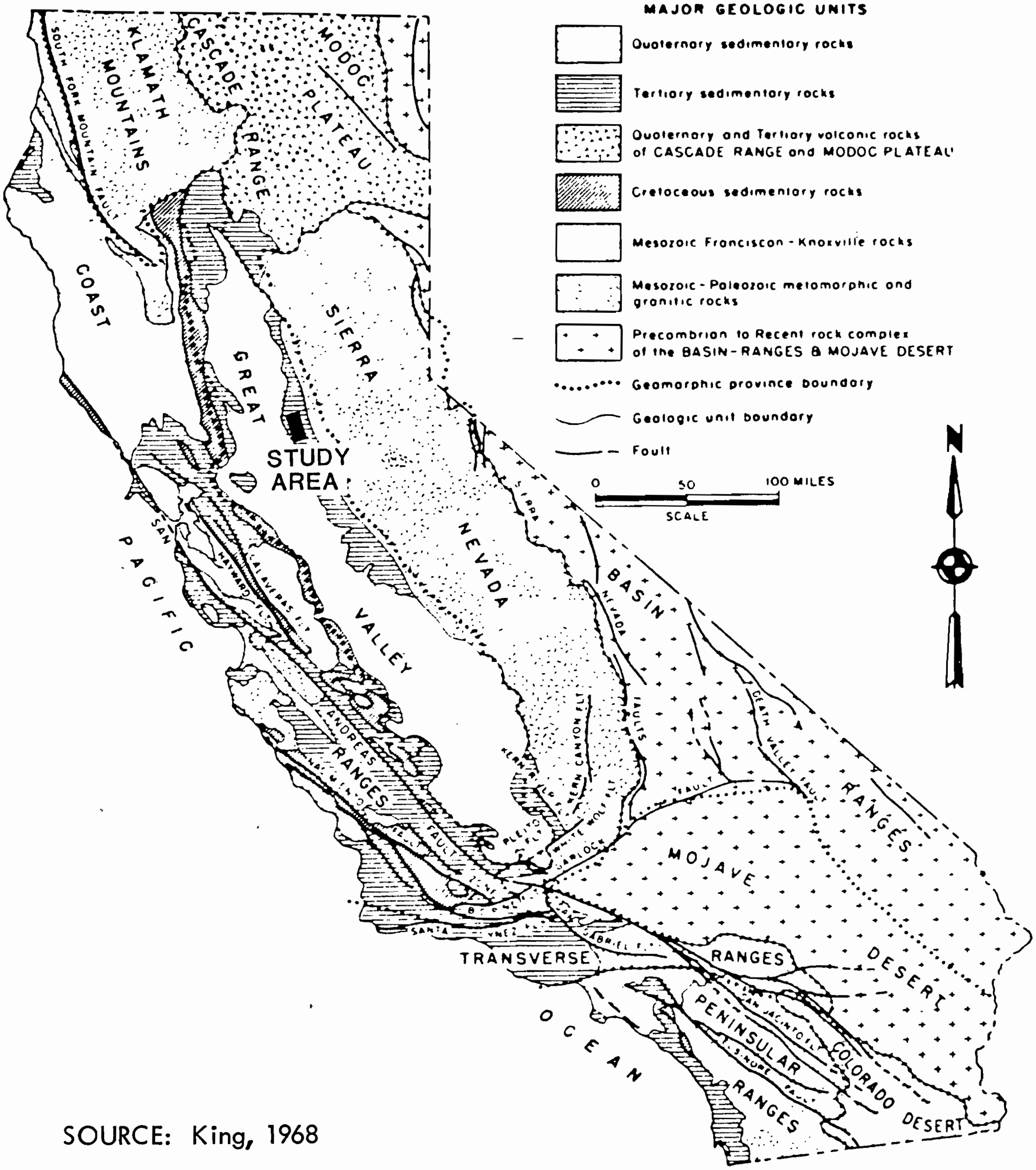
3.3 TERTIARY AND QUATERNARY ROCKS

Sedimentary and volcaniclastic rocks of Cenozoic age are found in great abundance in the Great Valley, and to a lesser extent in the Sierra Nevada and Foothills. These rocks were deposited on the surface of an eroded basement composed of Paleozoic and Mesozoic metamorphic rocks and Mesozoic granitic plutons. The rocks may be divided into three stratigraphic groups based on lithology: pre-volcanic sediments, rhyolitic sediments, and andesitic volcanics (Lubetkin, et al, 1978, Bechtel, 1982).

The oldest rocks in the series are late Cretaceous marine and Eocene fluvial deposits of the Ione Formation within the Great Valley, and the Ione-equivalent "auriferous gravels" of the Sierran Foothills, deposited by major streams that debouched into the sea to the west. These conglomerates, sandstones, and shales interfinger with and are succeeded by rhyolite tuffs and rhyolitic sands and gravels deposited during Miocene volcanism. These volcanic and clastic deposits are called the Valley Springs Formation and its temporal equivalents, and form a continuous sheet in large areas of the subsurface of the Great Valley. They are exposed at the edge of the Valley and locally in the Sierras where they have not been eroded. These rocks unconformably overlie the older deposits, and were deposited during a period when local relief was relatively high in the Foothills and Sierras.

The youngest Tertiary rocks found extensively within the Foothills and Sierra are andesitic conglomerates, flows and flow breccias of the Mehrten Formation. These rocks were extruded in great quantity from vents in the high Sierra during Miocene and Pliocene time, (20-14 mybp) and buried existing topography under overlapping aprons of mud-flow breccias. These deposits of the Mehrten Formation which include clay, conglomerate, sandstone, tuff and breccia, generally lie unconformably on the Valley Springs Formation, but may interfinger with it locally, since andesitic volcanism may have begun in the north before rhyolitic volcanism had ended elsewhere. Still younger Tertiary andesitic volcanism has been reported in the southern Cascades and at Marysville. These rocks have been extensively eroded, and now occur as sinuous table mountains crossing the Foothills Belt at Auburn, the Mokelumne and Stanislaus Rivers, and in dissected aprons higher in the Sierras.

Late Tertiary and Quaternary deposits are most common as laterally extensive fluvial clays, silts and granitic sand and gravel deposited on the surface of the Great Valley and lower foothills by west flowing streams. Channel migration and changes in sediment character and load have occurred in response to climatic changes during the Quaternary. These effects are superimposed on structural deformation caused by uplift and westward tilting of the Sierras. Erosion has removed the Quaternary equivalent deposits from most Sierran and foothill channels and plains, but they are well exposed and preserved at the eastern valley edge, where it joins the foothills. Several levels of older river terraces may be recognized along the ancient channels of many valley drainages and can be used to provide relative dates on structural features observed within them. Alluvium is presently collecting only in small pockets along predominantly west-flowing streams within the Sierra and foothills: major deposition is confined to the larger rivers in the Sacramento and San Joaquin valleys.



SOURCE: King, 1968

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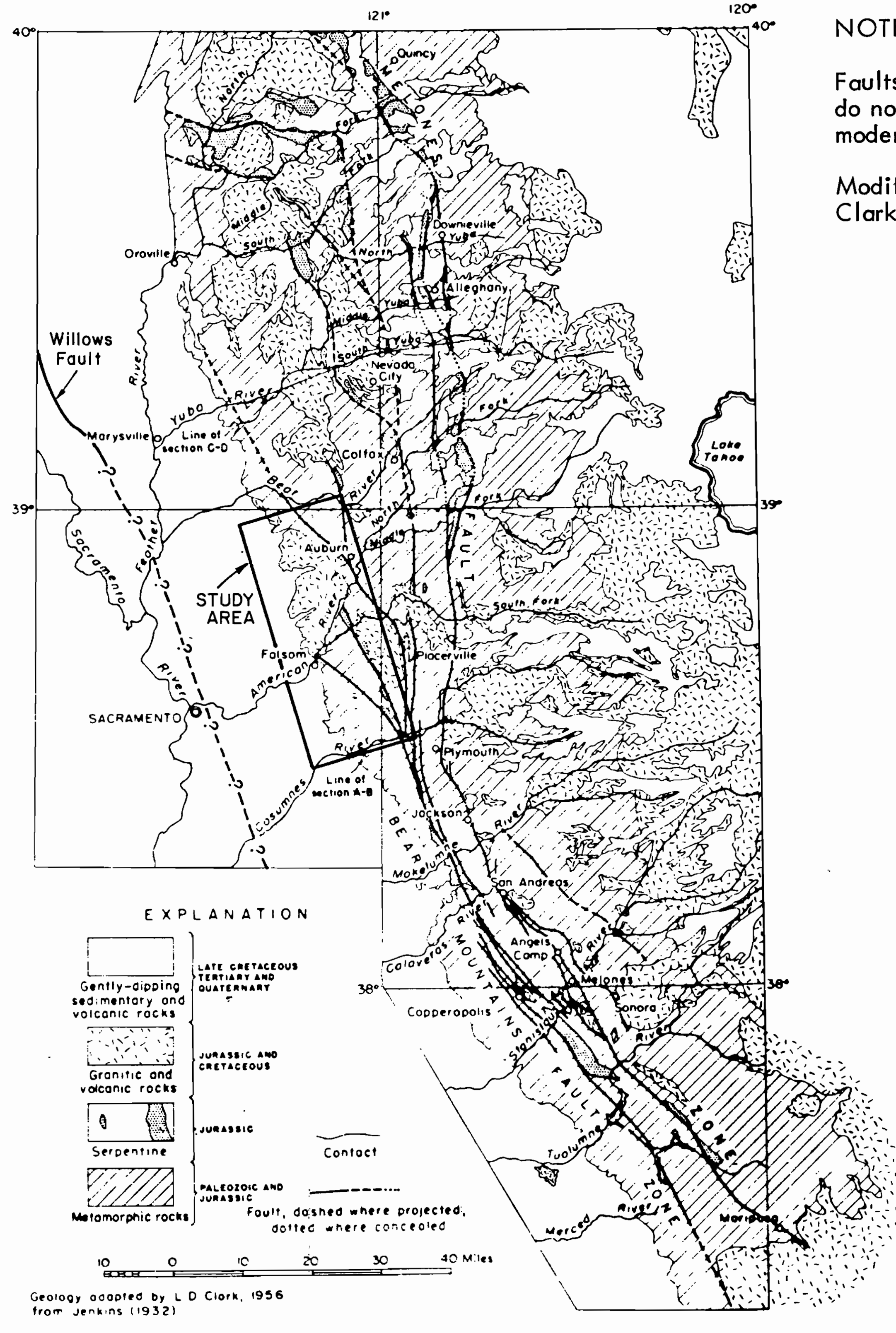
MAP OF CALIFORNIA SHOWING GENERALIZED GEOLOGY AND GEOMORPHIC PROVINCES

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 3-1



NOTE:

Faults in study area do not represent modern interpretation

Modified from Clark, 1960

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FOOTHILLS FAULT SYSTEM

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
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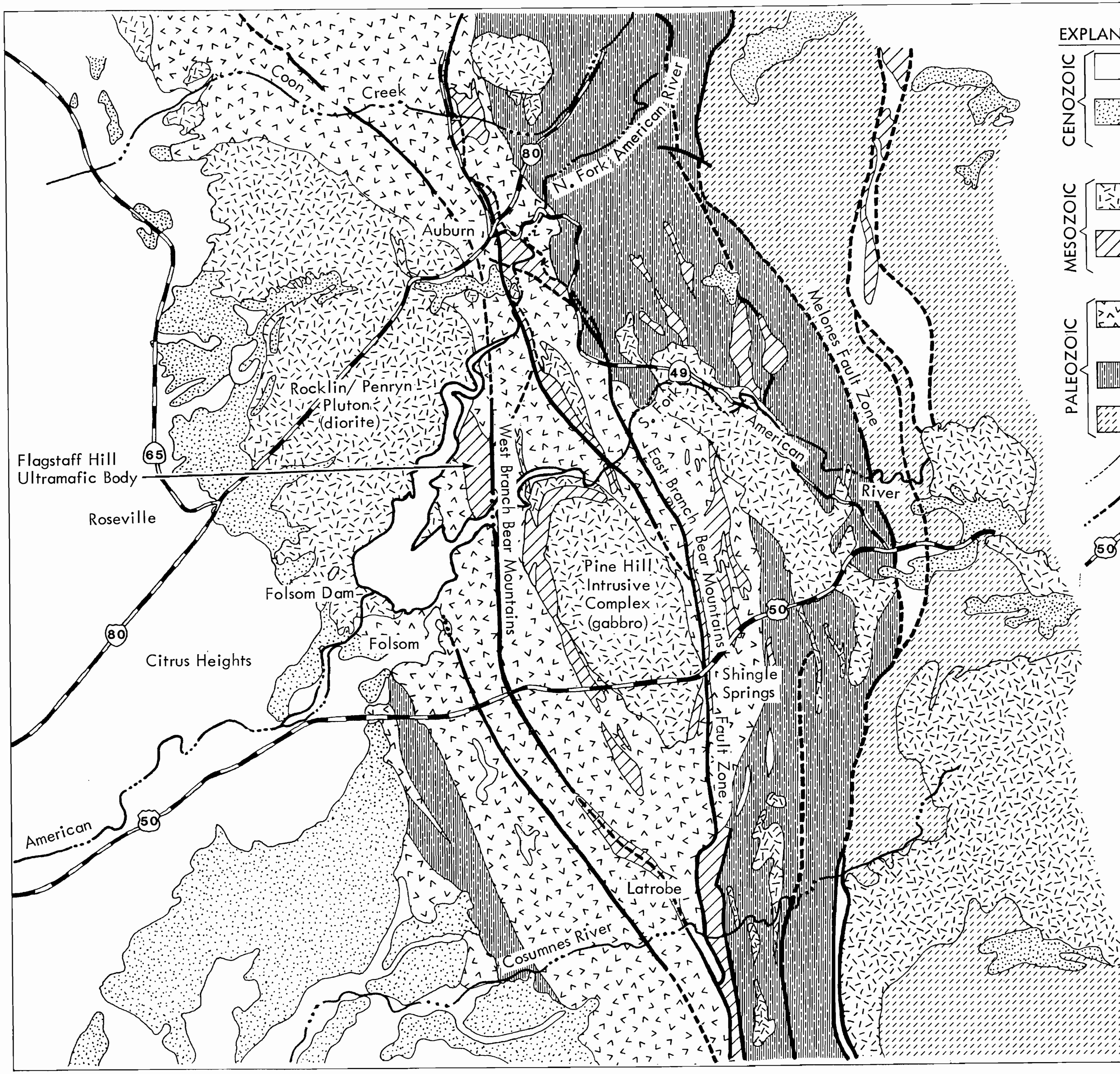
Plate No. 3-2



EXPLANATION:

CENOZOIC

- Quaternary Deposits: Basin alluvium, dredge tailings and Turlock Lake Formation (sand, silt and gravel).
- Tertiary Deposits: Laguna (consolidated alluvium), Mehrten (andesitic conglomerate, sandstone and breccia) Ione (quartzose sandstone and clay) and Valley Springs Formations.

MESOZOIC

- Mesozoic Intrusives: Granitic, dioritic and gabbroic plutonic rocks.
- Mesozoic Ultramafics: Serpentinite, dunite and pyroxenite plutonic rocks.

PALEOZOIC

- Metavolcanics: Partly to completely recrystallized flows, tuffs, lahar. Locally contains some thin bands of metasedimentary rocks.
- Metasediments: Partly to completely recrystalized sandstone, mudstone, conglomerate and associated rocks.
- Metasediments: Calaveras complex metasedimentary rocks.

Geologic contact, dashed where inferred, dotted where concealed.

Faults, dashed where inferred, dotted where concealed.

50 Major roads

-N-

0 5 10 Miles

Adapted from Wagner, 1981, CDMG Sacramento Sheet

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REGIONAL GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1 : 250,000	3-3

SECTION 4

4. PROJECT GEOLOGY

4.1 LITHOLOGIC FACIES

Rocks exposed within the study area may be divided into four principal groups: Paleozoic and Mesozoic metavolcanics and metasediments, Mesozoic granitic intrusives; Mesozoic gabbroic and ultramafic intrusives; and Tertiary and Quaternary volcanics and sediments. The following sections provide brief descriptions of these groups. Geologic maps covering the study area are included as Plates 4-1 through 4-5. Plates 4-6a through 4-6d are descriptions of map units and symbols. Plates 4-7 through 4-13 are strip outcrop maps, showing outcrops visited and described in selected areas during the investigation.

4.1.1 Metavolcanic and Metasedimentary Rocks

<u>4.1.1.1 Metavolcanics</u>. Two main types of metavolcanic rocks are most abundant in the area. Mixed greenstone and greenschist facies rocks are exposed in the northeast and south-central portions of the area. These rocks are separated from the Pine Hill and Rocklin/Penryn plutons by wide zones of amphibolite facies metavolcanic rock. Both groups contain scattered thin metasedimentary bands containing thin quartz

and calcite veins. Closely spaced felsic dikes also form sheeted dike complexes (Wright 1982, personal communication). The lower metamorphic grade greenstone and greenschist are characterized by an albite-chlorite-actinolite mineralogy and numerous accessory minerals. Typically, the greenstones are dark gray-green to buff-colored, fine-grained, massive to slightly phyllitic, and often contain some relict volcanic texture. Olmsted (1971) interpreted these rocks to be derived from recrystallization of lava flows. Intercalated thin, fissile greenschist zones were derived from both tuffs and from extensive shearing of bedrock. South of Folsom Reservoir, (Plates 4-4, 4-5), these rocks are equivalent to the Gopher Ridge and Copper Hill volcanics of Clark (1964). North of the reservoir, (Plates 4-1, 4-2, 4-3) the Gopher Ridge and Copper Hill equivalents consist of both greenschist facies and amphibolite facies rocks (described below).

Amphibolite-facies metavolcanics are found in bands parallel to the lower grade rocks and adjacent to the Mesozoic intrusive rocks of the area. Probably derived from slightly more mafic source rocks, they are commonly composed of a hornblende-plagioclase-epidote-chlorite mineral assemblage. Texture is generally fine-grained, relict features are much less common, and structure is variable from massive, locally hornfelsic beds, derived from flows, to thin, fissile schistose bands derived from intercalated tuffs (Olmsted 1971).

4.1.1.2 Metasediments. Metasedimentary rocks form a lesser part of the general metamorphic terrain. Thin phyllitic to schistose interbeds make up most of the medisediments within more extensive metavolcanic units. This group includes several bodies of metalimestone and marble located in the northeastern part of the area. The remaining metasedimentary rocks consist of fine-grained phyllite, schist and slate mixed with some massive metavolcanic interbeds. These rocks are a probable equivalent of the Salt Springs Slate of Clark (1964), exposed south of the reservoir and west of the main band of metavolcanic rocks (Plates 4-4, 4-5). Usual components include sericite, quartz, albite, chlorite, biotite and accessory minerals. The well developed black slates in the southwest part of the area are composed mainly of sericite; the more common dark green-gray phyllites are more quartzose and chloritic. Olmsted (1971) reports minor amounts of quartzite and various types of schist, mainly in igneous contact aureoles, as well as small lenses of metaconglomerate.

4.1.2 Granitic Intrusives

Most of the northern half of the project area consists of the quartz dioritic intrusives of the Rocklin and Penryn plutons (Plates 4-1, 4-2, 4-3). Dioritic outliers probably related to the Penryn pluton are also found at Oregon Bar on the North Fork of the American river, and in one outcrop area approximately 11 miles south-southwest of the Folsom Reservoir. Radiometric dates and structural relationships indicate that the more northerly Penryn pluton is slightly older than the Rocklin, and that both intruded approximately 130 million years ago, during late Jurassic and earliest Cretaceous time. The Penryn pluton is a medium to coarse-grained quartz diorite with a weakly developed dark mineral foliation parallel to plutonic margins. The rock is composed of plagioclase, quartz, hornblende, biotite and minor accessory minerals. Fine-grained dark inclusions and schlieren parallel to local foliation are also common. Composition of the Rocklin pluton is variable from hornblende quartz diorite to micaceous granodiorite and is lighter colored, finer grained, and contains less biotite and hornblende than the Penryn pluton. Foliation is also less well developed, and inclusions are less frequent.

Granitic rocks of both plutons are irregularly weathered, yielding hard, fresh masses of rock resembling large boulders in a matrix of residual soil retaining the original texture of the rock. This characteristic has resulted in the development of low, rolling terrain with occasional surface boulders on the plutons, and was the cause of difficulty during foundation excavation for the main dam at Folsom.

Detailed investigations focusing on the Rocklin and Penryn plutons (Olmsted, 1960 and 1971; Swanson, 1978) and associated rocks indicate that the intrusives caused deformation in the country rocks during emplacement, and this emplacement occurred at relatively shallow depth. Previously, the Rocklin pluton was thought to truncate the West Branch of the Bear Mountains fault zone, thus providing a minimum 130 million years before present (mybp) age for the most recent movement on the fault. More recent mapping, including this investigation, has revealed that the fault is not truncated by the intrusive, but continues northward just east of the pluton's margin. Little is known about the configuration of the pluton at depth. Gravimetric data indicate that it extends some distance westward under Tertiary and Quaternary valley fill (Oliver and Robins, 1974). Drillhole data from wells penetrating the sedimentary cover indicate the pluton may have a very steep western margin (Harwood and Helley, 1982). A similar inference can be made for the eastern margin, since the metamorphic rocks deflected by the pluton in this area tend to dip steeply, suggesting the nearby plutonic-metamorphic contact may dip steeply.

4.1.3 Gabbro and Ultramafic Intrusives

Mid-Mesozoic and older mafic and ultramafic rocks occur at several locations within the study area. Paleometric dating, structural interpretation, and petrographic work indicate that these intrusives pre-date the more silicic Rocklin/-Penryn plutons and the numerous felsic dikes probably associated with them. Rock types found within the area include peridotite, dunite, serpentinite, pyroxenite and gabbro (Olmsted, 1971). Most of these rocks are associated with two major structures, the Pine Hill intrusive complex and the Flagstaff Hill ultramafic intrusion, but there are a few isolated smaller outcrops, expecially along fault zones.

The Pine Hill intrusive complex is a layered mafic intrusion of late Jurassic age located east and southeast of Folsom Reservoir (see Plates 3-3, 4-3, 4-4 and 4-5). It is a north-northwest-trending 11 by 5 mile elliptical body of concentrically layered olivine gabbro, pyroxenite and associated serpentinite that intrudes the metavolcanic country rock of the Foothills Metamorphic Belt.

Internal layering within the complex generally parallels the margins and dips steeply to the east, indicating the structure has been tilted since the time of development of the originally horizontal layers (Springer, 1971). Large linear bodies of serpentinite and steeply dipping country rock are associated with the margins of the intrusion, and it has a contact thermal metamorphic aureole 4,000 to 6,000 meters wide. A semicontinuous band of serpentinite along the west side of the intrusion forms the Bass Lake lineament. Springer reported that this feature exhibits only thin, discontinuous zones of shearing and strong schistosity and little deformation of adjacent metamorphic rocks, in contrast with the frequent, irregular shear zones within the serpentinite along the east side of the complex. Gravimetric data indicate that the intrusive extends northward at depth, and that the steep eastward dip of the margins at the surface may become more shallow at depth. Springer concluded on the basis of previous work and his own petrographic studies that the main body of Pine Hill mafics and the marginal ultramafic stringers probably intruded during two separate episodes closely spaced in time, the serpentinite being emplaced first, since it shows evidence of metamorphic recrystallization by the intrusion of the main body.

The Flagstaff Hill ultramafic body is rougly centered on Flagstaff Hill, between the West Branch of the Bear Mountains fault zone and the Penryn pluton (Plates 3-3, 4-2 and 4-3). It consists of altered dunite, peridotite and pyroxenite within a larger mass of serpentine. The body shows contorted primary igneous layering and contains both relict primary igneous and secondary metamorphic minerals, and has been mined for chromite in the past (Wells, et al, 1940). The body is extensively faulted and sheared, though apparently not in connection with the Bear Mountains fault zone. Most of the faults occurring within the body are oriented at large angles to regional structure and cannot be traced into the surrounding country rock.

The Flagstaff ultramafics have not been radiometrically dated, but Springer (1971) reports that the body has not been contact metamorphosed by the Pine Hill intrusive, suggesting a later emplacement. The mode of emplacement and configuration at depth of the Flagstaff ultramafics have not been investigated in detail.

Other bodies of ultramafic and mafic rock within the area of study occur along the Pilot Hill lineament zone and along the West Branch of the Bear Mountains fault zone. The Pilot Hill body consists of sheared serpentinite, gabbro and metagabbro in an elongate body that defines a strong lineament zone (Plates 3-3, 4-3, 4-4 and 4-5). This feature was extensively investigated during seismicity studies for the proposed Auburn Dam. It approximately parallels the adjacent East Branch of the Bear Mountains fault zone, and has similar characteristics. For the purposes of this study, the Pilot Hill lineament zone was considered to be part of the East Branch of the Bear Mountains fault zone, along with the sheared and deformed eastern contact zone of the Pine Hill intrusion to the south.

Other substantial outcrops of ultramafic rocks occur along the West Branch of the Bear Mountains fault zone south of the reservoir. One isolated body of highly sheared sepentinite forms a high ridge along El Dorado Hills Boulevard north of U.S. Highway 50. A larger body of sheared serpentinite is exposed as an elongated streak up to 3,000 feet wide that partly defines the complex fault zone between U.S. Highway 50 and the Cosumnes River. The body contains a few small masses of gabbro probably related to the Pine Hill intrusion. These bodies are typical of Foothills fault zone serpentinites, and contain many irregular sheared and slickensided surfaces, strongly developed zones of discontinuous schistosity, and lenses of thermally and deuterically altered primary metamorphic minerals, including olivine, pyroxene, amphibole, talc and chlorite.

4.1.4 Tertiary and Quaternary Volcanics and Sediments

Post-Mesozoic rocks form a minor part of the geology within the study area. These units consist of a few high-standing bluffs of Mehrten Formation, small erosional remnants of the Valley Springs Formation and upper Cretaceous marine deposits, and an accumulation of late Tertiary and Quaternary fluvial sediments that overlap the metamorphic and igneous basement rocks along the eastern side of the Sacramento Valley.

<u>4.1.4.1 Volcanics</u>. The Mio-Pliocene Mehrten Formation occurs as a number of high-standing flat-topped hills located on top of the Rocklin/Penryn plutons. These hills are erosional remnants of andesitic Mehrten tuffs, breccias and flow deposits that unconformably covered the whole study area. A series of aligned hills and ridges extending discontinuously westward across the metamorphic and igneous terrain near

Auburn represents a topographic inversion of a deep pre-Mehrten river channel that was filled with volcanic debris, and has subsequently resisted erosion to form a table mountain. These deposits consist of andesitic sands, gravels, conglomerates and tuff breccias overlain by a resistant mudflow breccia. Locally, smaller hills are formed by remnant conglomerate deposits from which the mudflow caprock has been removed (Plates 4-2, 4-3). The Mehrten ridges and hills are distinctive in that they stand up to 500 feet higher than the surface of the plutonic and metamorphic rocks, and often exhibit an unusual surface pattern developed along numerous parallel fracture traces within the caprock. Though the origin of these traces is unclear, they are probably non-tectonic features (Shlemon, 1973). Cenozoic faulting has been identified by the U.S. Bureau of Relamation within the Mehrten Formation along the Maidu lineament, a lineament of the East Branch of the Bear Mountains fault zone.

4.1.4.2 Sediments. Sedimentary rocks found within the mapping area range in age from upper Cretaceous to Holocene, and are concentrated along the valley-metamorphic belt contact. The oldest deposits are a few small exposures of upper Cretaceous marine sediments found in the American River canyon southwest of Folsom, and along the west margin of the Rocklin pluton. The Eocene Ione Formation occurs as small erosional remnants on the pluton's surface, and in more extensive outcrops on the southwest edge of the study area. Rhyolitic sediments of the Valley Springs Formation also exist in small patches in this area. The most extensive deposits in the vicinity of Folsom are upper Tertiary and Pleistocene fluvial gravels, sands, silts and clays deposited by Tertiary channels of the American and Cosumnes Rivers (Plates 4-3, 4-5). Formation names applied to this assemblage by previous workers include the Laguna, Turlock Lake, Riverbank, and Modesto Formations, in order of decreasing age. These deposits cover the metamorphic and plutonic rocks along the west side of the area, and locally form several terrace levels that have been used to interpret the history of Pleistocene deposition, glaciation and uplift in the area (Shlemon, 1972). The main Tertiary terraces and gravel-filled channels of the old American River south of Folsom have been extensively dredged, forming large fields of dredge tailings that resist re-vegetation.

Holocene alluvium is presently collecting within the study area only along a few streams that crosscut the metamorphic grain, including the Cosumnes River, Deer Creek and the ancestral South Fork of the American River (Blue Ravine) below Folsom, and in Miner's and Secret Ravines and Doty Creek within the Rocklin/Penryn plutons. These deposits consist of thin beds of conglomerate, sands, silts, and clays derived from various sources, including granitic, metamorphic and volcanic rocks. Colluvium developing directly on plutonic and metamorphic rock locally attains a substantial thickness when it collects in topographic traps.

4.2 GEOLOGIC STRUCTURE

The Folsom area is one of the most structurally complex parts of the Foothills Metamorphic Belt. The well developed north-northwest striking grain of the belt is deflected to a north-south trend between the Rocklin/Penryn and Pine Hill intrusions. Both lithologic contacts and fault zones are deflected in this area. Schistosity, where apparent, is also frequently at an angle to the regional grain, though this divergence of trend is evident in many other parts of the province. Foliation, schistosity, bedding and contacts all tend to dip eastward at angles greater than 55 degrees. Metamorphic facies parallel structural grain in the northern and southern ends of the area, but often crosscut the grain near the intrusions, where contact metamorphism has recrystallized the rock.

4.2.1 Lineament Analysis and Selection of Study Features

Faults within the Sierran Foothills have previously been mapped on the basis of serpentine outcrops, zones of strong schistosity, pronounced deformation and cataclasis, and structural or stratigraphic discontinuity (Clark, 1964).

Since all of these elements are present within the project area, a systematic method was required to identify and investigate individual features and combinations of structural elements to determine if they are related to faulting. This was done by means of the comprehensive lineament analysis described in paragraph 2.7.2 and Appendix A.

Of the 500+ lineaments identified in the imagery analysis, over two-thirds were eliminated as too small and distant from the reservoir to have any significance if they were fault related. This group included mainly linears less than a few miles in length located in the far northern and southern parts of the project area. It did not include any groups of small lineaments that were judged by the field investigators to be part of a larger system, or any lineaments within 5 miles of any reservoir-impoundment structures.

Field checking, research and photoanalysis of the remaining lineaments was conducted, with special emphasis on the lineaments closest to the reservoir. Evidence used for fault identification included geomorphic evidence of recent fault activity, bedrock discontinuities, deformed or highly schistose zones, serpentine, fault gouge, springlines and abrupt soil or colluvium changes. Strip mapping was performed along several strong lineaments and detailed observations made at selected points along others. Lineaments eliminated from further consideration by this work were often found to be short straight reaches of streams developing parallel to the regional metamorphic grain. Numerous short, weak lineaments within the Rocklin/Penryn plutons were eliminated after fieldwork indicated that many were related to jointing within the pluton, and that others, while of unknown origin, were not related to major fault or lineament systems. Other lineaments were found to be caused by albedo contrasts arising from changes in bedrock lithology or moisture retention capacity of the soil.

4.2.2 Project Area Faults

Mapping of numerous fault zones and lesser shears is complicated by the gross similarities between these zones and schistose bands within massive units derived from metamorphism of tuffaceous or sedimentary interbeds. The major faults are characterized by zones of chlorite and talc-sericite mylonite schist up to several hundred feet wide, often including lenticular bodies of relatively unsheared greenschist, greenstone or massive amphibolite. The smaller, discontinuous shear zones, fairly common in the area, are difficult to distinguish from similar bodies of chloritic and micaceous schist or phyllite developed by recrystallization of granular interbeds. Generally, fault zones tend to be more extensive and continuous, and can sometimes be identified on the basis of other characteristics, such as occurrences of serpentinite bodies, zones of gouge or mylonitization, and shearing across foliation. The following paragraphs describe those linear features identified as being fault related within the study area.

4.2.2.1 West Branch Bear Mountains Fault Zone. The Bear Mountains fault zone is a system of north-northwest-trending faults, bedrock deformation zones and serpentinite bodies extending over 100 miles along the west flank of the Sierras. The fault is part of the Foothills fault system, which also includes the Melones fault. Both fault zones were initially identified and named by Clark (1960). Clark traced the Bear Mountains zone as a group of subparallel zones of schistosity and serpentinite bodies northward to the Cosumnes River, the northern limit of his investigations. Subsequent work in the project area (Behrman, 1978; Kiersch and Treasher, 1952; Springer, 1971) indicates that the Bear Mountains zone bifurcates near the Cosumnes (Plates 3-2 and 3-3). The eastern branch of the zone strikes nearly due north, passing on the east side of the Pine Hill intrusive complex. The West Branch of the zone had been previously mapped as striking approximately N. 35° W. and intersecting the Rocklin pluton under Folsom Reservoir. Recent work has shown, however, that the Western Branch of the zone does not intersect the pluton, but turns more northward, extending between the reservoir and the Pine Hill intrusion. The two branches coalesce in the vicinity of Auburn and diverge again to the north (see Plates 3-3, 4-1, 4-14). The West Branch of the Bear Mountains fault zone is easily the most prominant and continuous linear feature visible on project area imagery, and was a natural focus for more detailed investigation.

4.2.2.1.1 Remote Sensing Evaluation. Lineament analysis on high and low altitude aerial imagery as part of this investigation aided in the identification and location of the West Branch of the Bear Mountains fault zone. The western Sierran foothills are generally characterized by a strong regional lineation that results from alignment of drainages and cultural features approximately parallel to the pervasive metamorphic grain. The detailed analysis used in this study was necessary to separate natural and artificial features and to locate the linear elements associated with the West Branch of the Bear Mountains fault zone. The procedures used are discussed in detail in Appendix A; the following is a synopsis of the most diagnostic characteristics observed.

The ground surface within the study area near the Cosumnes River is composed of many approximately parallel northwest striking linear valleys and ridges. Differences in moisture content between moist valleys and drier ridges result in a north-south-trending striped pattern visible on U2 color infrared photos, and also visible as vegetation lineaments on low altitude imagery. The pattern is discontinuously traceable northward past Highway 50 to within a few miles of Folsom Reservoir. Within this strongly linear pattern, the west branch is identified by the overall continuity of linear elements that extend from the Consumnes River northward to the region between the North and South Forks of the American River (Plate 4-14). Just north of Highway 50, the zone, defined by a semi-continuous alignment of linear ridges and valleys bends to the north, away from its north-northwest trend south of the highway. To the north of this bend the fault zone is clearly defined by the aligned strongly linear New York and Hancock Creek drainages. Between Hancock Creek and Auburn, the zone is only weakly expressed as a collection of very roughly aligned ridges and weak saddles, most clearly apparent on color low altitude, low-sun-angle photography. The fault is not clearly defined by lineaments in the immediate vicinity of Auburn. North of Auburn the West Branch is associated with two nearly parallel zones of lineaments with many similarities. These lineament zones, termed the "Deadman" (western) and "Dewitt" (eastern) lineament zones in the USBR Auburn studies, are broadly arcuate lineament zones composed of many smaller linear elements, including aligned stream segments, vegetation lineaments, and aligned topographic features. The Deadman and Dewitt zones give way to a series of more northerly trending narrowly defined lineaments east of Camp Far West Reservior.

4.2.2.1.2 Physiography and Geologic Conditions. Two separate branches within the Bear Mountains fault zone become clearly defined at the latitude of the Consumnes River.

Between Auburn and the Consumnes, the West Branch has many of the features of the nonsplit zone to the south. The zone is characterized by numerous aligned narrow valleys and aligned saddles in areas of rougher topography (Plate 4-14).

Geologically, the West Branch consists of a variable suite of sheared serpentinite bodies, talc schist bands, and highly deformed bedrock with local gouge zones. Between the Consumnes River and Highway 50, the zone occurs as small isolated bodies of serpentine and more or less continuous narrow bands of talc-sericite mylonite schist. Locally, the foliation in these schists diverges from the N. 35^{o}-40^{o} W. strike of the zone. Between Highway 50 and Green Valley Road, the zone is defined by relatively broad (500 to 3,000 foot-wide) shallow valleys with thin colluvial soil cover over highly weathered bedrock. A large body of serpentine bounded by two such valleys forms the high ridge between the Oak Ridge High School site and Highway 50 (Plates 4-3, 4-4). The margins of this body are largely covered by colluvium and recent alluvium, but a road cut across the northern tip of the body reveals it to be intensely sheared internally.

North of the serpentinite body the fault zone is relatively poorly exposed. It is located in a broad, relatively flat-bottomed alluviated valley of New York Creek that has been extensively developed as part of the community of El Dorado Hills. The valley narrows northward and drains into Folsom

Reservoir. Infrequent exposures along New York Ravine show that the fault zone is characterized by intensely sheared and strongly foliated massive metavolcanic rocks, with local zones of fissile greenschist.

Wagner, et al (1981) placed the West Branch of the Bear Mountains fault zone on the east flank of Iron Mountain, rather than in the flooded northern reach of New York Creek. Mapping for this study indicates that the zone of deformation, including strong foliation, schistosity and slatey cleavage, extends on both sides of New York Creek, and that there is no compelling reason to restrict the mapped shear zone to the flank of Iron Mountain (Plate 4-3). A small body of highly sheared serpentinite on the north end of Iron Mountain is probably associated with this zone.

Between the North and South Forks of the American River, the fault zone is characterized by a zone of strong schistosity and local shearing in otherwise generally massive amphibolites. Along southward draining Hancock Creek, the zone is approximately parallel with the contact between the serpentinite/ultramafic complex at Flagstaff Hill (Plate 4-3).

Lack of occurrences of undeformed amphibolites between the mapped serpentinite contact and the Hancock Creek valley suggests that the fault zone is probably coincident with the contact. Olmsted (1961, 1971) mapped the shear zone on the east flank of the creek valley, probably on the basis of the strong foliation and local quartz filled joints and shears exposed on the hillside. Outcrops within the stream channel are quite variable in aspect, ranging from massive to highly sheared and strongly schistose over a few tens of feet. One outcrop in the stream channel approximately 2,500 feet south of the Rattlesnake Bar-Russell Hollow Road intersection exposed a fine-grained dark dike that crosscuts the strong north-northwest country rock foliation (Plate 4-8). This dike has been thermally metamorphosed to the amphibolite grade of the host rock, probably during the intrusion of the Pine Hill or Rocklin plutons, both occurring well over 100 million years ago. The dike shows no evidence of fracturing or shearing associated with more recent movement.

The West Branch fault zone is intersected by a splay fault located in Russell Hollow (Plates 4-2, 4-3). This fault strikes N. 40° E., across the regional grain and connectes the west branch fault zone with the shear zone mapped by Olmsted (1961), termed the "Pilot Hill" lineament zone in the USBR Auburn studies. The Russell Hollow fault is located entirely within amphibolite bedrock, and is mapped mainly on the basis of its strong topographic expression and the presence of a sheared quartz vein along the inferred trace near its intersection with the Pilot Hill lineament zone. The fault was shown by Olmsted to offset a contact between amphibolite subunits. This seems speculative, however, in view of the gradational nature of these contacts and their generally poor exposure. The topographic low associated with the Russell Hollow fault is truncated at its west end by the West Branch of the Bear Mountains zone, and on the east by the Pilot Hill zone.

North of the head of Hancock Creek, the west branch fault zone becomes less well defined topographically. Between Hancock Creek and the North Fork of the American River, the zone is defined by only the crudest alignment of weakly developed saddles. It is exposed in the North Fork river canyon as a wide zone of strong shearing and schistosity with local gouge zones up to a few tens of feet in width. These gouge zones appear to show effects of thermal metamorphism associated with the intrusion of the adjacent Rocklin pluton. North of the river canyon, the fault zone loses nearly all topographic expression, and is defined only by infrequent outcrops of greenschist and schistose amphibolite occurring in a wide band. Several thin bodies of gabbro elongated parallel to the general north-south stike of the fault zone are also located in the general vicinity. In the vicinity of Auburn, the fault zone is completely obscured by overlying volcanic and sedimentary rocks of the Mehrten Formation, and the detritus derived from the high-standing Mehtren ridges.

Geologic structure in the vicinity of Auburn is quite complex (Plates 4-1, 4-2). In this area, the East and West Branches of the Bear Mountains fault zone and the Pilot Hill lineament zone coalesce, and bedrock structure is characterized by numerous bands of strong schistosity and shearing, elongated bodies of sheared serpentinite, fault gouge and an obscuring cover of Tertiary Mehrten deposits (Taylor, 1979); North of Auburn, the Bear Mountains zones are defined by the Deadman and Dewitt lineament zones of the USBR (1977a). Direct correlation of one or both of these lineaments with the West Branch fault south of Auburn is speculative. Detailed exploration at several places along the Dewitt lineament zone during the Auburn Dam studies did not conclusively establish whether the zone represents an active or inactive fault (USBR criteria).

4.2.2.2 Mormon Island Fault. The area immediately west of the West Branch of the Bear Mountains fault zone between the Cosumnes River and Folsom Reservoir contains many moderately well developed linear valleys with parallel strike. The approximate alignment of several of these valleys along a line trending toward the Mormon Island Dam focused attention on the possibility of a through-going fault in this area (Plate 4-14).

4.2.2.2.1 Remote Sensing Evaluation. The Mormon Island fault zone is expressed at the ground surface by a zone of strongly expressed discontinuous lineaments extending from south of the Cosumnes River to one mile south of the Mormon Island

Dam. The lineament zone is best expressed along the west side of Ben Bolt Ridge from the Cosumnes River northward to a few miles south of Highway 50, and one mile north of the highway up to the area below Mormon Island Dam. These valleys show up as aligned lineaments on small scale imagery, especially U-2 color infrared (Plate 4-14). Larger scale imagery reveals numerous smaller vegetation and outcrop lineaments within the valleys, as well as albedo contrasts from changes in bedrock or soil types. In particular, a very strong, sharp vegetation lineament exists along the east side of the valley with axis centered on the El Dorado-Sacramento County line just south of Mormon Island Dam. This lineation dies out before reaching the dam, and the larger valley lineament loses definition also. None of these lineaments can be traced through Mormon Island Dam or north of it. Disturbance of surface deposits adjacent to the dam during construction or gold dredging has obscured the traces of any lineaments that might have existed there.

4.2.2.2.2 Physiography and Geologic Conditions. The Mormon Island lineament zone lies within low grade metavolcanics included with the Copper Hill Volcanics by Clark (1964). These rocks consist of andesitic to basaltic tuffs, lapilli tuffs and breccia now altered to greenstone. Field observations along the lineament zone south of Highway 50 show that it follows a zone of closely foliated greenstone that lies between more massive rock east and west of the lineament

(Plates 4-4, 4-5, 4-11). Near the Consumnes River, the lineament zone is underlain by strongly deformed and foliated greenstone, slate and schist. The central part of the lineament exposed in the Cosumnes River canyon is a 50 to 150-foot-wide zone of sheared and crushed greenstone. North of the Southern Pacific Railroad crossing at Deer Creek the lineament loses definition, but the same pattern of strongly foliated zones separating more massive zones can be observed in outcrop. The zone is not exposed in roadcuts along the highway.

North of Highway 50, the lineament zone is well expressed in a linear valley that contains strongly deformed greenstone and local outcrops of gouge. This valley widens to the north such that the lineament disappears in the area where the ancient South Fork of the American River channel begins to bend westward. Poor exposures prevent precise estimation of the width of the fault zone, but it probably ranges in width from 500 to 1,000 feet.

4.2.2.3 Other Local Faults and Major Lineaments

4.2.2.3.1 The Linda Creek Lineament. The Linda Creek lineament: First mapped as the Linda Creek fault zone by Aune (1971; 1973), the Linda Creek lineament is a northwest-trending zone of aligned low hills, gullies and topographic depressions located along the west side of the study area

(Plate 4-14). The feature is clearly visible on high altitude imagery, including Skylab and U-2 color infrared. Aune mapped the feature as a potentially active fault zone based on geomorphology, inferring the alignment of topographic features to be the result of relatively recent faulting, though no distinct offsets, juxtaposed lithologies or other direct evidence of faulting was observed.

Attention was focused on the Linda Creek "fault zone" at several times during the 1970's, in the form of geophysical investigation (Gasch and Associates, 1973) and reconnaissance by CDMG personnel. The magnetic, gravity and seismic refraction surveys carried out by Gasch and Associates suggested "there is not a discontinuity in rock density, magnetic properties and/or seismic velocity across the Linda Creek lineament zone at the locations investigated" (Gasch and Associates, 1973, in USBR, 1977a). Several CDMG senior personnel who visited the site also expressed the opinion that the feature was not a fault. (USBR, 1977a). The most exhaustive treatment of the feature was made as part of the Auburn Dam earthquake evaluation studies for the U.S. Bureau of Reclamation. In this study, geologic mapping, airphoto interpretation and exploratory trenching were used in attempt to characterize the feature (USBR, 1977a). Two trenches were excavated along an eastern trace identified by Aune, and one along a western trace. No evidence of faulting was observed in the trenches, and it was concluded on the basis of stratigraphic and paleomagnetic evidence uncovered in the excavation that "a fault associated with the Linda Creek lineament zone does not exist in Pleistocene and younger units, as mapped".

Based on the above, it is concluded that if the Linda Creek lineament is fault related, it is not a capable fault under Corps criteria. For this reason, further investigations of the lineament were not conducted.

4.2.2.3.2 The Scott Road Lineament. The Scott Road lineament lies at the westward base of a ridge that trends northwest from Deer Creek south of Highway 50 to the American River on the north (Plate 4-14). The Southern Pacific Railroad line is coincident with the lineament along much of its length, as is Scott Road north of Highway 50. The lineament becomes more subdued in the proximity of Folsom, where is is overlapped by old American River gravels. The lineament is most strongly expressed between Carson and Willow Creeks a few miles southeast of Folsom. The lineament marks a break in slope, separating a 100 to 400-foot-high ridge east of the lineament from the lower hills to the west. The feature is most visible on high altitude U-2 color infrared photographs where there is a large total contrast between the light colored ridge to the east and the darker lowlands to the west. The strength of this lineament is exaggerated by the presence of the railroad and roadway at the base of the ridge.

Geologic reconnaissance along the Scott Road lineament indicates that this feature has developed through differential erosion along a contact between ridge-forming metavolcanic rock to the east and interlayered slate and metavolcanic rock in the western lowlands. Rock exposed in railroad cuts along the break in slope consists mainly of recrystallized breccia of graywacke fragments in a slatey matrix. The brecciation is interpreted to be pre-metamorphic or contemporaneous with metamorphism, as the rock is a hard, coherent material. Post metamorphic deformation would be expected to yield soft, weak breccia. Such recrystallization may have occurred during regional metamorphism, since expected changes in metamorphic facies with distance from the Rocklin/Penryn or Pilot Hill plutons were not observed.

Near Folsom, the Scott Road lineament is not visible. However, its projection extends northward under late Pliocene Laguna Formation river gravels deposited in the now abandoned South Fork Channel of the American River (Blue Ravine). The projection of the lineament is approximately coincident with a 1 to 2 degree, down-to-the-west break in slope on the eroded upper surface of these gravels. A less distinct slope break on the eroded upper surface of the Mehrten Formation immediately north of the American River may be inferred from topographic profiles. The lineament is not visible on aerial imagery north of the old South Fork Channel, but the projection of the lineament coincides with the mapped intrusive contact between the Rocklin and Penryn plutons (Plate 4-3). This intrusive contact is poorly exposed, but contains small slivers of metamorphic country rock similar to other inclusions within the plutons (Swanson, 1978). This contact also has no distinct expression on aerial imagery. Photoanalysis and geologic reconnaissance reveal no aligned topographic depressions, scarps, vegetation lineaments or other geomorphic or geologic evidence of recent faulting. This suggests the slope breaks are related to erosion or paleotopography. Based on the lack of evidence of fault activity and the unfaulted nature of the main, strongly expressed segment of the lineament to the south, the Scott Road lineament is interpreted to be an unfaulted geologic contact.

4.2.2.3.3 The Bass Lake Fault. The Bass Lake fault is located within a group of aligned north-northwest-trending broad linear valleys extending approximately 18 miles along the west flank of the Pine Hill intrusion, from the South Fork of the American River to the Cosumnes River area (Plate 4-14). Lineaments associated with the zone are not visible north of the South Fork, and become indistinguishable in the south where the lineament zones associated with the East and West Branches of the Bear Mountains fault zone coalesce. Along most of its length it is characterized by wide, irregular valleys with slightly higher slopes on the east side. The name is derived from Bass Lake, located in one of the larger valleys making up the zone. The zone is less distinctive on aerial imagery than other large lineament zones, primarily because of heavier tree cover along much of its length.

The geology of different parts of the Bass Lake lineament zone has been previously mapped by Olmsted (1971), Springer (1971) and Behrman (1978). Along most of its length the zone is underlain by serpentinite, strongly foliated amphibolite and mixed metasedimentary rocks including metachert and marble. East of the lineament zone these rocks are in contact with gabbro and ultramafic rock of the Pine Hill intrusion, and thin bodies of amphibolite country rock. West of the lineament the rocks are in contact with massive amphibolite. Rocks within the lineament zone are generally more strongly foliated than surrounding rocks. The serpentinite usually contains localized shears, but Springer (1971) reported that the pervasive shearing and well developed slickensides and gouge zones commonly found in sepentinite bodies along fault zones elsewhere in the Foothills is lacking. Some shears and gouge zones are present along the western margins of the more northerly sepentinite bodies. These shears and gouge zones appear to be concentrated at the contact and within the serpentinite, rather than extending into the adjacent amphibolite.

Based on mapping and petrographic work performed on the rocks of the Bass Lake lineament zone, Springer (1971) concluded that serpentinite along the zone had intruded along bedding planes within the metavolcanic rock, and that if the serpentine was emplaced along a fault zone, subsequent thermal metamorphism owing to the intrusion of the Pine Hill complex destroyed any evidence of such a mode of emplacement. He noted that internal shearing may develop in serpentine bodies during emplacement along bedding planes in stratified rock, and that such shearing is not evidence for major fault offset along the zone. Springer also noted major differences between the rocks underlying the Bass Lake lineament and those found on the east side of the Pine Hill complex. East side rocks show evidence of extensive post-metamorphic shearing and displacement, probably associated with the East Branch of the Bear Mountains fault zone.

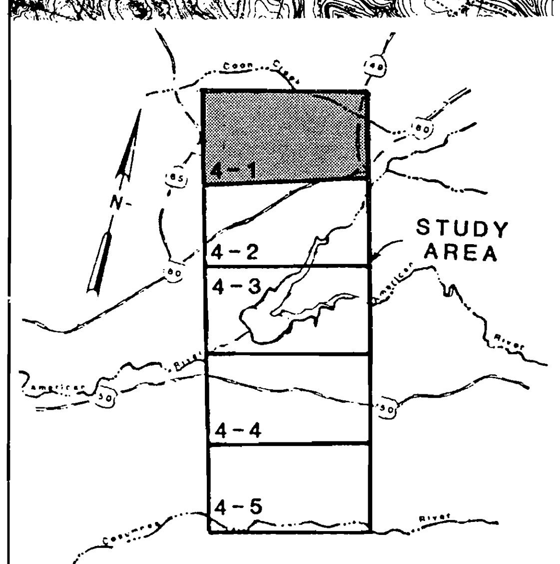
Field work performed in this study supports the work of Springer. The relatively minor shears observed are consistent with shearing found within the unfaulted rocks elsewhere in the region. Based on the undeformed rocks in and adjacent to the lineament zone, the lack of continuous and pervasive shearing within the serpentinite, and the absence of geomorphic indicators of recent faulting, it is concluded that the Bass Lake lineament zone is not a capable fault.

4.2.2.3.4 Willows Fault. The Willows Fault was discovered during gas well development in the 1950's in the northern Sacramento Valley. Later it was extended southeast to the vicinity of the Sutter Buttes by Redwine (1972, *in* Harwood and Helley, 1982). Recent mapping (Harwood & Helley) suggests the Willows fault might be projected southward in the subsurface along the east side of the Valley (Plate 3-2). This projection, based on borings and seismic data, locates the postulated fault in an area of steeply inclined upper Cretaceous sediment surface. The fault has no surface expression south of Sutter Buttes, and does not apparently displace late Tertiary or Quaternary stratigraphic units. The existence of the fault south of Sutter Buttes is unproven, and the location of the projected trace passing within 15 miles of Folsom Reservoir is highly speculative. In the absence of strong evidence for the existence of this fault near the Folsom project area, it is judged to present no significant seismic hazard to the project.

SYMBOLS

- Contact, dashed where approximate, dotted where inferred, queried where uncertain
- Gradational contact, queried where uncertain
- Contact from Lindgren (1894) or Lindgren and Turner (1894). Location approximate
- Contact from interpretation of air photos
- Fault, dashed where approximate, queried where uncertain
- Fault zone
- Trench sites or detailed study areas
- Strip map location (A)
- J—J' Magnetometer profile
- 71 Strike and dip of foliation in bedrock
- Strike of vertical foliation
- 48 Strike and dip of joint or fracture in bedrock
- Strike of vertical joint or fracture in bedrock
- ◄18 Location and direction of field photograph

See Plates 4-6a through 4-6d for Geologic Unit Descriptions



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PROJECT GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION

FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

Sacramento District

DATE	SCALE	PLATE NO.
1-12-83	1:62,500	4-1

SYMBOLS

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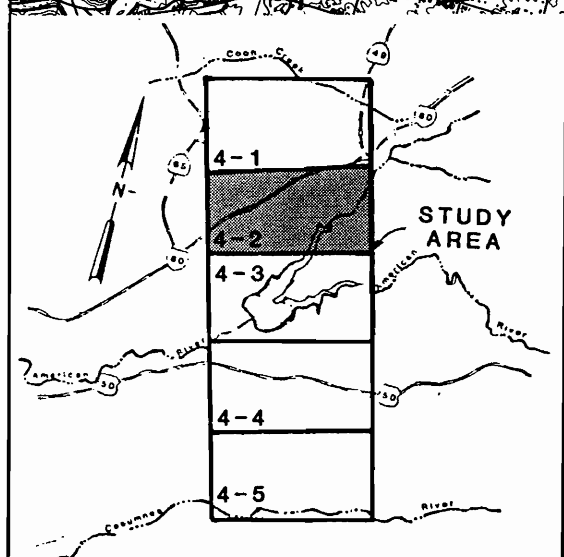

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PROJECT GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION

FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

Sacramento District

DATE	SCALE	PLATE NO.
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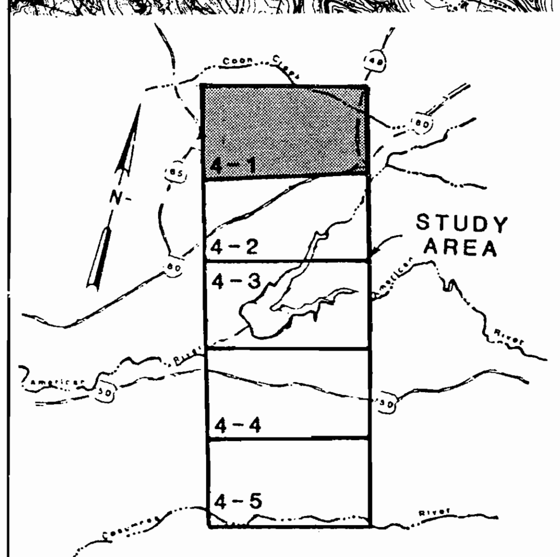

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PROJECT GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION

FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

Sacramento District

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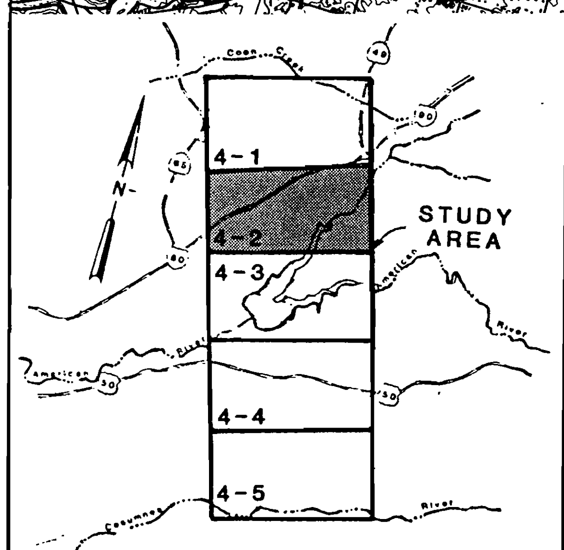

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See Plates 4-6a through 4-6d for Geologic Unit Descriptions

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PROJECT GEOLOGY

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FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

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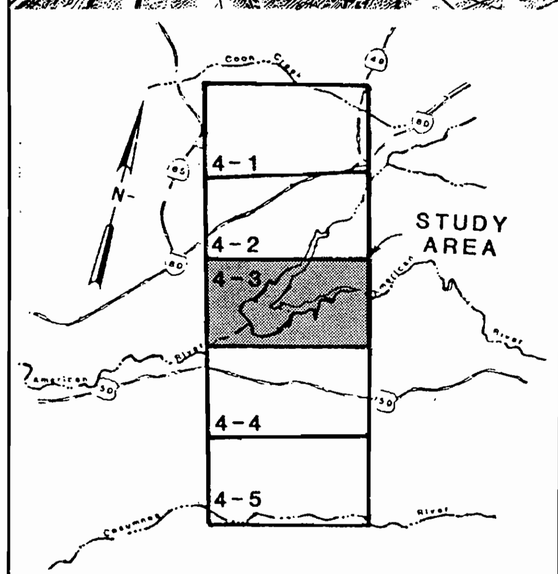

See Plates 4-6a through 4-6d for Geologic Unit Descriptions

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PROJECT GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION

FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

Sacramento District

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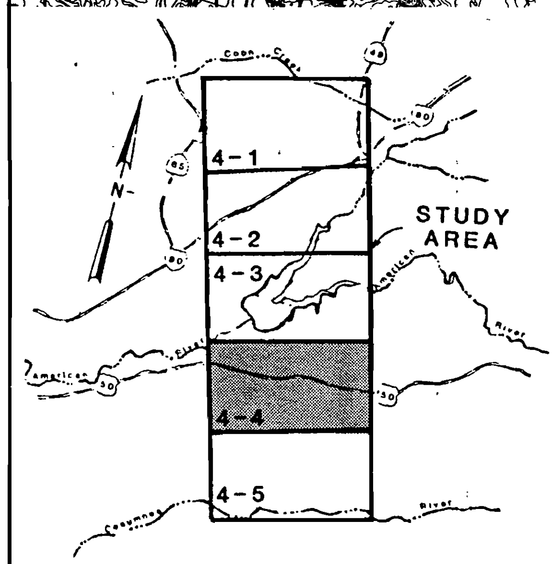

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505/982-2846

PROJECT GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION

FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

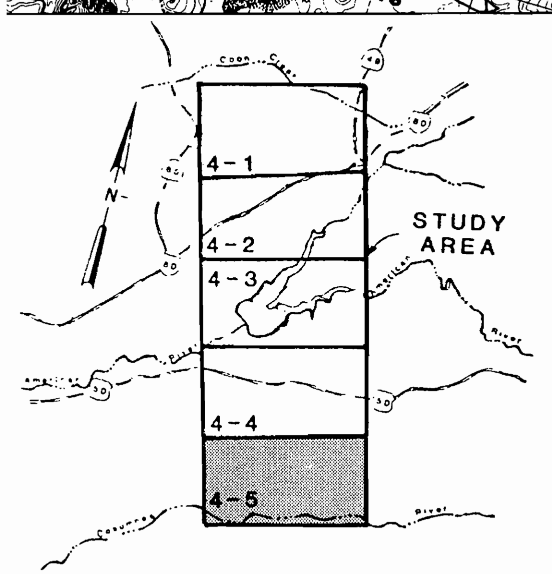
Sacramento District

DATE	SCALE	PLATE NO.
1-12-83	1:62,500	4-4

SYMBOLS

- Contact, dashed where approximate, dotted where inferred, queried where uncertain
- Gradational contact, queried where uncertain
- Contact from Lindgren (1894) or Lindgren and Turner (1894). Location approximate
- Contact from interpretation of air photos
- Fault, dashed where approximate, queried where uncertain
- Fault zone
- Trench sites or detailed study areas
- (A) Strip map location
- J–J' Magnetometer profile
- 71 Strike and dip of foliation in bedrock
- Strike of vertical foliation
- 48 Strike and dip of joint or fracture in bedrock
- Strike of vertical joint or fracture in bedrock
- 18 Location and direction of field photograph

See Plates 4-6a through 4-6d for Geologic Unit Descriptions



N

0 1 2 Miles

Contour Interval 20 feet

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PROJECT GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
1-12-83	1:62,500	4-5

GEOLOGIC UNITS - DESCRIPTION
(Cenozoic units after Wagner, et al,1981)

af - Artificial fill

t - Dredge tailings

Qha - Holocene alluvium

Qu - Undifferentiated alluvial deposits

Qm - Modesto Formation

Qr - Riverbank Formation

Qtl - Turlock Lake Formation

Tl - Laguna Formation

Tm - Mehrten Formation

Tvs - Valley Springs Formation

Ti - Ione Formation

Ku - Undifferentiated Upper Cretaceous sediments

Kr - Quartz diorite. Contains biotite, muscovite, and hornblende.

KJp/KJpl/KJpm/KJpd - Quartz diorite. Contains hornblende and biotite.

- KJp - undifferentiated quartz diorite of Penryn Pluton.
- KJpl - light phase
- Kjpm - medium phase
- Kjpd - dark phase

Kjqd - Quartz diorite. Present mainly in the Lincoln, Gold Hill, and Auburn quadrangles. Probably equivalent to the quartz diorite of the Penryn pluton mapped by Olmsted (1971) in the Rocklin and Pilot Hill quadrangles.

gb - Gabbro and Metagabbro. Includes the layered gabbro of the Pine Hill intrusive complex, the metagabbro of Pilot Hill as well as smaller bodies of mafic intrusive rock including sills and dikes of diabase and metadiabase.

pg - Pyroxenite and gabbro. Banded having layers too thin or too poorly exposed to map separately. Identified within the Pine Hill intrusive complex by Olmsted (1971)

py - Pyroxenite and Metapyroxenite

sp - Serpentinite and peridotite

gmx - Mixed gabbro. Mixture of fine-to coarse-grained gabbro within the Pine Hill intrusive complex. Identified by Springer (1971).

Jes - Jurassic epiclastic rocks. Slate, siltstone, graywacke, and minor conglomerate. Probably equivalent to the Salt Spring Slate of Clark (1964)

Jv - Jurassic metavolcanic rocks. Greenstone. Derived from mafic to intermediate tuff, breccia, and minor flow rock. Foliation generally weak to absent. The unit between the West Branch of the Bear Mountains fault zone and Jves is equivalent to the Copper Hill Volcanics of Clark (1964) The unit west of Jes and Jves is probably equivalent to the Gopher Ridge Volcanics of Clark (1964). Metamorphosed to hornblende hornfels near margin of Rocklin and Penryn Plutons.

Jves - Jurassic metavolcanic and epiclastic rocks, undifferentiated. Intercalated greenstone and epiclastic rock. Probably equivalent to the Salt Spring Slate of Clark (1964)

Jmv - Jurassic metavolcanic rocks. Lithologically similar to Jv. Occur within the melange belt immediately east of the Bear Mountains fault zone

Mv - Undifferentiated metavolcanic rocks west of Bear Mountains fault zone. Greenstone and greenschist northwest of the granitic rocks of the Rocklin and Penryn plutons. Lithologically similar to the metavolcanic rocks of Jv and possibly, in part, statigraphically equivalent to them. Metamorphosed to hornblende hornfels near margin of Rocklin and Penryn Plutons.

am - Amphibolite. Mafic to intermediate pyroclastic rocks, flows and dikes; minor intercalated silicic tuff and epiclastic rocks. Locally includes gabbro and serpentinite not differentiated on the map. Metamorphosed chiefly in amphibolite facies.

gs - Greenschist and phyllitic greenstone. Lithologically similar to rocks of unit "am" but metamorphosed to a lower grade. Gradational contact with the amphibolite of unit "am".

msc - Siliceous and calcareous metasedimentary rocks. Metachert, crystalline limestone, and associated epiclastic rocks. occurs within the amphibolite unit only.

BMFz - Metamorphic rocks of the Bear Mountains fault zone. Primarily greenschist and sericite schist with some intercalated slate and associated epiclastic rocks. Foliation in these fault zone rocks is often tightly crenulated.

SYMBOLS

Symbol	Description
——— – – –?–?·······	Contact, dashed where approximate, queried where buried or projected.
—··—··—··?—··?—··—	Gradational contact, queried where uncertain.
—····—····—····—····—	Contact from Lindgren (1894) or Lindgren and Turner (1894). Location should be considered as very approximate.
+ + + + + + + + + +	Contact from interpretation of aerial photography.
——— — —?— —?—	Fault, dashed where approximate, queried where uncertain.
74	Dip and strike of foliation in metamorphic rock or of foliation or layering in intrusive rock.
✦	Strike of vertical foliation in metamorphic rock or of foliation or layering in intrusive rock
~~	Zone of sheared or relatively more closely foliated rock.
37	Dip and strike of bedding.

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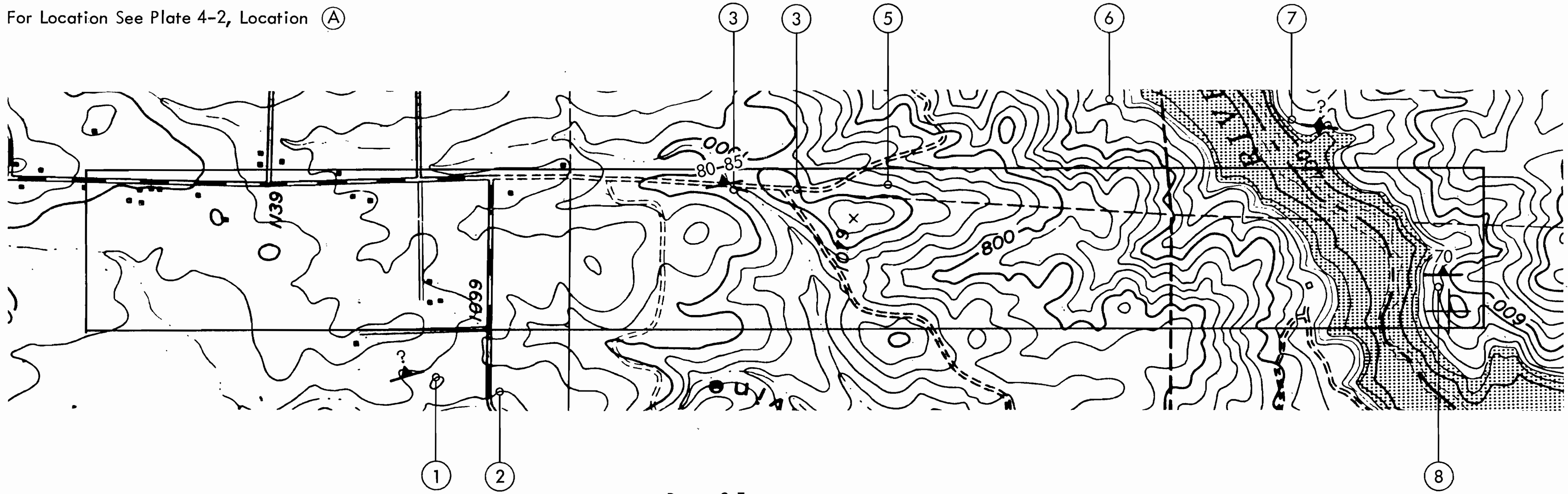
MAP SYMBOLS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 4-6d

For Location See Plate 4-2, Location (A)



Range 8 East
Township 11 North, Sections 3, 4
Township 12 North, Sections 27, 28, 33, 34
Pilot Hill Quad

N

SCALE IN FEET

0 1000 2000

(1) Chlorite schist, foliated.

(2) Chloritic semi-schist, foliated, weathered, phyllitic.

(3) Medium gray amphibolite schist with micaceous partings. Small, discontinuous veins contain slightly coarser grains (up to 1 mm) of epidote and hornblende.

(4) Actinolite schist, highly weathered, 10-20% actinolite in clayey matrix.

(5) Amphibolite float, phyllitic, gray, slightly weathered.

(6) Fault gouge in sheared highly weathered amphibolite.

(7) Shear zone within amphibolites. Consists of streaky, granulated fault gouge, locally pervasively slickensided.

(8) Contact between quartz-diorite pluton and amphibolite. Rock is thinly foliated, semi-schistose, fine grained. Amphibolite is streaky, contains lightly colored irregular foliations, probably containing plagiodase. Amphibolite is less resistant to weathering.

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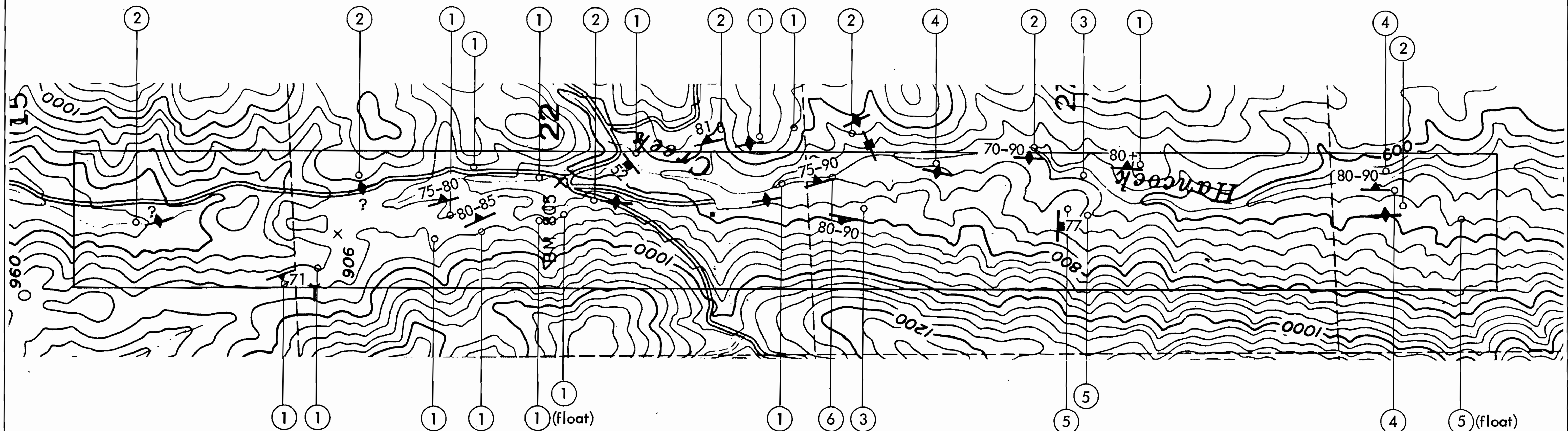
OUTCROP GEOLOGIC MAP: AUBURN-NORTH FORK AMERICAN RIVER AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-7

For Location See Plate 4-2 and 4-3, Location (B)



Range 8 East
Township 11 North, Sections 15, 22, 27, 34
Pilot Hill Quad

N

SCALE IN FEET

0 1000 2000

(1) Amphibolite, medium gray-green, fine grained, massive, variably spaced closed irregular fractures, medium weathered, locally strongly foliated but with poorly developed to absent schistocity and cleavage.

(2) Amphibolite, medium gray-green to buff, fine grained, phyllitic to schistose, variably spaced closed irregular fractures, medium to highly weathered, locally strongly sheared in direction sub-parallel to schistocity.

(3) Amphibolite, dark gray, fine grained, partially recrystallized cataclastic texture, locally phyllitic, locally strongly foliated, medium to highly weathered.

(4) Amphibolite, dark gray, fine grained, porphyritic, locally phyllitic to schistose, well foliated, medium weathered, subhedral amphibole porphyroblasts up to 1mm.

(5) Serpentinite and chlorite schist, green-gray to buff, closely sheared, highly weathered, contains dark microcrystalline quartz veins and local inclusions of massive to strongly foliated dark gray amphibolite.

(6) Dike, dark gray, fine grained, recrystallized, 6" - 1' wide, crosscuts foliation and schistocity in fine grained dark gray amphibolite country rock. Strike is variable between N0°E and N15°E over 50' exposure.

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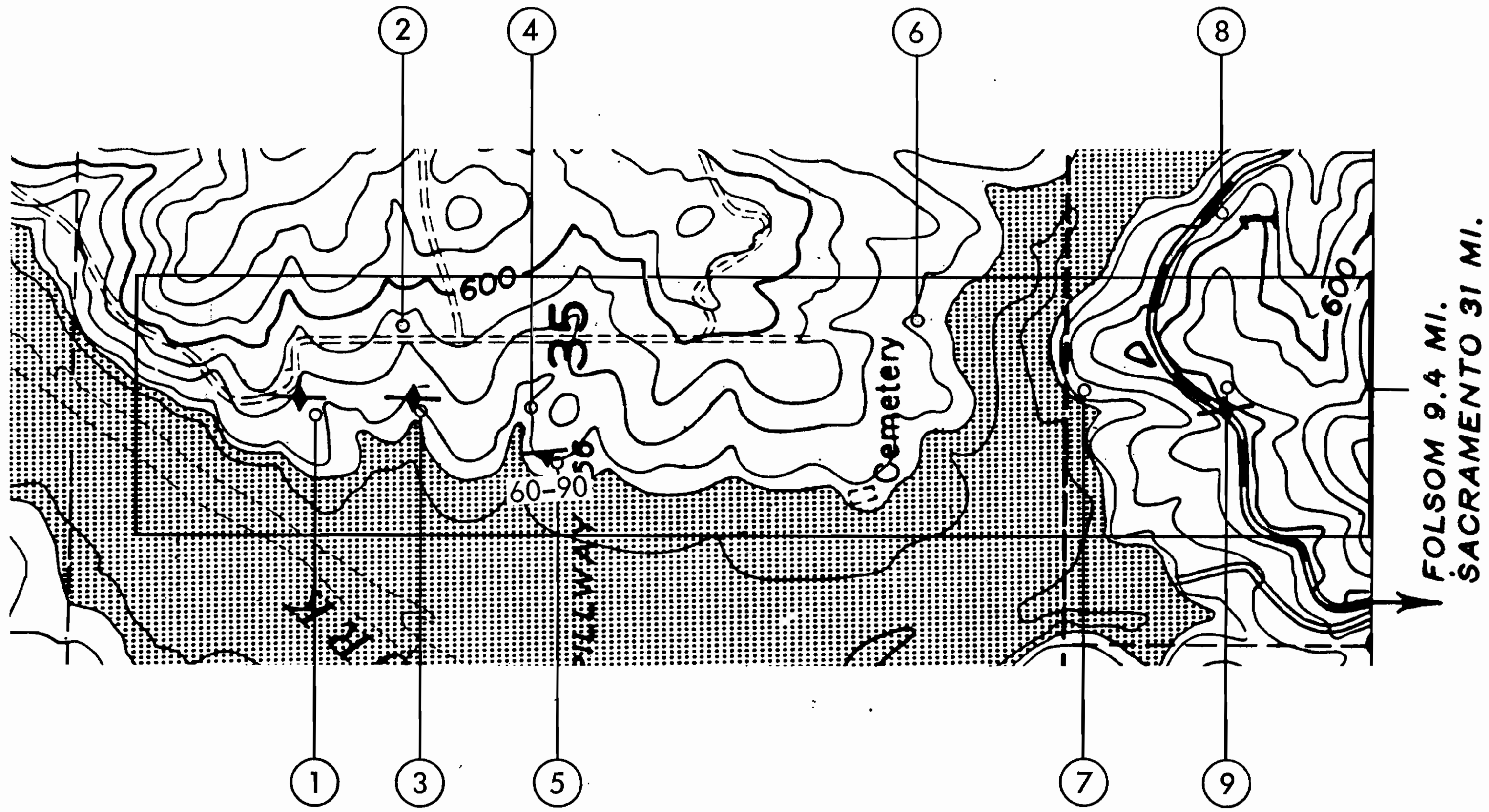
OUTCROP GEOLOGIC MAP: HANCOCK CREEK AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-8

For Location See Plate 4-3, Location Ⓒ



Range 8 East
Township 11 North, Section 35
Township 10 North, Section 1
Pilot Hill Quad

N

SCALE IN FEET

0 1000 2000

(1) Amphibolite, fissile, medium to highly weathered.

(2) Felsic dike, medium to highly weathered, slightly foliated, local dark bands sub-parallel to foliations up to 3 mm wide, widely fractured.

(3) Amphibolite, fissile, medium weathered, slight phillitic sheen.

(4) Amphibolite float, weakly slaty, developed slaty texture.

(5) Amphibolite, light gray-green, highly weathered, fissile, foliated.

(6) Serpentinite, mafic breccia dark green, gray, black, low hardness, numerous small chrysotile at various orientations.

(7) Gabbro/amphibolite contact. Float contains felsic dike material. Amphibolite shows no evidence of shearing or schistocity.

(8) Serpentinite and peridotite, medium grained, black, with small green olivine crystals, layering roughly N-S, parallel to body, very hard, bluish coatings on widely spaced closed smooth joints.

(9) Amphibolite, contains epidote, highly sheared and fractured, main axis of shearing trends N± 10W with nearly vertical dips.

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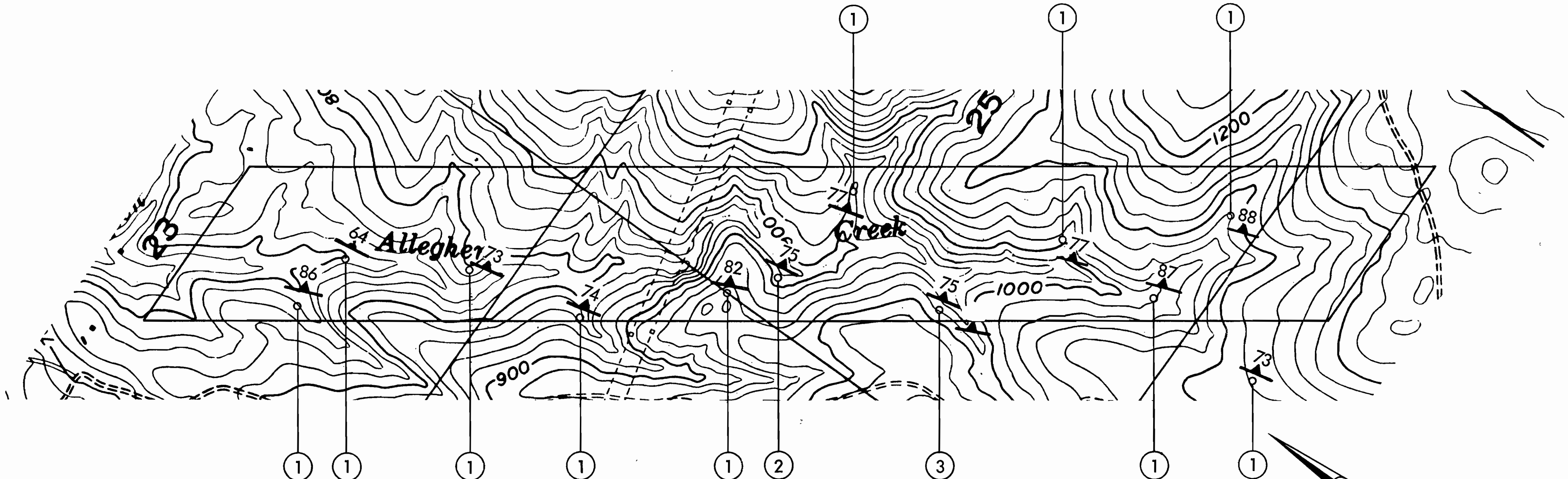
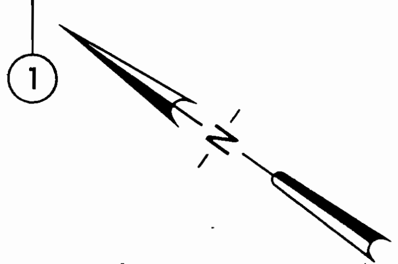
OUTCROP GEOLOGIC MAP: SOUTH FORK AMERICAN RIVER AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-9

For Location See Plate 4-3 and 4-4, Location (D)





Range 8 East
Township 10 North, Sections 23, 24, 25, 26, 36
Clarksville Quad

SCALE IN FEET
0 1000 2000

(1) Amphibolite, weakly foliated.

(2) Amphibolite, fine to very fine grained, foliated.

(3) Amphibolite, with 1-ft. wide zone of brecciated amphibolite striking N10°E, dipping 78°E.

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OUTCROP GEOLOGIC MAP: ALLEGHENY CREEK AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-10

(1) Slate and greenstone, dark gray, highly weathered, unsheared.

(2) Slate, argillite, greenstone and closely sheared mixed slate and greenstone.

(3) Metavolcanics, greenstone, sheared.

(4) Metavolcanics, greenstone, cataclastic, medium to highly weathered, moderately developed fracture cleavage. Fragments flattened in plane of foliation.

(5) Metavolcanics, greenstone tuffs and black meta-argillites, well foliated. Tuffs contain euhedral actinolite.

(6) Fault gouge, consists of fine grained comminuted greenstone surrounding unbroken fragments of greenstone up to several feet in long dimension. Preferred alignment of these fragments determines foliation.

(7) Metavolcanics, greenstone (tuff), weakly foliated.

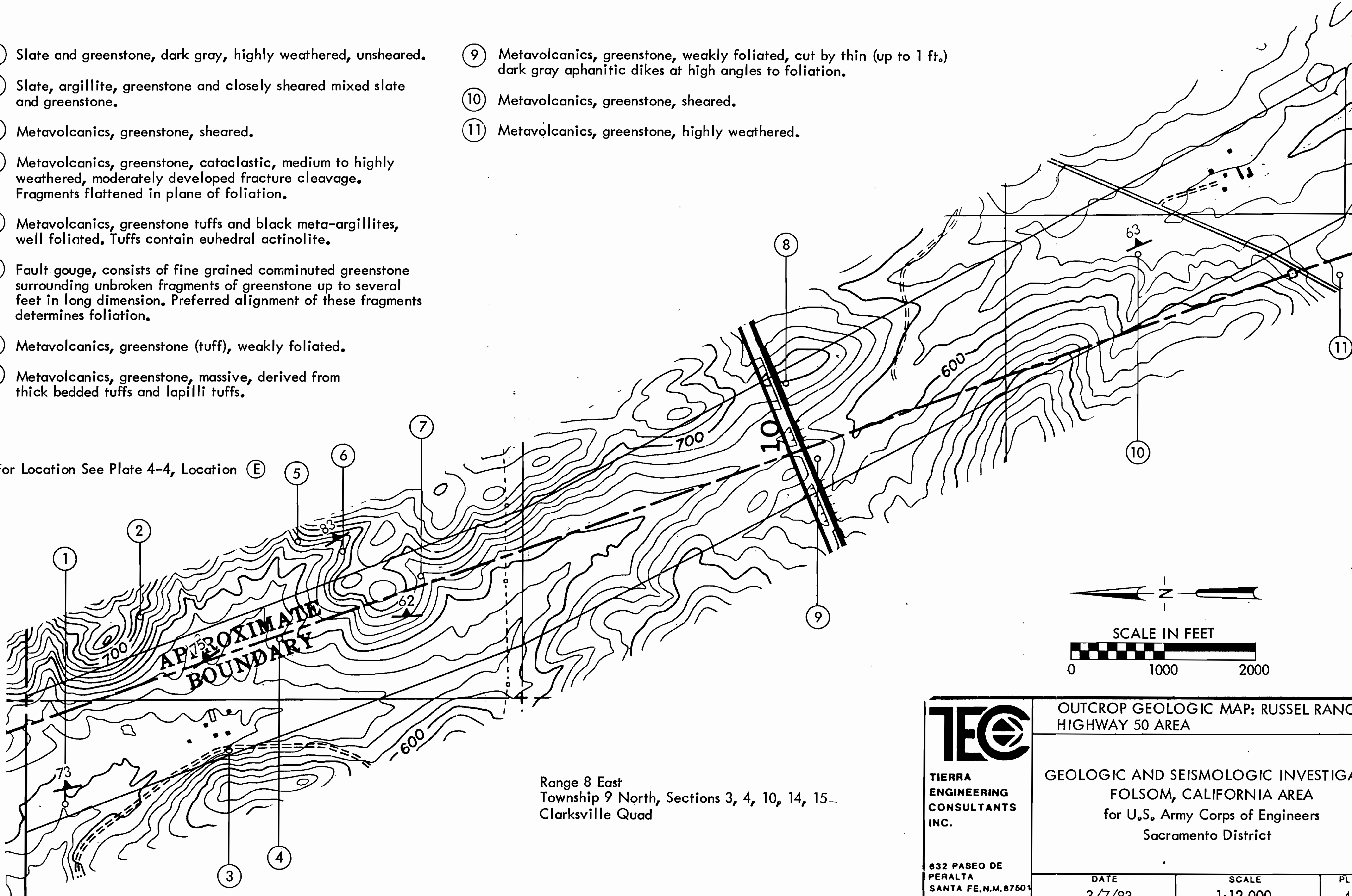
(8) Metavolcanics, greenstone, massive, derived from thick bedded tuffs and lapilli tuffs.

(9) Metavolcanics, greenstone, weakly foliated, cut by thin (up to 1 ft.) dark gray aphanitic dikes at high angles to foliation.

(10) Metavolcanics, greenstone, sheared.

(11) Metavolcanics, greenstone, highly weathered.

For Location See Plate 4-4, Location (E)



Range 8 East
Township 9 North, Sections 3, 4, 10, 14, 15
Clarksville Quad

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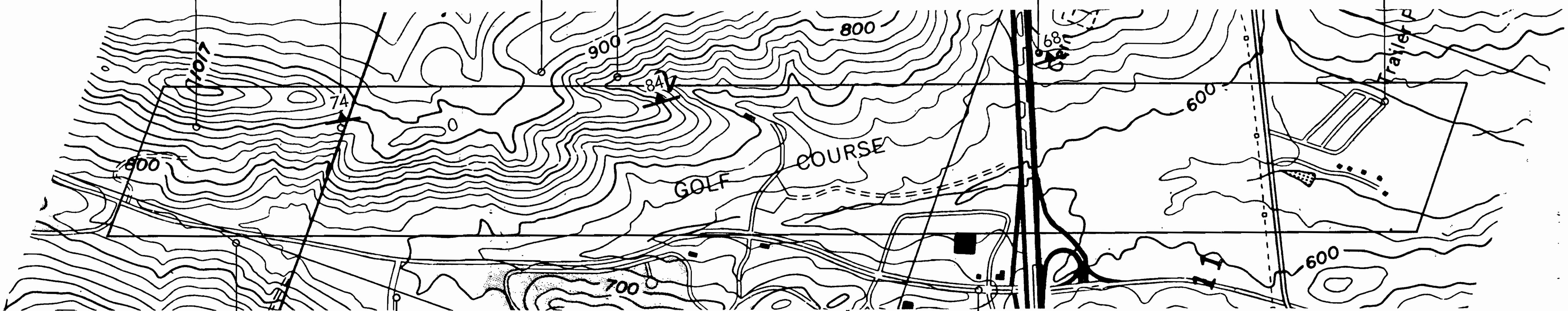
OUTCROP GEOLOGIC MAP: RUSSEL RANCH-HIGHWAY 50 AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-11

For Location See Plate 4-4, Location (F)



Range 8 East
Township 9 North, Sections 2, 3, 11
Township 10 North, Sections 34, 35
Clarksville Quad

N

SCALE IN FEET

0 1000 2000

(1) Metavolcanics, phyllite, crenulated, with sericite sheen along foliation.

(2) Metavolcanics, greenstone.

(3) Metavolcanics, greenstone, sheared.

(4) Metavolcanics, phyllite, crenulated, with chloritic schist.

(5) Metavolcanics, phyllitic greenstone.

(6) Metavolcanics, phyllitic greenstone, strongly foliated.

(7) Metavolcanics, massive, locally sheared.

(8) Talc-sericite schist, crenulated.

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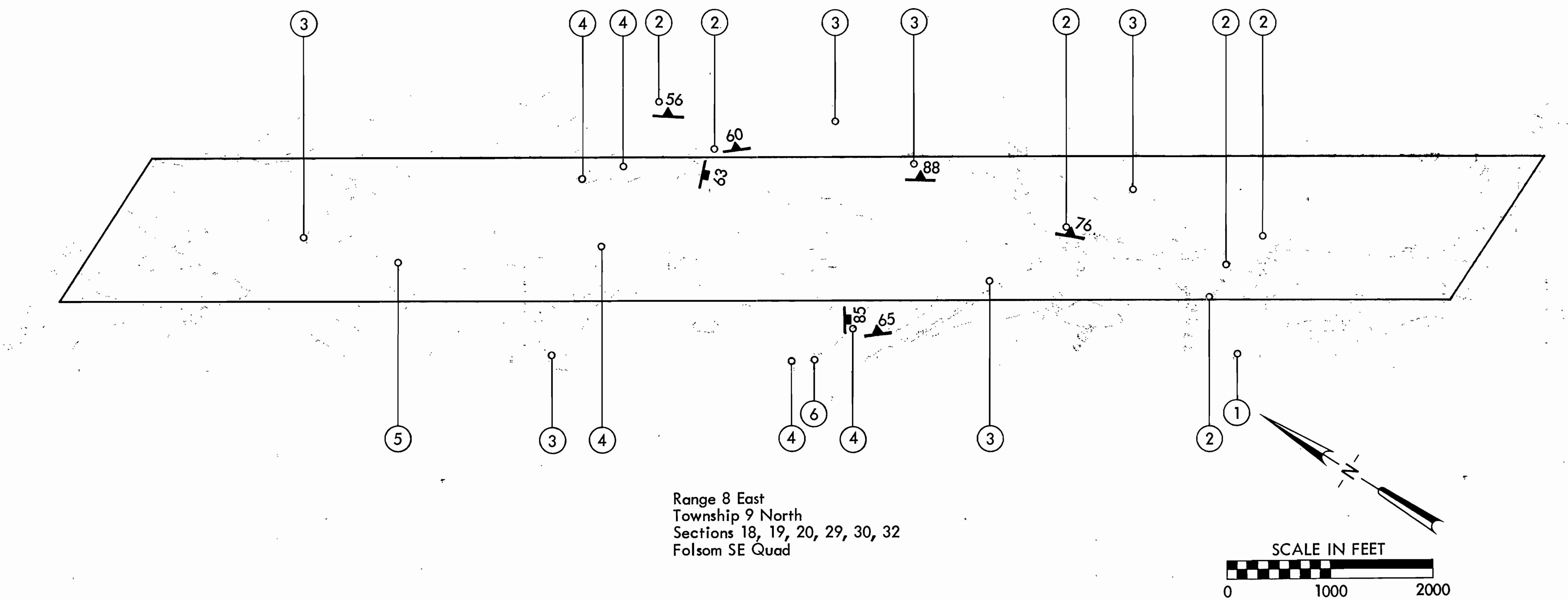
OUTCROP GEOLOGIC MAP: EL DORADO HILLS GOLF COURSE AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-12

For Location See Plate 4-4 and 4-5, Location (G)



(1) Greenschist, gray-green to buff, fine grained, well foliated, medium weathered, medium hard, locally contains microcrystalline quartz veins parallel to schistocity.

(2) Greenschist, gray-green to buff, fine grained, medium to highly weathered, closely sheared, locally contains fine grained partly recrystallized cataclastic bands and breccia zones, quartz lenses and veins.

(3) Metavolcanics, greenstone, dark gray-green, fine grained, medium to highly weathered, hard, variably spaced closed fractures of variable roughness, locally highly sheared, slightly phyllitic or containing relict vesicles.

(4) Slate, dark gray, very fine grained, strongly fissile, slightly to medium weathered, hard, variably spaced closed fractures, locally shows compositional layering oriented approximately perpendicular to cleavage.

(5) Fault gouge, fine to coarse comminuted greenstone breccia.

(6) Meta-cataclastic (float), fine to coarse grained, massive, hard.

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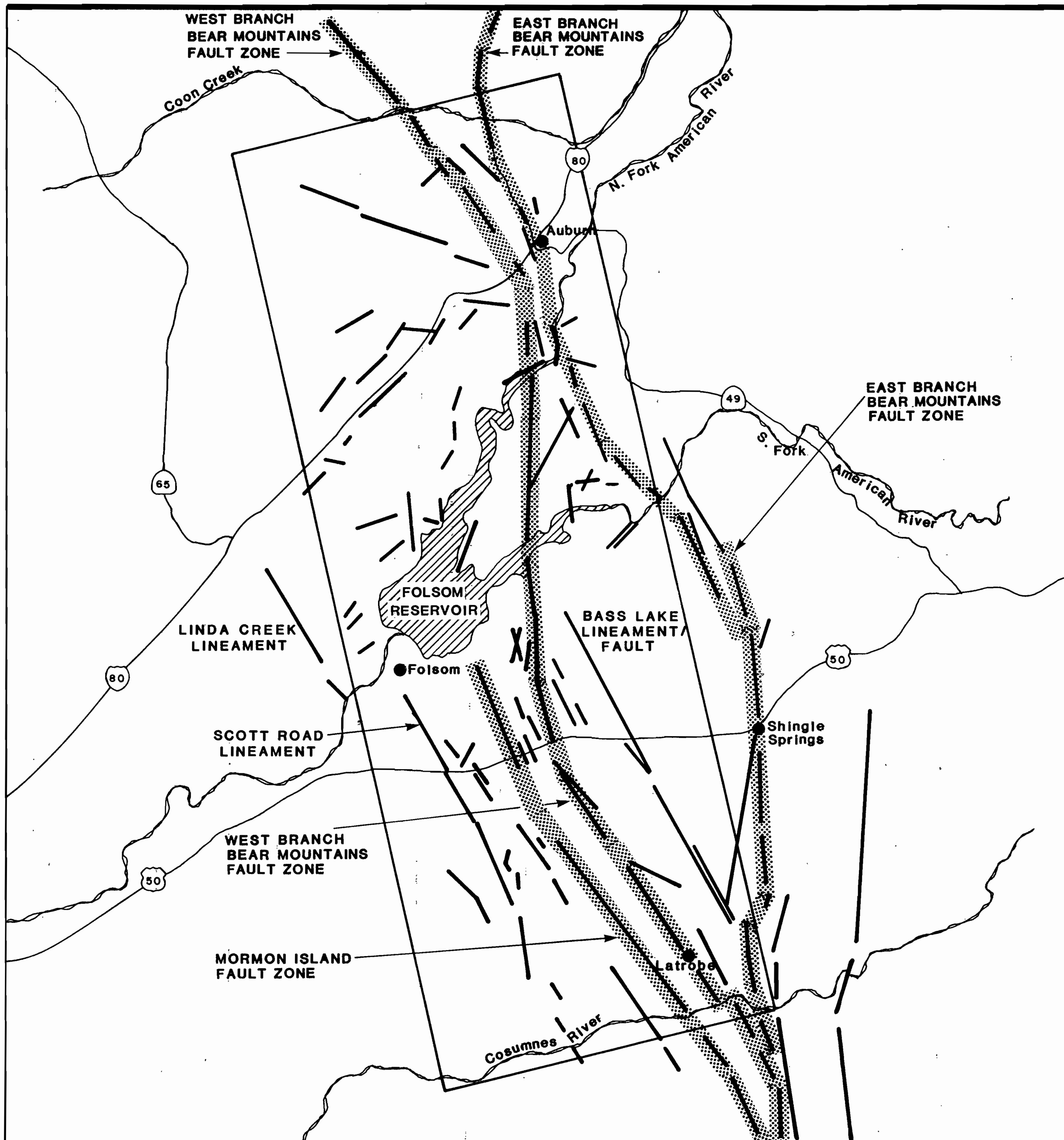
OUTCROP GEOLOGIC MAP: LATROBE ROAD AREA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:12,000	4-13



EXPLANATION

Strongly expressed lineament (visible on several types of imagery and at various scales)

Approximate locations of mapped fault zones

(80) Highway

River

SOURCES: Photographic Interpretation Corporation (1982)
USBR (1977a)

-N-

0 5 10 Miles

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REGIONAL LINEAMENT MAP

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3-5-83	1:250,000	4-14

SECTION 5

5. EVALUATION OF FAULT CAPABILITY

Following lineament analysis, geologic mapping established the location and aspect of the fault zones within the study area. Studies then determined which sites along the zones would be most suitable for further detailed exploration aimed at determining whether the faults were capable under Corps criteria. Aerial imagery covering the length of each fault zone was examined for potential trenching sites. Sites judged promising on the basis of photoanalysis or previously suggested based on geologic reconnaissance were visited. Potential exploration sites were ranked using the following criteria, in approximate order of importance:

1) Presence (or estimated potential of presence) of datable Tertiary or Quaternary deposits overlapping the fault zone;
2) Narrowness and clarity of definition of the fault zone as inferred from aerial imagery and ground reconnaissance;
3) Distance from important Folsom Reservoir impoundment structures;
4) Feasibility of access for trenching or test pits.

As had been anticipated at the outset of this study, by far the most restrictive criterion was the first, since datable Quaternary deposits are rarely found along the fault zones within the study area. In many locations suitable deposits may have existed in the past, but have since been disturbed, removed or covered by placer mining or residential development. More extensive later Tertiary or early Quaternary deposits covered the area at one time, but have since been removed by erosion.

5.1 WEST BRANCH BEAR MOUNTAINS FAULT ZONE

Initially, attention was focused on four potential areas for detailed investigation. These included one site at the Mehrten-bedrock contact along the fault zone just south of Auburn, several areas along Hancock Creek, one area between the Sunset Trailer Park and Highway 50, and several sites along the fault zone between the Cosumnes River and Highway 50.

A potential study site near Auburn was located at the base of a large Mehrten ridge between Shirland Tract Road and the Auburn-Folsom Road. Called the Shirland Tract Road site, the site was judged unacceptable on the basis of poor definition of the fault zone. The fault zone is extremely diffuse north of the North Fork of the American River, and cannot be isolated as a reasonably narrow zone in the area south of Auburn.

In addition, exposure of the Mehrten-bedrock contact zone by reasonable trench excavation was considered unlikely, as the area is mantled by a thick accumulation of very recent bouldery slopewash. Marshy conditions and an adjacent stream suggested that water problems might also impede trenching. This site was not selected for further study.

The West Branch of the Bear Mountains fault zone is topographically well defined by a long, north-south trending linear valley in the vicinity of Hancock Creek. Because of its proximity to the proposed Auburn dam site, this area was studied in some detail during the Auburn fault evaluation studies. The area was deemed unsuitable for fault evaluation trenching after mapping indicated a lack of Tertiary and Quaternary deposits within the valley.

Geologic mapping during this study was extended southward to the South Fork of the American River, and soil profiles were examined at several points within the linear valley. Based on this work, it was concluded that suitable age-datable deposits were present at one time within the southern end of the Hancock Creek drainage, but that placer mining operations have since removed or destroyed them. The Hancock Creek site was rejected on the basis of a lack of undisturbed potentially age-datable Quaternary deposits.

Air photo study and ground reconnaissance revealed the presence of a persistent vegetation lineament on the rangeland south of Highway 50. Geologic mapping showed this lineament to be caused by a higher proportion of tarweed among the range grasses in a linear zone associated with schistose and intensely sheared bedrock and many aligned topographic saddles. The lineament was usually close to, though not coincident with, a break in slope. This lineament was especially strongly expressed in a pasture located between Highway 50 and the Sunset Trailer Park on White Rock Road. Though there are relatively few outcrops in this pasture to permit precise definition of the fault zone, the area was selected for futher study. This decision was based on the sharpness of the lineament, the narrowly-defined fault zone immediately to the north and south bordering the area, and the likelihood that a colluvial soil stratigraphy remained undisturbed. The detailed study area is named the Sunset site (Plate 5-5).

Approximately one mile south of the Sunset exploration site, another area was identified for further study. This area, due east of the large wastewater treatment lagoon at the El Dorado Hills Sanitation District's sewage facility, is similar to the Sunset area in that a strong vegetation lineament composed of tarweed passes through the area. The area differs in that the tarweed lineament connects several aligned well developed saddles. In addition, bedrock crops out on the adjacent hillsides. Geologic mapping confirmed that the lineament and saddle alignment were coincident with a zone of intensely sheared metavolcanic bedrock, and that the zone was relatively continuous, narrow and well defined. Later attention was focused on Quaternary deposits and soil profile development within the area. Alluvial units were absent along the zone. Consequently, special attention was devoted to finding topographically stable areas on which datable soil profiles might have developed. A trenching site was selected at the crest of a broad, flat-topped saddle where colluvium was potentially thick (see Plate 5 for location). The area was termed the Lagoon site (see details in Appendix C).

5.1.1 Trenching

<u>5.1.1.1 Sunset Trench.</u> The Sunset exploration (Plate 4-6) site lies along the same lineament and shear zone as the Lagoon site. It is located between Highway 50 and White Rock Road, approximately one mile north of the Lagoon area. This site was chosen because of the strong tarweed lineament, a break in slope nearly coincident with the lineament, the presence of gouge and strongly sheared rock in the vicinity, and the high probability of encountering a relatively datable soil stratigraphy. Two approximately parallel trenches were excavated across the lineament in August, 1982 (Plate 5-3), one 220 feet in length (Sunset North (SS-N)) and one 70 feet long (Sunset South (SS-S)).

5.1.1.1.1 Bedrock. Mesozoic bedrock geology exposed in the Sunset trenches consisted of massive to strongly foliated metavolcanics with a few zones of strong shearing and sheared sericite-talc schist. Shears occurred at all orientations within the rock, with a weak preferential orientation toward a steep (50-85°) eastward dip. Numerous thin quartz veins also cut the rock at high angles.

5.1.1.1.2 Soil Stratigraphy. Three pebbly colluvial units were uncovered in the Sunset trenches. The uppermost pebbly colluvium extended the full length of the trench at ground surface (Plates 5-4 and 5-5). A weakly developed soil on this colluvium is presently developing as a result of slow downslope transport and soil pedogenesis. It unconformably overlies two older colluvial units, one an erosional remnant directly below the modern colluvium, the second below that, deposited directly onto the bedrock surface. The two lower units were interpreted to have formed under different climatic conditions than are present today; they contain many more coarse pebbles, cobbles and generally have a much coarser texture than the upper colluvium. These colluvial units are less extensive than the upper unit, the lower and middle units pinching out at stations 116 and 195, respectively (Plate 5-4b). Locally the lower colluvium contains strongly prismatic clay-rich zones, mapped on the logs as separate units. These clay zones are the result of local preservation of the clay-rich upper portions of the pedogenic profile, most of which has been removed by erosion. Similarly, the middle colluvium does not exhibit a complete profile, the upper portions having been eroded away.

Soil-stratigraphic analysis of the lowermost colluvium indicates the soil profile developed about 80,000 to 125,000 years ago on a colluvial unit deposited earlier, probably between 125,000 to 190,000 years ago. No displacements were observed in this colluvium or the soil profile developed upon it, indicating the last displacement of the West Branch of the Bear Mountains fault zone occurred at least 125,000 years ago, and possibly more than 195,000 years ago.

5.1.1.2 Lagoon Trench. The Lagoon trench was excavated in late July 1982. It extended 220 feet across the relatively level crest of a saddle adjacent to steeper west-facing slopes (see location map and detailed trench logs, Plates 5-1 through 5-2b). Mapping showed that this saddle was the northernmost member of a group of similar aligned saddles that were coincident with a bedrock shear zone within relatively massive metavolcanic rock. The shear zone was associated with a well expressed, seasonally persistent vegetation lineament caused by concentration of tarweed. South of the trench, this lineament extends across and visually connects several aligned saddles. Here the lineament is usually sharply defined along both its eastern and western sides. At the trench site only the western edge of the lineament is sharply defined, the eastern edge gradationally fades uphill. North of the site the lineament and shear zone become slightly less defined on aerial imagery, though its northward extension is marked by strongly sheared rock and gouge exposed in Carson Creek adjacent to the Sunset Trailer Park. North of White Rock Road the lineament again becomes strongly expressed in the Sunset exploration site.

The exact placement of the Lagoon trench was selected after a review of local mapping, aerial imagery, and hand excavation of small soil test pits. The trench was excavated across the widest and northernmost saddle in a group of aligned topographic breaks. It extended from an outcrop field eastward across the tarweed lineament and well up the hillside to the east, where soil cover became thin. This location was most preferable on the basis of the strong lineament, clearly defined shear zone, and the topography, which was judged to be the most conducive to long term geomorphic stability and soil profile development in the area. The following paragraphs describe the features exposed in the trenches. Graphic logs of the trench are included as Plates 5-2a and 5-2b at the end of this section.

<u>5.1.1.2.1 Bedrock.</u> Pervasively sheared mylonite schist, greenschist and sericite-talc schist exposed in the Lagoon trench confirmed the presence of a bedrock fault zone at the site. The trench contained massive greenstone, foliated

greenstone, amphibolite, serpentinite, mylonite schist, sericite-talc schist and greenschist irregularly intermixed, generally with steeply dipping contacts. Locally the bedrock was cut by thin clay-filled fractures that crosscut some contacts and are truncated at others. The most significant feature observed within the bedrock is a 110-foot-wide zone of strongly sheared and highly weathered mylonite, greenschist and sericite talc schist in the western end of the trench. This zone also contains a narrow vertical body of sheared serpentinite. Particularly near stations 25, and 61 to 90, this zone and the less sheared sericite-talc schist near stations 10-20 are interpreted to be a fault zone within the more massive metavolcanic country rock. This interpretation is based on: (1) discontinuous foliation, (2) siliceous nodules elongated parallel to foliation, and (3) locally chaotic shearing within the schists support this interpretation.

5.1.1.2.2 Soil Stratigraphy. The Lagoon trench exposed an unbroken surficial colluvial unit datable by soil stratigraphic techniques. Older colluvial units remain in a few pockets on the bedrock surface, along with two types of residual soil, developing in-place on top of the bedrock. The older soils, much less laterally continuous than the covering colluvium, all share certain characteristics derived from long-term exposure to weathering and soil forming processes. They tend to be relatively clay-rich, with well developed prismatic structure, fairly sharp erosional upper contacts and obscure lower contacts. Repeated shrink-swell cycles have obliterated most evidence of original rock fabric in the residual soil, except at the deepest part of the unit. The uppermost colluvium provided the only unbroken soil stratigraphic marker. Analysis of the pedogenic profile developed on this colluvium indicates it is probably slightly less than 20,000 years old. The uppermost colluvium is not displaced or offset across any shears in the underlying bedrock, and so provides a minimum age for the last displacement of the West Branch of the Bear Mountains fault zone at this site. Details of the soil-stratigraphic comparisons and analyses are contained in Appendix C.

5.1.2 Other Studies

<u>5.1.2.1 Magnetics.</u> Magnetometer surveys were made at each trench site and across the lineament zone in adjacent areas in order to aid in trench location. Locations of these profiles are shown on Plates 4-5, 4-6, 5-1 and 5-3. In each case it was noted that strong magnetic signatures are not generally associated with faults, shear zones or individual surface lineaments in the areas investigated. Contrasts in magnetic susceptibility are not great enough between sheared and massive rock, in the absence of large buried scarps or bedrock steps, to result in distinctive features on magnetic profiles. Serpentinite outcrops within fault zones produced

large contrasts in total field intensity, but were not present universally. Generally, large contrasts would not be expected across fault zones that do not juxtapose significantly different lithologies or lack wide gouge zones. This also applies, although to a lesser extent, to resistivity and seismic refraction surveys, pointing up the difficulty in identifying fault zones in the Foothills zone on the basis of geophysical techniques. It is concluded that geophysical studies have limited utility for identification of fault zones in the foothills.

<u>5.1.2.2 High School Site.</u> A site study completed in 1980 by George A. Wheeldon and Associates of Placerville reported an active fault (USBR criteria) associated with a north-south-trending lineament extending from the site of the proposed high school to Highway 50 (Wheeldon and Associates, 1980). Bedrock shears similar to those found in the Lagoon and Sunset trenches were reported to be exposed in the Wheeldon trenches, but other evidence or lack of evidence suggests the lineament does not represent a capable fault:

1) No evidence of displacement or offset of soils by underlying shears was reported;
2) Mapping in the area of Highway 50 shows that the trenched lineament dies out rapidly to the south;
3) The lineament is not aligned with structural discontinuities south of Highway 50;

4) Numerous faint linear elements occur across the valley containing the lineament suggest the pattern is related to foliation or Mesozoic structure.

Based on these observations and recent communications with Mr. Wheeldon, it is concluded that a capable fault, as defined by Corps criteria, was not discovered during the high school site study.

5.1.3 Age of Last Faulting

Lineaments trenched along the West Branch of the Bear Mountain fault zone were associated with zones of strongly sheared or schistose rock, mylonite and sericite-talc schist, serpentinite and clay-filled fractures within bedrock. No bedrock shears were observed extending into colluvial soils overlying the bedrock. The Lagoon exploration site could not provide a conclusive determination of age of faulting beyond the approximate 20,000 year minimum age of the lower section of the youngest colluvium, owing to discontinuous occurrence of older paleosols. Both trenches excavated at the Sunset site contained continuous buried paleosols that remain undisplaced by major bedrock shears in the rock below. The relative ages of these buried soils have been estimated by soil profile analysis and stratigraphic correlation to be at least 50,000 to 70,000 years old (middle colluvium) and possibly older than 125,000 to 190,000 years (lower colluvium). From this evidence and the lack of geomorphic and geologic indicators of recent faulting elsewhere in the area, it is concluded that no faulting has occurred along the West Branch of the Bear Mountains fault zone in this vicinity during at least the last 65,000 years. Therefore the fault is not judged to be a capable fault under Corps criteria.

5.2 MORMON ISLAND FAULT

After identification by aerial imagery analysis and geologic mapping, the Mormon Island fault zone was investigated along its entire definable length to locate areas suitable for evaluations of capability. As with the West Branch of the Bear Mountains fault zone, the most difficult task was to locate accumulations of Quaternary sediments that were suitable for age-dating. The search was facilitated by the more gentle topography of the land through which the fault zone passes between the Cosumnes River and Folsom Reservoir, and the relative lack of commercial or residential development south of the reservoir and west of El Dorado Hills.

Several potential exploration sites along the zone were identified on the basis of strong linear elements on imagery. Field visits to these sites, near the Cosumnes River, Deer Creek, the toe of Mormom Island Dam and south of the Mormon Island Dam, resulted in the selection of two areas judged to be the best candidates. Attention was also directed at the area near the toe of the Mormon Island Dam. The other sites were rejected on the basis of a lack of potentially useful Quaternary deposits, presence of disturbed soils, or both.

5.2.1 Trenching

<u>5.2.1.1 Russell Ranch Trench.</u> The Mormon Island fault zone was trenched at the north end of the Russell Ranch, approximately one mile south of the east end of Mormon Island Dam (Plate 4-5). The trench location was chosen to intersect the most northerly linear element clearly visible within the lineament zone. Hand sampling of soil at this site had previously indicated that at least one buried soil was present. A trench approximately 550 feet long and trending N64-68° E was excavated across the lineament, an adjacent slope break, and up a west-facing hill-slope to an outcrop of relatively massive rock during November, 1982. The location of this trench is shown on Plate 5-6, detailed logs on Plates 5-7a through 5-7e.

<u>5.2.1.1.1 Bedrock.</u> The Russell trench contained massive to strongly foliated and phyllitic metavolcanic bedrock. Foliation and schistosity trended north-northeast. Thin clay-filled shears were found both parallel to foliation and crosscutting it. Depth and intensity of weathering were variable. Between stations 110 and 125 an iron-stained and highly weathered zone of rock was observed and interpreted to be formed as a result of accelerated weathering owing to a

fluctuating perched water table. The vegetation lineament occurred over a gently sloping gradual up-to-the-east step in bedrock between trench stations 225 and 245, against which the lower colluvium pinched out. Between stations 250 and 285, the highly to completely weathered bedrock contained a web of subhorizontal veins of kaolinite clay. The eastern half of the trench consists mainly of slightly foliated to massive metavolcanic rock with a few thin zones of strong foliation or minor fracturing. A small dike or recrystallized volcanic interbed occurs between stations 338 and 344.

5.2.1.1.2 Soil Stratigraphy. Quaternary stratigraphic units exposed within the Russell trench consisted of two colluvial units (divided into three mapped units on Plates 5-7a through 5-7e) and a residual soil developed directly on bedrock. The upper colluvium is red-brown and pebbly, and has been disturbed by plowing in the 6 to 8 inches nearest the surface, except eastward (uphill) from approximately station 450 (Plate 5-7d). The undisturbed soil on the hillside is darker brown, thinner, and is forming on an active slope. The lower colluvium consists of a remnant argillic B-horizon, the original A-horizon having been removed by erosion (see Appendix C for an explanation of soil profile development and terminology). The soil weathering profile superimposed on this thicker, coarser and more pebbly colluvium is also superimposed on the bedrock surface in the lower end of the trench, west of station 76 (Plate 5-7a) where the lower colluvium pinches out. Neither of these soil units were observed to be disrupted in the vicinity of bedrock shears.

Soil stratigraphic age-dating indicates the basal, undisturbed portion of the upper colluvium is about 15,000 to 17,000 years old (Appendix C). The much more highly developed partial soil profile superimposed on lower colluvium and bedrock formed about 35,000 to 45,000 years ago, and possibly 80,000 to 125,000 years ago. No shears displace these units, indicating the last movement of the Mormon Island fault in this area took place at least 50,000 to 70,000 years ago, and possibly more than about 125,000 years ago, based on conservative relative age estimates for the colluvial unit bearing the dated pedogenic profile (Appendix C).

5.2.1.2 Dunlap Ranch Trench

Detailed study at the Dunlap Ranch was initiated after reconnaissance along the adjacent Deer Creek drainage showed that Pleistocene stream terrace gravels might be found on strike with a strong vegetation lineament within the valley encompassing the Mormon Island fault zone. The location of the Dunlap Ranch exploration site is shown on Plate 4-6. Two test pits were excavated between the Southern Pacific railroad right-of-way and the stream channel. These pits showed older gravels at a depth of 1 to 3 feet below the ground surface. Permission was obtained to dig a trench at right angles to the projected strike of the lineament, approximately 150 feet east of the test pit locations. A 76-foot-long trench was excavated across the projection of this lineament in August, 1982 (Plates 4-6, 5-8).

5.2.1.2.1 Bedrock. The Dunlap Ranch trench was excavated into massive metavolcanic bedrock, containing localized clay and gouge-filled shears, and zones of very closely spaced fractures. Details and descriptions of the bedrock are shown on Plate 5-8.

5.2.1.2.2 Soil Stratigraphy. Bedrock in the Dunlap trench was overlain by a 1 to 3 foot-thick accumulation of rounded stream cobbles and pebbles in a dark brown sandy matrix (Plate 5-8). This soil was found to be an artificially emplaced mixture of native stream gravel and foreign rock rubble. It is likely the native gravels were stripped during gold dredging operations or railroad construction and regraded at a later time. Bedrock shears were not observed to penetrate the overlying gravels, however, the disturbed gravels were not useful for dating (Appendix C).

5.2.2 Other Studies

Additional studies performed on the Mormon Island fault included a magnetometer survey along the toe of the dam, and an extensive review of dam construction records and as-built drawings to evaluate the possibility of pre-dam fault displacements in the foundation and abutments. The magnetometer profile proved inconclusive owing to disturbed soils, irregularity of artificial fill, and interference from powerlines, pipelines and metal debris. A discussion of the review of the damsite geology is included in the following paragraphs.

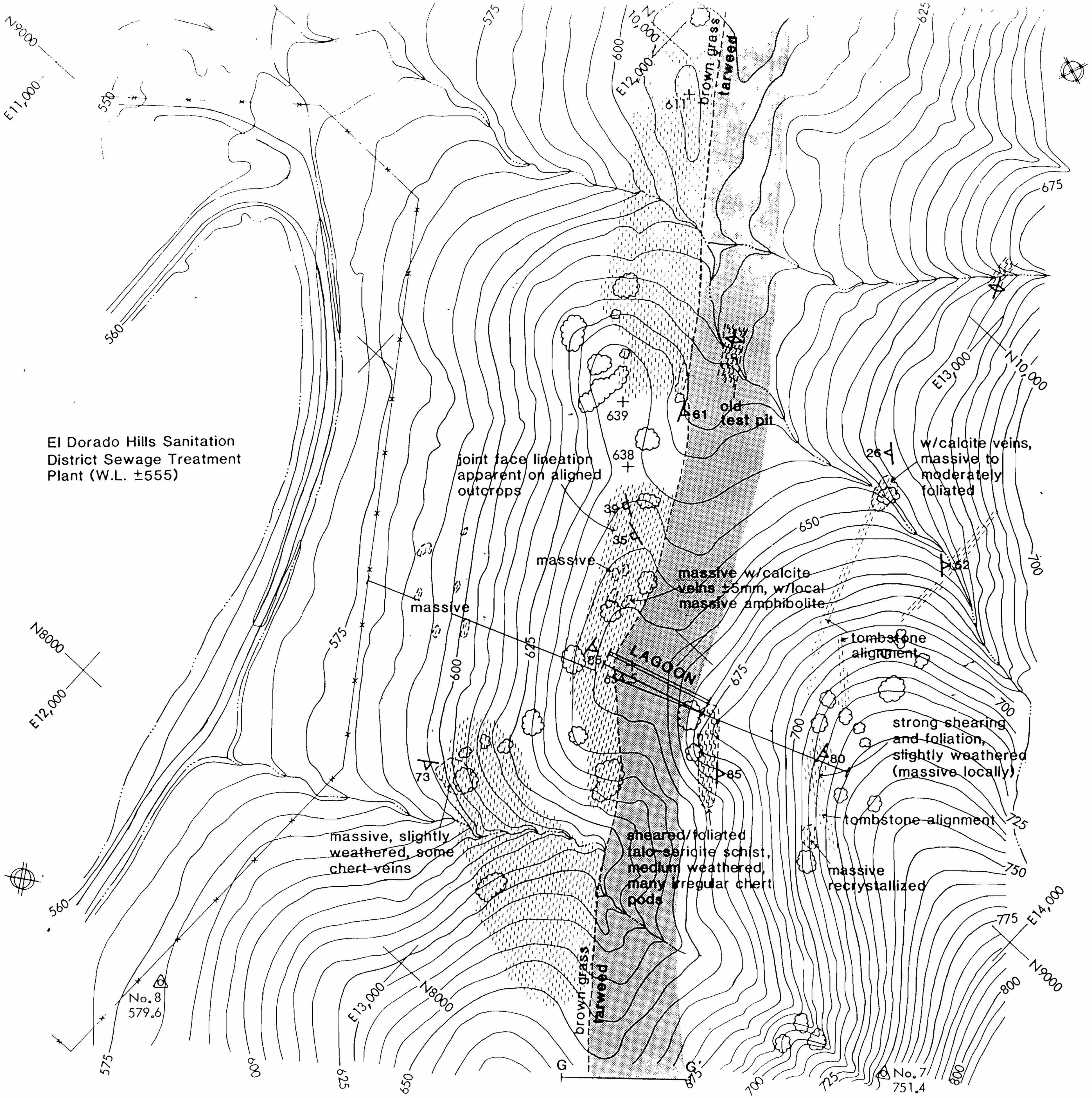
Construction records for the Mormon Island Dam show that the dam was placed across the abandoned South Fork channel of the American River. Preconstruction geology indicates that this channel consisted mainly of dredged sands and gravels underlain by metamorphic bedrock similar to that encountered in the Russell trench. A small wedge of undisturbed river alluvium was located at the old channel margin near the left (eastern) dam abutment. This wedge has been truncated on the west side by gold dredging operations. Documents show that bedrock was exposed in the core trench excavated along the entire length of the 4,820-foot-long dam, and consisted of foliated to massive and locally schistose metavolcanics. This rock contained foliation and schistosity striking from N. 10° - 60° E., as well as 50 to 75-foot-wide soft zones of close fracturing and fissile schist, separated by ribs of blocky schist. The extent and amount of shearing and soft schist apparently decreased toward the left abutment. A 4-foot-wide gouge zone striking N 20° E mapped near the right abutment comprised the only substantial occurrence of gouge observed in the foundation. No evidence of intensive, localized shearing or faulting within or adjacent to the undredged sediments at the left abutment is shown on the drawings, suggesting that these rocks are in depositional contact with the underlying metavolcanics. No evidence of shearing or displacement in the lower gravels adjacent to the core trench is reported in the records, and no through-going shear zones have been mapped in the Rocklin pluton, located less than a mile to the north.

5.2.3 Age of Last Faulting

Buried colluvial soils and a soil-weathering profile on bedrock in the Russell trench are undisplaced by shears within the underlying bedrock. Soil stratigraphic analysis of these units indicates they may be at least 65,000 years old and possibly older than 130,000 years. No determination of the age of last faulting could be made at the Dunlap Ranch trench, owing to the disturbed soils. No evidence suggesting recent faulting was found in a review of construction records of the Mormon Island Dam. Geomorphic features indicative of Holocene faulting such as fault scarps, fault line scarps, displaced drainages and springlines are lacking along the Mormon Island fault. The fault zone does not extend into a Mesozoic pluton located north of the dam site. These data indicate that the Mormon Island fault zone has not undergone displacement during the last 65,000 to 70,000 years as a minimum, and probably has not been the locus of large displacements since late Mesozoic (± 65 m.y.b.p.) time.

5.3 REVIEW OF DAM AND DIKE SITES

Preconstruction geology, as-built drawings and the original geologic site reports for the Folsom project were reviewed and compared with other data developed during the lineament analysis and geologic mapping of this study. With the exception of the Mormon Island fault, discussed separately in the paragraphs above, no faults or lineaments striking toward or extending through the main dam or saddle dikes were found. The main dam, wingwalls and saddle dikes 1 through 8 are constructed on the highly weathered and fractured surface of the Rocklin/Penryn pluton. The pluton is not cut by through-going faults related to the Bear Mountains system at any point near the reservoir investigated in this study. Faulting and shearing observed in the main dam foundation excavations (unpub. Corps construction records, Kiersch and Treasher, 1955) may perhaps be related to the intrusion of the pluton. In the absence of strong lineaments on pre-reservoir or recent imagery, mapped fault zones or geomorphic indicators of faulting near Folsom Reservoir impoundment structures, it is concluded that the possibility of fault displacements within the foundations of these structures is extremely remote.



EXPLANATION

Strike and dip of joint

Strike and dip of foliation

Contact, dashed where approximate or inferred

Power lines, telephone lines and fences

Trench

Magnetometer survey line

Mixed metavolcanics (greenstone predominant with minor hornblende amphibolite), green to buff, very fine to fine grained, massive to strongly foliated, closely to widely spaced closed fractures, medium weathered, medium to very hard.

Dashed border indicates a single, predominant outcrop. Non-dashed border indicates an area of smaller outcrops that form a more or less continuous "field". Locally forms long alignments of "tombstones".

Talc-sericite mylonite schist, buff to white, fine grained, medium to highly weathered, soft, frequent Fe and Mn stains, local irregular quartz pods derived from sheared quartz veins.

Zone of most strongly sheared and deformed rock.

Topography by: Hammon, Jensen & Wallen, 1982
Contour interval 5 feet, MSL datum, Local coordinates

N (grid)

Scale In Feet
0 200 400

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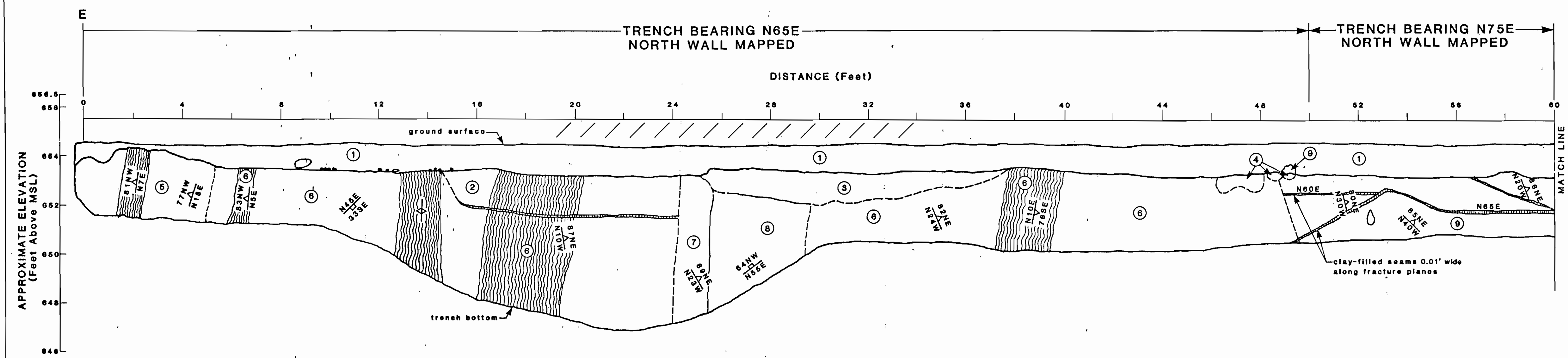
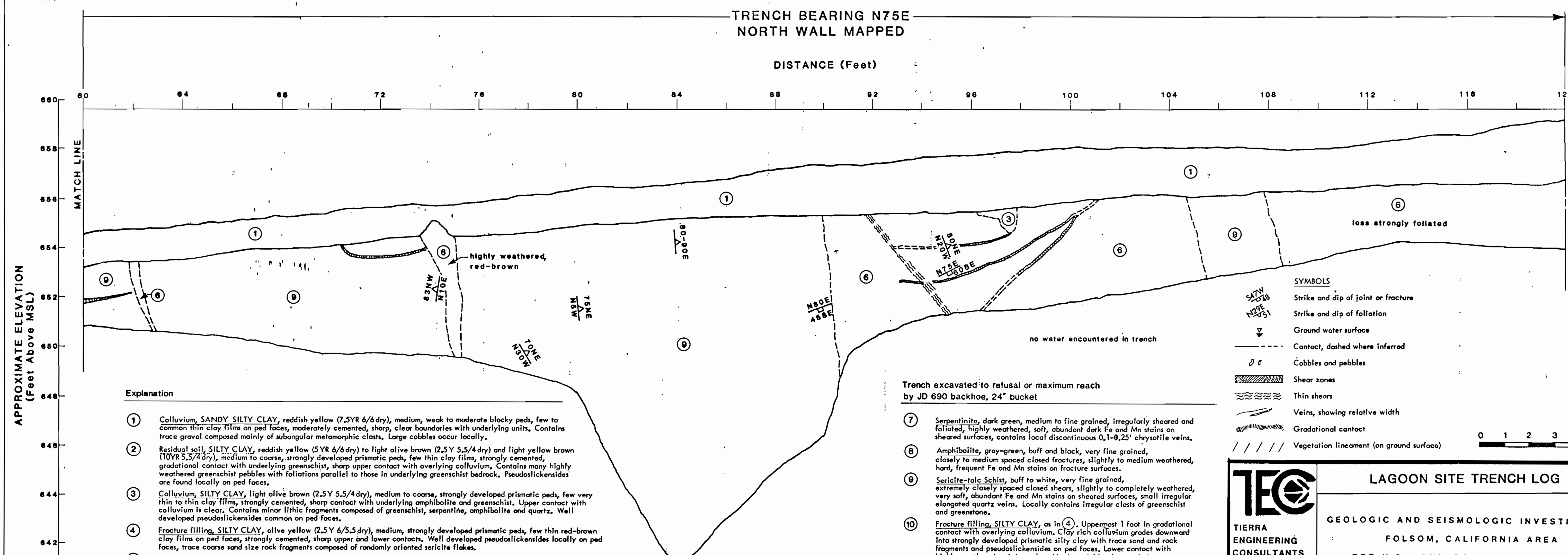
LAGOON SITE GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:2,400	5-1





Explanation

1. Colluvium, SANDY SILTY CLAY, reddish yellow (7.5YR 6/6 dry), medium, weak to moderate blocky peds, few to common thin clay films on ped faces, moderately cemented, sharp, clear boundaries with underlying units. Contains trace gravel composed mainly of subangular metamorphic clasts. Large cobbles occur locally.
2. Residual soil, SILTY CLAY, reddish yellow (5 YR 6/6 dry) to light olive brown (2.5 Y 5.5/4 dry) and light yellow brown (10YR 5.5/4 dry), medium to coarse, strongly developed prismatic peds, few thin clay films, strongly cemented, gradational contact with underlying greenschist, sharp upper contact with overlying colluvium. Contains many highly weathered greenschist pebbles with foliations parallel to those in underlying greenschist bedrock. Pseudoslickensides are found locally on ped faces.
3. Colluvium, SILTY CLAY, light olive brown (2.5 Y 5.5/4 dry), medium to coarse, strongly developed prismatic peds, few very thin to thin clay films, strongly cemented, sharp contact with underlying amphibolite and greenschist. Upper contact with colluvium is clear. Contains minor lithic fragments composed of greenschist, serpentine, amphibolite and quartz. Well developed pseudoslickensides common on ped faces.
4. Fracture filling, SILTY CLAY, olive yellow (2.5 Y 6/5.5 dry), medium, strongly developed prismatic peds, few thin red-brown clay films on ped faces, strongly cemented, sharp upper and lower contacts. Well developed pseudoslickensides locally on ped faces, trace coarse sand size rock fragments composed of randomly oriented sericite flakes.
5. Metavolcanics, greenstone, green to buff, very fine grained, very closely foliated, locally phyllitic, closed, very closely to widely fractured, medium weathered, hard, abundant dark Fe and Mn stains on fracture surfaces. Locally very small subhedral epidote crystals visable in matrix.
6. Greenschist and mylonite schist, pale green to buff, very fine grained, extremely to very closely foliated, closed, very closely spaced shears, highly to completely weathered, medium hard, abundant dark Fe and Mn stains on fracture surfaces, strongly developed schistocity parallel to foliation. All relict texture has been eliminated by recrystallization. Also occurs as irregular angular pebbles and cobbles in sericite-talc schist zones.

Trench excavated to refusal or maximum reach by JD 690 backhoe, 24" bucket

7. Serpentinite, dark green, medium to fine grained, irregularly sheared and foliated, highly weathered, soft, abundant dark Fe and Mn stains on sheared surfaces, contains local discontinuous 0.1-0.25' chrysotile veins.
8. Amphibolite, gray-green, buff and black, very fine grained, closely to medium spaced closed fractures, slightly to medium weathered, hard, frequent Fe and Mn stains on fracture surfaces.
9. Sericite-talc Schist, buff to white, very fine grained, extremely closely spaced closed shears, slightly to completely weathered, very soft, abundant Fe and Mn stains on sheared surfaces, small irregular elongated quartz veins. Locally contains irregular clasts of greenschist and greenstone.
10. Fracture filling, SILTY CLAY, as in (4). Uppermost 1 foot in gradational contact with overlying colluvium. Clay rich colluvium grades downward into strongly developed prismatic silty clay with trace sand and rock fragments and pseudoslickensides on ped faces. Lower contact with highly weathered sericite-talc schist is variably clear and obscure.
11. Residual soil, SILTY CLAY, light yellow brown (10 YR 55.5/4 dry) to light olive brown (2.5 Y 5/4 dry), moderate to strongly developed prismatic peds, common thin to thick clay films, strongly cemented, clear upper contact with overlying colluvium, gradational contact with underlying sericite-talc schist. Schistose texture obliterated on unit except in lower contact zone. Contains well developed nearly vertical desiccation cracks. Occurrence between 150' - 162' rests in sharp contact with a clay filled fracture along the bedrock surface.

SYMBOLS

- S47W 48 — Strike and dip of joint or fracture
- N29E 51 — Strike and dip of foliation
- Ground water surface
- Contact, dashed where inferred
- Cobbles and pebbles
- Shear zones
- Thin shears
- Veins, showing relative width
- Gradational contact
- / / / / / — Vegetation lineament (on ground surface)

0 1 2 3 4 Feet

TEC
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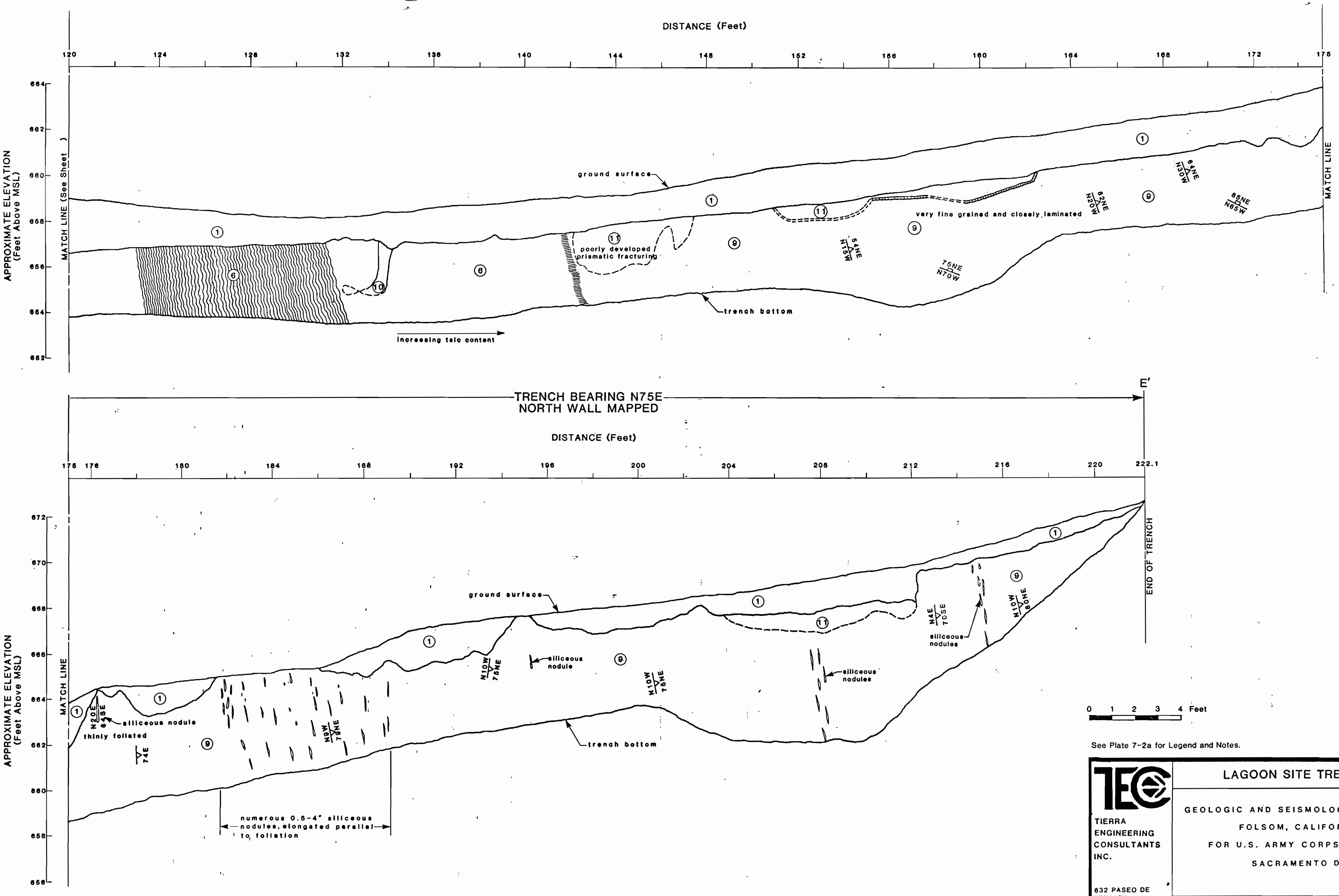
505/982-2845

LAGOON SITE TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

DATE	SCALE	PLATE NO.
3/7/83	1:24	5-2a



See Plate 7-2a for Legend and Notes.

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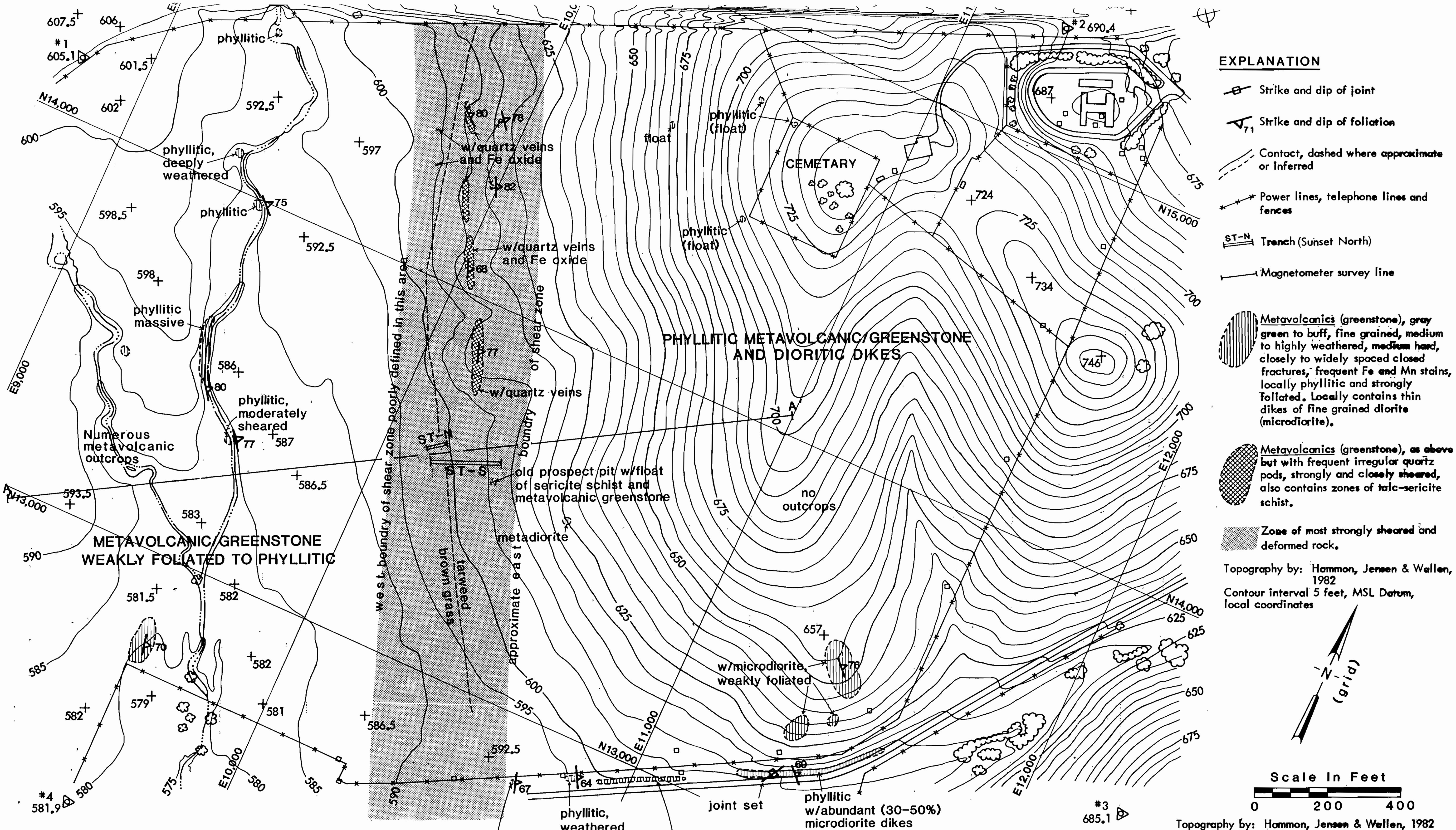
LAGOON SITE TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATIO
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

DATE	SCALE	PLATE NO
3/7/83	1:24	5-2b

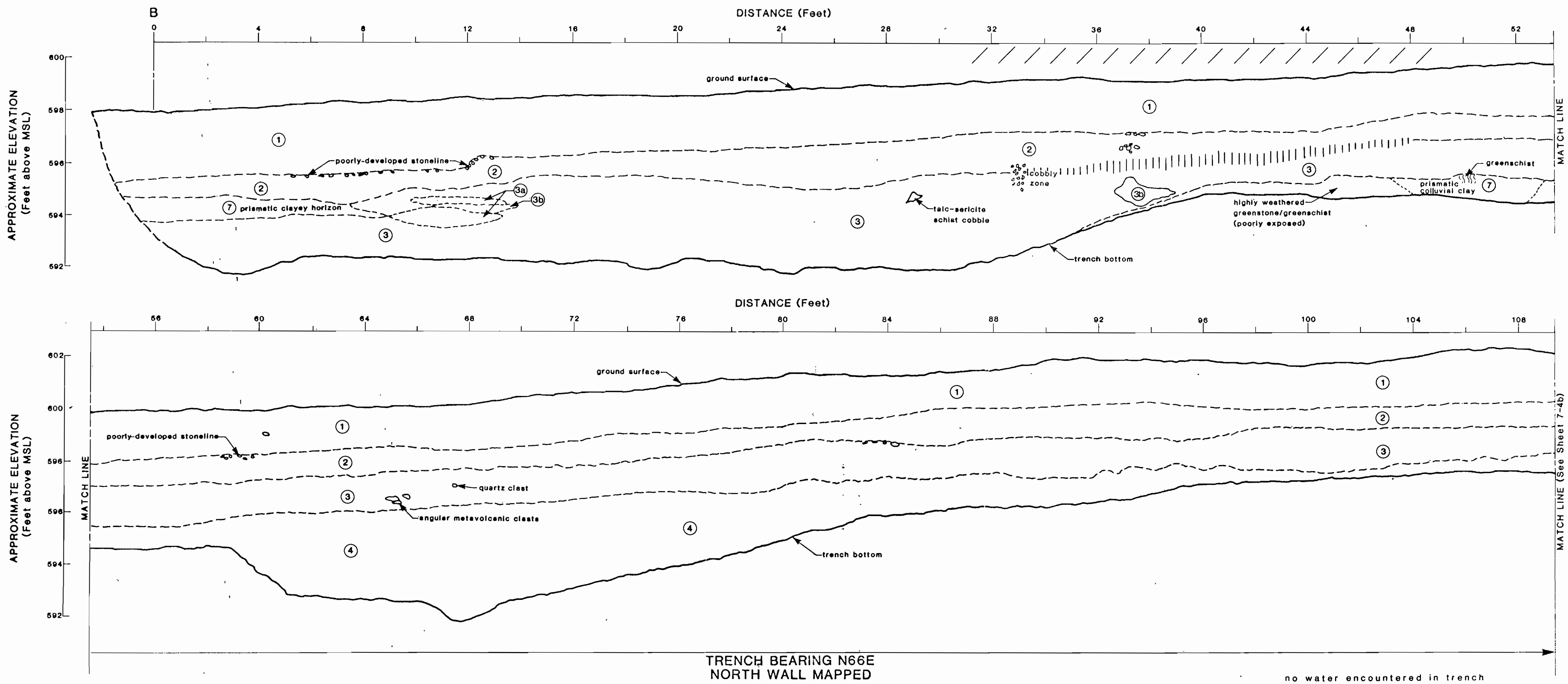


SUNSET SITE GEOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

TIERRA ENGINEERING CONSULTANTS

Plate No.: 5-3



no water encountered in trench

EXPLANATION

(1) Colluvium, SILTY CLAY, strong brown (7.5 YR 5.5/7 dry), coarse, moderate to weak peds, common clay films coating peds and occasional subangular gravel clasts, moderately cemented, clear contact with underlying unit. Textural break occurs at ±6" depth, above roots and insect holes abundant, below moderate to strong peds, coarse to very coarse, well cemented. Locally percentage of gravel clasts (quartz, metavolcanics, greenschist, amphibolite) exceeds 12%.

(2) Colluvium, SILTY GRAVELLY CLAY, mottled red (2.5 YR 4/6 dry) and yellowish red (5 YR 5.5/6 dry) with local dark gray Fe and Mn staining, (5 YR4/3), medium weak to moderate, few to common moderately thick clay films on ped faces, weak to strong, contact with (1) is gradational, lower contact is locally gradational over short distance, locally clearly defined by discontinuous stonelines. Pebble content exceeds 50% in some reddish lenses with very weakly developed peds. Strong horizontal fabric defined by sandy and pebbly lenses 2-5" thick and 0.5 - 2' long oriented with long axes subparallel to the ground surface, and preferential horizontal orientation of oblong clasts of chert, metavolcanics, greenschists and amphibolites. Yellowish-red portion of unit is relatively clay rich and contains better developed peds and is strongly cemented.

(3) Colluvium, SILTY GRAVELLY CLAY, mottled red (2.5 YR 4/6 dry) and strong brown (7.5 YR 5.5/6 dry) with abundant dark brown (5 YR 4/3 dry) Fe and Mn stains. Divided into two subunits:

- (3a) strong brown silty clay, medium-coarse, weak, few to common thick clay films, weakly cemented, gradational and clear contacts, lacks a strong horizontal fabric. Contact with (3b) is variably clear or gradational, contact with (2) is marked by a color/texture change and a weak stoneline.
- (3b) red pebbly silty clay, coarse, strong, common thick clay films, strongly cemented, gradational contacts. Strong horizontal fabric defined by preferential orientation of pebbles with long axes horizontal. Metamorphic clasts show fairly well developed weathering rinds. Lower contact with bedrock is variably sharp and indistinct.

(4) Phyllitic metavolcanics, gray-green to brown, fine grained, medium to highly weathered, medium hard, closely to very widely spaced closed to narrow fractures, frequent dark Fe and Mn stains, well foliated.

(5) Talc-sericite schist, reddish-yellow to white, fine grained, highly to completely weathered, soft, very closely spaced closed fractures, abundant Fe and Mn stains, strongly but discontinuously foliated.

(6) Phyllitic metavolcanics, gray-green to buff, fine grained, medium to highly weathered, medium hard, closely to widely spaced closed fractures, frequent dark Fe and Mn stains, well foliated, foliations closely spaced and discontinuous owing to local penetrative shearing. Contains irregular quartz pods probably derived from shearing of thin quartz veins.

(7) SILTY CLAY, mottled dark brown (7.5 YR 4/4) and olive yellow (2.5 Y 6/6), with abundant dark brown (7.5 YR 3/2) and black Fe and Mn stains. Medium, strongly developed prismatic peds, few to common moderately thick to thick dark brown clay films, strongly cemented, clear upper and gradational lower boundaries. Local well developed pseudoslickensides on ped faces. Unit contains trace coarse sand and very small pebbles. Color varies along the length of the trench, but strong prismatic aspect is persistent.

Trench excavated to refusal by
JD 690 backhoe, 36" bucket

Trench excavated to refusal by
JD. 690 backhoe, 36" bucket

SYMBOLS

S47W 48	Strike and dip of joint or fracture		Shear zones
N29E 51	Strike and dip of foliation		Thin shears
	Ground-water surface		Veins, showing relative width
	Contact, dashed where inferred		Gradational contact
	Cobbles and pebbles	/ / / / /	Vegetation lineament (on ground surfc

0 1 2 3 4 Feet

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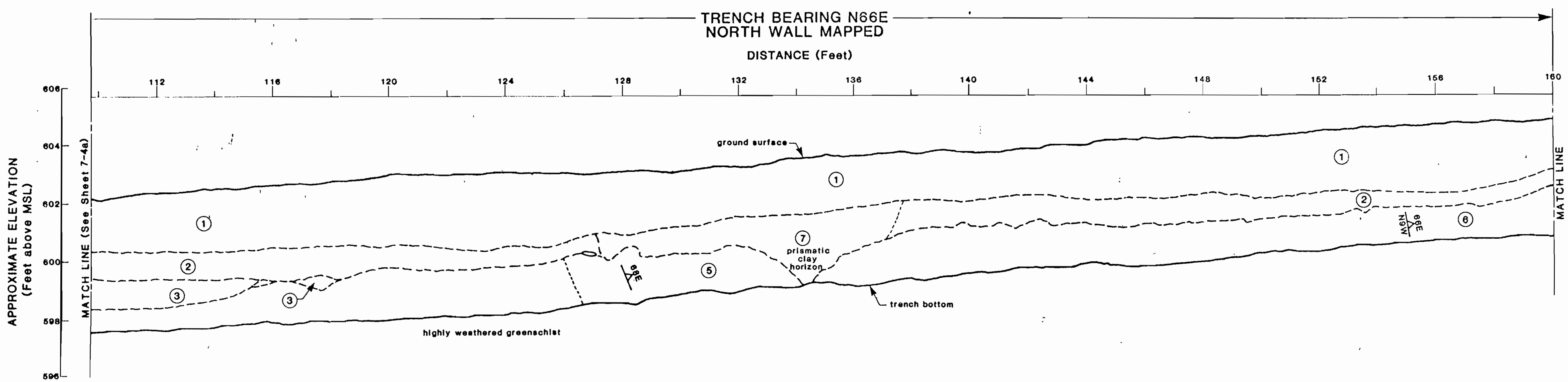
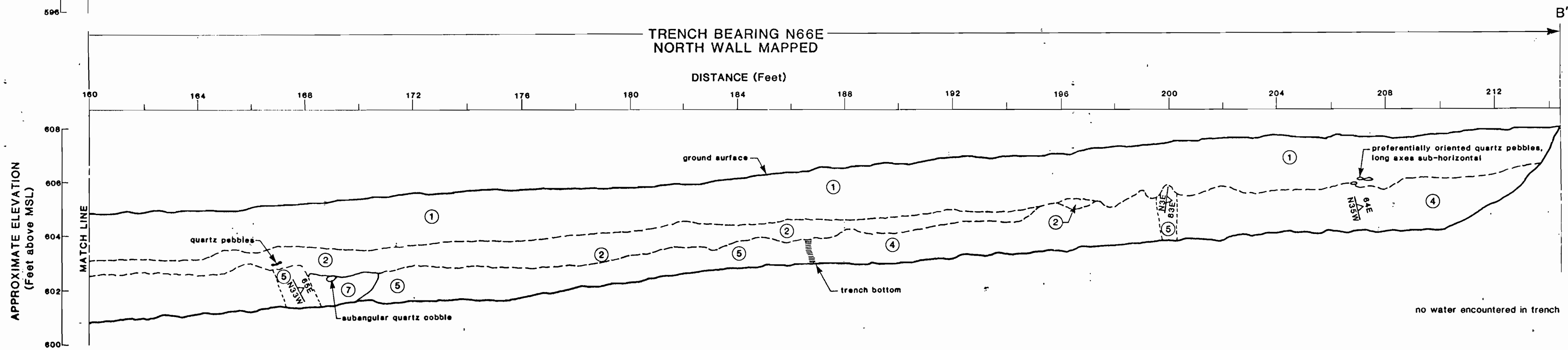
SANTA FE, N.M. 87501
505/982-2845

SUNSET SOUTH TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATIO
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

DATE	SCALE	PLATE NO
3/7/83	1:24	5-4a





0 1 2 3 4 Feet

See Plate 5-4a for Explanation and Notes.

SUNSET SOUTH TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

TEC
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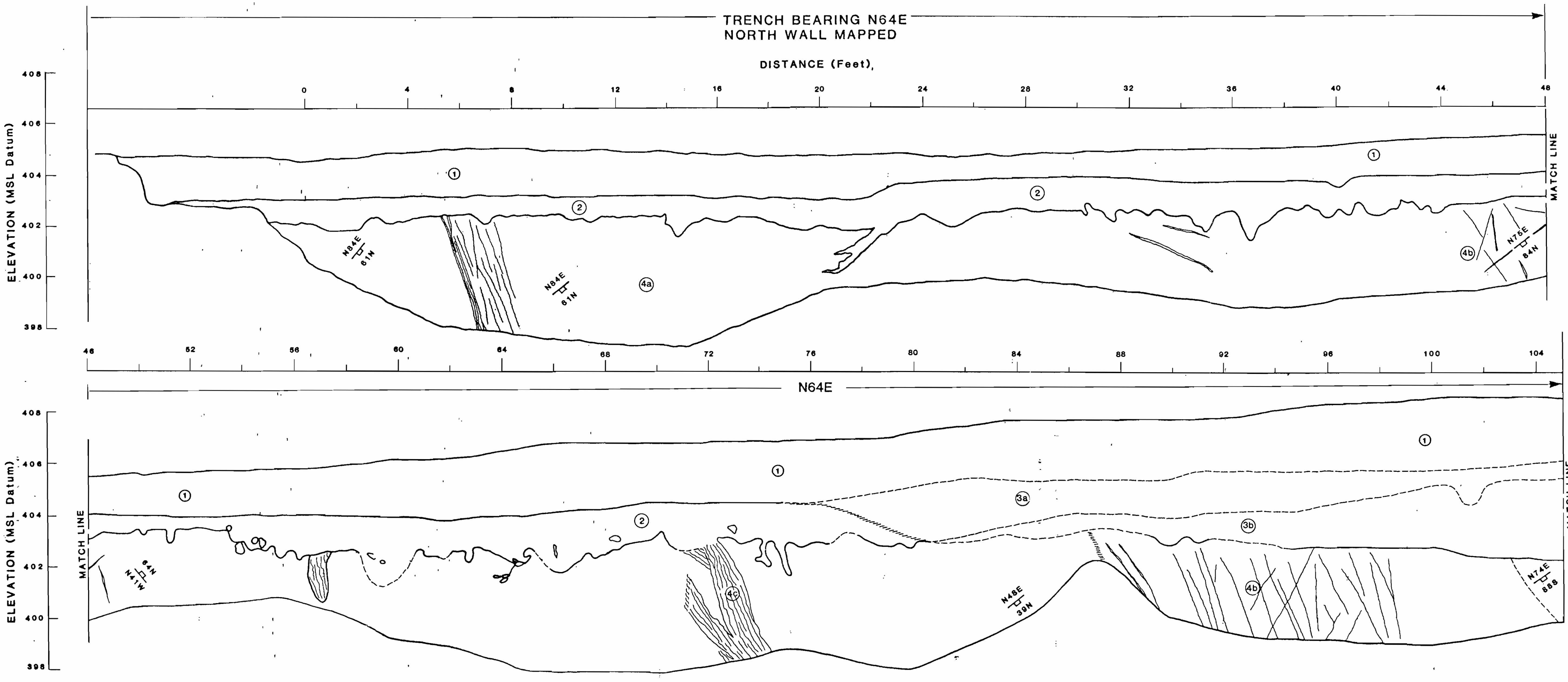
DATE	SCALE	PLATE NO.
3/7/83	1:24	5-4b



Explanation

(1) Colluvium, SANDY SILTY CLAY, strong brown (7.5 YR 55/7 dry) to red (2.5 YR 4/6 dry), coarse, moderate to weak prismatic peds, few thin clay films on peds and occasional gravel clasts, weakly cemented, generally clear unconformable contact with underlying unit. Between stations 0' to ±420' uppermost 8" has been disturbed by cultivation. Weak stonelines found locally along base contact, especially between stations 0' to 250'.

(2) Residual soil, SILTY SANDY CLAY, dark brown (7.5 YR 4/4 moist) to reddish gray (5 YR 5/2 moist), medium, strongly developed prism prismatic peds, few to common thin clay films, moderately to strongly cemented, clear upper boundary (unconformable), usually gradational lower boundary. This unit is the result of development of a soil profile on metavolcanic bedrock. Its characteristics are variable depending on the type of underlying bedrock.

(3a) Colluvium, SILTY SANDY GRAVELLY CLAY, dark brown (7.5 YR 4/4 moist) to light brownish gray (2.5 Y 6/2 moist), medium, strongly developed prismatic peds, common thin clay films, moderately to strongly cemented, clear upper boundary (unconformable), gradational lower boundary. Contains frequent subangular gravel clasts derived from volcanic, metavolcanic and granitic rock, local weakly developed stonelines on upper surface and within unit. This unit is the result of development of a soil profile on unit (3b).

(3b) Colluvium, CLAYEY SANDY GRAVELLY SILT, dark brown (7.5 YR 4/4 moist) to light brownish gray (2.5 Y 6/2 moist), medium, weak to moderately developed prismatic peds, moderately tc strongly cemented, gradational upper boundary with (3b), clear upper boundary (unconformable) with (1). Contains frequent subangular to angular gravel clasts as in (3a).

(4a) Metavolcanics (greenstone), gray-green to brown, fine grained, medium weathered, medium hard to hard, medium to widely spaced closed medium rough fractures; frequent dark Fe and Mn stains, generally massive. Locally cut by thin (±2-5 mm) quartz veins in web pattern. Contains local relict volcanic minerals, amygdules and vesicles. Local slightly weathered, extremely hard zones result from strong silicification of rock, forming bedrock steps in trench and gentle slope breaks on the ground surface.

(4b) Metavolcanics (greenstone), gray to gray-green, fine grained, medium to highly weathered, medium hard, closely to medium spaced medium rough parallel fractures filled by calcite (?) altered to light toned clay. Contact with adjacent (4a) is gradational over several feet.

(4c) Metavolcanics (greenstone), similar to (4a), but with closely spaced shears and local phyllitic texture. Much of the original metamorphic texture destroyed by shearing. Zone of highly weathered material extends below bottom of trench.

(4d) Metavolcanics (greenstone), similar to (4a), but highly weathered, soft and friable due to location in zone of fluctuating perched groundwater table. Fe staining ubiquitous.

(5) Metavolcanics (greenstone), gray-brown to light gray, fine grained, highly weatered, soft, no open fractures evident. Contains numerous interconnected subhorizontal veins up to 1" thick, filled with friable pinkish-gray to white soft granular material, possibly an "intrusive" clay or altered hydrothermal deposit. Host rock locally shows color variation and obscure relict volcanic texture.

(6) Metavolcanics (dike?) gray-brown to black, fine grained, medium to highly weathered, soft, medium spaced closed medium rough fractures. This rock probably represents a dike or more mafic interbed within the metavolcanic country rock.

SYMBOLS

S47W 48	Strike and dip of joint or fracture
N29E 51	Strike and dip of foliation
▽	Ground water surface
———— - - - -	Contact, dashed where inferred
	Cobbles and pebbles
	Shear zones
≈≈≈≈≈	Thin shears
	Veins, showing relative width
	Gradational contact
/ / / / /	Vegetation lineament (on ground surface)

Trench excavated to refusal by JD 710 backhoe, 36" bucket

0 1 2 3 4 Feet

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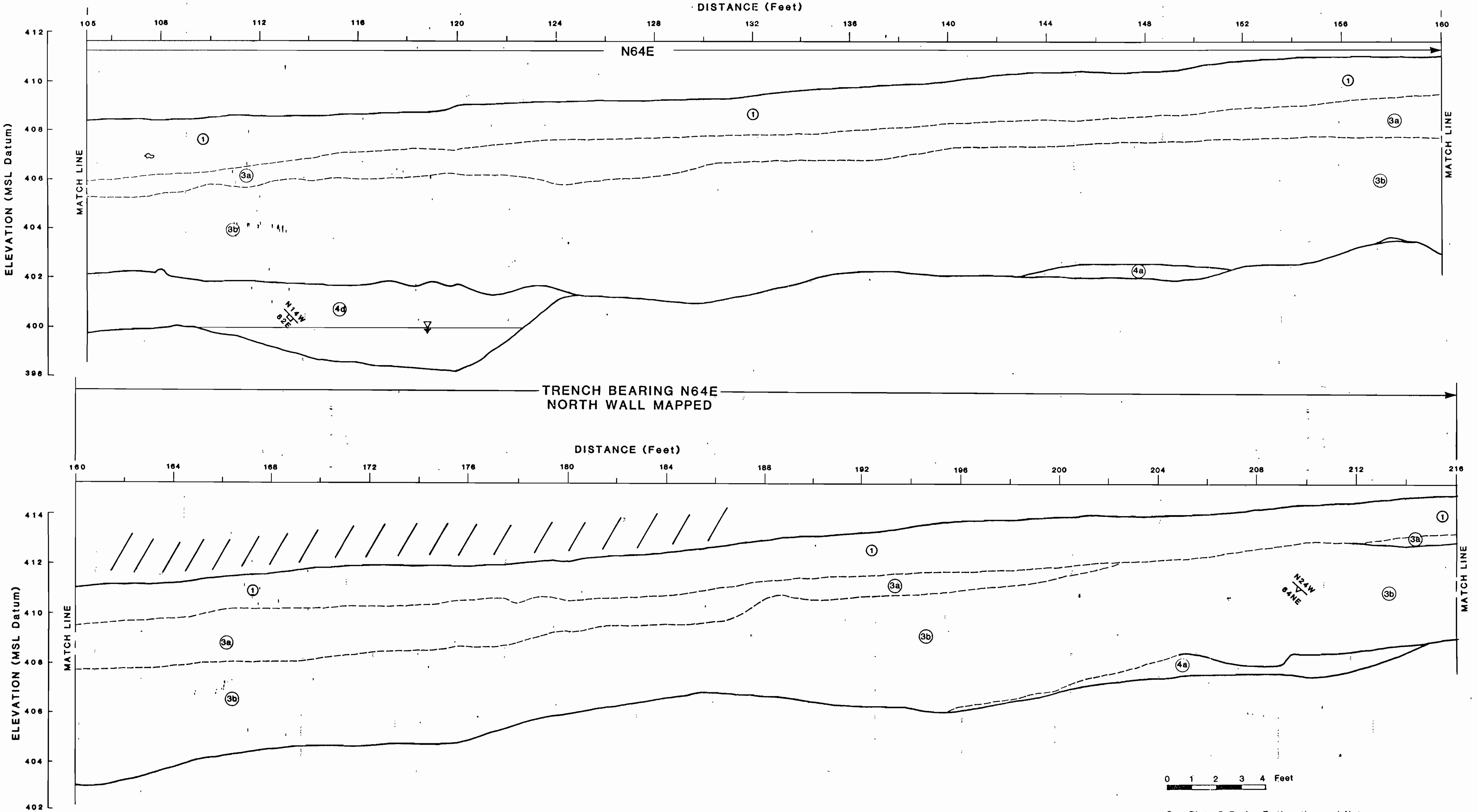
RUSSELL RANCH TRENCH LOG

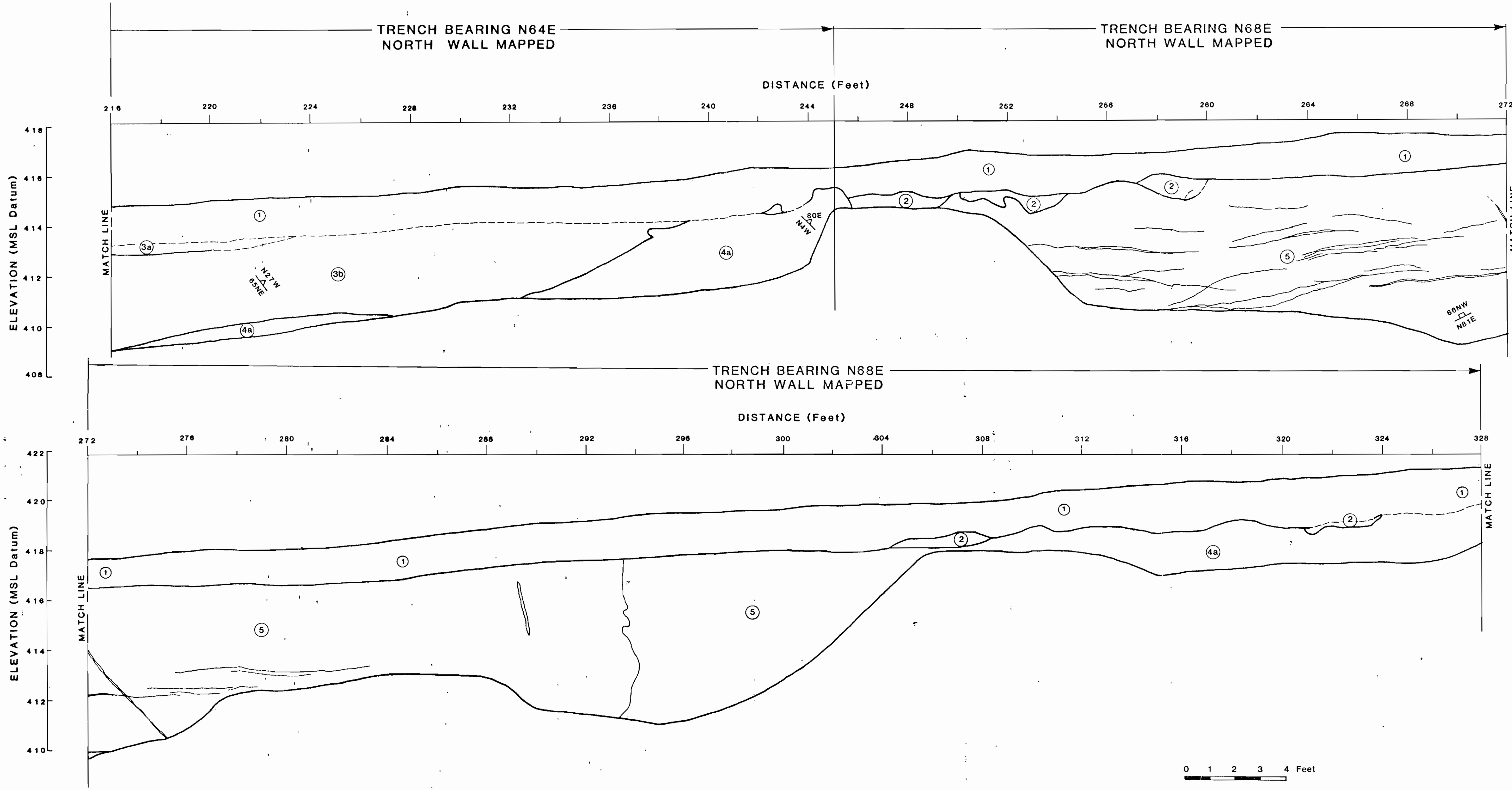
GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

DATE	SCALE	PLATE NO
3/7/83	1:24	5-7a



See Plate 5-7a for Explanation and Notes.

TEC TIERRA ENGINEERING CONSULTANTS INC.	RUSSELL RANCH TRENCH LOG		
	GEOLOGIC AND SEISMOLOGIC INVESTIGATION FOLSOM, CALIFORNIA AREA FOR U.S. ARMY CORPS OF ENGINEERS SACRAMENTO DISTRICT		
632 PASEO DE PERALTA SANTA FE, N.M. 87501 505/982-2845	DATE 3/7/83	SCALE 1:24	PLATE NO. 5-7b



See Plate 5-7a for Explanation and Notes.

TEC
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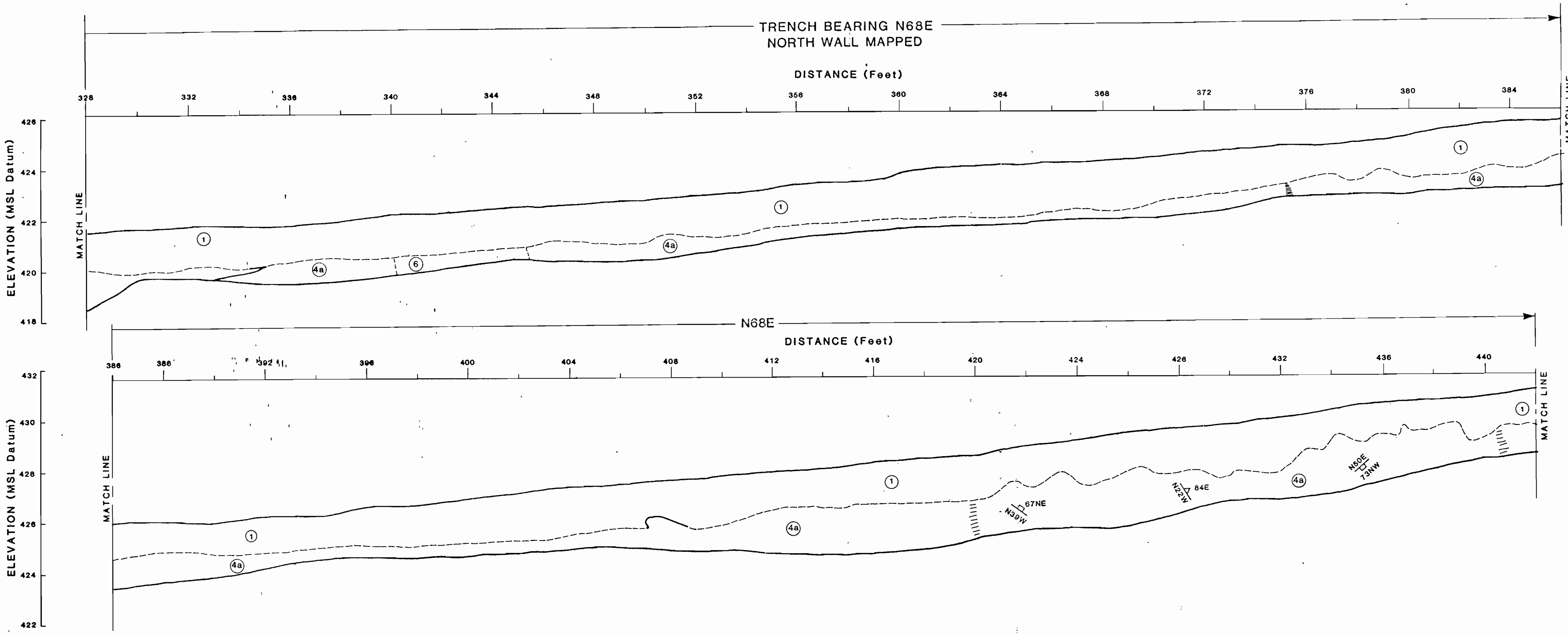
RUSSELL RANCH TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

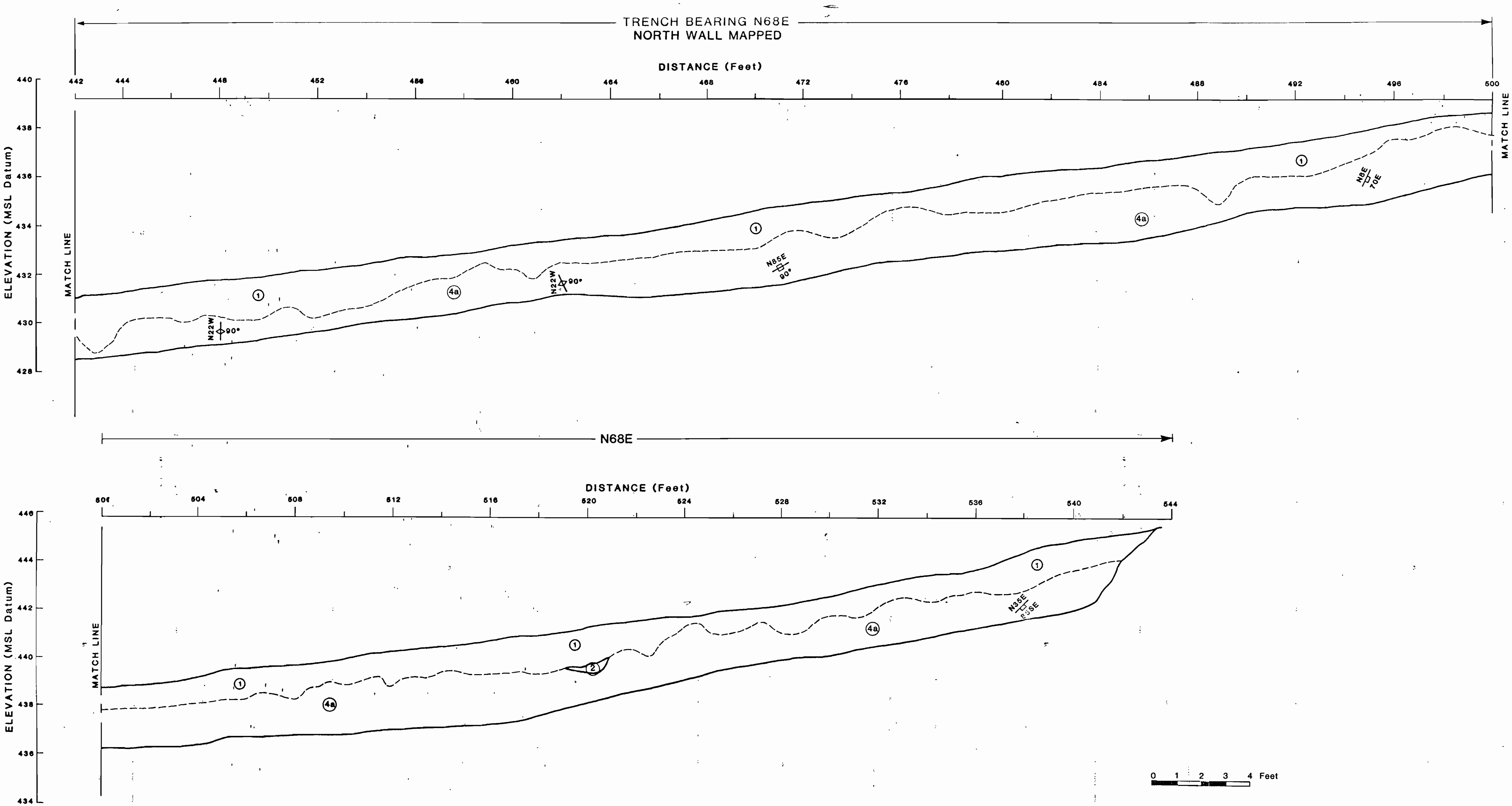
DATE	SCALE	PLATE NO.
3/7/83	1:24	5-7c



0 1 2 3 4 Feet

See Plate 5-7a for Explanation and Notes.

TEC TIERRA ENGINEERING CONSULTANTS INC.	RUSSELL RANCH TRENCH LOG		
	GEOLOGIC AND SEISMOLOGIC INVESTIGATION FOLSOM, CALIFORNIA AREA FOR U.S. ARMY CORPS OF ENGINEERS SACRAMENTO DISTRICT		
632 PASEO DE PERALTA SANTA FE, N.M. 87501 505/982-2645	DATE 3/7/83	SCALE 1:24	PLATE NO. 5-7d



See Plate 5-7a for Explanation and Notes.

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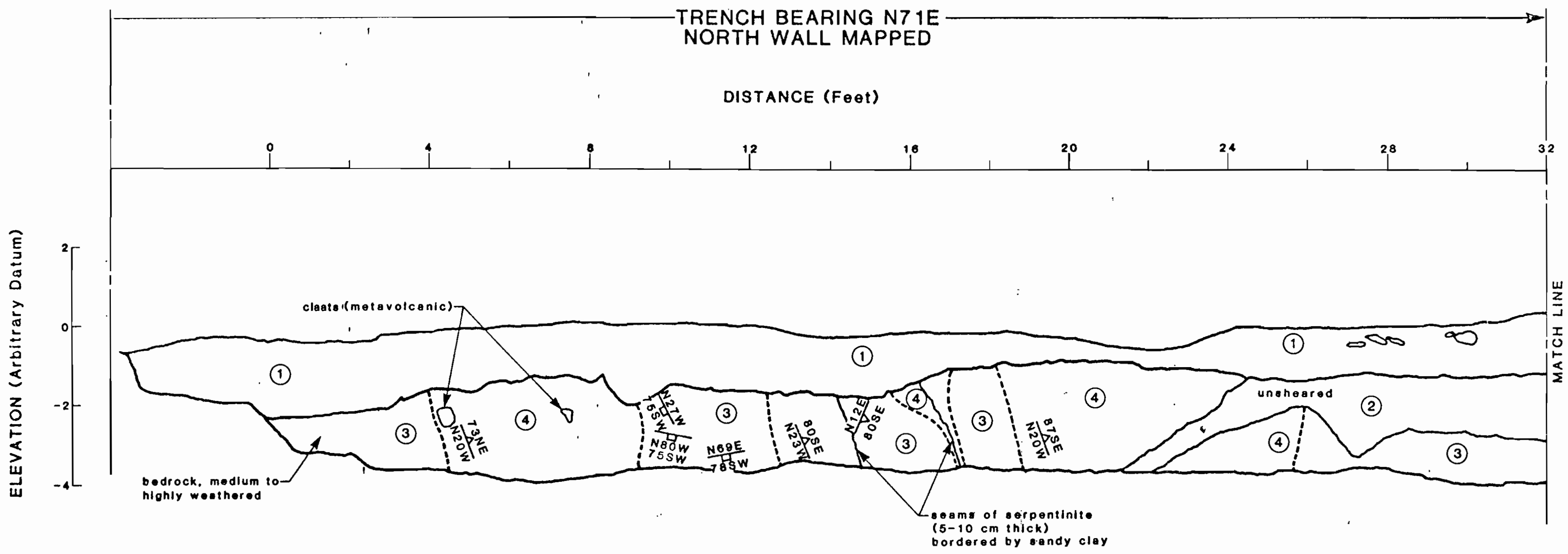
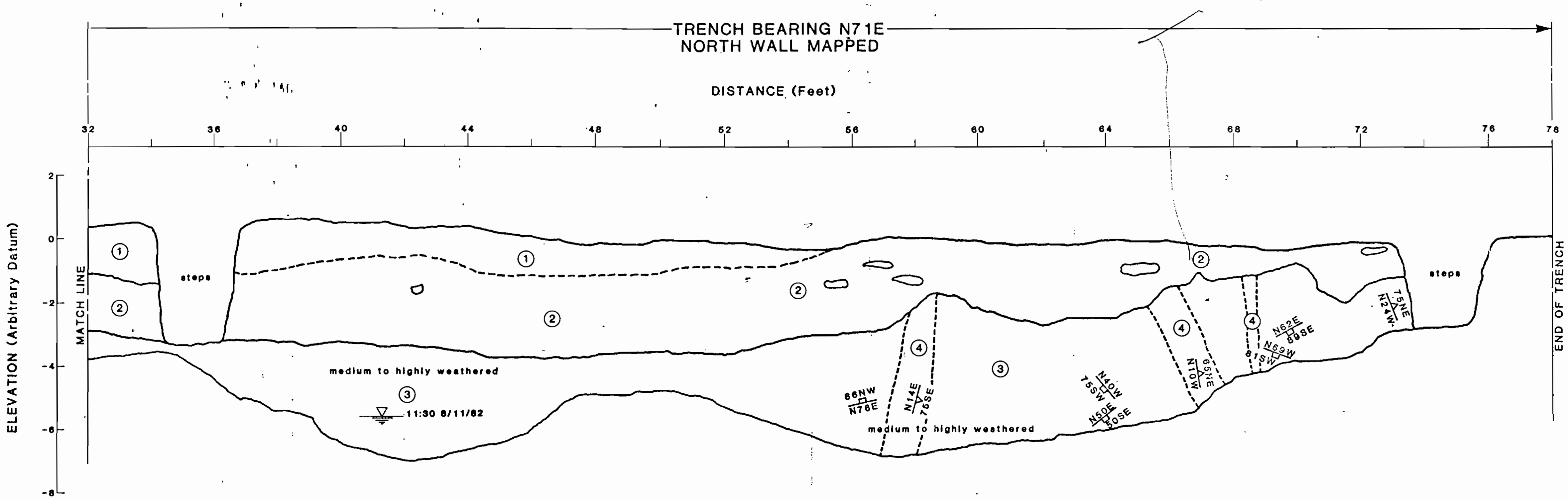
RUSSELL RANCH TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

DATE	SCALE	PLATE NO.
3/7/83	1:24	5-7e





Trench excavated to refusal by JD 510B backhoe, 24" bucket

EXPLANATION

(1) Colluvium (disturbed), SANDY SILTY CLAY, reddish brown, medium— coarse, weak to moderate blocky peds, few to common thin clay films on peds, weakly cemented, indistinct boundaries with underlying units. Contains many large, unweathered rounded amphibolite, greenschist and metavolcanic cobbles. This soil is disturbed, and is probably old fill.

(2) Colluvium (disturbed), GRAVELLY SANDY CLAY, dark gray to dark reddish brown, weak, few thin clay films on peds, moderate to weakly cemented, clear boundary with underlying bedrock. Local pseudoslickensides on ped faces, contains many large, unweathered rounded amphibolite, greenschist and metavolcanic cobbles. This soil is highly disturbed.

(3) Metavolcanics, green to buff, fine grained, medium to highly weathered, widely fractured, medium hard, dark Fe stains on fracture surfaces, locally fractures coated with fine sandy clay.

(4) Metavolcanics, gray green to buff, very fine to fine grained, medium to highly weathered, closely sheared and fractured, medium hard, abundant dark Fe stains on surfaces, locally contains medium to highly weathered unsheared clasts of metavolcanics or irregular chert (elongated parallel to foliation and shearing). Local 2-4" thick lenticular serpentinite bodies oriented parallel to shearing.

0 1 2 3 4 Feet

SYMBOLS

S47W 48	Strike and dip of joint or fracture
N29E 51	Strike and dip of foliation
▽	Ground water surface
———— - - - -	Contact, dashed where inferred
	Cobbles and pebbles
	Shear zones
	Thin shears
	Veins, showing relative width
	Gradational contact
/ / / / /	Vegetation lineament (on ground surface)

TEC
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DUNLAP RANCH TRENCH LOG

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
FOR U.S. ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

DATE	SCALE	PLATE NO.
3/7/83	1:24	5-8

SEPARATION OF FRACTURE WALLS

Description	Separation of Walls In mm
Closed	0
Very Narrow	0 - 0.1
Narrow	0.1 - 1.0
Wide	1.0 - 5.0
Very Wide	5.0 - 25.0 +

FRACTURE FILLING

Description	Definition
Clean	No fracture filling material
Stained	Discoloration of rock only, no recognizable filling material
Filled	Fracture filled with recognizable filling material

SURFACE ROUGHNESS

Classification	Description
Smooth	Appears smooth and is essentially smooth to the touch, may be slickensided.
Slightly Rough	Asperities on the fracture surfaces are visible and can be distinctly felt.
Medium Rough	Asperities are clearly visible and fracture surface feels abrasive to touch.
Rough	Large angular asperities can be seen. Some ridge and high side angle steps evident.
Very Rough	Near vertical steps and ridges occur on the fracture surface.

TIERRA ENGINEERING CONSULTANTS

SOIL AND ROCK DESCRIPTIVE TERMINOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 5-9a

DEGREE OF WEATHERING

Descriptive Term	Discoloration Extent	Fracture Condition	Surface Characteristics	Original Texture	Grain Boundary Condition
Unweathered	None	Closed or Discolored	Unchanged	Preserved	Tight
Slightly Weathered	Less than 20% of fracture spacing on both sides of fracture.	Discolored, may contain thin filling	Partial discoloration	Preserved	Tight
Medium Weathered	Greater than 20% of fracture spacing on both sides of fracture.	Discolored, may contain thick filling	Partial to complete discoloration not friable except poorly cemeted rocks	Preserved	Partial opening
Highly Weathered	Throughout	—	Friable and possiby pitted	Mainly preserved	Partial separation
Completely Weathered	Throughout	—	Resembles a soil	Partly preserved	Complete separation

ROCK HARDNESS

Classification	Field Test
Very Soft	Can be peeled with a knife, material crumbles under firm blows with the sharp end of a geologic pick.
Soft	Can just be scraped with a knife, indentations of 2 to 4 mm with firm blows of the pick point.
Medium Hard	Cannot be scraped or peeled with a knife but can be scratched with knife point. Hand held specimen breaks with firm blows of the pick.
Hard	Difficult to scratch with knife point, cannot break hand held specimen.

DISCONTINUITY SPACING

Spacing	Description for Joints, Faults or Other Fractures
More than 6 feet	Very widely (fractured or jointed)
2 - 6 feet	Widely
8 - 24 inches	Medium
2-1/2 - 8 inches	Closely
3/4 - 2-1/2 inches	Very closely
1/4 - 3/4 inch	Extremely close
Less than 1/4 inch	

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SOIL AND ROCK DESCRIPTIVE TERMINOLOGY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 5-9b

SECTION 6

the broader aspects are repeated here, to provide a general context for the tectonic model.

Folsom Reservoir is located on the west side, slightly north of the mid-section, of the Sierra Nevada Foothills Belt, a zone about 30 to 50 miles wide and 200 miles long along the northwest flank of the Sierra Nevada. The Foothills Belt is underlain mainly by metamorphic rocks of Paleozoic and middle Mesozoic age, but the metamorphic rocks were intruded in the reservoir area by the Rocklin and Penryn plutons of late-middle Mesozoic age (about 128 to 136 mybp; Swanson, 1978). The geologic structure of the foothills belt is complex, but its major elements are roughly parallel to the overall trend of the Sierra Nevada. Details of the geologic structure, as it may influence seismicity, are discussed in paragraph 6.3.1.

The Foothills Belt is bounded on the east by the Sierra Nevada batholith, a complex of chiefly granitic intrusive rocks, predominantly of middle to late Mesozoic age. Individual plutons comprising the batholith intruded and locally contain inclusions (roof pendants) of metamorphic rocks similar to those exposed in the Foothills Belt. Both the foothills metamorphic rocks and the granitic rocks of the higher Sierra Nevada were beveled by erosion to a relatively planar surface before general uplift of the mountain range to its present topographic form.

The metamorphic and igneous rocks of the foothills and Sierra Nevada descend westerly beneath younger sedimentary formations of the Great Valley. As much as 10 miles of sedimentary fill overlies metamorphic "basement" in the Great Valley (Hackel, 1966). In the Sacramento Valley, the great majority of these deposits are Mesozoic (older than about 65 mybp) in age, but an upper section of Cenozoic (younger than 65 my) sediments reaches a thickness of roughly 3,000 to 6,000 feet west of the study area. The axis of thickest Cenozoic sediments is located on the western side of the Great Valley. In the Sacramento Valley, it is about one-third of the distance, west to east, between outcrops of pre-Cenozoic rocks at the valley margins (Harwood and Helley, 1982).

If the topographic surface of the western Sierra Nevada is extended perpendicular to regional strike beneath the Sacramento Valley, it projects near or somewhat about the base of Cenozoic sediments (see Plate 6-1). Thus, it has been implicitly or explicitly assumed that the metamorphic and igneous block underlying both the Sierra Nevada and Great Valley has behaved during Cenozoic time as a more-or-less intact unit that was regionally tilted to the west during the tectonic activity that gave the Sierra Nevada its present form (for example see Batemen and Wahrhaftig, 1966 and Grant and others, 1977). A low level of earthquake activity in the Sierra Nevada and Great Valley, as compared to more tectonically active adjoining regions, also suggests contemporary tectonic unity of the Sierra Nevada and Great Valley. This combined unit is referred to here as the Sierran Block. The following subsections outline the bounding tectonic elements of the Sierran Block and describe geophysical evidence regarding its internal character.

6.1.1 Tectonic Boundaries of the Sierran Block

Geologic boundaries of the Sierran Block are well marked to the east, west, and south, but are poorly defined on the north. The eastern and southern boundaries are seismically active, and the very active San Andreas fault parallels the western boundary.

6.1.1.1 Western Boundary. The Coast Ranges, transected by the San Andreas fault, are located west of the Great Valley and Sierran Block. In the extreme southwest part of the Great Valley, only a narrow (5 mile wide) range separates the valley from the San Andreas fault. The belt of mountains between the San Andreas fault and the Great Valley widens gradually to a maximum of about 75 miles at the north end of the Sacramento Valley. On a line through Folsom perpendicular to the structural grain, about 50 miles lie between the San Andreas fault and the west edge of the Sacramento Valley. Other faults, some geologically active, trend generally parallel to the Coast Ranges and to the San Andreas fault in this 50-mile interval. Motion on these faults is considered to be related to the San Andreas system (see paragraph 6.2.1).

The Coast Ranges province abuts the Great Valley along a zone of thrust faulting that is exposed over most of the length of the Sacramento Valley and is inferred in the San Joaquin Valley. The thrust system was formed by subduction of oceanic crust (possibly including continental fragments) eastward beneath the Sierran Block (Bailey and others, 1970). The main part of this tectonic activity occurred in the Late Mesozoic Era, prior to about 65 my ago. Varying interpretations describe the fault zone as vertical (Blake and Jones, 1981) to east-dipping at less than 45° (Etter and others, 1981).

Deformation along the west Great Valley margin continued much later, as evidenced by folded and faulted Cenozoic sediments that are mostly Pliocene in age (about 3 to 5 my). Cenozoic deformation resulted in an assymetric downwarp of the Great Valley. The downwarp is much steeper on the west; on the east it merges with the regional westward tilt of the Sierra Nevada. Between the east and west limbs of the downwarp is a zone 15 to 20 miles wide in which the Cenozoic strata reach their maximum thickness but are relatively flat-lying. The geometry of these strata suggests deposition was contemporaneous with down-folding on both sides of the valley.

In the Sacramento Valley, structural relief on the steep west limb of the downwarp is about 2,000 feet (Page, 1974). This limb of the fold, which viewed by itself has the form of a monocline, is steepest in the area about 20 miles either side of Putah Creek, roughly across the valley from Folsom. The monoclinal fold probably formed by movement at depth on the Coast Range Thrust fault or on zones of plastic deformation within the Franciscan rocks of the Coast Ranges. The position of the fold 10 to 20 miles east of the surface trace of the Coast Range fault supports the interpretation of an easterly dip for the Sierran Block-Coast Range boundary.

In the vicinity of the Sacramento Delta, east-north-east of San Francisco, the Sierran Block-Coast Range boundary abruptly changes strike, from about N10^{O}W along the Sacramento Valley margin, to about N30^{O}W in the San Joaquin Valley. This is paralleled by a change in orientation of the Sierra Nevada. The monoclinal fold along the west side of the Great Valley is also interrupted in the Sacramento Delta area. Disturbance on a complex branching structure of the San Andreas fault system permitted breaching of the Coast Ranges and diversion of the Great Valley drainage to San Francisco Bay instead of to its former outlet in the southwest part of San Joaquin Valley. This change in the drainage pattern is dated at about 0.5 mybp (Hall, 1966; Meyers and others, 1980). At least one fault on trend with the monocline in the delta area, the Antioch fault (Burke and Helley, 1973), has moved historically. Stratigraphic evidence suggestive of Quaternary vertical displacement on inferred faults in the delta area has also been presented by Shlemon (1971) and Shlemon and Begg (1975).

The Coast Range Thrust is associated with micro-earthquake activity (Bruce Bolt, personal communication, 1982), but there is no discernible relationship of macro-seismicity to the Coast Range Thrust or to the west boundary of the Sierran Block in the Sacramento Valley. Historically, damaging earthquakes in the Coast Ranges have been located along or near faults that are clearly related to the San Andreas system (Real and others, 1978: Jennings, 1975). Fault-plane solutions for earthquakes in the Coast Ranges almost invariably indicate right-lateral strike-slip motion on planes roughly parallel to the San Andreas fault. Focal depths are generally less than 10 miles (Hill, 1978).

6.1.1.2 Eastern Boundary. East of the Sierra Nevada lies the Basin and Range Province, an area of crustal extension reaching from near the California-Nevada border to central Utah. This region of fault-block mountains and valleys terminates near the eastern escarpment of the Sierra Nevada. The escarpment is not generally a single front, but is typically formed along a series of en echelon normal faults separated by warped blocks. The eastern boundary of the Sierran Block and of the Sierra Nevada is here considered to be the westernmost zone of Basin-and-Range type normal faulting that includes the main Sierra frontal escarpment(s). This belt of normal faults, most with prominent topographic expression, bends from north or north-northwest along the southern Sierra to northwest along the northern Sierra. Faults comprising the boundary south of Lake Tahoe trend somewhat more north-south than the boundary itself, because individual faults step westward en echelon from south to north.

Christensen (1966) summarized the character and age of faulting on the eastern escarpment, as part of a general analysis of late Cenozoic crustal movement in the Sierra Nevada. His interpretations, which are generally supported by more recent work cited below, indicate the following:

1) Structural relief on the escarpment, which may reach 20,000 feet, resulted from a combination of warping/downfaulting to the east and westward tilting of the down-thrown blocks.

2) Parts of the Basin and Range Province rose along with the Sierra Nevada prior to formation of the eastern escarpment.

3) The last major increment of uplift of the Sierra Nevada occurred between 9 and 3 mybp,

while faulting along the eastern escarpment took place mostly in the past 3 my.

4) The northern Sierra Nevada (between the Yuba and Tuolumne Rivers) behaved to a first approximation as a rigid block that was tilted westward with only very minor faulting or folding within the block.

5) Uplift of the southern Sierra Nevada was probably accompanied by warping along the Sierra Nevada-Great Valley boundary, such that the range crest has been uplifted more than the foothills.

The greatest topographic relief, seismicity, and continuity of individual faults along the eastern boundary is in the southern Sierra Nevada, abuting the Owens Valley. This is in accord with other indications (Marchand, 1977; Saleeby and Sharp, 1980) that uplift has been greatest in the south. Geologic evidence (Bacon and others, 1982) indicates downwarping of the Owens Valley began about 6 mybp and that downfaulting of the Owens Valley graben was underway by 3 mybp. Before this tectonic activity, the Owens Valley area appears to have been part of a broader uplift that included the Sierra Nevada, as well as part of the present Basin and Range Province (Slemmons and others, 1979; Stewart, 1978).

On the order of 15,000 feet of vertical offset is typical on faults bounding the southern Sierra Nevada. This is believed to have occurred mostly over about the last 3 my. Offset of about 3,000 feet has been observed on the 700,000-year-old Bishop Tuff, and 13 feet of vertical fault displacement occurred in the Owens Valley earthquake of 1872. Right-lateral slip was also observed, but horizontal slippage along the eastern escarpment is limited by the en echelon arrangement of individual faults.

North of Owens Valley, the range-front fault-escarpment steps west along volcano-tectonic depressions in Long Valley and Mono Basin. Faults there are geologically young, and vertical offset is comparable to the Owens Valley, but historic displacement has not been recorded. However, many earthquake epicenters, including two over magnitude 6, have been located in Long Valley (Real and others, 1978). Work by Huber (1981) in the area west of Long Valley suggests uplift and tilt of the Sierra Nevada in that area has occurred at roughly constant rate for the past 10 my, but that down-faulting to the east has kept pace or slightly exceeded uplift over the past 3 my. Total uplift in the past 10 my is computed at about 7,000 feet, with downfaulting on the east, confined to the past 3 my, amounting to about half that figure.

From Owens Lake northward, the eastern escarpment typically has multiple steps representing individual fault traces, offset laterally by 5 to 15 miles. Tilting and warping affects the blocks between faults. Slemmons and others (1979) estimate uplift in the Carson Pass-Sonora Pass area (between Mono Lake and Lake Tahoe) at about 0.1 mm/year for the past 10 to 12 my. This is about 1/2 to 1/3 the rate computed by Huber (1981) near Long Valley.

Moderate earthquake activity has occurred historically in a diffuse band about 40 miles wide that extends roughly parallel to the California-Nevada state line from Mono Lake to Lake Tahoe, continuing northwestward on that trend beyond Lassen Peak, well north of the physiographic boundaries of the Sierra Nevada (Smith, 1978). Three earthquakes greater than magnitude 6, located 10 to 20 miles north of Lake Tahoe, are included in this band (Real and others, 1978). Surface displacement was recorded in the 1875 Mohawk Valley earthquake, about 40 miles northwest of Lake Tahoe (Jennings, 1975).

As elsewhere, the eastern boundary of the Sierra Nevada north of Lake Tahoe is a zone of normal faults, but the escarpment characteristic of the mountain front further south is replaced by a series of relatively symmetric, northwest-trending grabens. The westernmost line of fault valleys (Mohawk, Long, Spring Garden, and American) constitutes the Plumas Trench (Durrell, 1966), which is taken as the eastern boundary of the northern Sierran Block. This structure continues northwest of Lake Almanor into the volcanic terrain of the Cascade Range. The faults affect volcanic rocks of Pliocene age, and uplift in this part of the Sierra Nevada is probably comparable in age to that occurring further south, although somewhat less in magnitude. Durrell (1966) reported significant left-lateral offset on the southwest side of the Plumas Trench, in contrast to the right-lateral displacement along the southern Sierra escarpment.

6.1.1.3 Northern and Southern Boundaries The north and south boundaries of the Sierran Block are remote from Folsom but they provide evidence concerning the mode of deformation of the block as a whole. Geologic evidence and earthquake activity indicate a much more substantial and tectonically active break in the south than in the north. Indeed, it is difficult to define the northern boundary precisely.

The metamorphic and plutonic rocks of the Sierra Nevada abut northward against volcanic rocks of the Cascade Range that crop out in a 60-mile-wide, northeast-trending zone separating the Sierra Nevada and Klamath Mountains. The southern edge of the zone, which is taken as the boundary between the Sierra Nevada and Cascade Range, passes just south of Lake Almanor. Windows in the volcanic cover on both sides of the zone expose late Mesozoic-early Cenozoic rocks, suggesting that the area was not included in uplift of the Sierra Nevada or Klamath Mountains.

While the Sierra Nevada is considered to terminate northward at the Sierra Nevada-Cascade Range boundary, the Great Valley portion of the Sierran Block extends further, to approximately the southern end of the Klamath Mountains. The Great Valley has subsided relative to volcanic rocks of the Cascades, along a line that is the extension of the eastern valley margin further south. This subsidence formed the southwest-dipping Chico Monocline. Many anastamosing faults and fractures occur in the Pliocene volcanics (Tuscan Formation) along the monocline axis (Harwood and others, 1981). The monocline fault zone aligns generally with western elements of the Foothills fault system, including the Cleveland Hills fault, which broke in the 1975 Oroville earthquake. Fault displacement is interpreted to have occurred progressively during deposition of the Tuscan volcanics, possibly averaging as much as 0.01 mm/year, but probably decreasing over time. Last displacement reportedly occurred within the past 1.1 my.

Geologic evidence favors extension of the Sierran Block northward in the Great Valley at least to the north end of the Chico Monocline near Red Bluff, and probably including the structurally more complicated zone between Red Bluff and the valley terminus a few miles north of Redding (Harwood and Helley, 1982). A faint band of seismicity trends east-west through Redding, aligning approximately with the seismically very active Mendocino fault zone offshore (Real and others, 1978). This band of epicenters intersects a projection of the Plumas Trench just north of Lake Almanor.

A second diffuse band of low-level seismicity trends about N30°E through Lake Almanor and Chico, passing a few miles north of Sutter Buttes in the Sacramento Valley (Real and others, 1978). This band coincides approximately with the basement discontinuity forming the Cascade-Sierra Nevada boundary, but does not correlate with any known feature in the Sacramento Valley.

There is little question as to the location of the southern boundary of the Sierran Block. A major fault, the Garlock, separates the Sierra Nevada and Great Valley from the Mojave Block to the south. Late Cenozoic left-lateral movement of 35 miles or more has been documented along the fault, decreasing eastward to zero somewhere in the southern Death Valley (Wernicke and others, 1982; Wright, 1976). This westward movement of the southern Sierra Nevada is very likely related to crustal extension responsible for the Owens Valley and other pull-apart features along and east of the eastern escarpment of the Southern Sierra Nevada. Very strong earthquake activity is recorded in a band 40 to 50 miles wide parallel to and north of the Garlock fault. This band includes the historically active White Wolf fault, which parallels the Garlock, and smaller, poorly mapped faults east and north of Bakersfield that trend generally northwest, parallel to the Sierra Nevada and Great Valley.

6.1.2 Geophysical Character of the Sierran Block

The most direct measure of deep geologic structure is by observation and analysis of seismic wave propagation resulting either from earthquakes or from controlled explosions. Detailed modern studies find the internal structure of the earth's crust and underlying mantle to be very complex. A well-defined increase in seismic velocity with depth, from between 6 and 7 km/sec to about 8 km/sec, may approximate the boundary between the rigidly-behaving crust and the deeper zone of increasingly plastic deformation (the upper mantle and asthenosphere). Whatever its significance, this velocity contrast provides a useful marker for comparing crustal characteristics in different areas.

Seismic observations (see Hill, 1978 and Prodehl, 1979 for summaries) indicate the crust is relatively thick beneath the high Sierra Nevada, thinning both east and west. Assuming that the base of the crust is located at the depth of the maximum velocity gradient in the crust-mantle transition zone, Prodehl (1979) computed the crust beneath the northern high Sierras to be about 42 to 43 km (26 miles) thick, decreasing rather uniformly southeastward from Lake Tahoe through the Owens Valley to about 33 km (20 miles) thick at

China lake. An earlier interpretation of the same data (Eaton, 1966) shows crustal thickness beneath the Sierra Nevada increasing rather than decreasing southward, and other authors (e.g., Smith, 1978) estimate maximum thickness beneath the Central Sierra to exceed 50 km. The variation in estimated thickness relates in part to differing criteria used in defining the base of the crust.

While alternative interpretations differ in detail, the crust is clearly shown to be much thinner eastward beneath the Basin and Range Province in Nevada. On a line surveyed between San Francisco, California and Fallon, Nevada (passing just south of Folsom, crustal thickness is interpreted to decrease 25 to 50 percent from its maximum beneath the Sierra Nevada, to a minimum thickness 150 miles or less to the east. Published reports vary on whether this west-to-east transition in the Northern Sierra Nevada occurs abruptly at the eastern escarpment of the range or, as a more gradual transition, but more recent interpretations (e.g., Prodehl, 1979) favor a gradual transition.

Evidence of a relatively deep crust in the Foothills Belt comes from two well-located aftershocks of the 1975 Oroville earthquake originating at a depth of 40 km (25 miles), and from several earthquakes near Mariposa located deeper than 30 km (19 miles) (Marks and Lindh, 1978). Oroville and Mariposa are about 45 miles north and 75 miles south of Folsom, respectively.

The crust thins westward beneath the Coast Ranges, to about 25 km (16 miles). The transition zone from Great Valley to Coast Ranges is ill-defined and cannot be reliably characterized from seismic data. Older interpretations show a thinning of the crust to 20 km (12 miles) or less beneath the Great Valley, but this appears less likely in view of the deep earthquakes observed more recently in the Foothills Belt. Sharp discontinuities in crustal thickness are not observed either to the south or to the north. The relatively narrow, very thick crustal zone beneath the northern Sierra crest appears to thin slightly south of the latitude of Fresno, but remains relatively thick (30 to 36 km) southward through the Tranverse Ranges and Mojave Block. The transition from the Sierra Nevada northward to the Cascade Ranges is poorly explored, but the depth to the base of the crust is probably 35 to 40 km in the zone between Shasta Lake and Oroville.

Gravity data supplement the general crustal picture based on seismic information. A broad gravity low extending west to the eastern Great Valley is generally interpreted to represent a mafic "root" of the Sierra Nevada batholith, reaching into the more dense material below the crust (Oliver, 1977); however, Eaton and others (1978) observe that the low is not centered on the batholith exposed in the high Sierra, but on or near the eastern escarpment. This is in agreement with geologic evidence that the western Great Basin was once part of a more general crustal uplift that included the Sierra Nevada.

The gravitational force remains relatively low across the entire Great Basin, extending hundreds of miles east of the Sierra Nevada. In contrast, it increases steeply to a maximum in the Great Valley, slightly decreasing further west beneath the Coast Ranges. Thus, seismic velocities best define the eastern boundary to the Sierran Block, while gravity delineates the western boundary more clearly. Both these types of data suggest crustal variations between the Sierra Nevada and Great Valley.

In contrast to differing properties suggested by seismic velocities and gravity, a third geophysical measurement, heat flow, appears to define the Sierran Block as an integral unit. A symmetrical zone of anomalously cool crust is centered approximately on the Sierra Foothills Belt, becoming gradually warmer east and west to the Sierra Nevada-Great Basin and the Great Valley-Coast Ranges boundaries (Blackwell, 1978; Lachenbruch and Sass, 1978). North of the Sierra Nevada, the zone of low heat flow bends west to the Klamath Mountains, then extends north along the Pacific Coast from Cape Mendocino into Canada. The zone does not extend continuously southward through the Tranverse Ranges and Mojave Block, but picks up again in the Peninsular Ranges. This geometry is presumed to relate to subduction of oceanic crust along the western continental margin five or more million years ago.

6.2 STATE OF STRESS

The state of stress in the earth's crust is thought to result primarily from movements in a semi-fluid zone at depth, the asthenosphere, that rafts crustal fragments or "plates" over the earth's surface. Differences in density, rigidity, thickness, and other physical properties affect the ways moving plates interact at the plate boundaries. While the basic mechanics of plate tectonics are now understood relatively well, the details of plate interaction and particularly of intra-plate deformation cannot yet be fully explained. Thus, no scientific consensus exists on the specific geotectonic forces affecting the Sierran Block. Paragraph 6.2.1 describes geologic and seismologic evidence regarding the state of crustal stress between major crustal segments, including the Sierran Block; paragraph 6.2.2 discusses plate tectonic relations; and paragraph 6.2.3 addresses the state of stress within the Sierran Block.

6.2.1 Regional Stress Patterns

One method of assessing the state of stress in a given segment of the earth's crust is to analyze the orientation of fractures and other deformation, assuming elastic behavior (i.e., that the shearing and/or strain observed are analytical functions of the applied stress). Difficulties in applying this method result from 1) inhomogeneities and nonelastic behavior in the crust, and 2) the fact that features formed in even very recent geologic time may not reflect the contemporary state of stress. Earthquake focal mechanisims (fault-plane solutions) and in-situ stress measurements can, therefore, provide a useful check on geologic observations. In the few areas where many well-constrained fault-plane solutions are available (e.g., San Andreas fault system), that evidence is probably the best indicator of the contemporary stress regime.

Probably the most systematic determination of stress in the western United States is summarized by Zoback and Zoback (1980). They characterize the Coast Ranges, Sierra Nevada, and Basin and Range stress fields as follows:

	Principal Stress Orientation					
Province	Maximum		Intermediate		Minimum	Main Data
"San Andreas" (Coast Ranges)	N To NNE	>	Vertical	>	W to WNW	Seismologic
Sierra Nevada	NNE	=	Vertical	>	WNW	Geologic
Basin and Range (Western)	Vertical	=	NNE	>>	WNW	Geologic & Seismologic

These orientations are generally consistent with the directions inferred from fault-plane solutions (Smith and Lindh, 1978; Smith, 1978). In the area under San Andreas influence west of the Sierran Block, fault displacements are dominantly right-lateral, strike-slip with north-south shortening and east-west extension. In the western Basin and Range, fault-plane solutions are consistent to the nearest 45° azimuth with observed patterns of extension on N-S normal faults and conjugate movement on left-lateral NE-SW and right-lateral NW-SE strike-slip faults (Van Wormer and Ryall, 1980; Slemmons and others, 1979). The least principal stress direction is consistently WNW-ESE, so it is reasonable to infer that the style of faulting depends on the orientation of pre-existing fractures or zones of weakness, as well as on the applied stress field.

Stresses within the Sierran Block are commonly considered as transitional from Basin and Range to San Andreas fault-dominated regimes (see Section 6.2.3). The Sierran Block exhibits contrasting relations to these bounding provinces. The Sierran Block appears to be diverging from the Basin and Range province along the extensional faults of the eastern escarpment zone, while its western boundary appears to be in compression, based on the sub-parallel orientations of fold and uplift axes and the high fluid pressures (Berry, 1972) in the adjacent Coast Ranges. This behavior is discussed further in the following subsection.

6.2.2 Contemporary State of Stress

The state of crustal stress in the western United States will most likely ultimately be understood in the context of plate tectonics. A comprehensive synthesis of observed data has not yet been achieved, however, and perhaps cannot be until more data are available. Current knowledge of plate tectonic evolution of western North America is summarized by Dickinson (1981), and a chronology of major late Cenozoic tectonic and volcanic events is presented by Barrash and Venkatakrishnon (1982).

Of key importance in assessing stresses in the Sierran Block is the nature of Basin and Range deformation. Both the westward tilting of the Sierran Block, and the normal and strike-slip faulting at the block's east and south margins fit a larger pattern of tectonic development in the Basin and Range. This pattern is expressed in part by bilateral symmetry of topography, gravity, and heat flow, about a generally north-south axis located in eastern Nevada (Eaton and others, 1978). Contemporary seismicity is concentrated along the west (Sierra Nevada escarpment), east, and south margins of the northern segment of the Great Basin (Plate 6-2). This segment is defined on the south by a rough ENE extension of the Garlock fault, possibly encompassing the Las Vegas shear zone and Lime Ridge fault systems of southern Nevada.

Various plate tectonic theories advanced to explain tectonic evolution of the Basin and Range province are reviewed by Stewart (1978). It has been convincingly argued (e.g., Eaton, 1979; Eaton and others, 1978; Christiansen and McKee, 1978) that crustal spreading in the Basin and Range can explain the extensional tectonics and bilateral symmetry of that province, as well as the apparent westward displacement (Wright, 1976; Magill and Cox, 1981) of the Sierra Nevada. Contemporary displacement of the Sierran Block is occurring at the fastest rate in the south, where lateral release is provided along the Garlock fault. Extension is taking place all along the Sierra Nevada-Basin and Range boundary zone but appears most intense in the south, along the Owens Valley fault system. Persistent indications of right-lateral Holocene strain along the Sierra Nevada-Basin and Range boundary (Greensfelder and others, 1980) probably reflect the pervasive influence of the San Andreas transform system at the continental margin and near-interchange-ability of the maximum and intermediate principal stress axes between vertical and NNE.

Thompson (1972) noted that the observed isostatic equilibrium of the Great Basin is not compatible with accepted estimates of crustal extension unless mass transfer from the deeper mantle occurs sympathetically. This presumably requires some form of upwelling. Christensen (1966) observed that tilt of the Sierran Block cannot have been the result of mechanical rigidity. The crust is not strong enough to remain intact if stress were applied irregularly. A uniform gradient of uplift pressure is therefore required along the lower boundary of at least the uniformly titled northern part of the Sierran Block. Taken together, the observations of Thompson and Christensen are consistent with a down-turning of viscous mantle material beneath the Sierran Block, thus forming a complete convective or pseudo-convective circuit in conjunction with Basin-and-Range upwelling (Plate 6-3). This model is in agreement with the transition from very high to anomalously low heat flow westward from the Basin and Range to the Sierran Block. Moreover, crustal translation by "rafting" on viscous mantle flow can accommodate tilting and westward displacement of the Sierran Block and explain the seeming paradox (Lubetkin and others, 1978, p.61-62) of east-west tension along the eastern boundary, and compression along the western boundary of the block.

6.2.3 State of Stress in the Sierran Block

Because of the low frequency of earthquakes, seismologic data are sparse on the state of stress within the Sierran Block. Analyses of microseismic data from the Folsom are presented in Section 7 of this report, and in Appendix B.

Lockwood and Moore (1979) analyzed the orientations and displacements of microfaults in the eastern Sierra Nevada from Lake Tahoe south to the Mount Whitney area. This work indicated the direction of maximum extension changes from approximately east-west in the north to NW-SE in the south. However, displacement on these fractures is interpreted to have occurred prior to late Cenozoic westward tilting of the block. Late Cenozoic fault displacement (see Section 6.3.3) is predominantly along N-S to NW-SE planes and mainly down to the east.

Fault-plane solutions were obtained prior to this study for aftershocks of 1975 Oroville earthquake (for example, Langston and Butler, 1976) and for microearthquakes in the Rocklin pluton near Folsom (McNally and others, 1978). The Oroville sequence indicated normal faulting on a north-south plane dipping 60° west. The Rocklin pluton sequence also indicated general east-west extension; however, based on geologic inference, McNally and others interpreted this faulting to be down-dropped to the east on a plane dipping 60° to 70°. Seismologic investigations conducted by Urhammer for this study (Appendix B) support the alternative solution, downdropping to the west on a plane striking NNW to N and dipping 33° to 41° west. Urhammer's plot of the hypocenter plane dips about 70° west (Plate 7-5).

The low level of seismicity in the Sierran Block suggests a corresponding low level of stress buildup. The contrasting geophysical properties of adjacent crustal provinces and the tectonic model suggested in the previous subsection imply that the Sierran Block is only tenuously coupled with either the San Andreas or Basin and Range tectonic regimes. All three provinces have the least principal stress (direction of maximum extension) oriented roughly east-west. In the Coast Ranges, strong north-south compression results from the San Andreas transform system. In the Basin and Range, gravitational or other vertical forces have predominated, giving rise to normal faulting and crustal extension. Deformation in the Sierran Block appears to have elements of both tectonic styles, but tending to the extensional (Basin and Range) environment.

6.3 RELIEF OF STRESS

Relief of crustal stresses (strain) occurs by fault movement, by warping, or by regional uplift or subsidence. Abrupt fault movement is generally seismogenic, while other types of strain occur gradually and are not associated with earthquakes. The occurrence of earthquakes is, therefore, a function of the location and characteristics of faults in relation to crustal stresses. While the major faults bounding the Sierran Block are useful in assessing the regional stress regime, faults of immediate concern to this investigation are those that are within the block, particularly those relatively close to the Folsom area. Section 6.3.1 below discusses the locations of significant faults within the Sierran Block; Section 6.3.2 discusses geodetic measurements, and Section 6.3.3 is an overview of geomorphic evidence of Quaternary intrablock tectonism.

6.3.1 Faults Within the Sierran Block

The structural grain of the Sierra Nevada runs parallel to the overall trend of the range. This grain, established in Mesozoic time, is dominated by the Foothills fault system (Clark, 1960), elements of which separate distinct belts of metamorphic rock. Faults of the Foothills system in the Folsom area have been the subject of detailed study in this investigation and are described elsewhere in this report. The important characteristics of the Foothills system, as relates to the tectonic model, are as follows:

1. <u>Surface Traces</u>

   The Foothills system comprises two main faults, the Melones and Bear Mountains. These two faults are parallel and 5 to 10 miles apart south of the American River. Going north, both faults bend from a northwest to north strike between the Mokelumne and Cosumnes Rivers. The Melones continues on a north trend almost to the limit of the Sierran Block, but turns northwest for about 30 miles before terminating at the Cascade-Sierra boundary. The final 30-mile segment is parallel to and 5 to

10 miles southwest of the Plumas Trench (Section 6.1.1.2). The Bear Mountains fault diverges from the Melones near Auburn and splits into several discontinuous north to northwest-trending faults. A discontinuously-mapped shear zone extends northwest from Auburn, on approximate trend with the Cleveland Hills and other faults and with the Chico Monocline.

2. Character of Fault Zones

Recognizable fault zones typically exhibit braided traces that enclose block as much as 2 miles wide of relatively intact rock. Fragmental textures of cataclastic origin are common and may form phyllitic to brecciated zones hundreds of feet wide (Clark, 1960). Duffield and Sharp (1975) map the main Melones fault zone as 700 feet to over 1/2-mile-wide in Amador County, south of the Cosumnes River. They consider the Bear Mountains fault as mapped by Clark to be the western margin of a 2-1/2-mile-wide melange belt or tectonic breccia zone. Ultrabasic rocks, probably in part representing slivers of oceanic crust, have been intruded or tectonically mobilized into the fault zones along much of their lengths.

These rocks are altered to relatively plastic serpentinite.

3. Tectonic Relations

Faults of the foothills are thought to represent complex sutures and imbrications resulting from collision and fragmentation of crustal plates during the Mesozoic Era (Schweikert, 1981). The faults are steeply east-dipping to vertical, although they probably dipped more gently when originally formed. Schweikert and others (1982) report the following tectonic history of the Melones zone: "South of Placerville, the Melones fault zone forms the boundary between two related belts of Jurassic rocks, a slate belt to the west and a phyllite-greenschist belt to the east. This part of the Melones fault zone is therefore a zone of imbrication of Jurassic rocks and is not a major suture. A newly-mapped fault 1 to 7 km east represents the foothills suture. The Melones fault zone has had three distinct periods of activity, and different fault traces within the zone have different histories and styles. The Jurassic Melones fault (strict sense) is a narrow (<5 meters wide) ductile thrust zone which separates Mariposa slate in the footwall from more highly metamorphosed phyllite or metaserpentinite in the hanging wall... Faulting was most likely aseismic. Several ductile Jurassic thrust faults also occur in hanging wall phyllites and greenschists. Early Cretaceous brittle reverse faulting of tens of meters displacement generally occurred along parts of these Jurassic hanging wall faults, but also occurred locally in footwall slates. Such faults are marked by complex zones of quartz veining, brecciation, and redeposition of quartz in gouge zones up to 5 meters thick; these were probably seismic faults. Seismic, Cenozoic brittle normal faulting has occurred in many places along zones of Cretaceous faulting, indicating that these broad, weak zones have been preferentially reactivated. We find no evidence for strike-slip faulting along the Melones fault zone." The Bear Mountains fault and presumably other elements of the Foothills system west of the Melones fault are considered by Schweikert (1981) to be imbrications of west-to-east subducting or accreting plates.

4. Cenozoic Movements

As noted above, although the foothills system is clearly Mesozoic in origin, discontinuous Cenozoic displacement has been documented on many of its individual traces (Schwartz and others, 1977). Cenozoic displacements reportedly vary from tens to hundreds of feet (Alt and others, 1977). This displacement is not continuous along the faults, however, indicating that they have not been reactivated in total, but only respond to local stress conditions. The maximum age of last movement of faults in the Melones fault zone has been established at about 4 my where Pliocene beds in the Mehrten Formation are offset near Mokelumne Hill, about 35 miles southeast of Folsom Reservoir (Bartow, 1979).

From the geology of the Foothills system, it can be inferred that at least the faults representing major sutures likely extended the full depth of the crust at the time of their formation. Later tectonic and intrusive events warped and tilted the fault planes and may locally have disrupted them. It is likely, for example, that emplacement of the Rocklin pluton was influenced by and truncated some branches of the Foothills fault (Swanson, 1978).

The main seismic activity in the foothills has been on the northern Melones zone, near the northeast boundary of the Sierran Block, where three earthquakes of estimated magnitude 5 to 6 have occurred, along with many smaller shocks. It is a reasonable hypothesis that the relative intensity of seismic activity of the northern Melones fault zone is related to its close proximity to Basin and Range tectonism in the Plumas Trench zone.

Fault displacement in the 1975, magnitude 5.7 earthquake near Oroville was down-to-the-west on a fault that is interpreted to generally parallel the east edge of the Sacramento Valley. This trend aligns with the Bear Mountains fault to the south and with the Chico Monocline to the northwest. Recent microseismic recording on this zone (Cramer and others, 1978) supports the presence of weak seismicity along the trend.

Busacca and others (1982) report evidence of tectonic deformation as young as mid-Pleistocene (1 to 2 my) in the area generally between Oroville and Marysville. Similar evidence previously discussed of late Cenozoic deformation along the Chico Monocline (paragraph 6.1.1.3), and the sense of displacement at Oroville together suggest a pattern of Great Valley subsidence along the Bear Mountains and more northern fault zones on the same trend. Seismologic evidence from the Rocklin pluton (Appendix B) indicates this mode of deformation may extend as far south as the Folsom area. This pattern of displacement is opposite the dominantly down-to-east sense inferred for Basin-and-Range-related faulting, but it is in agreement with overall east-west crustal extension.

Harwood and Helley (1982) suggest that late Cenozoic, down-to-the-west displacement also occurred on northern segments of the Willows fault system, which they map as extending generally north-north-west through the Sacramento Valley from the vicinity of Stockton to near Red Bluff. Subsurface data indicate the last significant displacement on the Willows fault south of Sutter Buttes occurred tens of millions of years ago (Helley and Harwood, personal communication, 1982).

6.3.2 Geodetic Measurements

Analyses of repeated geodetic leveling traverses have been performed on several lines across the Sierran Block (Bennett, 1978; West and Alt, 1979; Bennett and others, 1977). Most significant to the Folsom area is a line from Newcastle, California (near Auburn), to Reno, Nevada. Results of these analyses are reported to indicate, in general, an inflection in crustal movement along the Melones fault zone and, less consistently, along the Bear Mountains fault zone.

The analyses indicate apparent reversals in the vertical direction of crustal movements over time periods of 1 to 2 decades. Indicated strain rates are much larger than calculated from observed fault displacements, but are in general agreement with rates computed from seismic energy release of earthquakes in the Foothills Belt (Uhrhammer, this report, Appendix B); however, geodetic measurements indicate similar amounts of movement in seismic and aseismic areas (Bechtel Corp., 1981, Appendix D). These facts plus recent suggestions of possible refraction or other errors in leveling (Strange, 1980) indicate that geodetic data should be interpreted with caution.

6.3.3 Geomorphic Evidence of Sierran Block Tectonism

Very comprehensive investigations of late Cenozoic faulting were conducted for the U.S. Bureau of Reclamation's Auburn damsite (1977a). Results of that study supplemented earlier descriptions (for example, Bateman and Wahrhaftig, 1966) of Late Cenozoic displacement on widely separated segments of the Foothills fault system. In the Auburn area, the USBR reports contained an interpretation of apparent fault offset of buried pedogenic soil horizons as evidence of tectonic displacement within about the past 100,000 years. At two of seven locations, a high level of confidence was attached to this interpretation.

The presence of a laterally extensive or continuous late Cenozoic fault system in the foothills is not supported by geomorphic expression. The relatively planar bedrock surface of the foothills was deeply incised during the Pliocene Epoch (3 to 5 mybp) by the major rivers flowing off the Sierra Nevada, and the inter-fluvial surfaces were stripped by erosion. Soils subsequently deposited over bedrock consist of colluvium transported downslope by creep and erosion. The colluvium thickens and interfingers with valley alluvium at the base of the slope. Distribution of the alluvial and colluvium units indicates the local base level in the stream valleys of the foothills has not been appreciably altered since the oldest soil units were deposited (Swan and others, 1977). Multiple colluvial layers separated by pedogenic horizons are observed in some areas. These relations indicate that erosion of the bedrock away from stream valleys has not been appreciable during the Quaternary Period (the past 3±my). Therefore, intermittent displacement corresponding to even very low average strain rates (e.g. 0.001 mm/year) should have formed a noticeable, continuous step in the bedrock surface if it occurred over the past million years or more. The scarcity and lack of continuity between such steps are evidence that the system of Cenozoic faults is not coextensive with the Mesozoic Foothills system.

The orientation of alluvial units in the northeastern San Joaquin Valley indicates that ongoing uplift of the Sierra Nevada affected deposition of units of Pliocene and older age (Marchand and Allwardt, 1981). Analysis of the dip of the various alluvial formations (Grant and others, 1977) is reported to indicate that units as young as the Modesto Formation (about 10,000 to 40,000 ybp) have been tilted toward the valley at a constant rate of about 24 feet per mile per million years, over the past 5 my. The supposed tilt of the Modesto Formation is so small, however, that these results are equivocal. Quaternary formations in the San Joaquin Valley were deposited in response to glacial episodes associated with climatic changes. Geomorphic and stratigraphic studies were conducted in the American River downstream of Folsom Reservoir by Shlemon (1972), who also concluded that variations in Quaternary deposition were most likely attributable to the influence of glaciations. These recent studies build on original geomorphological soil-stratigraphic studies in northern Sacramento County by Shelmon (1967) and in the northeastern San Joaquin Valley by Arkley (1962), Janda (1966), Marchand and Allwardt (1981).

6.4 CONCLUSIONS

The tectonic model proposed for the Sierra Nevada and Great Valley accommodates the main data and hypotheses regarding known earthquake occurrence, geologic structure, geophysical character of the crust, and geomorphic evidence of Quaternary tectonism. Knowledge in each of these areas is constantly expanding, and the conclusions presented here may be adjusted in the light of further research. The following are the main constraints on the model:

1. Earthquakes are much less frequent and severe within the Sierran Block than in adjacent provinces to the west, east and south. High seismicity is observed on or near the south and east fault boundaries of the block.

2. Major westward tilting of the Sierran Block took place between 3 and 10 mybp. In the northern Sierra Nevada and Sacramento Valley, differential deformation within the block appears to have been minor, consisting of discon-

tinuous gravity displacement on north- to northwest-trending elements of the Mesozoic Foothills fault system and possibly on faults within the northern Sacramento Valley. In the Foothills belt and the high Sierra, most fault displacement was down to the east. Down-to-the-west displacement is also observed, particularly near and west of the boundary between the northeastern Sacramento Valley and the Foothills. East-west extension (normal faulting) is indicated for both senses of displacement.

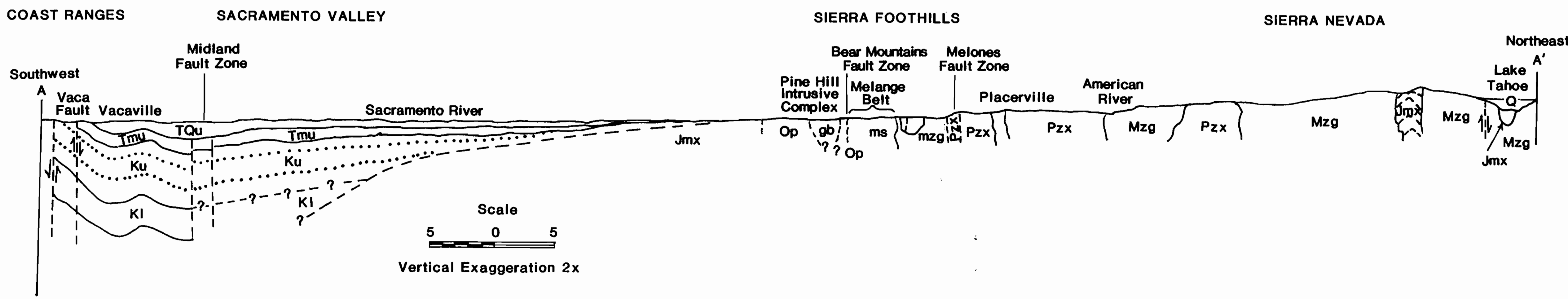
3. Minor Quaternary (younger than 3 mybp) displacement has occurred on faults in the Foothills system, at least from Auburn northward. This low-level of tectonic activity probably continues today.

4. The earth's crust is unusually thick beneath the Sierra Nevada, thinning westerly beneath the Great Valley and easterly beneath the Basin and Range Province. Heat flow is anomalously low throughout the Sierran Block. The Sierran Block and Basin and Range Provinces are both isostatically compensated, but a broad gravity low is centered approximately on the boundary between these provinces.

5. Crustal spreading within the Basin and Range Province is believed likely, and this is associated with westward displacement of the Sierran Block. Lateral release is

provided by the Garlock and associated faults, which bound the Sierra Nevada on the south. Seismogenic tectonism is ongoing in the extreme southern Sierran Block, but is very minor in the Sacramento and northern San Joaquin Valleys and adjacent foothills.

Based on the above constraints, tectonism in the Sierran Block is believed to result from crustal buoyancy and friction from viscous east-to-west flow within the mantle (Plate 6-3). This activity is presently concentrated in the extreme southern Sierran Block, but sympathetic extensional movement occurs along the entire eastern boundary of the Sierran Block, generally decreasing northward. A downturning of the mantle flow probably occurs beneath the Sierran Block, resulting in low heat flow and a rather uniform east-west gradient of uplift pressure on the base of the Block. This gradient induced rotation ("rigid" tilting) of the Sierran Block during the late Miocene and Pliocene Epochs (approximately 3 to 10 mybp). The apparent "axis of rotation" is located near the Foothills-Great Valley boundary. East-west extension occurring throughout the Block is expressed by gravity displacement on discontinuous fault planes that dip predominantly east in the Sierra Nevada and west in the Sacramento Valley. The Foothills belt is intermediate between these two extensional regimes. Minor and local adjustments continue in the northern Sierran Block, but displacements are small, and occur on short zones along major planes of weakness that may fully penetrate the crust. Conditions leading to major stress buildup and release, and associated large earthquakes, are not suggested by this model in the central or northern Sierran Block. Changes in the geotectonic environment necessary to cause such activity would occur extremely slowly on a human time scale.



Modified from Wagner, et al. (1981)

EXPLANATION

(Units simplified from the geologic map)

CENOZOIC

- Q — Quaternary alluvial deposits
- Qg — Glacial deposits
- TQu — Undifferentiated Tertiary and Quaternary continental deposits
- Tm — Mehrten Formation
- Tvs — Valley Springs Formation
  - (Tm and Tvs:) Shown in Sierra only; included with TQu beneath Sacramento Valley
- Tg — Tertiary "Auriferous" gravels
- Tmu — Undifferentiated early Tertiary marine deposits on west side and beneath Sacramento Valley grading into early Tertiary nonmarine deposits (Ione Fm) on east side of the Valley

PALEOZOIC - MESOZOIC

- Ku — Upper Cretaceous Great Valley Sequence
- Kl — Lower Cretaceous Great Valley Sequence
- Ju — Upper Jurassic Great Valley Sequence
  - (Ku, Kl and Ju:) Shown only on cross section
- Mzg — Mesozoic plutonic rocks of the Sierra Nevada
- Jmx — Jurassic metamorphic rocks of the Sierra Nevada
- Op — Ophiolitic terrane; includes metavolcanic, metasedimentary, and ultramafic rocks
- gb — Gabbroic rocks (in ophiolitic terrane)
- ms — Sheared Mesozoic-Paleozoic rocks of Foothill melange belt
- Pzx — Paleozoic metamorphic rocks of the Sierra Nevada

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DIAGRAMMATIC CROSS SECTION COAST RANGES - SIERRA NEVADA

GEOLOGIC AND SEISMOLOGIC INVESTIGATION

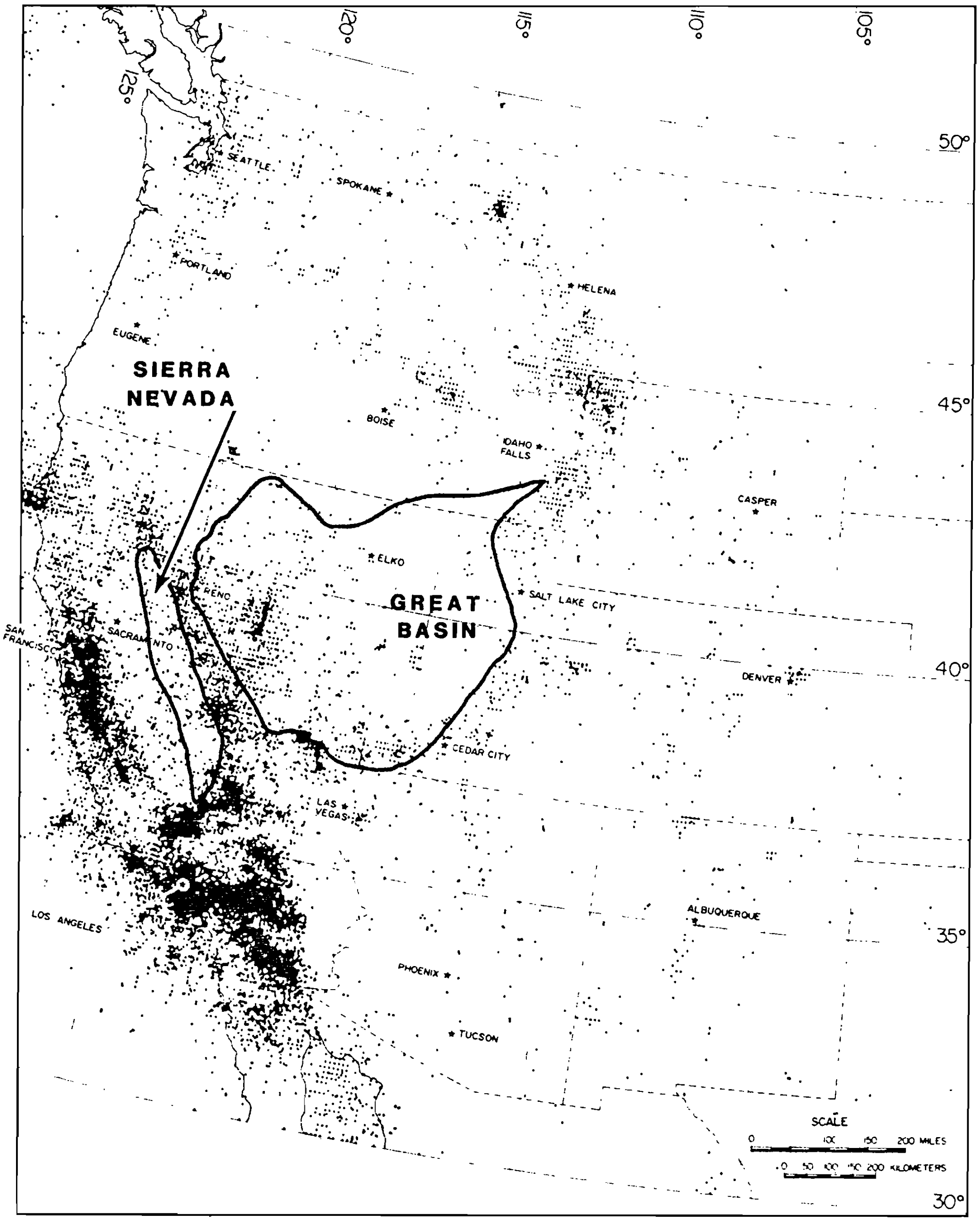
FOLSOM, CALIFORNIA AREA

for U.S. Army Corps of Engineers

Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	Approximate	6-1

Form No. D60/78



SOURCE: Adapted from Smith, 1978

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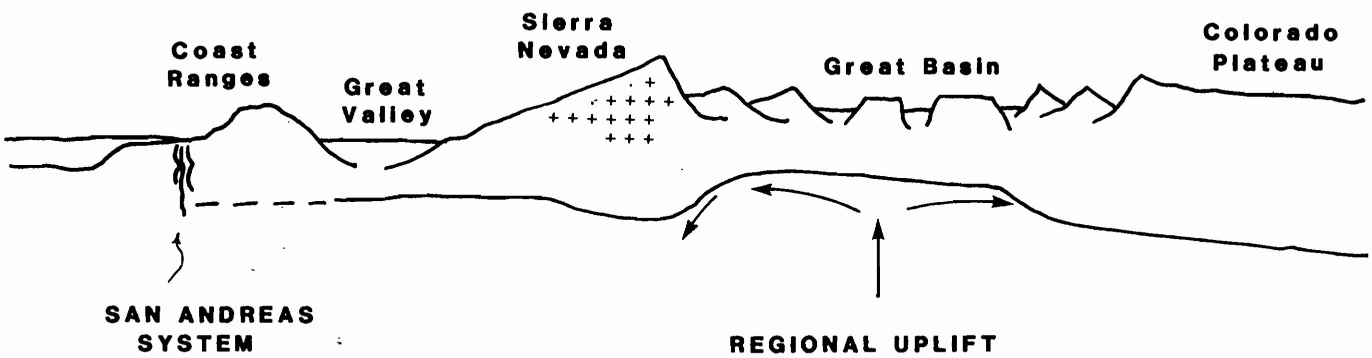
EPICENTER MAP OF WESTERN UNITED STATES

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 6-2



SOURCE: Adapted from Stewart, 1978

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SCHEMATIC SECTION THROUGH WESTERN U.S.

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 6-3

SECTION 7

7. SEISMICITY

7.1 SIERRAN FOOTHILLS SEISMICITY

The seismicity of the Sierra Nevada foothills continues to be re-evaluated as a result of the August, 1975 Oroville earthquake. Previously, the region had been thought to be relatively seismically quiet. Several new studies of regional geology and seismicity have provided a larger data base which was reviewed for this study. The following paragraphs summarize the results of this analysis. Detailed descriptions of the analysis and pertinent calculations are found in Appendix B.

Compilation of Sierra foothills seismicity prior to the 1940's was based on reports of earthquakes from newpapers. A search of several catalogs produced three historical events which may have occurred within 50 km of Folsom Reservoir. These events occurred near the town of Newcastle on February 23, 1885, April 21, 1892, and May 30, 1908. Of these events, the 1908 earthquake was the largest, with a maximum reported Modified Mercalli intensity (MMI) of IV-V. This event, estimated at local Richter magnitude (M_L) 4, is the largest earthquake reported in the general vicinity of Folsom. The largest instrumentally recorded earthquake in the area was a May 25,1951 M_L 3.0 event near Pilot Creek, approximately 30 km from the reservoir.

Statistical analysis of post-1937 instrumentally recorded seismicity indicates that the rate of seismicity derived from seismographs is consistent with that derived from newspaper reports from preceding years. For earthquakes $M_L \geq 3$, this rate is approximately 92 earthquakes per 100 years per 100 km linear segment of the foothills area. In comparison, the rate of seismicity for the central coast region of California is approximately 2,900 events per 100 years per 100 km, over thirty times as high. Plate 7-1 illustrates the low concentration of seismicity in the Sierran foothills relative to other parts of northern California. Plate 7-2 shows the distribution of all foothills seismicity recorded since 1937.

7.1.1 Auburn Net

Detailed monitoring of the Auburn-Folsom area seismicity was started in 1976 when the USGS installed 14 seismographic stations in the Auburn vicinity ("the Auburn net"). This net has been recording continuously since 1976. Analysis of the seismicity recorded in the net indicates no significant statistical difference exists between rates of seismicity inferred from regional and local data sets.

Plate 7-3 shows the disrtribution of all earthquakes recorded by the net through September, 1980.

7.2 ROCKLIN/PENRYN PLUTON

Between November 1976 and September, 1980, 149 earthquakes between M_L 0.1 and 2.8 were recorded by the Auburn net in the general vicinity of the Rocklin/Penryn pluton. The spatial distribution of these earthquake epicenters and hypocenters does not correlate with any known or inferred faults or discontinuities. Twenty-three well documented earthquakes were selected from the original 149 and used in a group relocation computer program in order to more precisely locate the hypocenters. This model includes an approximation of inferred crustal velocity structure in the vicinity of the Rocklin/Penryn pluton. These relocated epicenters cluster into three groups, as shown on Plate 7-4. The epicenters lie along a crescent shaped region, with deeper foci toward the south. Plate 7-5 shows constant-latitude and constant-longitude hypocenter plots of these earthquakes.

7.2.1 Focal Mechanisms

Fault-plane solutions derived for six earthquakes in the larger, southernmost cluster of earthquakes suggest normal faulting with east-west extension within the pluton. The inferred fault plane strikes $344^{\circ}(\pm 21^{\circ})$, dips 37° $(\pm 4^{\circ})$

west, with a slip direction of 71° (± 15°). An auxiliary solution plane strikes 188° (± 2°), dips 55° (± 1°) east, and slip 76° (± 12°). It was concluded that the west dipping fault plane was most reasonable, based on the good correspondence with the west dip shown by hypocenters on the constant-latitude plot (Plate 7-5), and with the location of two northwestern earthquakes within the pluton near the projection of this plane. The remaining group of hypocenters within the relocated set also plot near a normal to this plane at 12 km depth, within the 11 to 13 km depth range for the entire group. Plate 7-6 shows the stereonet diagram of these fault-plane solutions. A projection of this westward dipping plane up to the ground surface daylights near the mapped trace of the West Branch, Bear Mountains fault zone. It is unlikely that a fault plane defined by these hypocenters is related to the Bear Mountains zone, in that all geologic evidence points to a relatively steep eastward dip along the fault zone in this area.

There is no evidence that the microseismicity within the Rocklin/Penryn plutons can be correlated to major fault features, or that the seismicity is associated with any fault or discontinuity exposed at the ground surface. Characteristically, surface rupture would not be associated with earthquakes of the size recorded within the study area. A lack of detailed structural and geophysical data for the pluton precludes a precise downward projection of the plutonic-metamorphic contact to the 11 to 13km depth range of the hypocenters. Drilling and gravimetric data suggest that the margins dip steeply, at least near the surface, and that the pluton extends westward for some distance under a thin veneer of covering sediments. It is reasonable to infer from the hypocenter plot that the earthquakes are occurring within the pluton. The main cluster of earthquakes occur directly below the mapped contact between the Rocklin and Penryn plutons. The seismicity may be associated with this intra-pluton contact zone, rather than the igneous-metamorphic zone as thought previously.

7.3 STRAIN RELEASE AND SEISMIC MOMENT

Strain release and seismic moment rates for the Sierra Nevada and central coast regions were calculated and compared. The strain rate in the Sierra Nevada crustal block is two orders of magnitude lower than the coastal region's rate. If all strain accumulated within the Sierran block were released by earthquakes along a single fault, the rate of displacement on the fault for M_L 6.5 earthquakes would be 0.87 cm per 100,000 years. Such small strain rates have not been correlated with large earthquakes. If this accumulating strain were relieved through structural adjustment along a single fault, only small earthquakes would be expected to result. Strain may accumulate and be released along numerous faults, reducing the potential for large events along a single fault or fault zone.

7.4 RESERVOIR-INDUCED SEISMICITY

Reservoir induced seismicity has been the subject of increased attention in recent years as the number of large, deep reservoirs has increased. Special interest has been focused on the Sierra Nevada foothills since the 1975 Oroville earthquake. Although subject to question, and never proven, some investigators have concluded that the earthquake was induced by the Oroville Reservoir. An assesment of reservoir-induced seismicity (RIS) is pertinent to the Folsom study because the microseismicity recorded within the Rocklin/Penryn pluton is located near the area of influence of Folsom Reservoir.

A recent large-scale probabilistic analysis of RIS based on a world-wide data set consisting of large, deep reservoirs (>92m deep, volume $>1x10^{10}m^3$) concluded that of 64 cases of reported reservoir area seismicity considered, 45 were accepted as being reservoir induced. Sixteen of the 45 exhibited both macro ($M_L>3$) and microseismicity, 14 macroseismicity alone and 15 microseismicity alone (Packer, et al ,1980). These data indicate that where RIS occurs, there are approximately equal chances of macroseismicity, microseismicity, or both. This analysis also suggested an increasing probability of RIS with increasing water depth, reservoir volume, sedimentary rocks, and strike-slip (shear) stress regimes. Water depth and reservoir volume showed the strongest correlation with incidence of RIS. The worldwide data base is not yet sufficient to permit thorough evaluation of the relationship between RIS and geology or stress regime. The study also evaluated theoretical models for the prediction of RIS, and concluded that active faults are always present where RIS of $M_L > 5$ has occurred, and that reservoirs do not apparently cause seismicity along inactive faults. Recent detailed study of RIS at Nurek Reservoir in the USSR has suggested the local geologic structure and material characteristics may have a great effect on the pattern of RIS, at least in some cases (Leith, et al, 1981, and Simpson and Negmatullaev, 1981).

Generally, RIS is associated with the initial filling or first few years of operation of a reservoir. Only two earthquakes greater than M_L 3 have occurred in the vicinity of Folsom since instrumental records began in 1937. Both of these events (M_L 3.9, March 19,1943 and M_L 3.0, May 25,1951) occurred before the initial filling of Folsom Lake. No earthquakes greater than M_L 3 have occurred in the area since the reservoir was initially filled 28 years ago. Though it is not possible to conclude for certain that Folsom Reservoir is incapable of inducing macroseismicity on the basis of a 28-year-period of no seismicity, several lines of evidence indicate reservoir induced macroseismicity is highly unlikely at Folsom. The dam is located in an area of extensional tectonics (discussed in detail in Section 6), and of relatively low stress. The reservoir is small and shallow in comparison to many other reservoirs, with maximum water depth of approximately 275 feet, and maximum volume of $1.4x10^9$ m^3. Large, deep reservoirs of the Packer study were those over 92m (300 feet) deep and larger than $1x10^{10}m^3$, over seven times larger than Folsom Reservoir. Folsom is located on plutonic and metavolcanic rocks which typically lack the strongly anisotropic permeability of sedimentary and metasedimentary rocks that may be a contributing factor in RIS in some places (Leith,et al, 1981). No macroseismicity has been associated with the reservoir during or since the largest drawdown and most rapid refill since construction, during late 1977.

Attempts to statistically correlate observed miscroseismicity in the Rocklin pluton with water level-fluctuations in Folsom Reservoir are hampered by the extremely short period of time for which microseismic data are available. Presently, less than three years of data have been released, although the Auburn net has been in operation over six years. Baseline data for preimpoundment Folsom area microseismicity are also lacking (Appendix B).

A comparison of earthquakes in the pluton area with the water level history of the reservoir (Plate 7-9) shows the highest rate of seismicity, 17 earthquakes between October and December, 1977, occurred at the same time the reservoir was undergoing the transition between the deepest drawdown and most rapid refilling since first impoundment. It may be the correspondence is a coincidence, but the data are not extensive enough to fully evaluate the potential relationship. Other evidence suggests the microseismicity in the pluton may not be reservoir induced. The seismicity aligns with the contact between the Rocklin and Penryn plutons, which differ in age by at least 10 million years (Swanson, 1980). The northwestern group of events are located outside the typical radius of influence for RIS of one maximum reservoir diameter, 15km in this case. No correspondence exists between reservoir filling cycles and rates of seismicity in 1978 and 1979. A final conclusion whether the Rocklin/Penryn seismicity is RIS or not must wait until the data base becomes more extensive through time. Even so, the lack of pre-impoundment baseline data may preclude or complicate the process of inference, especially if large fluctuations in rates of seismicity are not observed.

No statistical corelation presently exists between induced macroseismicity and induced microseismicity. Based on the evidence available, including a knowledge of area faults and regional tectonic framework, and the lack of macroseismicity during the first 28 years of operation of the reservoir, it is concluded that damaging earthquakes resulting from the normal operation of Folsom Reservoir are most unlikely.

7.5 REGIONAL SEISMICITY AND MAXIMUM EARTHQUAKES

The Folsom Project is located in a relatively seismically quiet area of north-central California. The nearest highly active areas, shown on Plate 7-1, are located 70 to 100 miles west (the Calaveras-Hayward-San Andreas system) or over 70 miles east (Genoa-Jack Valley zone). These fault zones are known or thought to be active in Recent or historic time, and are thought to be capable of generating earthquakes in excess of M_L 7.0. Such large earthquakes associated with these zones would likely have some affect on the project area, however, owing to the strong attenuation of seismic energy over the large distance between the faults and Folsom Reservoir the expected effect would be small. Table 7-1 summarizes the characteristics of the capable fault zones near the project area. A review of this table clearly indicates that the closest capable fault is the East Branch, Bear Mountains fault zone, with capability for a M_L 6.5 earthquake. That earthquake is most likely to cause the strongest shaking at the site.

TABLE 7-1

ESTIMATED SEISMIC CHARACTERISTICS OF CAPABLE FAULTS (1)

Name of Fault Zone	Minimum Distance To Site	Type of Faulting	Maximum Earthquake Magnitude (2)	Approximate Slip Rate (3)	Most Recent Displacement Known (4)
San Andreas	102	Strike-Slip	8	1-2 cm/yr	Historic
Hayward	85	Strike-Slip	7	0.5 cm/yr	Historic
Calaveras	77	Strike-Slip	7	0.25 cm/yr	Historic
Genoa Jack Valley	70+	Normal-Slip	7.25	.01 - .02	Holocene
West Walker River	85	Normal-Slip	7.25	.01	Historic
Melones	16.5	Normal-Slip	6.5	0.0006 - .00001	Pleistocene ± 100,000
East Branch Bear Mountains	8.0	Normal-Slip	6.5 (5)	0.0006 - .00001	Pleistocene ± 100,000

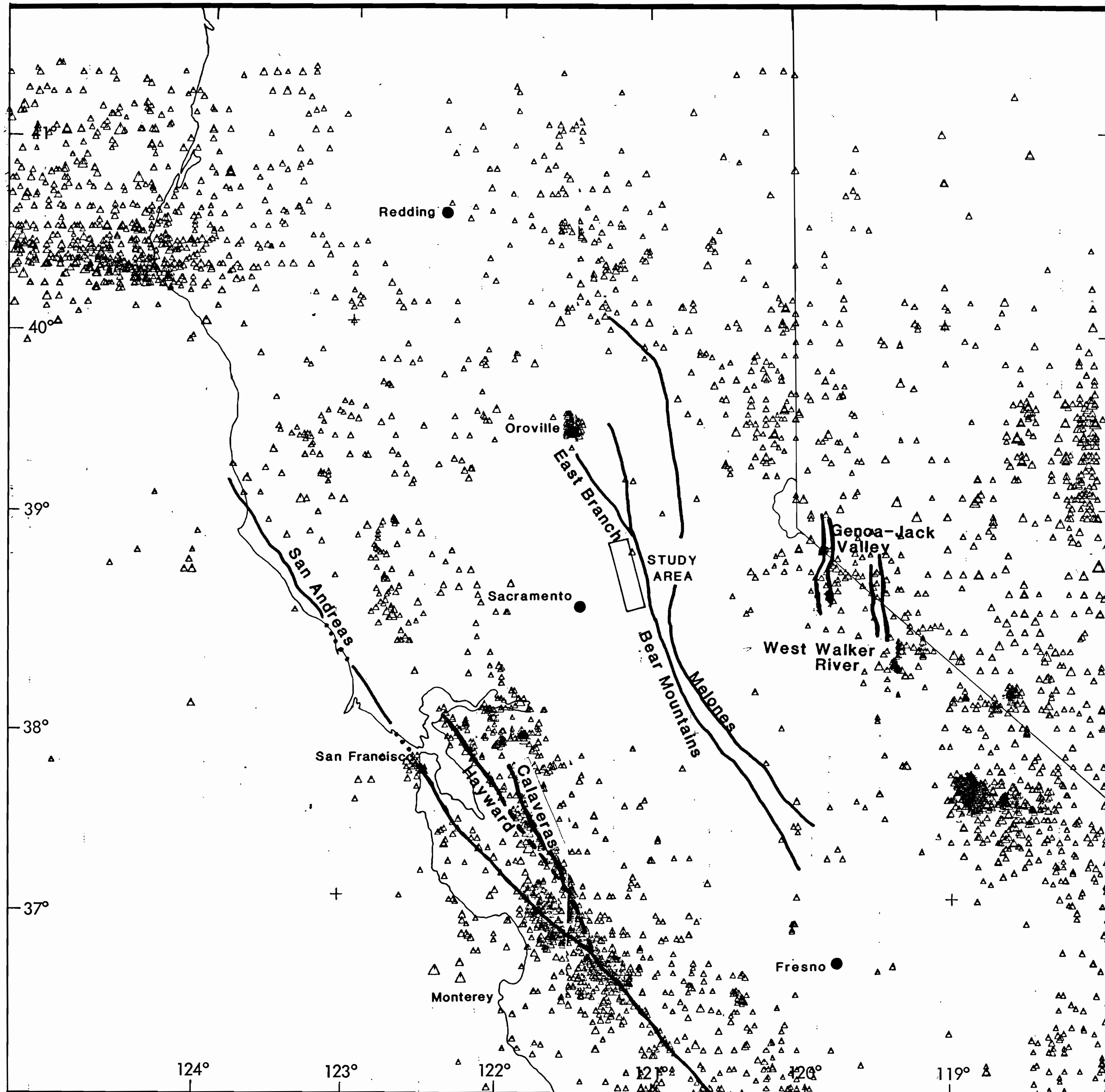
(1) Capable fault, under corps criteria, is one that exhibited displacement at or near the ground surface within the past 35,000 years, recurrent movement within the past 500,000 years, exhibits creep movement, and/or exhibits aligned macro ($M \geq 3.5$) seismicity determined from instruments.

(2) Maximum earthquake estimate on rupture length of continuous strands, type of faulting, fault displacement, historic earthquakes, seismic moment, experience and judgment.

(3) Slip rates estimated from historic, geomorphic, or geologic evidence.

(4) Late Pleistocene displacement may be as old as 500,000 years ago or as young as 10,000 years ago.

(5) Hypothetical value (acceptance based on USBR Auburn Dam studies).



Sample Interval: 1910-1981

Sample Threshold: Richter Magnitude ≥ 3

Sample Size: 6,161 Earthquakes

△ 6.0

△ 3.0

0.015 inch/Magnitude Unit

Major Capable Fault Zone

Source: Seismographic Station, University of California Berkeley

TEC

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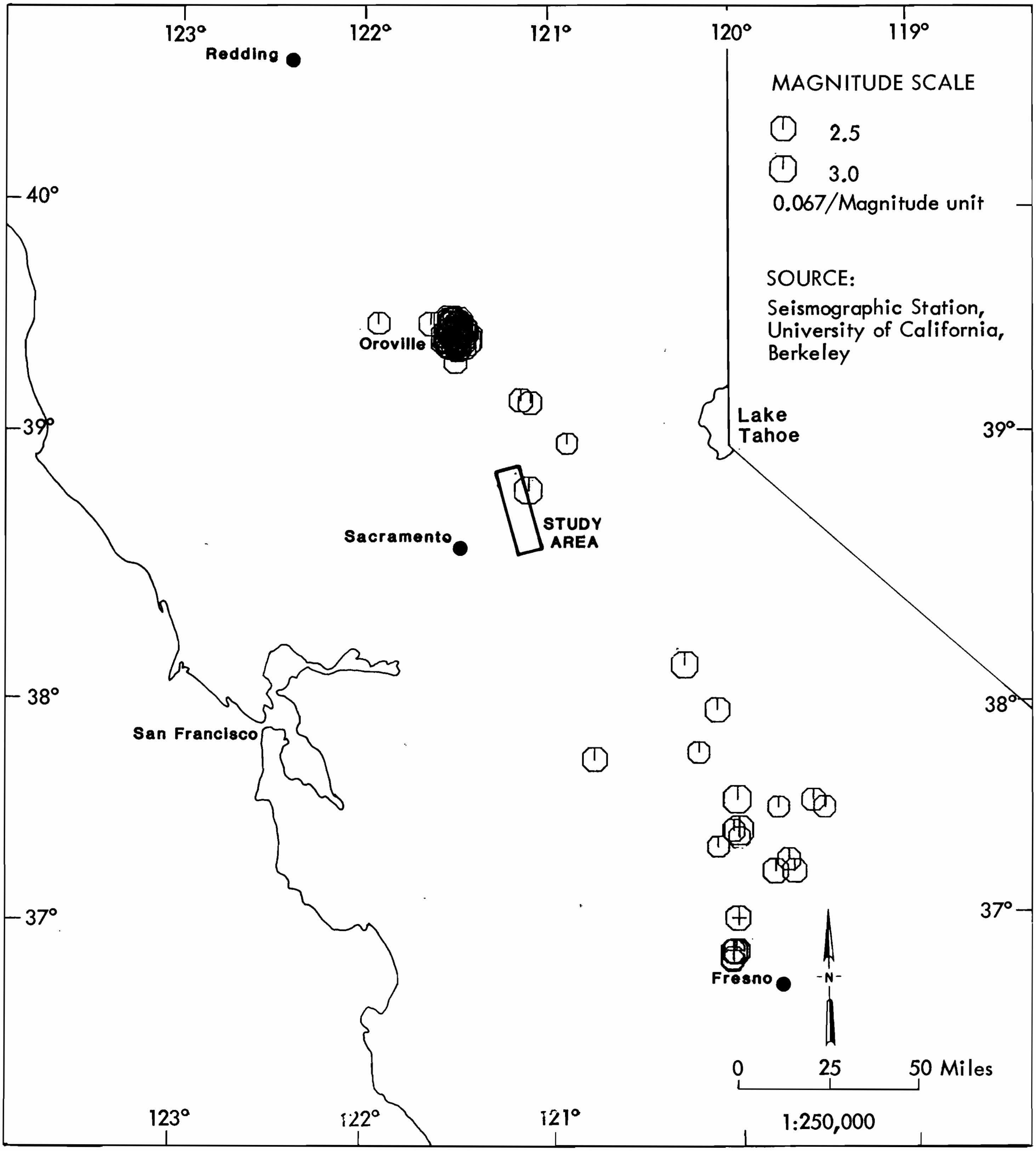
NORTHERN CALIFORNIA SEISMICITY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:250,000	7-1



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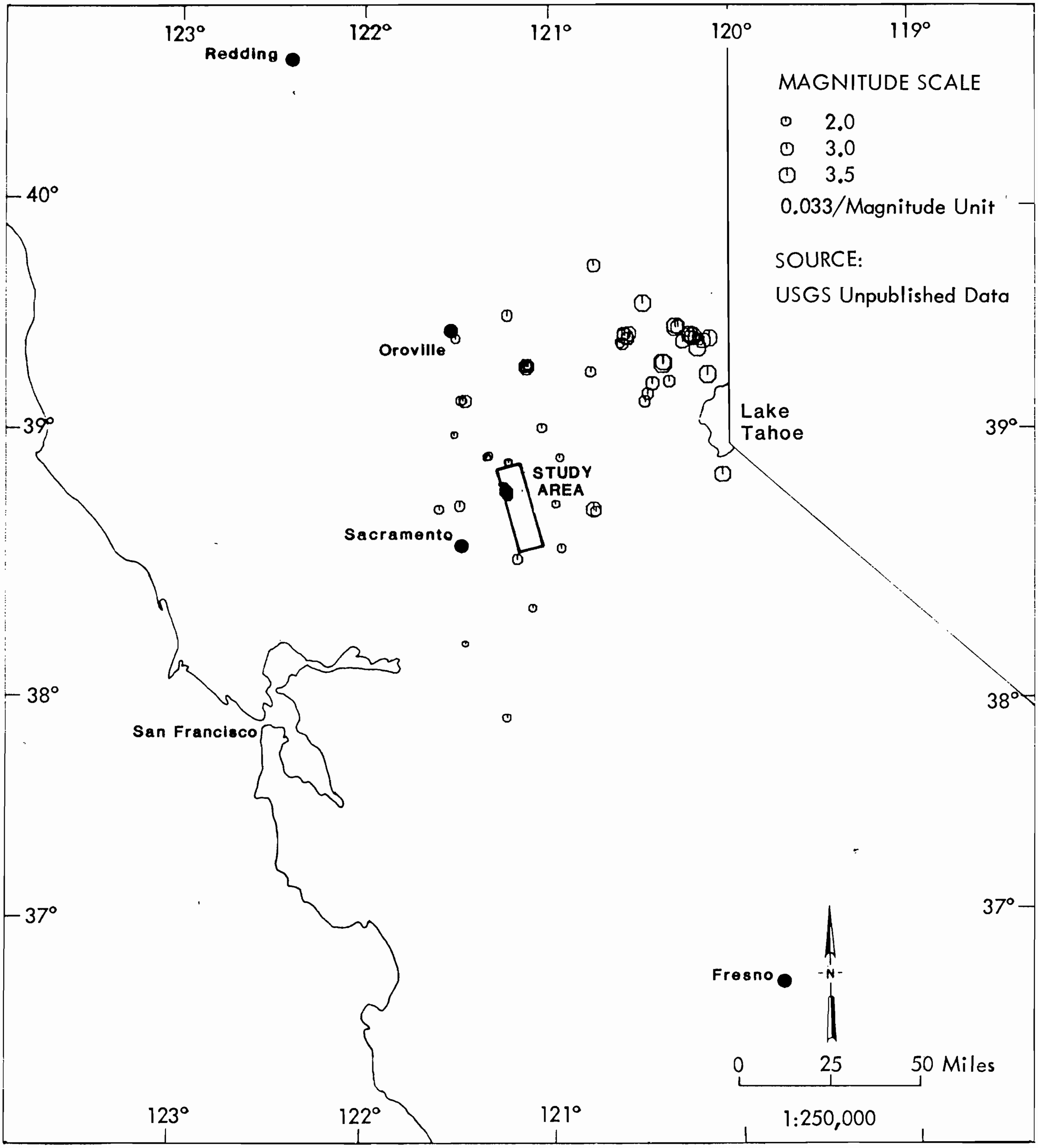
SIERRA FOOTHILLS SEISMICITY 1937-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7-2



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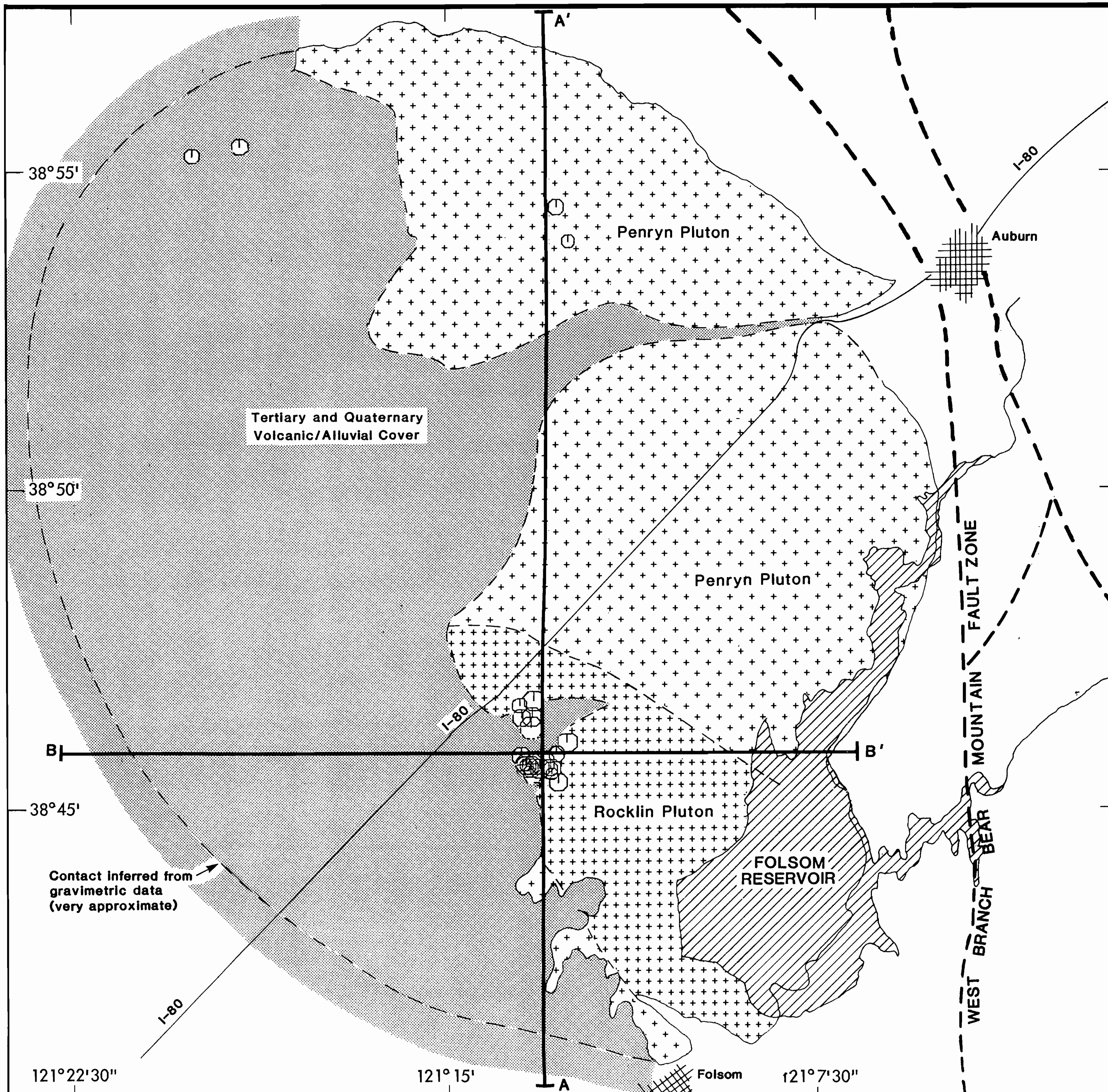
AUBURN NET SEISMICITY 1977-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7-3



EXPLANATION

1.0

2.0

Epicenter
(Scale 0.125"/unit Richter Magnitude)

Cenozoic surficial deposits

Mesozoic Rocklin pluton (granodiorite)

Mesozoic Penryn pluton (quartz diorite)

B B' Location of cross section
(See Plate 7-5)

Sample Interval: 1977-1980

Source: USGS Auburn Net

N

0 1 2 3 4 Miles

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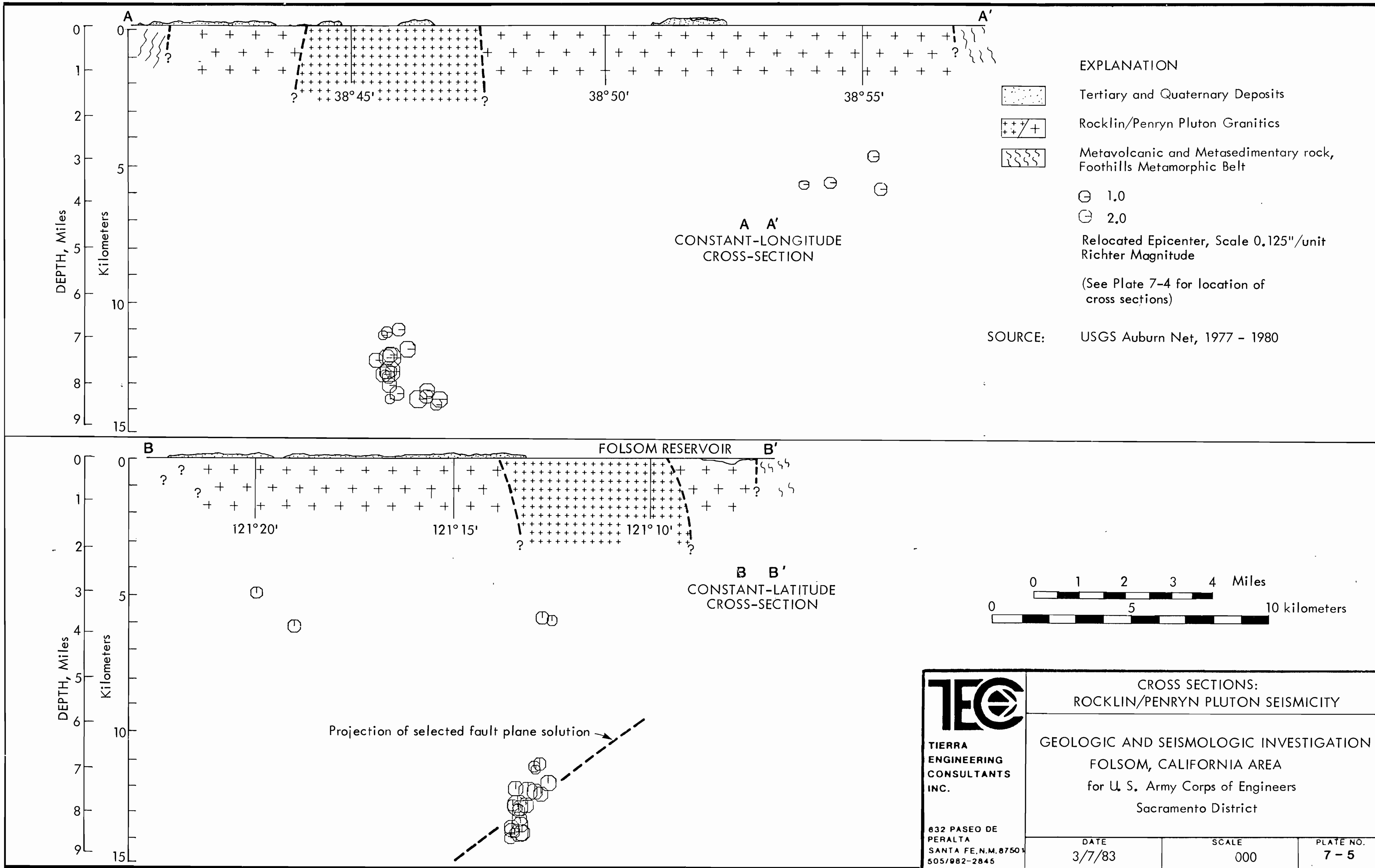
ROCKLIN/PENRYN PLUTON-
RELOCATED EPICENTERS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:125,000	7-4



A
A'
38° 45'
38° 50'
38° 55'
DEPTH, Miles
Kilometers
A A'
CONSTANT-LONGITUDE
CROSS-SECTION
EXPLANATION
Tertiary and Quaternary Deposits
Rocklin/Penryn Pluton Granitics
Metavolcanic and Metasedimentary rock, Foothills Metamorphic Belt
1.0
2.0
Relocated Epicenter, Scale 0.125"/unit Richter Magnitude
(See Plate 7-4 for location of cross sections)
SOURCE: USGS Auburn Net, 1977 - 1980
B
FOLSOM RESERVOIR
B'
121° 20'
121° 15'
121° 10'
B B'
CONSTANT-LATITUDE
CROSS-SECTION
Projection of selected fault plane solution
0 1 2 3 4 Miles
0 5 10 kilometers
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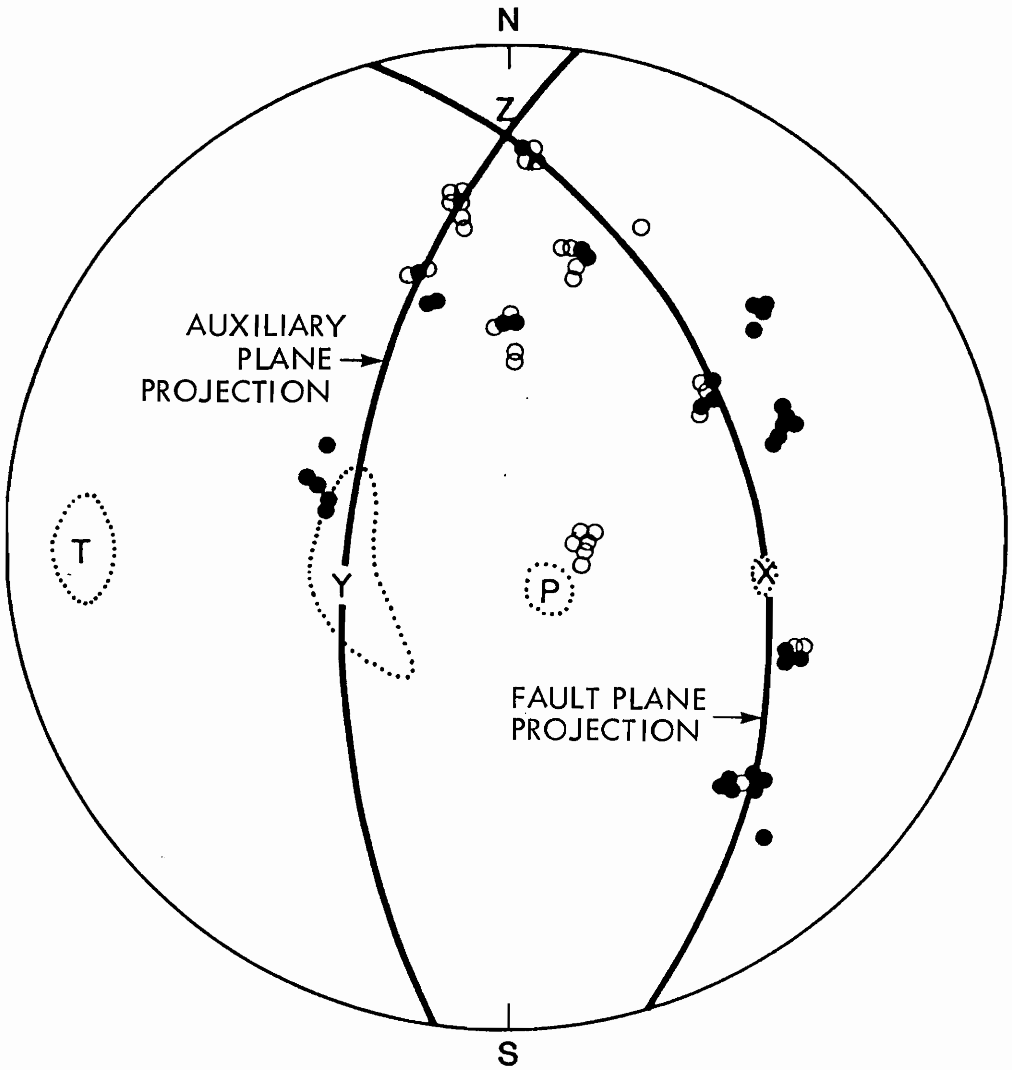
CROSS SECTIONS:
ROCKLIN/PENRYN PLUTON SEISMICITY
GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U. S. Army Corps of Engineers
Sacramento District
DATE 3/7/83
SCALE 000
PLATE NO. 7 - 5



UPPER HEMISPHERE PLOT

	FAULT PLANE	AUXILIARY PLANE
Strike	344° ± 21	188° ± 2
Dip	37° ± 4	55° ± 1
Slip	71° ± 15	76° ± 12

SOURCE: 1977-1980 Relocated Epicenters, USGS Auburn Net

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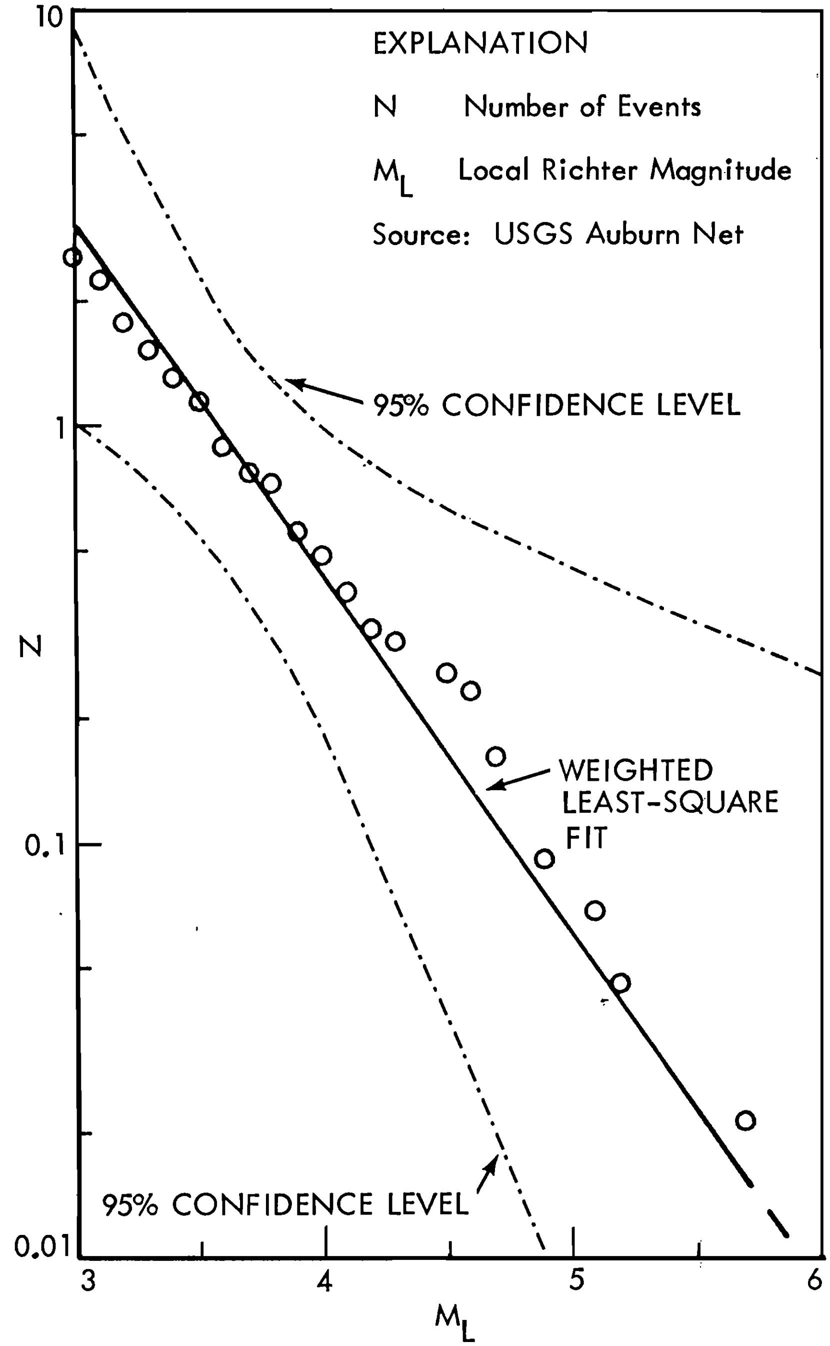
FAULT PLANE SOLUTIONS: ROCKLIN/PENRYN PLUTON

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7-6



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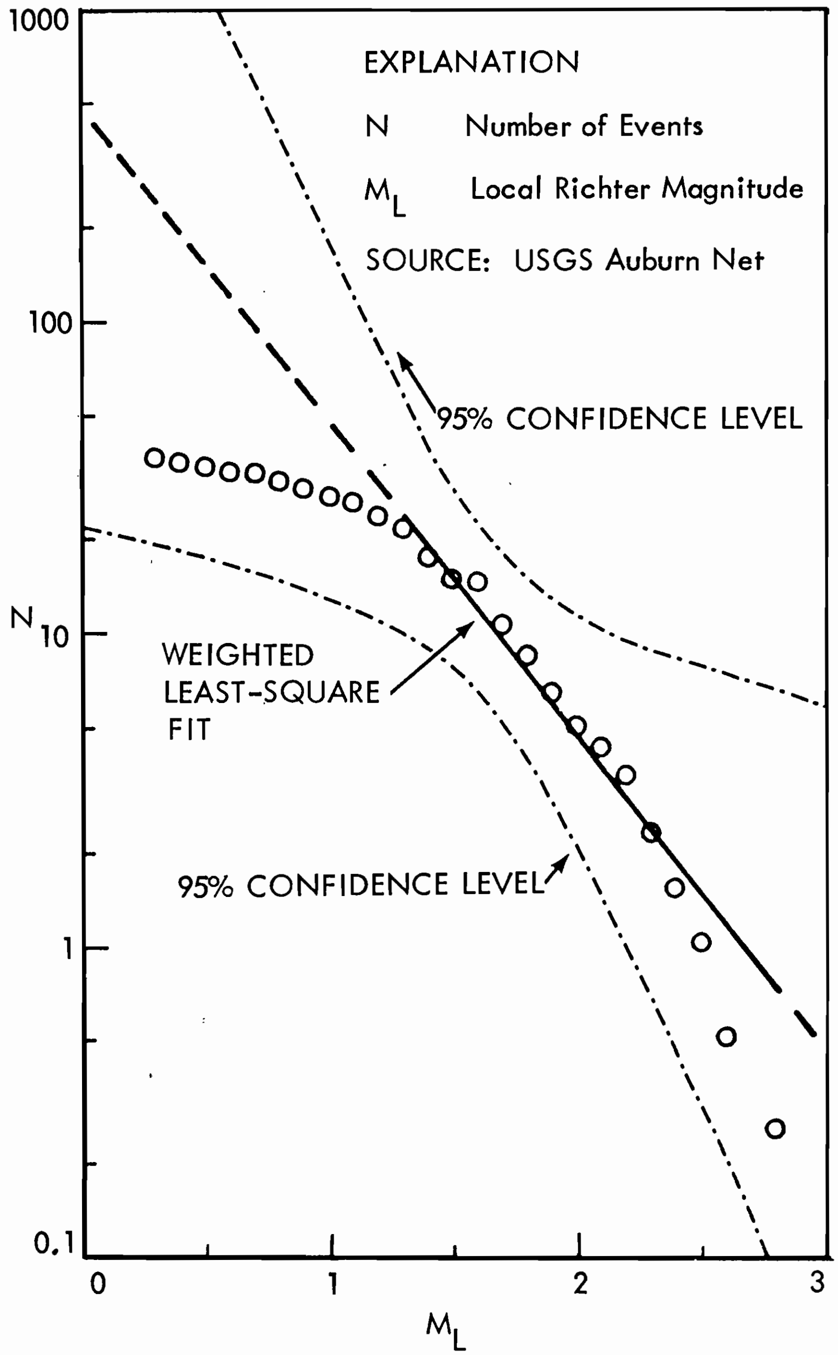
RATE OF SEISMICITY, NORTHERN CALIFORNIA 1937-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7-7



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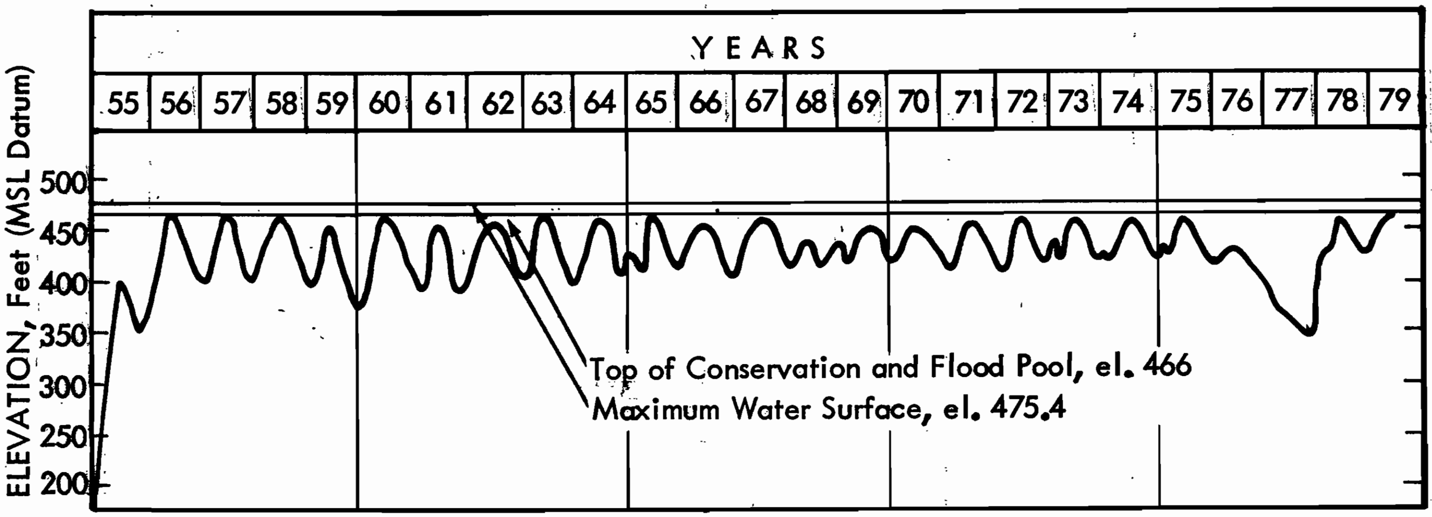
RATE OF SEISMICITY, AUBURN NET 1976-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7-8



Time Period: Initial Filling to July, 1979

Source: U.S. Army Corps of Engineers, Sacramento District

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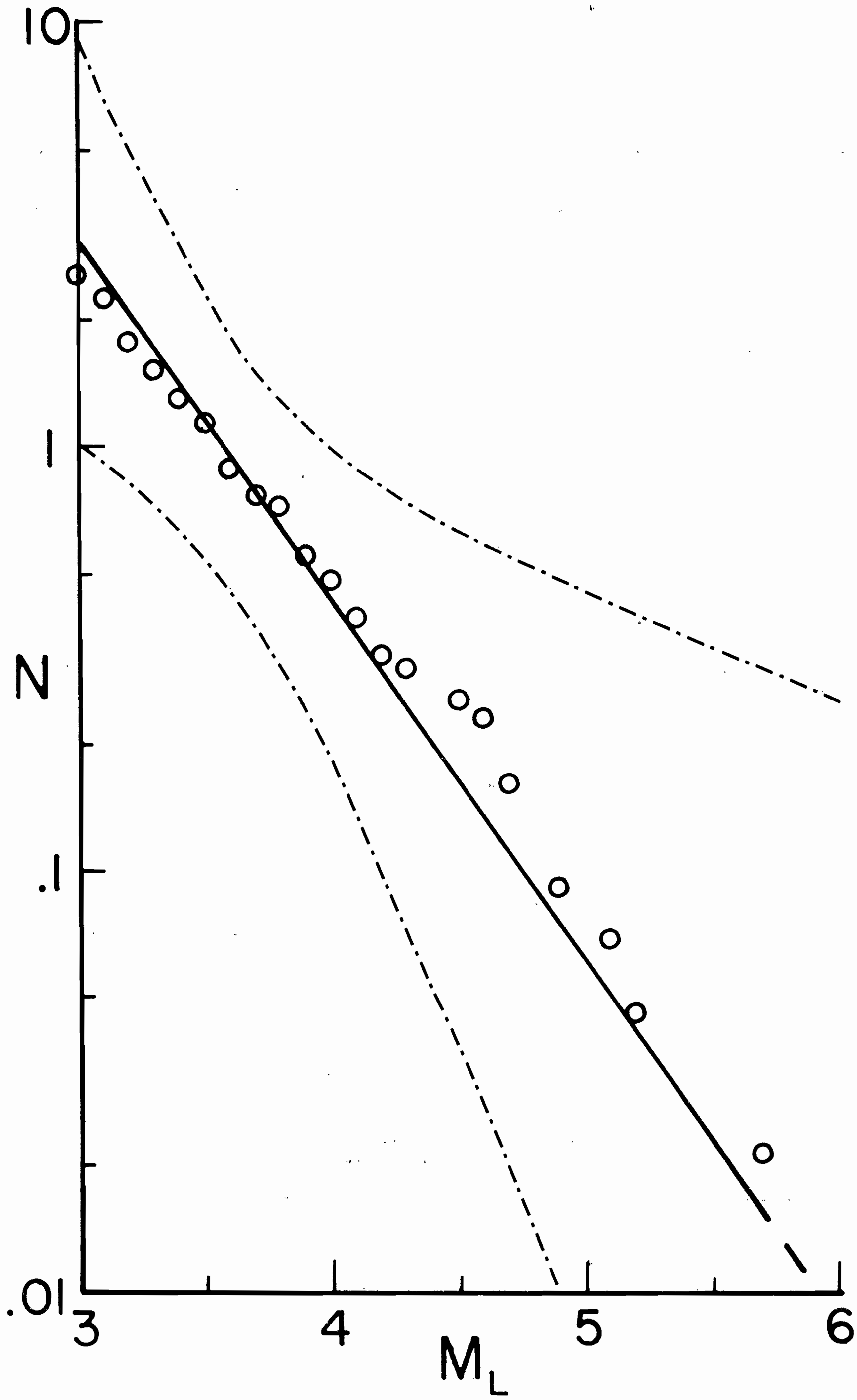
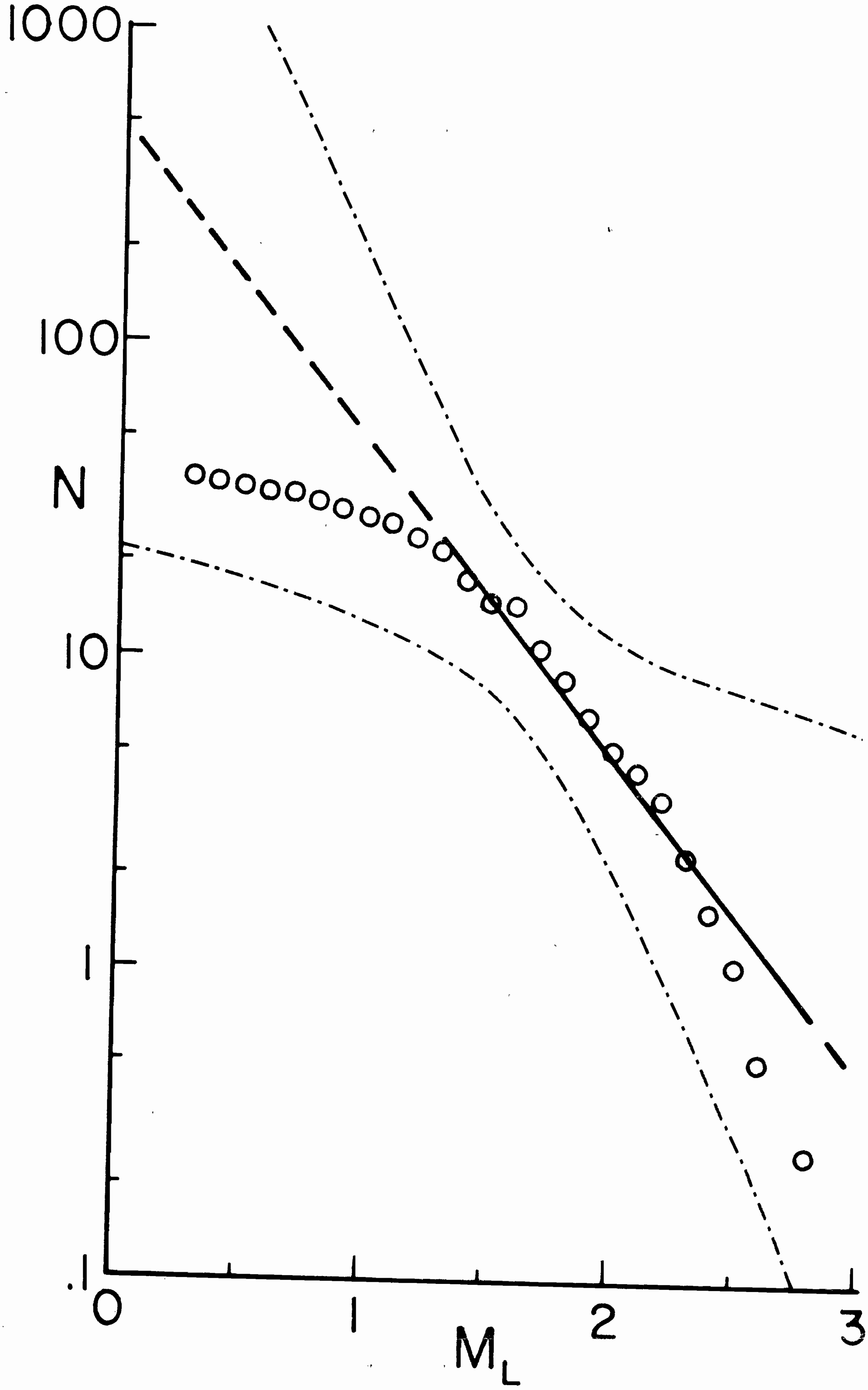
FOLSOM RESERVOIR LEVEL FLUCTUATIONS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7-9


10
1
N
.1
.01
3
4
5
6
M_L


1000
100
N
10
1
.1
0
1
2
3
M_L

SECTION 8

SECTION 8 - REFERENCES

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LINEAR SURFACE FEATURES

FOLSOM LAKE

Prepared for

TIERRA ENGINEERING CONSULTANTS

Santa Fe, New Mexico

July 1982

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- LINEAR SURFACE FEATURES -

FOLSOM LAKE

Introduction

The Photographic Interpretation Corporation (PIC) has conducted a surface linear mapping study using aerial photographs of the area surrounding the Folsom Dam and Lake near Folsom, California. The purpose of this study was to identify linears occurring on aerial photographs and satellite images in order that Tierra Engineering Consultants and its subcontractor, Converse Consultants, might investigate these features for their relevance in assessing earthquake potential in the vicinity of Folsom Dam and Lake. The area investigated in the study extended from Coon Creek on the north to the Cosumnes River on the south, and from a line through Pilot and Pine Hills on the east to a line 12 miles from this eastern boundary on the west.

The study is a part of a larger study by Tierra and Converse for the Sacramento District of the Corps of Engineers. The results of this study are presented in this report and on overlays to 7½-minute USGS topographic maps furnished to Tierra Consultants.

In 1911, Hobbs[1] began the systematic analysis of linear landscape features. In 1958, Lattman[2] described the technique of mapping these lineations on aerial photographs and in 1964, Bayer and McQueen[3] reported on a systematic comparison of photo derived linears with actual surface geologic mapping and concluded that...

"....results of this study indicate a close parallelism of fractures measured on the ground and airphoto linear features and suggest that the airphoto linear features are largely a reflection of fractures in the rocks emphasized by vegetation and topography."

Geologic maps covering the study area show geologic structure, which trends NNW/SSE, but show only two major documented fault zones, the East and West Branches of the Bear Mountain Fault Zone in the eastern portion of the area.

Linears mapped from aerial imagery in this study do not necessarily represent geologic faults. They may only reflect bedrock joint and fracture patterns without implying movement. Segments of the linears are often aligned with the drainage patterns which apparently are influenced by these fractures. However, the segments of known faults are not always reflected as either drainageways or as topographic features recognizable on the airphotos.

Remote sensor image lineament mapping is not new to this region of the Foothills. Several studies and projects have been accomplished in the area over the past few years, including studies by Schwartz, et al.[4] for Auburn Dam; by Wagner[5] in the Pine Hill area; and by Hodges[6] in the western Sierras and in the eastern Coast Range. Existing literature on the region was not consulted, however, until after all of the lineament mapping was finished and the weighted linear maps were being produced. Thus, an independent analysis was made.

Image Acquisition

Several types and scales of remotely sensed imagery were obtained for the analysis of linears. These included:

1) LANDSAT images - false color (CIR) composite and panchromatic (bands 5 and 6);
2) SEASAT (radar) ascending and descending modes;
3) SKYLAB, color enlargements;
4) 1:120,000 scale, CIR, NASA U-2 photographs;
5) 1:80,000 scale, panchromatic, USGS quad-centered photographs;
6) 1:63,000 scale, SCS controlled mosaics;
7) 1:36:000 scale, color, low sun angle aerial photographs;
8) 1:30,000 scale, CIR enlargements of the NASA U-2 photographs;
9) 1:24,000 scale, panchromatic enlargements of USGS quad centered photographs;
10) 1:20,000 scale, panchromatic aerial photographs taken 1971; and
11) 1:20,000 scale, panchromatic aerial photographs of the reservoir taken in 1952 (prior to reservoir filling).

Methodology

Lineament analysis for this project was accomplished by a team of three professionals - a civil engineer, a geologist, and a geographer. Each of the team was experienced in photointerpretation and lineament analysis. The team members examined each set of imagery individually and then produced his own interpretation. These interpretations were later combined by the team into the weighted linear maps.

Further input into the linear maps came from a Converse Consultants geologist, Mark Shaffer, who performed an independent analysis of some of the images in the field. His interpretation was later integrated into the weighted linear maps.

The images were viewed in one of three ways. Those images which, by their nature (Landsat or SEASAT) or by their size (NASA U-2 enlargements), could only be analyzed monoscopically were examined individually by the photo interpreters and individual interpretive overlays were created. These were then superimposed by the team and a weighted linear map was prepared.

Except for the 1971, 1:20,000 scale airphotos, the other images, which could be viewed stereoscopically, were mounted on chipboard and direct individual stereoscopic analysis of the linears was made by each of the team members. As was the case for the monoscopic analyses, the individual interpretations were evaluated by the team and a weighted linear map prepared.

The 1:20,000 scale panchromatic airphotos were laid in two stereo-mosaics in which only the alternate photos were used so that the remaining photos could be used to view the area stereoscopically. These mosaics, one for the north half of the project area and one for the south, were analyzed in stereo in order to create drainage overlays (Figs. 1a and 1b). The two drainage overlays first were analyzed individually by the team members and then by the group and a weighted linear map was produced (Figs. 2a and 2b).

Lineaments appearing on the aerial photographs or satellite images may be caused by cultural features or natural factors. For the most part, it was not difficult to eliminate from further consideration those linears which could be directly attributable to cultural features such as roads and highways, fence lines and field edges, and dredge tailing piles. Topographic maps and larger scale airphotos provided most of the evidence necessary to drop those linears from further consideration.

Linears related to geologic features may be manifested in several ways including stream alignments, straightness of stream segments, offset drainage features, scarps, incised valleys, lines of springs, abrupt changes in vegetation, changes in slope, and changes in photo tone or color. These lineaments may represent such features as bedding planes, faults, joints, fractures, changes in rock materials, or erosion scars.

The strength of a linear sometimes bears no obvious relationship to its geologic origin. However, in the Folsom area, various portions of the East and West Branches of the Bear Mountain Fault Zones are well defined by drainage and topographic indicators. Features such as Russell Hollow, Cooper Canyon, and New York Ravine are well defined topographically and appear as well defined elements on most images. In other areas these fault zones show few or no indications of being linears on any of the images.

The strong linear category includes linears which may be subtle both on the ground and on the images but are persistent across the imagery. Often these are indicated by slight changes in color or tone, by a fine line, or by breaks in slope.

In the Folsom study, indicators of natural linears were primarily aligned streams, incised valleys, lines of springs, changes in slopes, changes in phototone and/or color and changes in vegetation or aligned vegetation. Many of these lineaments were quite short (less than one-half mile) and not apparently aligned with any others. It is likely that these segments are not indicative of any significant geologic feature.

Drainage Mapping

The mapping of regional drainage patterns often reveals geologically significant lineations. This is because the locations of stream and gully systems are often controlled by the underlying bedrock. Where bedrocks are jointed and fractured, drainage patterns tend to be angular and contorted, reflecting zones of weakness in the underlying rock. A detailed mapping of surficial drainage in a region emphasizes these abrupt changes in the alignment of stream gullies and channels, thus providing good clues about the underlying geologic structure to the photo interpreter. The alignment of a number of angular adjustments of stream courses often is interpreted as a photo linear. In some instances, segments of entire stream channels are so exactly aligned that the stream valley is recognized as a natural linear feature on aerial imagery.

Because of the importance of surficial drainage patterns as indicators of bedrock influence (or lack of influence), a detailed drainage overlay was created for each 1:20,000 scale photomosaic through the process of stereoscopic viewing. One photointerpreter was responsible for all drainage mapping in order to maintain a consistent level of density and detail across the study area. These drainage overlays were analyzed by the individual team members and then by the group and revealed many of the linears mapped in the study. The majority of the drainage-related linears are short sections of straight stream channels or discontinuous sections of drainage which appeared to be aligned. Other drainage related linears are continuous incised valleys. Some known faults transverse the terrain with no apparent reflection in the drainage patterns.

Team Analysis of Mapped Linears

Following each individual's lineament mapping for each image type, the separate interpretations were compared by the team to create a weighted linear map for the image. Linears mapped by all three interpreters were categorized as strong linears with high confidence levels. Those mapped by two interpreters were categorized as moderate and those mapped by only one interpreter were categorized as weak with an associated low confidence level.

Weighted Linear Maps

The results of the individual and group mapping effort are the weighted linear maps (Figures 3 through 7). Three categories of lineations are depicted on these maps:

- Strong surface expression depicted by a wide, solid line,
- Moderate surface expression depicted by a medium weight, dashed line, and
- Weak surface expression depicted by a thin, solid line, or dotted line.

An individual map may have only one or two categories present or all three categories present.

Interpretation of the Airphoto Linear Maps

The airphoto linears plotted in Figures 3-6 represent the consensus of the photo interpretation team as to where natural terrain lineations occur on the photomosaics. Based on an evaluation of the number of coincident sightings linears were designated as strong, moderate, or weak. The mapped photo linears are not necessarily faults in the bedrock but likely represent zones of bedrock structure (joints, fractures, bedding or faulting) which express themselves in the form of some linear feature upon the photographic image.

Figure 7 is a composite map created by overlaying the lineament maps derived from the 1:20,000 scale airphotos (Fig. 3), the high altitude CIR airphotos (Fig. 4), the Landsat image (Fig. 5), and the Seasat image (Fig. 6). Lines on the composite map indicate where at least two linears depicted on Figures 3 - 6 coincided.

On several of the photomosaic overlays there are weak to faint indications of linears extending beyond, or connecting, strong pronounced linear features. While the entire analysis team could agree on the orientation of a particularly strong lineation, occasionally not all could agree as to exactly where the last trace of the feature expressed itself. This accounts for the diminished strength of many strong linears at their ends.

It is difficult to develop a comparison between linears mapped from satellite imagery (Landsat) even at an enlarged scale of 1:500,000 ($\pm$ 8 miles per inch) and those mapped in this study from aerial photographs at a 1:20,000 ($\pm$ 1667 feet per inch) scale. The difference in scale necessitates that each analysis be based on different criteria. At the satellite level, entire river valley systems extending for many miles may align themselves into one linear element while, at 1:20,000 scale, only straight segments of a river channel within a valley system might be mapped as linears. A linear drawn on a small scale satellite image will be hundreds of feet wide on the ground and, therefore, variations measured in hundreds of feet (that might be detected on a large scale airphoto) can be accommodated by a single, straight line on the satellite image. Each image, whether a small scale satellite image or large scale airphoto, provides differing levels of detail and, thus, care must be taken in comparing one scale image to another.

Discussion of Results

The results of the remote sensing linear analysis can best be appreciated by studying the weighted linear maps created for each set of imagery. The following is a summary of the determinations resulting from analysis of the weighted linear maps:

1. A strong linear was detected which corresponds with the West Branch of the Bear Mountain Fault Zone as depicted on the new (1981) 1:250,000 scale Sacramento Geology Map. The zone passes to the east of Mormon Island Dam and continues north, across both arms of the lake instead of passing under the Morman Island Dam and continuing to the Rocklin-Penryn Pluton as shown on earlier geologic maps. The northern end of the West Branch was trenched by Woodward-Clyde in the 1977 study of the Auburn Dam.[4] In the past the West Branch of the Bear Mountain Fault Zone has also been known as the Hancock Creek and the New York Ravine zones.

2. No linears appear to pass through or travel long distances in the Rocklin-Penryn Pluton. Most short linears (less than one mile) are apparently related to bedrock fractures or joints.

3. Only two strong linears persist west of the West Branch of the Bear Mountain Fault Zone and south of Folsom Lake. For this study these two have been named the Mormon Island Linear and the Linda Creek Extension since they have not been named in previous studies. The Linda Creek Extension is a persistent, although faint, linear which is evident on all imagery sources. It is generally aligned with the Linda Creek Linear which was mapped by Aune in 1971 and trenched by Woodward-Clyde for the Auburn Dam study in 1977.[4]

The Mormon Island Linear may be projected to pass beneath the east abutment of the Mormon Island Dam. It is most evident on the imagery between Highway 50 and the Mormon Island Dam.

4. The linears that are most persistent on the imagery between the East and West Branches of the Bear Mountain Fault Zone and south of Folsom Lake are the New York Ravine Linear (which may be part of the Bear Mountain System) and the Bass Lake Linear. The Bass Lake Linear has been noted by others but not named in any of the literature examined in this study.

5. Between the two arms of Folsom Lake and the East and West Branches of the Bear Mountain Fault Zone are three persistent linears - Pilot Hill, Russell Hollow, and a branch of the Hancock Creek - all of which have been mapped as faults by Schwartz et al.[4] and Wagner et al.[7]

6. No traces of either the East or West Branches of the Bear Mountain Fault Zone could be seen passing through the Mehrten formation cap rock at Auburn. The two branches could be followed to the North Fork of the

American River and, to some extent, beyond but on none of the images examined could either be seen extending into the Mehrten formation to the north. Only the West Branch showed any strong pattern north of Auburn.

7. For this particular study, the most useful imagery was the 1:120,000 scale, stereoscopic U-2 photographs. This imagery provided the best synoptic view of the study area and also revealed many linears.

8. Most of the very strong lineaments were detected on all imagery types. However each set of imagery revealed a few lineaments not seen on the other sets.

APPENDIX

Literature Cited

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7. Wagner, D.L., Jennings, C.W., Bedrossian, T.L. and Bortugno, E.J., 1981, Geologic Map of the Sacramento Quadrangle, California, 1:250,000, California Division of Mines and Geology.

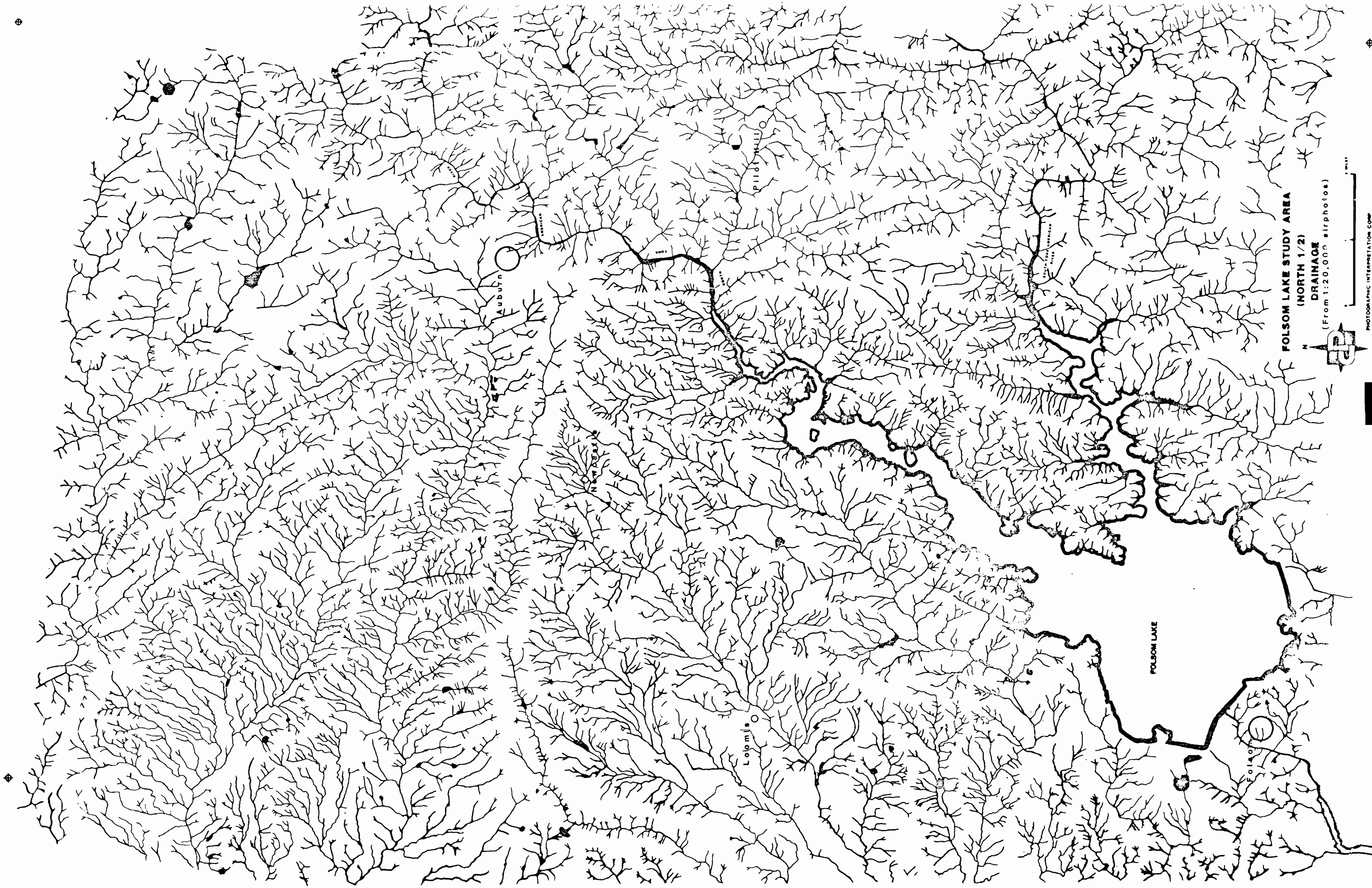

FOLSOM LAKE STUDY AREA
(NORTH 1/2)
DRAINAGE
(From 1:20,000 airphotos)
N
PHOTOGRAPHIC INTERPRETATION CORP
HANOVER, NEW HAMPSHIRE
Auburn
Pilot Hill
Newcastle
Loomis
Folsom
FOLSOM LAKE

figure 1a


Clarksville
Latrobe
FOLSOM LAKE STUDY AREA
(SOUTH 1/2)
DRAINAGE
(From 1:20,000 airphotos)
N
PHOTOGRAPHIC INTERPRETATION CORP.
HANOVER, NEW HAMPSHIRE

figure 1b

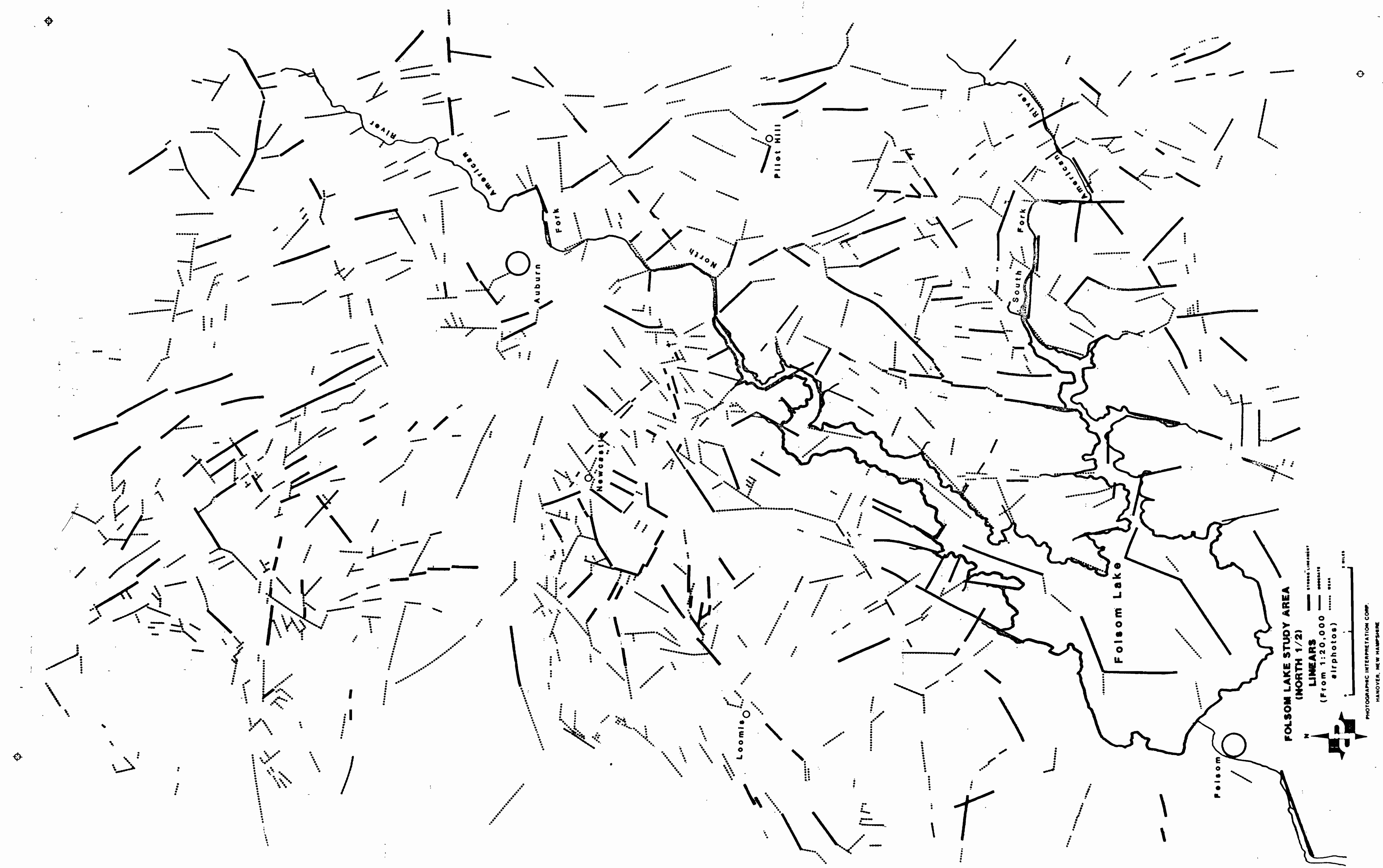
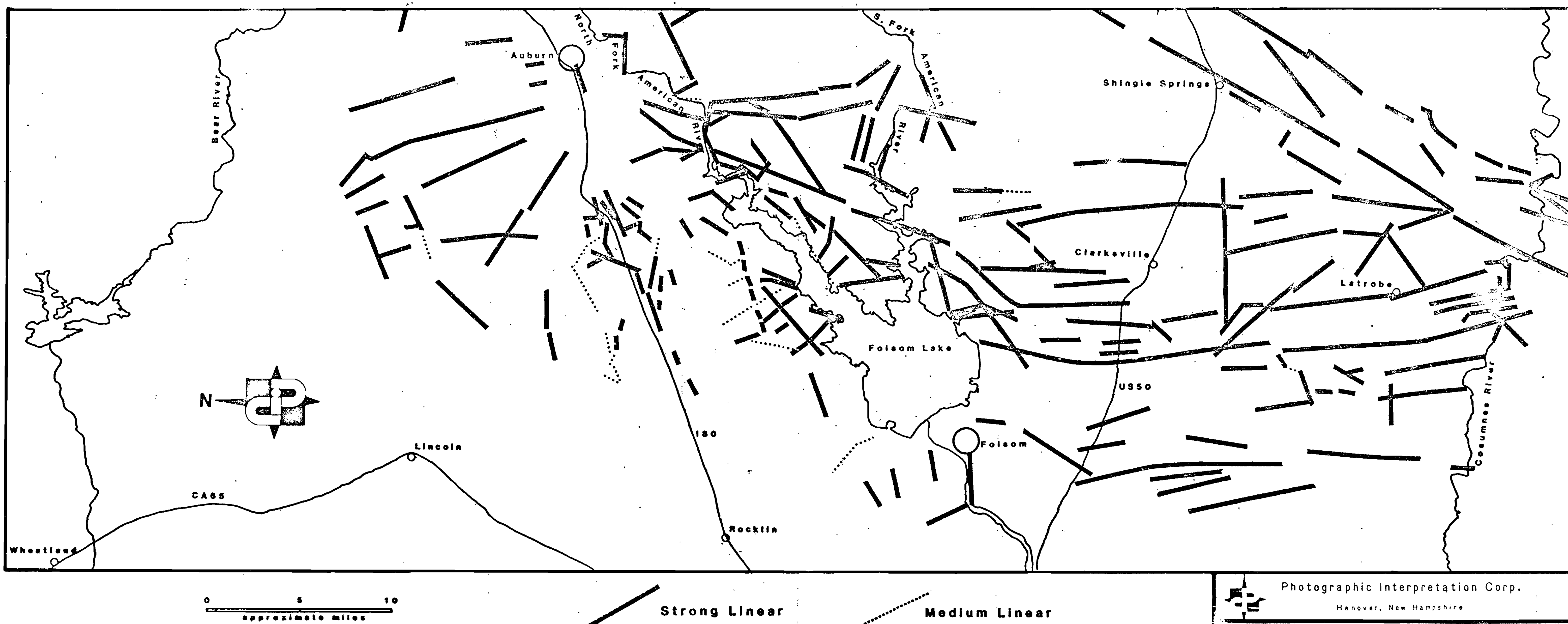

American River
North Fork
Auburn
Pilot Hill
American River
South Fork
Newcastle
Loomis
Folsom Lake
Folsom
FOLSOM LAKE STUDY AREA
(NORTH 1/2)
LINEARS
(From 1:20,000
airphotos)
N
PHOTOGRAPHIC INTERPRETATION CORP.
HANOVER, NEW HAMPSHIRE

figure 2a


Bass Lake
Clarksville
Creek
Deer
Latrobe
Cosumnes
River.
FOLSOM LAKE STUDY AREA
(SOUTH 1/2)
LINEARS
(From 1:2000
airphotos)
STRONG LINEAMENT
MODERATE
WEAK
N
PHOTOGRAPHIC INTERPRETATION CORP.
HANOVER, NEW HAMPSHIRE

figure 2b

Linears from 1:20,000-Scale Airphotos (1971)

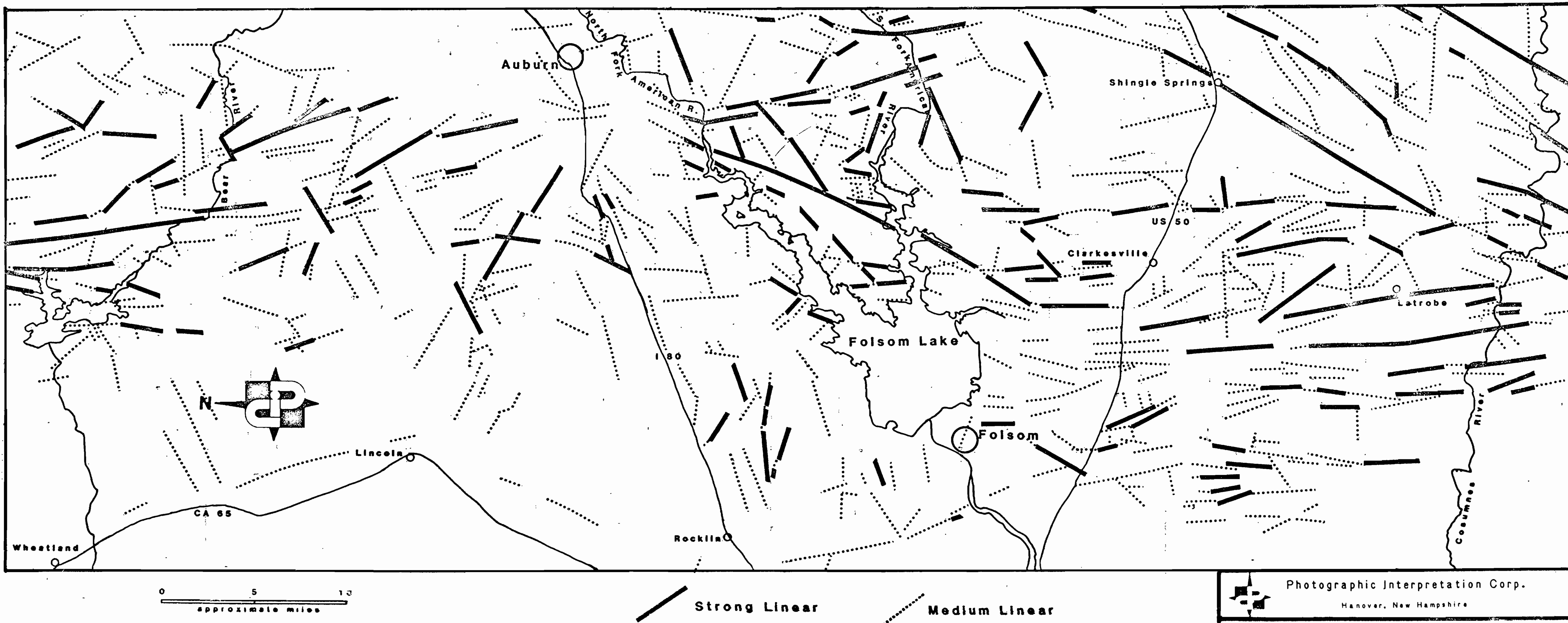


Photographic Interpretation Corp.
Hanover, New Hampshire

LINEAR SURFACE FEATURES – FOLSOM LAKE

Figure 3

Linears from 1:120,000 Scale CIR Airphotos (1974)

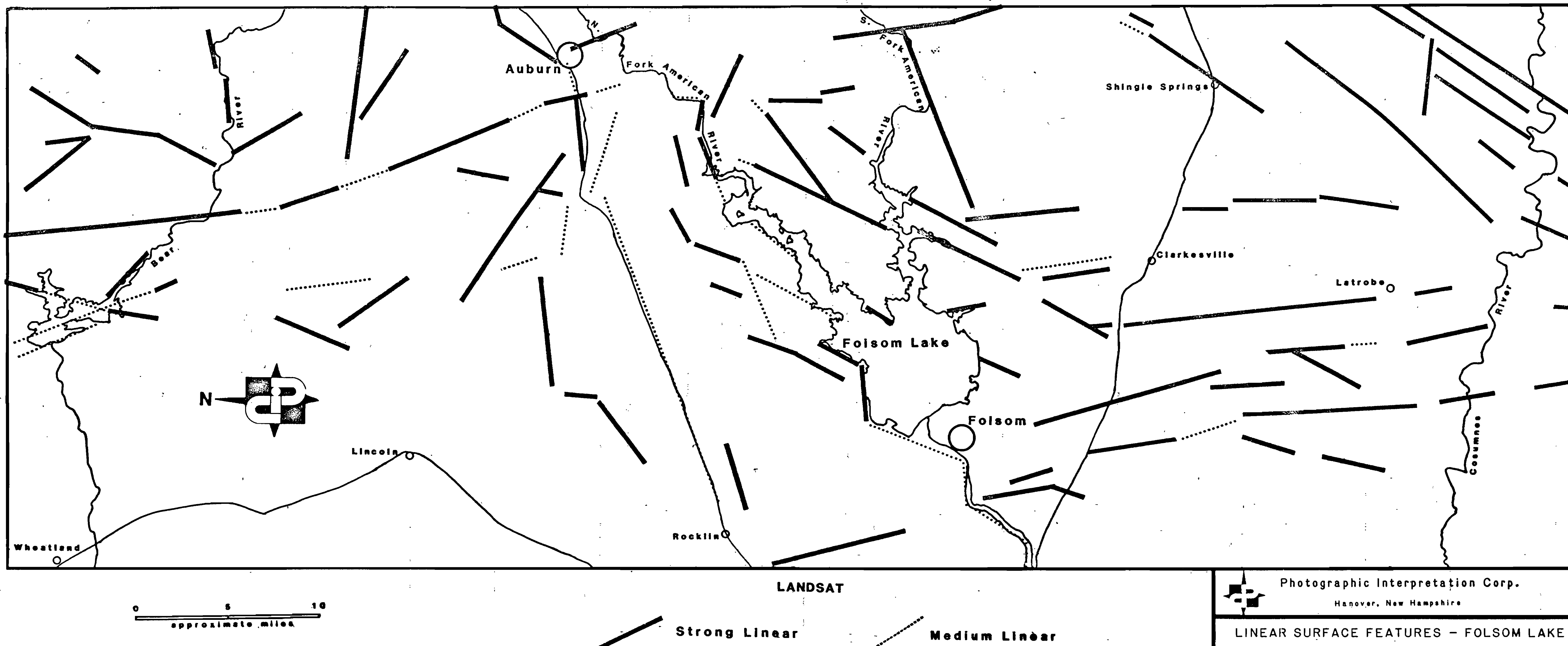


Photographic Interpretation Corp.
Hanover, New Hampshire

LINEAR SURFACE FEATURES – FOLSOM LAKE

Figure 4

Linears from 1:1,000,000 Scale Landsat Scenes - Bands 5,6, and Color Composite (1978)

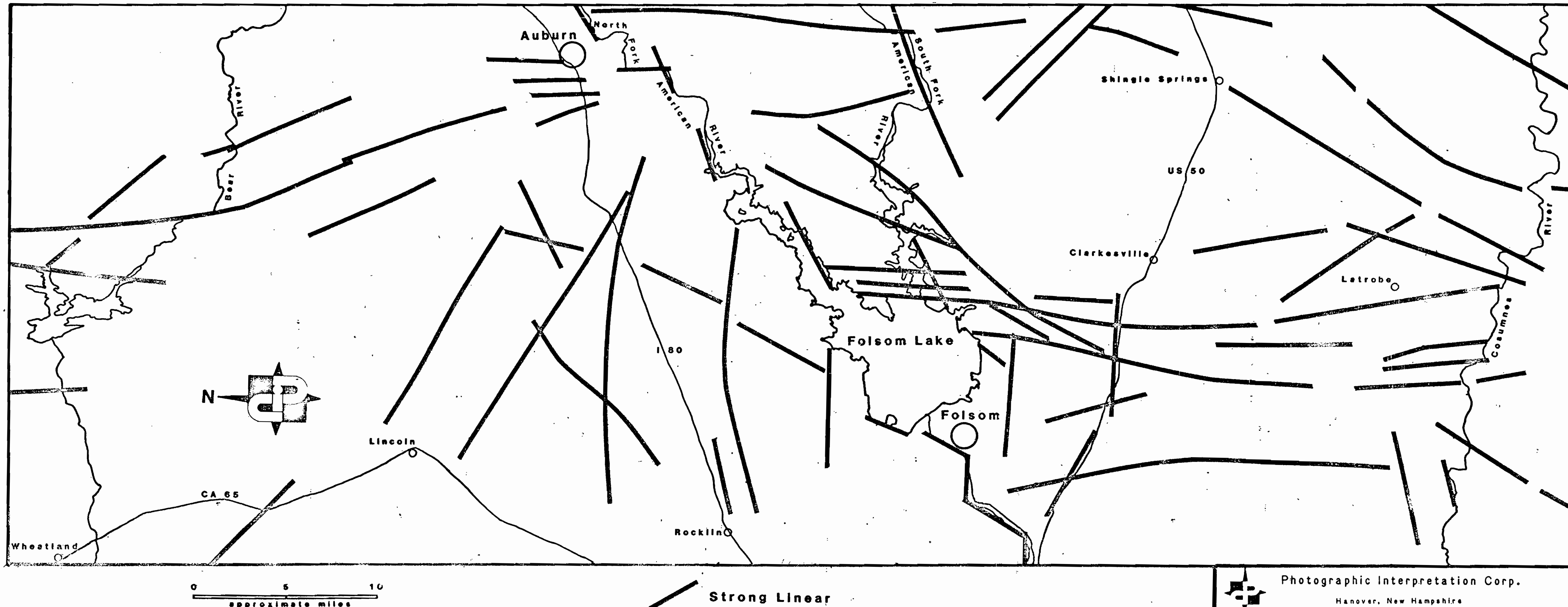


Photographic Interpretation Corp.
Hanover, New Hampshire

LINEAR SURFACE FEATURES - FOLSOM LAKE

Figure 5

Linears from approx. 1:500,000 Scale Seasat Radar Images (1978)

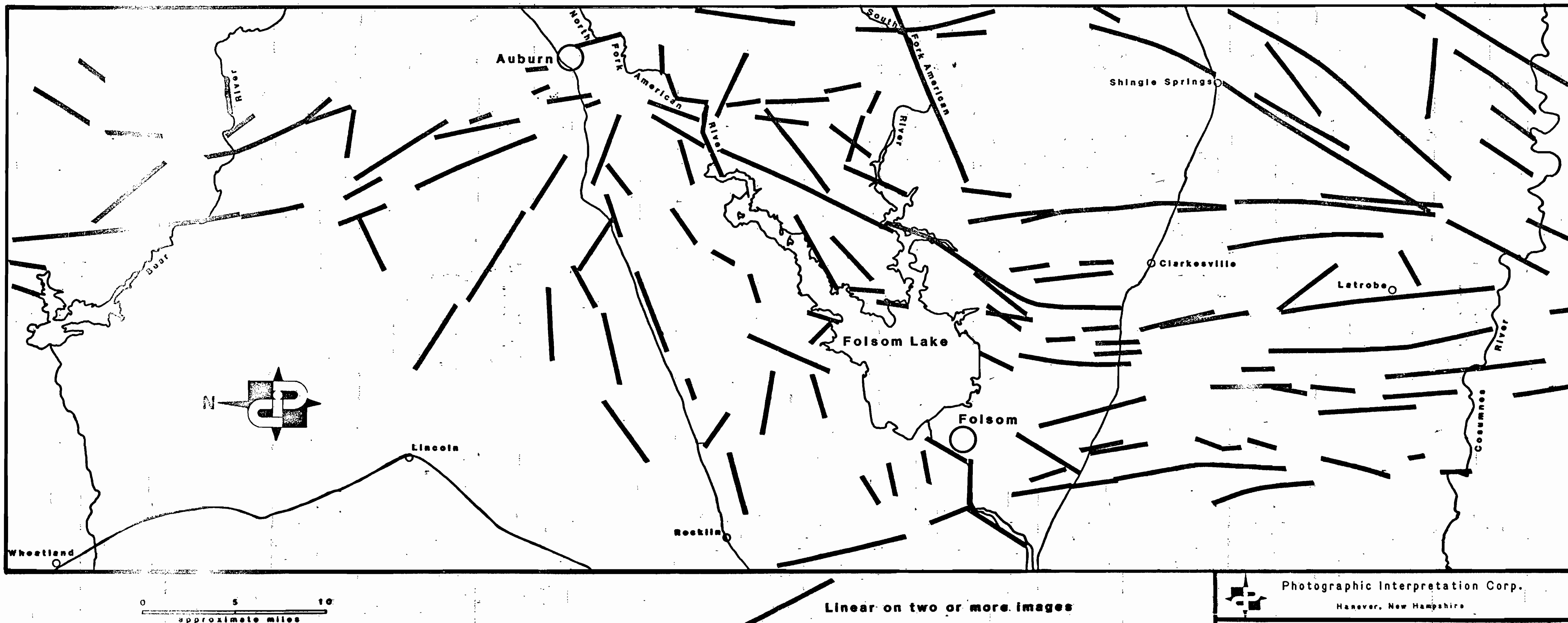


Photographic Interpretation Corp.
Hanover, New Hampshire

LINEAR SURFACE FEATURES – FOLSOM LAKE

Figure 6

Composite Linear Map (based on all imagery used)



Linear on two or more images

Photographic Interpretation Corp.
Hanover, New Hampshire

LINEAR SURFACE FEATURES - FOLSOM LAKE

Figure 7

Appendix B

SEISMICITY OF THE SIERRAN FOOTHILLS NEAR FOLSOM RESERVOIR, CALIFORNIA

by

Dr. Robert Uhrhammer

for

Tierra Engineering Consultants, Inc.

March, 1983

APPENDIX B - SEISMICITY

SEISMICITY OF THE SIERRA NEVADA FOOTHILLS

Prior to the occurrence of the Oroville earthquake sequence (main shock $M_L = 5.7$) of August, 1975 (Morrison et al, 1976) the Foothills fault system was generally considered to be seismically inactive. As a consequence of the Oroville earthquakes, the seismic hazard to proposed and existing large reservoirs and dams in the foothills of the Sierra Nevada is being re-evaluated. For such evaluation the historical earthquake record is of basic importance. For convenience, the observed seismicity along the Sierra Nevada foothills can be separated into three overlapping time eras based on the source of information: 1) historical felt reports (newspapers, etc.) prior to 1928; 2) instrumentally recorded by regional seismographic stations (1928-present); and 3) instrumentally recorded by local seismographic stations (including micro-earthquake surveys with portable instruments) (1976-present).

As a regional reference the seismicity of Northern and Central California and vicinity within approximately 500 km of Folsom Dam is shown in Plate 1 as a reference for comparison with the seismicity of the Foothills fault system. Plate 1 depicts the location and magnitude of 6161 earthquakes of ML 3.0 or larger which are listed in the Bolt-Miller Catalogue (1910-1972) (Bolt and Miller, 1975) and the Bulletin of the Seismographic Station (1973-1980). In particular, the relatively low rate of seismicity of the western Sierra Nevada foothills should be compared with regions such as the central Coast Ranges of California and off the coast of Northern California.

Before the 1940's Berkeley (BRK) was the closest seismographic station (135 km southwest of Folsom Lake) the seismicity data for the Sierra Nevada foothills are based primarily on felt reports (Townley and Allen, 1939; Bolt and Miller, 1975; Toppozada et al, 1982). It should be noted that the local magnitude (M_L) required to produce a 1mm maximum trace amplitude (at a period of 1 second) on the seismograms recorded at Berkeley was about 4.8 before 1930; 3.2 from 1930 to 1933; and 2.2 after 1933. These earthquakes are thus about the minimum size earthquakes detectable in these time periods.

Reports of felt eathquakes in the vicinity of Folsom Lake (distance less than 50 km) are rare. Cloud (1976) reported only three historical events (February 23, 1885; April 21, 1892; and May 30, 1908) which may have occurred in the vicinity of Folsom Lake. The February 23, 1885 event was reported as felt in Newcastle with a modified Mercalli intensity of

III (MM III) and the April 21, 1982 event was reported felt in Newcastle (no intensity given). Newcastle is 15 km north of Folsom Lake. A search of old newspapers produced accounts of the May 30, 1908 earthquake (see Cramer et al, 1978). An isoseismal map based on the newspaper accounts gives a maximum reported intensity of MM IV-V and total felt area of approximately 10,000 km^2 which suggest a local magnitude (M_L) of approximately 4 for this earthquake. The intensity contours (Cramer et al, 1978) suggest the earthquake occurred between Auburn and Folsom in the vicinity of the Rocklin/-Penryn pluton. If this interpretation is correct this small ($M_L \leq 4.0$) earthquake of 1908 is the largest earthquake to have been reported in historical times in the vicinity of the Rocklin/Penryn pluton.

For the purpose of estimating the rate of seismicity along the Sierra Nevada foothills in the vicinity of Folsom Lake, a search was made of the available seismicity catalogue in the region of the Sierra Nevada foothills between approximately 36.5° N and 39.5° N latitude. A search of the Seeburger revision of the "Townley-Allen" historical earthquake catalogue produced felt information for 125 earthquakes which occurred between 1850 and 1927. The list is given in Table 1. The Seeburger revision is recompilation of the Townley-Allen catalogue (Townley and Allen, 1939) based on five sources (Bolt and Miller, 1975; Gutenburg and Richter, 1954; Holden, 1898; Townley and Allen, 1939; and Ward and Meek, 1951). In the Seeburger revision the intensities given are modified Mercalli and not Rossi-Forel as given in the original sources. In the 78 years from 1850 through 1927, ten earthquakes were assigned a maximum modified Mercalli (MM) intensity of V, six earthquakes were assigned a maximum MM intensity of VII. Maximum MM intensities of V, VI, and VII correspond approximately to local magnitudes (M_L) of 4, 4-1/2, and 5, respectively. From these historical felt reports, the inferred rate of seismicity at the $M_L \geq 4$ level is of the order of two dozen per century and the inferred rate at the $M_L \geq 5$ level is on the order of two per century.

A search of the Bolt-Miller catalogue and the Bulletin of Seismographic Stations for instrumentally recorded eathquakes of $M_L \geq 3$ which have occurred in region of the western Sierra Nevada Foothills between 36.5°N and 39.5°N latitude produced 112 earthquakes between 1937 and 1979. The earthquakes are listed in Table 2 and plotted in Plate 2. Two of the earthquakes listed in Table 2 (a M_L 3.9 on March 19, 1943 and a M_L 3.0 on May 25, 1951) were estimated as centered within 30 km of the Folsom Reservoir site. Of particular interest is the location of the M_L 3.9 earthquake of March 19, 1943 (38.8° N, 121.1° W) which is about 8 km southwest of Auburn and 12 km north of Folsom Lake. If this location is correct, this mild earthquake (M_L 3.9) would be the largest instrumentally recorded earthquake to have occurred in the vicinity of Folsom Lake. Because of this feature, the M_L 3.9 earthquake hypocenter was relocated using the reported phase onset time data (Herrick and Pendevy, 1950) which was checked against the original seismograms kept on store at Berkeley. Trial locations were determined using several subsets of the phase onset time data and two velocity models (a central coast and a Sierra model). The solution for the relocated epicenter (38.9^{o} N, 119.9^{o} W) with a 95 percent confidence interval of $\pm$ 35 km) was adopted as the most likely. This adopted solution was found to be robust and nearly independent of the model and phase onset time subset used in the solution. It is important to note that the relocation shifts the epicenter to a point between Markleeville and Lake Tahoe, approximately 100 km east of Folsom Lake and thus outside of the region of interest. The M_L 3.0 earthquake of May 25, 1951 (Tocher, 1952) was also relocated using the procedure outlined above and the improved epicenter (39.95^{o} N, 120.05^{o} W; with a 95 percent confidence interval of $\pm$ 7 km) was adopted. This reversed solution is in agreement with the originally reported epicenter. Thus this earthquake (May 25, 1951) is the largest instrumentally reported earthquake (M_L = 3.0) to have occurred in the vicinity of the Folsom Reservoir site (i.e. in the last 43 years).

In order to estimate the rate of seismicity from the above sample of 112 earthquakes $M_L \geq 3$ in 43 years, the earthquakes were divided into 43 consecutive one year bins and the cumulative number of earthquakes (N) of magnitude M_L or longer was fitted with weighted least-squares to the standard form $\log N = a - bM_L$. The result is $\log N = 3.042 - 0.854\ M_L$. The variance of log N is $\sigma^2 \log N = 0.0306 - 0.0166\ M_L + 0.00229 M_L^2$.

From the equation $\log N = a - bM_L$, the rate of seismicity (r) in terms of the number of earthquakes per century per 100 km along the Foothill fault system can be inferred. The estimated values are:

$M_L \geq$	r	σ
3	92	15
3.5	34	3.5
4	13	1.6
4.5	4.8	1.0
5	1.8	0.52
5.5	0.67	0.26
------	------	------
6	0.25	0.12
6.5	0.094	0.055

where σ is the standard error of the rate r. It is important to stress that the estimate below the dashed horizontal line is an extrapolation as the largest earthquake in the observed data set is the M_L 5.7 Oroville earthquake of August 3, 1975.

Note that approximately 70 percent of the earthquakes listed in Table 2 are associated with the M_L 5.7 Oroville earthquake sequence of August, 1975. If these earthquakes are not included in the above calculations, the rate of seismicity drops by a factor of three. However, the estimates of the rates of seismicity for earthquakes of M_L 4.5 and larger are based on an extrapolation from the recurrence equation and the uncertainties in the extrapolated rate are such that there is no significant difference (at the 95 percent confidence level) between the rates of seismicity computed with and without the Oroville earthquake sequence data.

Relatively few of the instrumentally recorded epicenters plotted in Plate 2 are located in the central third of the plot in the vicinity of Folsom Dam. In the above calculations it is assumed that the rate of seismicity (in earthquakes per century per 100 km linear segment) is independent of position along the Foothills fault system. Given the uncertainties in the rate of seismicity this assumption is compatable with the observed data in Table 2 (at the 95 percent confidence level).

From the above calculations there is no significant difference (at the 95 percent confidence level) between the rates of seismicity inferred from the historical felt reports and inferred from the instrumental data (in the magnitude 4 to 5 range). As a comparison, the rate of seismicity along the central coast of California is 2875 $\pm$ 589 earthquakes ($M_L \geq 3$) per century per 100 km linear segment (estimated from seismicity data published in the Bulletin of the Seismographic Stations, 1960-1979). The rate for the central coast region is approximately 30 times the rate for the Sierra Nevada foothills (for $3.0 \leq M_L \leq 6.0$ approximately).

The expected number of earthquakes with magnitude above 5.5 along a 100 km segment of the Foothills fault system per 100 years is about one. Based on numerical extrapolation only, a magnitude 6 or greater earthquake might be expected in the same zone only once every 400 years.

Following the Oroville earthquake sequence of August 1975, improved regional seismographic station coverage resulted in the detection of a small number of microearthquakes ($M_L \geq 1$) along and in the vicinity of the Foothills fault system between Folsom and Oroville (Cramer et al, 1978). Subsequently two microearthquake surveys with portable networks which were operated during the summer and fall of 1976, detected microearthquakes ($0 \leq M_L \leq 1$) in the Rocklin/Penryn pluton and vicinity (see McNally et al, 1978; Cramer et al, 1977).

A network of 14 local seismographic stations (telemetered to Menlo Park) was installed in the Auburn region by the U.S. Geological Survey starting in July 1976. The signals were telemetered to Menlo Park for recording and analysis. Between November, 1976 and September, 1980, 149 local earthquakes $0.1 \le M_L \le 2.8$ were recorded by this Auburn net (Eaton and Simirenkco, 1980; Dr. Jerry Eaton, USGS, personal communication, 1982).

An analysis of the spatial distribution of the epicenters plotted on Plate 3 shows no significant linear trends which might correlate with the surface traces of the Foothills fault system.

The recorded micro earthquakes are listed in Table 3 and plotted in Figure 2. The distribution of magnitudes is such that the list is probably not complete for $M_L < 1.3$. The 85 earthquakes $M_L \ge 1.3$ were divided into 12 consecutive four month bins and the cumulative number of earthquakes was fitted by weighted least-squares to the standard form

$$\log N = a - bM_L \text{ where } \log N = 4.380 - 1.005M_L$$

and

$$\sigma^2 \log N = 0.928 - 1.083M_L + 0.328M^2_L.$$

Log N is normalized to the expected number of earthquakes per century per 100 km length of the fault zone where N is the cumulative number of earthquakes of magnitude M_L or larger. From this data, there is no significant difference (at the 95 percent confidence level) between the rates of seismicity inferred from the regional data and inferred from the local data at the M_L3 level (= 92 ± 15 and = 23 ± 42, respectively).

The observed cumulative rate of seismicity and the least-squares fit to the cumulative rate are plotted on Plate 8. Note the apparent change in slope of the observed data at a magnitude of 1.2. Three reasons for this change might be suggested. First, both amplitude and duration are used to estimate the magnitude of the earthquakes. If the event is small enough that recorded waves in the high-gain vertical sesimograms are not clipped, then the amplitude and period of the maximum trace amplitude are measured and converted to an equivalent Wood-Anderson amplitude for estimation of the local magnitude (M_L). For larger events or for stations where the maximum trace amplitudes are clipped, the duration of the coda is used to estimate the local magnitude (Dr. Jerry Eaton, USGS, personal communication, 1982). Thus, the apparent slope change in Plate 8 could be due to an inconsistency in the magnitude estimation. Second, no station adjustments were used for computing M_L using the Auburn station data and for the smallest earthquakes only the more sensitive stations will yield useful amplitude data. This leads to a bias in the magnitude estimation because the magnitude of the smaller earthquakes may be overestimated. The result might be an apparent slope change. Third, there may be a real upper limit to the dimensions of the causative fault on the order of a few hundred meters to a kilometer. Such a small unit would result in an upper limit to the magnitude of earthquakes which are centered in the vicinity of the Auburn net. Because the current data set of 63 microearthquakes is small, it is not possible to distinguish between the above three explanations.

Considering that there is no significant difference (at the 95 percent confidence level) in the rates of seismicity for the three data sets described above, the rate of seismicity as inferred by the regionally recorded earthquakes will be adopted as representative of the Sierra Nevada foothills. Thus:

$$\log N = 4.523 - 0.854M_L$$

and

$$\sigma^2 \log N = 0.556 - 0.302M_L + 0.0416M_L^2$$

will be used for the Sierra Nevada Foothills. Log N is normalized to the cumulative number of earthquakes per century per 100 km linear segment of the Foothills fault system.

ROCKLIN/PENRYN PLUTON SEISMICITY

As mentioned previously, the earthquakes located in the Rocklin/Penryn pluton and vicinity (indicated by * in Table 3 and plotted on Figure 3) were recorded by a 14-station network near Auburn operated by the USGS in Menlo Park. Twenty-six of the best recorded earthquakes ($M \geq 0.7$) were selected for relocation using a group location procedure (see Bolt et al, 1978) which estimates the hypocentral coordinates and the station adjustments simultaneously. The group location method leads to a higher relative precision in the locations of the hypocenters. The velocity model used in relocating the earthquakes is a gradient layer over a half-space where the P- and S-wave velocities are

(6.30 + 0.014z) and (3.70 + 0.008z) km/sec,

respectively in the layer and 8.0 km/sec and 4.7 km/sec in the half-space and the depth (z) to the half-space is 35 km. The velocity model is an approximation to the structure in the Rocklin/Penryn pluton region as determined by refraction profiles which were constructed using blasting by local construction and quarry operations as sources (Cramer et al, 1977).

The relocated hypocenters are given in Table 4. It should be noted in particular that uncertainties in the hypocentral coordinates are quite small (averaging about 0.2 km for the epicenter and 0.3 km for the depth) due to the use of the group location method in locating the earthquakes. The corresponding P- and S-wave station adjustments are given in Table 5 and all of the station adjustments are significantly different from zero as the standard error in one adjustment average as less than 0.01 second. No significant trend of the station adjustments with either distance, azimuth, or wave type (P-wave average = -0.05 ± 0.03 sec. and S-wave average = 0.08 ± 0.05 sec.) is apparent in the data and thus there is no indication of a significant bias in the assumed velocity model. The 26 relocated hypocenters are plotted in a plan view and two cross-sectional views in Plates 4 and 5.

Plate 4 shows that the epicenters cluster into three groups within the Rocklin/Penryn pluton. These will be called the southern, northern, and northwestern groups, respectively. The three groups are judged to be located within the pluton based on surface expression and gravity data (see Plate 4). All but four of the relocated epicenters are associated with the southern group where the earthquakes cluster in an area which is approximately 2.4 km north-south by 1.6 km east-west. In order to determine whether the hypocenters lie along a plane, the hypocenters were plotted on the east-west cross-section shown in Plate 5. The plots show that the hypocenters do indeed trend along a westerly dipping plane; and the (north-south) cross-section shown in Plate 5 indicates that the hypocenters lie along a cresent shaped region with the deeper foci towards the north. A formal least-squares fit of a plane through the hypocenters on a southern group gives a strike of $348^{\circ} \pm 12^{\circ}$ and a westerly dip of $70^{\circ} \pm 7^{\circ}$. For comparison the strike and dip for a similarity defined plane for the Oroville earthquake sequence (Morrison et al, 1976) is $348^{\circ} \pm 10^{\circ}$ and $35^{\circ} \pm 12^{\circ}$ (westerly), respectively.

It is of interest to note that (referring to the east-west cross-section in Figure 5) the two earthquakes in the northern group lie near to a northwestern extrapolation of the fitted plane for the hypocenters of the southern group. The northwestern group is nearly normal to the plane (at a depth of 12 km).

Before reaching any conclusions from these results one must consider how inadequacies on the assumed known gradient velocity model may affect the apparent orientation of the plane fitted through the hypocenters. The assumed velocity model does not take into account plausible lateral velocity gradients. In the case where the average crustal velocity increases towards the east in a direction perpendicular to the Sierra Nevada, the effect of such a velocity gradient is to increase the apparent dip angle of the hypocentered plane. It cannot be ruled out that the dip angle of the plane is biased in a direction which is too steep by perhaps as much as 20°. Given the limited information on crustal velocity variations now available it is possible (if not likely) that the computed simulations of orientations of the northern and northwestern groups with respect to the southern group may be a coincidence.

FOCAL MECHANISMS

A composite focal mechanism solution was determined for the six best recorded earthquakes from the southern group (using the method of Brillinger et al, 1980). Each earthquake has 9 or more first motion polarities reported. The observed first motion data were carefully scrutinized for stations which had known or suspected reversal polarity during some of the time that they were operational.

The composite fault plane solution is given in Plate 6 and it shows that the mechanisms within the Rocklin/Penryn pluton are normal faulting with east-west extension. This mechanism is compatible with the regional extensional tectonics and the mechanism of the magnitude 5.7 Oroville earthquake (Morrison et al, 1976) (the largest well recorded earthquake to have occurred along the Sierra Nevada foothills fault system).

The average fault plane for the group of six earthquakes has a strike of $344^{\circ} \pm 21^{\circ}$, a dip of $37^{\circ} \pm 4^{\circ}$ towards the west, and slip of $71^{\circ} \pm 15^{\circ}$. The auxiliary plane has a strike of $188^{\circ} \pm 2^{\circ}$, a dip of $55^{\circ} \pm 1^{\circ}$ to the east, and slip of $76^{\circ} \pm 21^{\circ}$. The westward dipping plane was chosen as the fault plane because it dips in the same direction as the plane described by the hypocenters ($70^{\circ} \pm 7^{\circ}$). Alternatively, if the auxiliary plane were the fault plane, en echelon faulting would be required to explain simultaneously the focal mechanism and the distribution of hypocenters. It should be noted that the dip of the composite focal mechanism ($37^{\circ} \pm 4^{\circ}$) and the dip of the plane described by the hypocenters ($70^{\circ} \pm 7^{\circ}$) are significantly different at the 95% confidence level. However, as mentioned earlier, the model used in computing the solutions does not include provisions for lateral velocity gradients. There is a suggestion from the regional tectonics that the crustal velocity increases towards the east; the model used could as a consequence put a bias in the plane mapped out by the epicenters so that the resulting dip was too steep towards the west.

Again, from the lack of recordings from the microearthquakes in the northern and northwestern groups, their focal mechanisms cannot be precisely determined individually or as separate groups. Consequently, the first motion data for these Two groups were combined with the first motion data for the southern group and a composite focal mechanism was computed for all 10 earthquakes. The resulting composite gives a normal faulting mechanism with east-west extension and the fault plane has a strike of $186^{\circ} \pm 1.5^{\circ}$, a dip of $52^{\circ} \pm 0.7^{\circ}$, and a slip of $79^{\circ} \pm 18^{\circ}$. The auxiliary plane has a strike of $348^{\circ} \pm 37^{\circ}$, a dip of $39^{\circ} \pm 3.8^{\circ}$, and a slip of $76^{\circ} \pm 21^{\circ}$. As before, the westward dipping plane was chosen as the fault plane because it dips in the same direction as the plane described by the southern group of hypocenters.

For comparison, the composite fault plane solution for the Oroville earthquake sequence of August, 1975 (Morrison et al, 1976) indicated that the faulting involved in the sequence is predominantly normal with a NNW strike and a west dip of around 30° to 40°. The area east of the fault moved up relative to the west.

STRAIN RELEASE - MOMENT RATES

Now we consider the relationships between seismic energy release (E_s) and the local magnitude (M_L) for an earthquake:

$$\log E_s = 11.8 + 1.5 M,$$

and the calculated annual rate of seismicity for the Sierra Nevada foothills:

$$\log N = 3.042 - 0.854M.$$

these equations allow the annual seismic energy release to be estimated for an assumed upper bound on the largest earthquake that can occur in the Sierra Nevada foothills. The annual seismic energy release along a 100 km segment of fault for a range of assumed upper M_L limits is set out in the following table.

M_L max	E_s x 10^{18} ergs/year	J_{Es} x 10^{18} ergs/year
5	0.54	0.24
5.5	1.2	0.54
-------	-------	-------
6	2.5	1.2
6.5	5.2	2.7

The symbol J_{Es} is the standard error of the energy release. The values below the dashed horizontal line are extrapolated. (The largest earthquake in the observed data set is the M_L 5.7 Oroville earthquake of August 1, 1975.)

The rate at which strain (E) is accumulating in the Sierra Nevada foothills is estimated from:

$$E^2 = (2E_s/nuV)$$

where:

n = seismic efficiency

u = shear modulus,

and V = strained volume.

Plausible values for the seismic efficiency are 0.1 ± 0.05, for the shear modulus 3×10^{11} dyne/cm^2, and for the strained volume 2×10^{20} cm^3 (100 km x 100 km x 20 km with an uncertainty of 50%). The annual strain rate can then be estimated for a range of assumed upper magnitude limits.

M_L max	E x 10^{-6}/year	J_E x 10^{-6}/year
5	0.42	0.18
5.5	0.62	0.26
------	------	------
6	0.91	0.39
6.5	1.3	0.57

As before the estimate below the dashed line is extrapolated.

For comparison, the strain rate inferred from the uplift of the Sierra Nevada in the vicinity of Auburn is of the order of a few parts in 10^7 per year (Bennett, 1978) and the strain rate in the central coast region of California is of the order of 1 part on 10^7 per year. Thus the strain rate inferred above for the Sierra Nevada is comparable to the uplift strain rate and is two orders of magnitude lower than the strain rate for the central coast region.

If all the strain energy is released by earthquakes occurring along one fault, the rate of displacement of the fault (D) and its uncertainty J_D can be computed for a range of assumed upper magnitude limits.

M_L max	D $\times 10^{-6}$ cm/year	J_D $\times 10^{-6}$ cm/year	D_1 cm/10^5 years
5	0.89	0.79	0.089
5.5	1.89	1.7	0.19
----------	----------	----------	----------
6	4.1	3.6	0.41
6.5	8.7	7.6	0.87

The last column (D_1) gives the expected displacement in one-hundred-thousand years and as before, the values below the dashed line are extrapolated. The values indicate that for earthquakes of magnitude 5.5 and above the overall rate of vertical displacement along the Foothills fault system is only about 2 cm in one million years. Such a small displacement would be unobservable from the usual geological field evidence.

INDUCED SEISMICITY

The historical seismicity record ($M_L \geq 3$; 1937-1979) of instrumentally located epicenters (Table 2) lists only one earthquake which has definitely occurred within approximately 30 km of the Folsom reservoir site (a M_L 3.0 on May 25, 1951). The initial filling of Folsom Lake took place in 1955 and in March and April, 1955 the elevation of the lake increased at a rate in excess of 3 feet per day; none of the subsequent annual fluctuations have exceeded this rate. The maximum water level for Folsom Lake was first attained in May, 1956. The available data on reservoir induced earthquakes (M_L 33.5)(Gough, 1978) indicate that induced earthquakes occur within a few months to a few years of the initial filling. Because it has been 28 years since Folsom Lake was first filled, the strong inference is that Folsom Lake will not induce significant earthquakes ($M_L \geq 3.5$).

The available microseismicity record used in this report spans November 1976 through May 1980. As mentioned previously the USGS Auburn net recorded 64 earthquakes ($0.1 \leq M_L \leq 1.8$) within approximately 30 km of Folsom Lake (see Table 3). Most of this activity was associated with the sequence of earthquakes with sources making up the southern group within the Rocklin/Penryn pluton (Plate 4) approximately 8 km northwest from the center of the reservoir. As a comment on the danger of non-causal correlations it might be instructive to note that the highest rate of recorded seismicity within the pluton (17 earthquakes; $0.15 \le M_L \le 1.8$; October-December 1977) occurred when the water level in Folsom Lake was the lowest that it had ever been since the initial filling in 1955-56. Even with allowance for the short available record of microearthquake activity (less than 4 years) this is most likely coincidence. Because there is no seismographic historical record of microearthquakes ($M_L < 3$) prior to 1976 it is not known whether Folsom Lake induced nearby low-level microseismicity ($M_L \le 2$) during the decades after its initial filling.

SUMMARY AND CONCLUSIONS

Prior to the occurrence of the M_L 5.7 Oroville earthquake sequence of August, 1975 the Foothills Fault system of the Western Sierra Nevada was generally considered to be inactive. As a consequence of the Oroville earthquake, the seismic hazard to proposed and existing large reservoirs and dams in the Western Foothills of the Sierra Nevada is being reevaluated.

The available information from historical felt reports and instrumentally recorded earthquakes (with regional and local seismographic networks) has been analyzed in this study. Reports of felt earthquakes in the vicinity of the Folsom reservoir site are rare and the largest historical earthquake which may have occurred in the vicinity of the Rocklin/Penryn plutons (based on reported intensity data) is the earthquake of May 30, 1908. An isoseismal mapbased on newspaper accounts gives a maximum reported intensity of MM IV-V and a total felt area of approximately 10,000 km^2 which suggests a local magnitude (M_L) of approximately 4 for this earthquake. The largest earthquake instrumentally recorded by a regional network occurred in the vicinity of the Folsom reservoir site (approximately 30 km to the northeast) with M_L 3.0 on May 25, 1951. The largest instrumentally recorded earthquake (by a local network) to have occurred in the proximity of Folsom Lake is a M_L 1.8 earthquake which occurred on November 27, 1977 centered in the southern part of the Rocklin/Penryn plutons approximately 8 km northwest of Folsom Lake. This M_L 1.8 earthquake is the largest earthquake in a sequence of earthquakes which have been observed in the southern part of the Rocklin and Penryn plutons starting in 1976. The characteristics of these earthquakes in terms of their focal mechanisms and hypocentral distribution require special attention because of their proximity to the reservoir.

The rate of seismicity of the Foothills Fault system between approximately 36.5°N and 39.5°N is estimated from three sets of seismicity data: the historical felt reports; the regionally recorded earthquakes; and the locally recorded earthquakes. The historical felt reports indicate that in the 78 years from 1850 through 1927, ten earthquakes were assigned a maximum Modified Mercalli (MM) intensity of V, six earthquakes were assigned a maximum MM intensity of VI, and two earthquakes were assigned a maximum MM intensity of VII. These maximum MM intensities of V, VI, VII correspond approximately to local magnitudes (M_L) of 4, 4 1/2, and 5, respectively. From these historical felt reports, the inferred rate of seismicity along the Foothills Fault system at the $M_L \geq 4$ level is on the order of two dozen per century and the inferred rate at the $M_L \geq 5$ level is on the order of two per century.

The instrumentally recorded seismicity observed in the vicinity of the Foothills Fault system consisted of 112 earthquakes $M_L \geq 3$ which occurred between 1937 and 1979. The cumulative number of earthquakes in this data set of magnitude M_L 3 or larger were fitted by weighted least-squares to a weighted linear magnitude relationship. The result for the cumulative number of earthquakes is considered valid over the magnitude range of M_L 3.0 to M_L 5.7. (The largest earthquake in the data set is the M_L 5.7 Oroville earthquake of August, 1975.) The inferred rate of seismicity at the $M_L \geq 5$ level is approximately 2 per century and at the $M_L \geq 6$ level it is approximately one every four centuries (normalized to events per 100 km linear segments of the fault system). It should be stressed that inferences for $M_L \geq 6$ are based on extrapolation. For comparison, the rate of seismicity in central California Coastal region is 30 times that observed for the Sierra Nevada foothills.

Following the Oroville earthquake sequence of August, 1975, improved local seismographic station coverage in the foothills of the Sierra Nevada resulted in the detection of several microearthquakes ($M_L \geq 1$) along the Foothills Fault system between Folsom and Oroville. Between November, 1976 and September 1980, 149 local earthquakes ($0.1 \leq M_L \leq 2.8$) were recorded by the USGS Auburn net (installed starting in July 1976). An analysis of the spatial distribution of epicenters shows no significant linear trends which might correlate with the surface traces of the Foothills Fault system (see Plate 4). The observed local data set of 149 earthquakes is not considered complete for $M_L < 1.3$. The earthquake statistics for $M_L \geq 1.3$ were analyzed in the same manner as the regional seismicity.

There are no significant differences between the rates of seismicity as inferred from the historical felt reports and the regional instrumental data (in the M_L 4 to M_L 5 range). Neither are there any significant differences between the rates of seismicity as inferred from the regional instrumental data and the local instrumental data (in the M_L 3 range). Considering that no significant differences are apparent in the rates of seismicity from the three data sets described above, the rate of seismicity from the regionally recorded earthquakes are adopted as representative of the rate of seismicity for the Sierra Nevada foothills. Thus the cumulative rate of seismicity for earthquakes of magnitude M_L 3 or larger are used in strain rate and probability calculations.

Of particular interest is the observation of earthquakes occurring within the Rocklin/Penryn plutons and vicinity were specially studied. Twenty-six of the best recorded of these earthquakes ($M_L \geq 0.7$) were separated for relocation using a group location procedure which simultaneously estimates the hypocentral coordinates and the station adjustments. The group location procedure leads to a higher relative precision in the locations of the hypocenters (the uncertainties average about 0.2 km for the epicenters and 0.3 km for the depth). No significant trends were observed in the station adjustments and thus there is no indication of a significant bias in the assumed velocity model used to locate the earthquakes. The relocated earthquakes cluster into three groups which are called the southern, northern, and northwestern groups, respectively. All but four of the relocated hypocenters are associated with the southern group which is within the pluton. These earthquake foci cluster in a crescent shaped region a few kilometers along a westerly dipping plane with the deeper foci towards the north (Plate 4). A formal least-squares fit of a plane through the foci in the southern groups gives a strike of $348^{\circ} \pm 12^{\circ}$ and a westerly dip of $70^{\circ} \pm 7^{\circ}$. The foci range between 11 km and 13 km in depth.

It is of interest to note that the two earthquakes in the northern group lie very near to an extension of the above plane which was least-squares fit through the southern group of hypocenters. Also the two earthquakes in the northwestern group lie very close to a normal (projected from a depth of 12 km) to the same. These observations may be largely coincidental because the least-squares fit plane may be biased due to lateral velocity gradients perhaps present in the vicinity of the pluton.

A composite focal mechanism solution was determined for six selected earthquakes from the southern group which had 9 or more first motion polarities reported for P waves. The composite mechanism shows that the mechanisms within the Rocklin/Penryn pluton are normal faulting with east-west extension. This mechanism is compatible with the regional extensional tectonics and the mechanism of the M_L 5.7 Oroville earthquake of August 1, 1975. The average fault plane solution for the group of 6 earthquakes has a strike of $344^{\circ} \pm 21^{\circ}$, a dip of $37^{\circ} \pm 4^{\circ}$ towards the west, and a slip of $71^{\circ} \pm 15^{\circ}$ while the auxilliary plane has a stike of $188^{\circ} \pm 2^{\circ}$, a dip of $55^{\circ} \pm 1^{\circ}$ towards the east, and a slip of $76^{\circ} \pm 12^{\circ}$. The westward dipping plane was chosen as the fault plane because it dips in the same direction as the plane described by the hypocenters. If the inferred auxiliary plane were in fact the fault plane, the distribution of hypocenters would require that en echelon faulting take place.

The focal mechanisms of the northern and northwestern groups are not well determined individually or as separate groups from the available first motion data. The mechanisms are, however, compatible with the normal faulting mechanism with east-west extension as described above.

The annual seismic strain energy release can be estimated for an assumed upper bound on the largest earthquake that can occur along the Foothills Fault system. From the calculated annual rate of seismicity for the region, the annual seismic energy release along a 100 km linear segment of fault is $(0.54 \pm 0.24) \times 10^{18}$ ergs/year for an assumed upper magnitude limit of M_L 6. From the seismicity data alone, the upper magnitude limit cannot be determined. The largest observed earthquake in the region is the M_L 5.7 Oroville earthquake. The rate at which strain is accumulating can be estimated from the seismic energy release upon assuming the upper magnitude limit and plausible values for the seismic efficiency, shear modulus, and strained volume. The resulting estimate of the annual strain rate is 0.42 ± 0.18 microstrain (10^{-6}) per year for an upper magnitude limit of M_L 5 and 0.91 $\pm$ 0.39 microstrain per year for an upper magnitude limit of M_L 6. For comparison, the strain rate inferred from the uplift of the Sierra Nevada in the vicinity of Auburn is on the order of a few tenths of a microstrain per year and the strain rate for the central coast region of California is on the order of a hundred microstrain per year. Thus the strain rate of the foothills of the Sierra Nevada as inferred from seismicity is compatible with the uplift strain rates for the same region and about two orders of magnitude lower than the strain rate for the central coast region.

If all of the strain energy is released by earthquakes occurring along one fault, the rate of displacement of the fault can be computed for a range of assumed upper magnitude limits. For example, if the assumed upper magnitude limit is

M_L 5.5, the rate of displacement along a dominant fault will be approximately (1.9 $\pm$ 1.7)cm per million years. Note that the uncertainty is large. If the seismic energy release takes place along a group of faults rather than one fault, the displacements will be proportionally smaller. Such small fault displacements are difficult to detect by geological field observations.

The initial filling of Folsom Lake took place in 1955. In March and April, 1955 the elevation of the lake increased at a rate in excess of 3 feet per day. None of the subsequent annual fluctuations have exceeded this rate. The maximum water levels was first attained in May 1956. The available data on reservoir induced earthquakes ($M_L \geq 3.5$) indicated that induced earthquakes occur within a few months to a few years of the initial filling and are often associated with either high rates of filling or attainment of the maximum water level. Considering that no significant nearby earthquakes have been recorded in the 28 years since Folsom Lake was first filled, the inference is that the tectonic strain and fault systems near Folsom Lake are not appropriate for the inducement of earthquakes ($M_L \geq 3.5$).

Microseismicity has been observed within approximately 30 km of Folsom Lake since the USGS Auburn net was installed starting in 1976. Sixty-four earthquakes ($0.1 \leq M_L \leq 1.8$) were observed between November 1976 and May 1980 and most of this activity was centered approximately 8 km northwest of the center of the reservoir. In the southern group within the Rocklin/Penryn plutons it is of interest to note that the highest rate of observed seismicity within the southern group (17 earthquakes; October-December 1977) occurred when the water level in Folsom Lake was the lowest that it had ever been since the initial filling. Considering the relatively short microseismicity record, this is most likely a coincidence. Because there is no historical record of microearthquake ($M_L < 3$) activity prior to 1976 and thus it is not known whether Folsom Lake induced low-level seismicity ($M_L \leq 2$).

TABLE 1

EARTHQUAKES IN CALIFORNIA (1769-1927)

SEISMICITY LIST PREPARED FOR THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION BY DONALD A. SEEBURGER UNDER THE SUPERVISION OF BRUCE A. BOLT, DIRECTOR OF THE SEISMOGRAPHIC STATIONS, UNIVERSITY OF CALIFORNIA, BERKELEY. PROGRAMMING AID BY ROBERT UHRHAMMER. STUDY COMPLETED IN JUNE, 1976.

- SOURCES -

B. A. BOLT AND R. D. MILLER, "CATALOGUE OF EARTHQUAKES IN NORTHERN CALIFORNIA AND ADJOINING AREAS, 1 JANUARY 1910 - 31 DECEMBER 1972", SEISMOGRAPHIC STATIONS, UNIVERSITY OF CALIFORNIA, 1975.

"EARTHQUAKE HISTORY OF THE UNITED STATES", REVISED 1970, U. S. DEPARTMENT OF COMMERCE, U. S. PRINTING OFFICE, 1973.

B. GUTENBERG AND C. F. RICHTER, "SEISMICITY OF THE EARTH", 1954, PRINCETON UNIVERSITY PRESS.

E. S. HOLDEN, "CATALOGUE OF EARTHQUAKES ON THE PACIFIC COAST, 1769 - 1897", REPRINTED FROM THE SMITHSONIAN MISCELLANEOUS COLLECTIONS, NO. 1087.

S. D. TOWNLEY AND M. W. ALLEN, "DESCRIPTIVE CATALOG OF EARTHQUAKES OF THE PACIFIC COAST OF THE UNITED STATES, 1869 TO 1928", B. S. S. A., V. 29, NO. 1, JAN 1939.

H. O. WOOD AND N. H. HECK, "EARTHQUAKE HISTORY OF THE UNITED STATES, PART 22", U. S. C. AND G. S. SERIAL NO. 609, REVISED 1951.

TABLE 1

- INTRODUCTION -

THIS LIST IS ESSENTIALLY AN EDITED ABSTRACT OF THE TOWNLEY-ALLEN CATALOG OF CALIFORNIA EARTHQUAKES, 1769-1927. THE TOWNLEY-ALLEN CATALOG HAS BEEN REVISED WHERE NECESSARY AFTER MAKING SEISMOLOGICAL INFERENCES BASED ON THE MODERN UNDERSTANDING OF EARTHQUAKES, TECTONIC STRUCTURE, PUBLISHED FIELD OBSERVATIONS AND DAMAGE REPORTS AVAILABLE, AND AFTER MAKING ASSESSMENTS OF THE HISTORICAL ACCURACY OF THE CATALOG ENTRIES BY MEANS OF INTERCOMPARISON AND INTERNAL CONSISTENCY CHECKS. ACCOUNT WAS ALSO TAKEN OF SOME RECENT SPECIAL STUDIES OF INDIVIDUAL EARTHQUAKES.

THE LIST ENTRIES GIVE THE DATE, TIME (GMT), LOCATION, AND A SUMMARY OF THE MORE SIGNIFICANT OBSERVATIONS ASSOCIATED WITH THE EARTHQUAKE. INCLUDED IN THE DESCRIPTION IS AN ESTIMATE OF THE MAXIMUM MODIFIED MERCALLI INTENSITY EXPERIENCED DURING THE EARTHQUAKE. THE TOWNLEY-ALLEN CATALOG USES THE ROSSI-FOREL INTENSITY SCALE. A LISTING OF THE MODIFIED MERCALLI SCALE AND AN APPROXIMATE CONVERSION SCHEME FROM ROSSI-FOREL TO MODIFIED MERCALLI ARE TO BE FOUND IN RICHTER, "ELEMENTARY SEISMOLOGY", PP. 135-39, 650-52. MODIFIED MERCALLI INTENSITIES WERE ASSIGNED BASED UPON THE FOLLOWING CRITERIA:

1) IF A DESCRIPTION OF EARTHQUAKE EFFECTS EXISTS, A MODIFIED MERCALLI INTENSITY WAS ASSIGNED AFTER CONSIDERING BOTH THE GIVEN ROSSI-FROEL INTENSITY AND THE DESCRIPTION.

2) IF NO DESCRIPTION WAS AVAILABLE, THE CONVERSION WAS MADE BASED UPON RELATIONS SUCH AS THOSE PRESENTED IN RICHTER, REFERRED TO ABOVE. IF THE CONVERSION RELATIONS GIVE AN INTERMEDIATE VALUE, THEN, LACKING FURTHER EVIDENCE, THE GIVEN MODIFIED MERCALLI INTENSITY IS THE LOWER OF THE TWO VALUES.

ALL MAGNITUDES LISTED ARE TAKEN FROM GUTENBERG AND RICHTER, "SEISMICITY OF THE EARTH".

- NOTES -

1) TIME LISTED IS GREENWICH MEAN TIME.

2) EARTHQUAKE LOCATIONS ARE PLACED AT THE INFERRED CENTER OF THE ZONE OF HIGHEST INTENSITY.

3) ENTRY REFERENCE:
   - F - THE TOWNLEY-ALLEN ENTRY IS GEOGRAPHICAL, THE LIST ENTRY GIVES THE TIME AND LOCATION
   - G - THE TOWNLEY-ALLEN ENTRY GIVES A DESCRIPTION OF THE EARTHQUAKE EFFECTS, THE LIST ENTRY IS AN ABSTRACT OF THE TOWNLEY-ALLEN ACCOUNT.
   - H - THE LIST ENTRY IS A MAJOR REVISION OF THE TOWNLEY-ALLEN ACCOUNT, THE SOURCE OF THE REVISION IS NOTED.

TABLE 1

SEEBURGER REVISION - "TOWNLEY-ALLEN" HISTORICAL EARTHQUAKES CATALOGUE (1769-1927)

125 EARTHQUAKES WERE SELECTED USING THE FOLLOWING CRITERIA:
- WITHIN POLYGON WITH CONSECUTIVE VERTICES AT THE FOLLOWING 6 POINTS:
  37.00°N-119.00°W 38.75°N-120.75°W 39.75°N-121.00°W 39.50°N-122.00°W 38.00°N-121.25°W 36.50°N-119.75°W

DATE	TIME	LAT	LONG	MAG	S	COMMENTS
8/ 4/1850	00:00:00.	38.25	121.32		F	V STOCKTON AND SACRAMENTO.
1/ 2/1853	00:00:00.	37.50	120.00		F	MARIPOSA.
1/ 3/1854	00:00:00.	37.50	120.00		G	MARIPOSA.
6/26/1854	00:00:00.	38.75	120.82		F	PLACER COUNTY. 2 LIGHT SHOCKS.
7/10/1854	00:00:00.	38.92	120.82		F	GEORGETOWN.
7/14/1854	00:00:00.	38.92	120.82		F	GEORGETOWN.
7/10/1855	17:30:00.	38.92	120.82		F	III GEORGETOWN.
8/12/1855	17:30:00.	38.92	120.82		G	III GEORGETOWN.
1/22/1857	00:00:00.	37.50	120.00		F	V MARIPOSA.
12/ 6/1858	10:00:00.	37.50	120.00		F	MARIPOSA.
8/30/1859	06:30:00.	37.50	120.00		F	MARIPOSA COUNTY. 3 SHOCKS.
6/ 2/1860	00:00:00.	37.50	120.00		F	MARIPOSA. EVENING.
9/16/1861	10:00:00.	39.25	121.00		F	SIERRA VALLEY.
7/ 3/1862	01:00:00.	39.67	121.00		F	VI LA PORTE.
10/18/1863	00:00:00.	39.17	121.67		F	YUBA CITY.
5/21/1864	02:00:00.	38.58	121.50		G	VI SACRAMENTO.
8/16/1864	05:53:00.	36.75	119.75		F	V FORT MILLER.
8/18/1864	06:39:00.	39.25	121.00		F	IV NEVADA CITY.
8/18/1864	13:18:00.	39.25	121.00		F	VI GRASS VALLEY, NEVADA CITY, MARYSVILLE, YUBA CITY.
5/24/1866	17:05:00.	38.58	121.50		F	SACRAMENTO.
7/15/1866	06:30:00.	39.67	121.00		G	V LA PORTE, ROWLAND FLAT, ST LOUIS, PORT WINE, SACRAMENTO, SAN FRANCISCO, AND STOCKTON.
9/ 5/1866	13:00:00.	39.67	121.00		F	LA PORTE, ROWLAND FLAT, ST. LOUIS, AND PORT WINE.
12/ 1/1867	07:12:00.	39.25	121.00		F	VI NEVADA CITY AND FOREST CITY.
9/17/1868	00:00:00.	39.25	121.00		F	NEVADA CITY. 2 SHOCKS.
12/26/1868	00:00:00.	39.25	121.00		F	NEVADA CITY. 2 SHOCKS.
1/ 7/1869	00:00:00.	38.33	120.75		F	IV NEWTON COPPER MINE. 2 SHOCKS.
9/15/1869	00:00:00.	38.58	121.50		F	SACRAMENTO.
12/21/1869	04:00:00.	39.17	121.07		G	V GRASS VALLEY.
12/29/1869	00:00:00.	38.58	121.50		F	SACRAMENTO AND RENO.
12/30/1869	00:00:00.	38.58	121.50		F	SACRAMENTO AND RENO.
3/ 4/1870	00:00:00.	39.17	121.07		F	GRASS VALLEY.
5/ 4/1870	00:00:00.	39.17	121.07		F	GRASS VALLEY.
6/ 7/1871	05:00:00.	37.50	120.00		G	BEAR VALLEY. 2 SHOCKS.
2/ 0/1872	00:00:00.	36.75	119.75		F	FRESNO COUNTY.
3/25/1872	00:00:00.	38.33	120.75		F	IV JACKSON.
3/28/1872	00:00:00.	39.25	121.00		F	NEVADA CITY.
4/11/1872	03:20:00.	38.00	120.25		G	IV STOCKTON, TUOLUMNE, MOKELUMNE HILL, SACRAMENTO.
4/11/1872	12:00:00.	38.00	120.25		G	VI TUOLUMNE. FELT ALSO IN STOCKTON, SACRAMENTO, AND SAN FRANCISCO.
4/11/1872	13:30:00.	38.00	120.25		F	TUOLUMNE.
4/11/1872	19:00:00.	38.00	120.25		F	TUOLUMNE.
4/12/1872	05:30:00.	38.00	120.25		F	TUOLUMNE.
4/12/1872	06:00:00.	38.00	120.25		F	TUOLUMNE.
4/12/1872	10:30:00.	38.00	120.25		F	TUOLUMNE.
4/12/1872	12:00:00.	38.00	120.25		F	TUOLUMNE.
4/23/1872	00:00:00.	38.75	120.82		F	PLACERVILLE.

TABLE 1

4/28/1872	00:00:00.	36.75	119.82	G	MILLERTON.
4/28/1872	00:00:00.	39.25	121.00	F	IV NEVADA CITY.
4/30/1872	00:00:00.	39.17	121.57	F	III MARYSVILLE. 2 LIGHT SHOCKS.
6/15/1872	00:00:00.	36.75	119.82	F	MILLERTON.
10/18/1872	00:00:00.	36.75	119.82	F	MILLERTON.
10/19/1872	00:00:00.	36.75	119.82	F	MILLERTON.
12/10/1874	00:00:00.	39.25	121.00	F	NEVADA CITY.
1/24/1875	12:00:00.	39.50	121.57	G	VI BUTTE, PLUMAS, AND SIERRA COUNTIES. OROVILLE, TAYLORSVILLE, GREENVILLE, DOWNIEVILLE, AND CARSON CITY, NEVADA.
12/ 2/1875	22:40:00.	39.17	121.57	F	MARYSVILLE. 3 SHOCKS.
12/ 3/1875	00:00:00.	39.17	121.07	F	V GRASS VALLEY. CARSON CITY, NEVADA.
12/23/1875	00:00:00.	38.75	120.82	F	PLACER, NEVADA, YUBA COUNTIES. NIGHT.
12/25/1875	00:00:00.	39.17	121.07	F	GRASS VALLEY. EVENING.
7/10/1877	07:10:00.	38.58	121.50	F	SACRAMENTO, CARSON CITY, NEVADA.
10/22/1878	01:40:00.	38.58	121.50	F	SACRAMENTO. 2 SHOCKS.
10/22/1883	14:00:00.	37.50	120.25	G	SOUTH SIDE OF MERCED RIVER, BELOW MERCED FALLS.
1/31/1885	05:38:00.	38.58	121.50	F	III SACRAMENTO.
2/23/1885	02:53:00.	38.83	121.17	F	III NEWCASTLE.
4/ 2/1885	15:15:00.	38.58	121.50	F	III SACRAMENTO.
4/ 3/1885	18:15:00.	38.58	121.50	F	III SACRAMENTO. 2 SHOCKS.
5/ 5/1885	00:00:00.	36.75	119.57	F	SANGER.
5/24/1886	00:00:00.	36.75	119.75	F	FRESNO.
9/19/1887	00:00:00.	37.50	120.00	F	III MARIPOSA.
4/29/1888	04:48:00.	39.25	121.00	G	VII NEVADA CITY. PRECEDED BY RUMBLING SOUNDS. GRASS VALLEY - FELT IN THE IDAHO MINE BELOW THE 1600 FEET LEVEL. MARYSVILLE, DOWNIEVILLE, TRUCKEE, COLFAX, SACRAMENTO, DUTCH FLAT, DIXON, BIGGS, SANTA ROSA, OROVILLE, SAN FRANCISCO.
9/30/1889	04:10:00.	37.50	119.67	G	VI WAWONA, YOSEMITE, FRESNO, VISALIA, BAKERSFIELD, HAVILAH, BISHOP CREEK, KINGSBURG, AND RANCHO LAGUNA DE TACHE.
9/30/1889	05:30:00.	37.50	119.67	G	WAWONA.
9/ 5/1890	22:15:00.	37.33	120.50	F	MERCED.
3/28/1892	15:30:00.	38.33	120.75	G	DRYTOWN.
4/19/1892	13:45:00.	36.75	119.77	H	FRESNO SEE V.C. MCKIM, "THE HISTORY OF THE SEISMOLOGICAL STATION OF FRESNO, CALIFORNIA", BSSA, V. 39 NO. 4, PP. 239-242.
4/20/1892	06:00:00.	38.58	121.50	F	SACRAMENTO AND NEVADA CITY.
4/21/1892	13:00:00.	38.83	121.17	F	NEWCASTLE.
4/21/1892	20:46:00.	36.75	119.77	H	FRESNO SEE V.C. MCKIM, "THE HISTORY OF THE SEISMOLOGICAL STATION OF FRESNO, CALIFORNIA", BSSA, V. 39 NO. 4, PP. 239-242.
3/ 3/1893	14:15:00.	39.17	121.07	F	GRASS VALLEY.
3/ 3/1893	14:40:00.	39.25	121.00	F	NEVADA CITY, IOWA HILL.
5/26/1893	00:00:00.	37.50	120.00	F	MARIPOSA.
7/14/1894	04:50:00.	37.00	119.50	G	V PINE RIDGE. ACCOMPANIED BY ELECTRICAL DISPLAYS AND A RED CLOUD WHICH DISAPPEARED WHEN THE QUAKE SUBSIDED.
7/30/1894	08:14:00.	36.75	119.77	H	FRESNO SEE V.C. MCKIM, "THE HISTORY OF THE SEISMOLOGICAL STATION OF FRESNO, CALIFORNIA", BSSA, V. 39 NO. 4, PP. 239-242.
8/24/1894	09:12:00.	36.75	119.77	H	FRESNO SEE V.C. MCKIM, "THE HISTORY OF THE SEISMOLOGICAL STATION OF FRESNO, CALIFORNIA", BSSA, V. 39 NO. 4, PP. 239-242.
8/17/1896	11:30:00.	37.33	120.50	G	V MERCED, VISALIA, BAKERSFIELD, HANFORD, AND FRESNO.
3/ 2/1898	21:52:00.	36.75	119.75	G	FRESNO AND VISALIA.
3/22/1898	03:52:00.	36.75	119.77	H	FRESNO SEE V.C. MCKIM, "THE HISTORY OF THE SEISMOLOGICAL STATION OF FRESNO, CALIFORNIA", BSSA, V. 39 NO. 4, PP. 239-242.
3/16/1902	00:00:00.	39.33	121.07	F	NORTH SAN JUAN.
5/21/1902	09:22:00.	38.58	121.50	F	SACRAMENTO.
10/29/1904	00:00:00.	39.50	121.50	F	BRUSH CREEK.
5/15/1905	00:00:00.	39.25	121.00	F	NEVADA CITY, OAKDALE, AND YOSEMITE.
5/20/1905	00:59:00.	38.58	121.50	F	SACRAMENTO.

TABLE 1

4/18/1906	16:00:00.	38.58	121.50	F	SACRAMENTO.
4/18/1906	16:30:00.	38.00	120.25	F	II STOCKTON AND TUOLUMNE.
4/19/1906	23:25:00.	38.58	121.50	F	III SACRAMENTO.
4/20/1906	19:30:00.	38.00	120.25	F	TUOLUMNE.
5/15/1906	09:32:00.	39.17	121.07	G	V GRASS VALLEY. 3 DISTINCT SHOCKS.
6/16/1906	05:20:00.	38.00	120.42	F	SONORA.
9/ 9/1906	12:55:00.	39.17	121.07	G	GRASS VALLEY, NEVADA CITY, AND PILOT CREEK. FELT IN NEVADA.
2/ 5/1907	12:25:00.	39.67	121.00	G	LA PORTE.
5/ 2/1908	00:00:00.	39.67	121.00	G	LA PORTE.
5/30/1908	19:38:00.	38.67	121.17	G	FOLSOM, SACRAMENTO, REPRESA, AND NEWCASTLE
5/31/1908	04:50:00.	38.58	121.50	F	REPRESA.
3/ 3/1909	12:00:00.	39.25	121.00	G	V NORTH CENTRAL SIERRA. NEVADA CITY, DOWNIEVILLE, IOWA HILL, MAGALIA, NORTH BLOOMFIELD, PILOT CREEK. REPRESA, SACRAMENTO, SONORA, AND BECKWITH.
5/23/1909	04:40:00.	39.67	121.00	G	LA PORTE.
6/ 7/1909	07:00:00.	37.75	120.17	F	DUDLEY"S (COULTERVILLE).
6/23/1909	07:24:00.	39.33	120.92	G	VII SIERRA COUNTY. AT DOWNIEVILLE CHIMNEYS DAMAGED, AFTERSHOCKS CONTINUED FOR TEN DAYS. ALSO HEAVY AT NORTH BLOOMFIELD, DOWNIEVILLE, AND BOWMAN"S DAM. VI AT NEVADA CITY, GRASS VALLEY, TRUCKEE, EMIGRANT GAP, LA PORTE, AND QUINCY. HEAVY AT RENO, NEVADA, MARYSVILLE, OROVILLE, AND SACRAMENTO. IV AT CHICO AND SUSANVILLE. III AT RED BLUFF, REDDING, AND PLACERVILLE. WILLOWS, COLUSA, TEHAMA. AND DUNSMUIR AND SPARKS, NEVADA ALSO REPORTED. THE AREA WITHIN WHICH THE INTENSITY WAS II OR HIGHER PROBABLY APPROACHED 50,000 SQUARE MILES.
6/23/1909	07:41:00.	39.33	120.92	G	AFTERSHOCK OF 7-24-0.
6/23/1909	07:53:00.	39.33	120.92	G	AFTERSHOCK OF 7-24-0.
6/23/1909	10:00:00.	39.33	120.92	G	AFTERSHOCK OF 7-24-0.
6/23/1909	12:30:00.	39.33	120.92	G	AFTERSHOCK OF 7-24-0.
5/10/1910	05:00:00.	39.33	121.17	F	DOBBINS.
5/16/1910	06:20:00.	38.08	120.57	F	ANGEL"S CAMP.
5/16/1910	06:25:00.	38.08	120.57	F	ANGEL"S CAMP.
9/ 4/1910	03:30:00.	39.67	121.00	G	LA PORTE.
4/24/1911	06:17:00.	36.75	119.77	H	FRESNO SEE V.C. MCKIM, "THE HISTORY OF THE SEISMOLOGICAL STATION OF FRESNO, CALIFORNIA", BSSA, V. 39 NO. 4, PP. 239-242.
1/15/1912	18:30:00.	39.25	121.00	G	NEVADA CITY, STERLING CITY, AND WEST BRANCH.
3/ 3/1913	09:40:00.	39.67	121.00	F	LA PORTE.
9/27/1913	05:00:00.	39.67	121.00	F	LA PORTE.
9/27/1913	09:00:00.	39.67	121.00	F	LA PORTE.
4/27/1914	05:30:00.	38.83	121.00	G	PILOT CREEK. SAME OR DIFFERENT EARTHQUAKE FELT AT NEVADA CITY AT 5-50-0.
6/14/1914	06:00:00.	38.17	120.82	F	VALLEY SPRINGS.
12/ 9/1914	07:00:00.	38.75	120.82	F	CATHEDRAL PARK.
8/12/1918	16:30:00.	37.75	120.17	G	IV COULTERVILLE. PRECEDED BY LOUD RUMBLE. IV AT KAISER DIGGINGS, 15 MILES NE OF NORTH FORK.
4/15/1923	07:15:00.	39.25	121.00	F	NEVADA CITY.
12/ 4/1923	20:50:00.	39.42	121.07	F	IV CAMPTONVILLE.
12/29/1927	00:12:00.	39.17	121.07	F	III GRASS VALLEY.

- END OF LISTING -

TABLE 2

EARTHQUAKES IN CALIFORNIA AND WESTERN NEVADA

SELECTED FROM MASTER LIST (JAN 1910 TO DEC 1980)

ON RETRIEVE TAPE OF THE SEISMOGRAPHIC STATIONS

UNIVERSITY OF CALIFORNIA AT BERKELEY

AS UPDATED JUL 1982 BY DR. ROBERT UHRHAMMER

- SOURCES -

"DESCRIPTIVE CATALOG OF EARTHQUAKES OF THE PACIFIC COAST OF THE UNITED STATES", S.D. TOWNLEY AND M.W. ALLEN, B.S.S.A., VOL. 29, NO. 1, JAN. 1939.

"UNITED STATES EARTHQUAKES", U.S.C.G.S., 1928 TO 1967.

"ABSTRACTS OF EARTHQUAKE REPORTS FROM THE PACIFIC COAST AND THE WESTERN MOUNTAIN REGION", U.S.C.G.S. 1929 TO 1967.

"SEISMICITY OF THE EARTH", B. GUTENBURG AND C.F. RICHTER, 1954, PRINCETON UNIVERSITY PRESS.

"BULLETIN ON LOCAL SHOCKS", CALIFORNIA INSTITUTE OF TECHNOLOGY, 1932 TO 1962.

"BULLETIN OF THE SEISMOGRAPHIC STATIONS", UNIVERSITY OF CALIFORNIA, BERKELEY, 01 JULY 1941 TO DATE. LATITUDE AND LONGITUDE OF EPICENTER LOCATIONS ARE FROM THIS BULLETIN AFTER 30 JUNE 1941.

"CRUSTAL STRAIN AND FAULT MOVEMENT INVESTIGATION, FAULTS, AND EARTHQUAKE EPICENTERS IN CALIFORNIA", STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES, BULL. 116-2, JAN. 1964 (SECONDARY SOURCE).

(NOTE: ON 20 DEC. 1932 THE INTENSITY SCALE CHANGED FROM THE ROSSI-FOREL TO THE MODIFIED MERCALLI.)

THE LISTED EARTHQUAKE DATA WERE PUNCHED FROM THE ABOVE LISTS AND COMPILED ON MAGNETIC TAPE FOR IN-HOUSE USE. ALTHOUGH CONSIDERABLE CARE WAS TAKEN IN THE TRANSFER PROCEDURES, SOME ERRORS WERE INTRODUCED FROM THIS SOURCE. THEREFORE, FOR PRECISE AND DETAILED STUDIES USING THESE TAPE LISTS, THE ORIGINAL SOURCES SHOULD BE CONSULTED. SOME AMENDMENTS AND CORRECTIONS HAVE BEEN SUCCESSIVELY INCORPORATED IN THE TAPE LISTS. ANY REMAINING INCONSISTENCIES OR SUSPICIOUS VALUES SHOULD BE DRAWN TO THE ATTENTION OF THE DIRECTOR. CHECKS CAN THEN BE CARRIED OUT AGAINST THE ORIGINAL SEISMOGRAMS KEPT IN STORE AT BERKELEY.

- CONTACT -

DIRECTOR OF THE SEISMOGRAPHIC STATIONS
475 EARTH SCIENCES BUILDING
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720

TABLE 2

NORTHERN CALIFORNIA EARTHQUAKES CATALOGUE (JANUARY 1910 - DECEMBER 1980)

112 EARTHQUAKES WERE SELECTED USING THE FOLLOWING CRITERIA:
- MAGNITUDE RANGE: 3.0 TO 8.3.
- WITHIN POLYGON WITH CONSECUTIVE VERTICES AT THE FOLLOWING 6 POINTS:
  37.00°N-119.00°W 38.75°N-120.75°W 39.75°N-121.00°W 39.50°N-122.00°W 38.00°N-121.25°W
  36.50°N-119.75°W

DATE	TIME	LAT	LONG	MAG	COMMENTS
8/23/1937	00:32:00.0	37.50	120.00	4.0	10 MI. W OF MARIPOSA. FELT AT YOSEMITE, EL PORTAL, AND TUOLOMNE MEADOWS.
10/14/1938	13:10:00.	37.00	120.00	3.5	VERY UNCERTAIN (PASADENA REPORT).
3/27/1941	10:44:42.	37.20	119.80	3.5	MADERA COUNTY. FELT AT RAYMOND, YOSEMITE NATIONAL PARK, KNOLLS, AND MARIPOSA COUNTY.
10/ 4/1942	17:49:54.	38.07	120.27	3.8	EAST OF SONORA.
3/19/1943	22:08:40.	38.80	121.10	3.9	NEAR AUBURN.
7/27/1943	03:04:05.	37.67	120.75	3.5	EAST OF OAKDALE.
3/12/1950	04:22:52.	39.17	121.10	3.3	SOUTH OF GRASS VALLEY.
5/25/1951	17:52:06.	39.00	120.90	3.0	NE OF AUBURN.
1/26/1958	20:22:33.	37.20	119.70	3.4	NORTH OF FRESNO.
6/25/1960	05:07:11.	37.30	120.10	3.0	NORTH OF FRESNO.
10/ 5/1960	01:18:06.	39.18	121.15	3.3	EAST OF MARYSVILLE.
11/ 7/1960	21:11:17.	37.25	119.73	3.2	NORTH OF FRESNO.
7/ 4/1962	08:26:38.2	37.88	120.10	3.5	SOUTHEAST OF SONORA.
2/21/1965	17:22:07.2	37.47	119.54	3.1	S OF YOSEMITE NATIONAL PARK.
3/30/1965	09:45:14.4	37.47	119.78	3.0	S OF YOSEMITE.
7/ 9/1965	13:16:43.	37.50	119.60	3.2	YOSEMITE NATIONAL PARK.
12/22/1965	00:19:17.	37.70	120.20	3.1	YOSEMITE NATIONAL PARK.
2/ 1/1971	22:16:05.9	37.37	120.02	3.2	NEAR MARIPOSA. INTENSITY V 2-1/2 MI N OF MARIPOSA. LOUD EARTH NOISES. SOME CRACKING IN CEILINGS, WALKS
8/ 2/1971	04:44:44.0	36.82	120.03	3.1	W OF FRESNO. INTENSITY V AT BIOLA (FELT BY MANY, PICTURES MOVED, FURNATURE SHIFTED). INTENSITY IV AT KERMAN
3/31/1972	21:14:05.6	36.86	120.01	3.7	NW OF FRESNO. FELT AT FRESNO AND MADERA.
4/11/1972	16:09:22.0	39.50	121.92	3.1	S OF CHICO
6/28/1975	04:19:53.7	39.47	121.52	3.5	OROVILLE FORESHOCK
8/ 1/1975	15:45:37.8	39.45	121.53	3.8	OROVILLE FORESHOCK
8/ 1/1975	16:27:17.8	39.44	121.54	4.7	OROVILLE FORESHOCK
8/ 1/1975	17:26:50.1	39.46	121.54	3.0	OROVILLE FORESHOCK
8/ 1/1975	20:20:04.8	39.44	121.53	4.5	OROVILLE FORESHOCK
8/ 1/1975	20:20:12.9	39.44	121.53	5.7	OROVILLE MAINSHOCK. MODERATE DAMAGE (MM VII) IN THE OROVILLE AREA. SOME MINOR INJURIES. WIDELY FELT IN NORTHERN CALIFORNIA. MOST OF THE AFTERSHOCKS WERE FELT IN OROVILLE AND THROUGHOUT BUTTE COUNTY. DETAILED INFORMATION GIVEN IN - THE OROVILLE EARTHQUAKE SEQUENCE OF AUGUST 1975, BY PAUL W. MORRISON, JR.,BRIAN W. STUMP, AND ROBERT UHRHAMMER, BULL. SEISM. SOC. AM., VOL. 66, NO. 4, AUGUST 1976
8/ 1/1975	20:25:00	39.44	121.53	4.7	OROVILLE AFTERSHOCK
8/ 1/1975	20:29:00	39.44	121.53	4.6	OROVILLE AFTERSHOCK
8/ 1/1975	20:32:39.8	39.45	121.51	3.0	OROVILLE AFTERSHOCK
8/ 1/1975	20:37:00	39.45	121.51	3.5	OROVILLE AFTERSHOCK
8/ 1/1975	20:45:18.4	39.47	121.50	3.0	OROVILLE AFTERSHOCK
8/ 1/1975	20:46:00	39.47	121.50	3.8	OROVILLE AFTERSHOCK
8/ 1/1975	21:05:39.8	39.43	121.49	3.0	OROVILLE AFTERSHOCK
8/ 1/1975	21:16:23.8	39.44	121.53	3.2	OROVILLE AFTERSHOCK
8/ 1/1975	21:21:50.7	39.44	121.53	4.1	OROVILLE AFTERSHOCK
8/ 1/1975	21:25:59.0	39.47	121.52	3.3	OROVILLE AFTERSHOCK
8/ 1/1975	21:29:24.1	39.45	121.55	3.6	OROVILLE AFTERSHOCK
8/ 1/1975	22:04:56.0	39.43	121.52	3.1	OROVILLE AFTERSHOCK
8/ 1/1975	22:11:04.7	39.44	121.49	3.1	OROVILLE AFTERSHOCK

TABLE 2

8/ 1/1975	22:23:43.9	39.43	121.52	3.2	OROVILLE AFTERSHOCK
8/ 1/1975	23:44:41.0	39.49	121.52	3.4	OROVILLE AFTERSHOCK
8/ 2/1975	00:52:48.5	39.48	121.51	3.8	OROVILLE AFTERSHOCK
8/ 2/1975	06:31:57.2	39.45	121.48	3.2	OROVILLE AFTERSHOCK
8/ 2/1975	10:11:53.7	39.49	121.51	3.1	OROVILLE AFTERSHOCK
8/ 2/1975	10:49:00.1	39.43	121.47	3.3	OROVILLE AFTERSHOCK
8/ 2/1975	11:51:50.7	39.47	121.49	3.4	OROVILLE AFTERSHOCK
8/ 2/1975	14:44:38.7	39.42	121.49	3.2	OROVILLE AFTERSHOCK
8/ 2/1975	16:51:45.1	39.42	121.48	3.7	OROVILLE AFTERSHOCK
8/ 2/1975	17:24:29.2	39.47	121.47	4.3	OROVILLE AFTERSHOCK
8/ 2/1975	17:43:24.1	39.48	121.47	4.0	OROVILLE AFTERSHOCK
8/ 2/1975	19:58:36.9	39.45	121.54	3.1	OROVILLE AFTERSHOCK
8/ 2/1975	20:22:16.3	39.44	121.46	5.1	OROVILLE AFTERSHOCK
8/ 2/1975	20:35:48.6	39.47	121.48	3.9	OROVILLE AFTERSHOCK
8/ 2/1975	20:58:55.7	39.43	121.47	3.8	OROVILLE AFTERSHOCK
8/ 2/1975	20:59:00	39.43	121.47	5.2	OROVILLE AFTERSHOCK
8/ 2/1975	21:11:44.5	39.45	121.47	3.1	OROVILLE AFTERSHOCK
8/ 2/1975	21:40:01.3	39.43	121.47	3.9	OROVILLE AFTERSHOCK
8/ 3/1975	01:03:05.8	39.49	121.52	4.6	OROVILLE AFTERSHOCK
8/ 3/1975	02:47:08.8	39.48	121.50	4.1	OROVILLE AFTERSHOCK
8/ 4/1975	09:47:45.0	39.42	121.52	3.5	OROVILLE AFTERSHOCK
8/ 5/1975	02:28:57.4	39.42	121.49	3.3	OROVILLE AFTERSHOCK
8/ 5/1975	20:44:24.5	39.41	121.51	3.2	OROVILLE AFTERSHOCK
8/ 6/1975	03:50:29.9	39.48	121.52	4.7	OROVILLE AFTERSHOCK
8/ 6/1975	13:03:28.6	39.51	121.54	3.0	OROVILLE AFTERSHOCK
8/ 6/1975	16:25:47.9	39.45	121.46	3.1	OROVILLE AFTERSHOCK
8/ 6/1975	16:41:52.1	39.50	121.53	3.6	OROVILLE AFTERSHOCK
8/ 6/1975	21:00:33.5	39.44	121.49	3.0	OROVILLE AFTERSHOCK
8/ 6/1975	21:01:00	39.44	121.49	3.0	OROVILLE AFTERSHOCK
8/ 7/1975	20:31:20.4	39.52	121.53	3.1	OROVILLE AFTERSHOCK
8/ 8/1975	07:00:50.1	39.50	121.51	4.9	OROVILLE AFTERSHOCK
8/ 8/1975	13:37:53.9	39.50	121.49	3.2	OROVILLE AFTERSHOCK
8/ 8/1975	19:03:27.2	39.39	121.49	3.1	OROVILLE AFTERSHOCK
8/ 9/1975	07:38:47.5	39.41	121.48	3.0	OROVILLE AFTERSHOCK
8/10/1975	05:16:40.5	37.37	119.99	4.2	NW OF FRESNO. FELT IN FRESNO
8/11/1975	02:40:16.7	39.46	121.44	3.0	OROVILLE AFTERSHOCK
8/11/1975	06:11:36.3	39.45	121.48	4.3	OROVILLE AFTERSHOCK
8/11/1975	15:59:05.3	39.47	121.55	3.6	OROVILLE AFTERSHOCK
8/12/1975	11:58:52.1	39.46	121.54	3.0	OROVILLE AFTERSHOCK
8/16/1975	05:48:09.4	39.47	121.52	4.0	OROVILLE AFTERSHOCK
8/16/1975	12:23:24.4	39.49	121.50	3.1	OROVILLE AFTERSHOCK
8/23/1975	18:31:53.3	39.50	121.49	3.1	OROVILLE AFTERSHOCK
8/24/1975	09:10:37.7	39.51	121.50	3.3	OROVILLE AFTERSHOCK
8/25/1975	13:35:11.7	39.34	121.51	3.2	OROVILLE AFTERSHOCK
9/ 4/1975	01:17:02.0	39.40	121.55	3.0	OROVILLE AFTERSHOCK
9/ 5/1975	21:01:39.2	39.41	121.52	3.2	OROVILLE AFTERSHOCK
9/10/1975	17:39:05.2	39.52	121.54	3.4	OROVILLE AFTERSHOCK
9/12/1975	02:00:47.9	39.50	121.49	3.5	OROVILLE AFTERSHOCK
9/26/1975	02:31:07.1	39.50	121.50	4.0	OROVILLE AFTERSHOCK
9/26/1975	09:57:16.3	39.44	121.50	3.1	OROVILLE AFTERSHOCK
9/27/1975	22:34:38.1	39.51	121.54	4.6	OROVILLE AFTERSHOCK
9/27/1975	23:04:30.9	39.52	121.52	3.1	OROVILLE AFTERSHOCK
9/27/1975	23:28:05.0	39.52	121.55	3.2	OROVILLE AFTERSHOCK
9/28/1975	21:07:15.	39.52	121.53	3.4	OROVILLE AFTERSHOCK
10/10/1975	07:44:47.6	39.46	121.49	3.6	OROVILLE AFTERSHOCK
10/13/1975	16:06:51.5	39.49	121.52	3.0	OROVILLE AFTERSHOCK
10/28/1975	03:41:16.1	39.49	121.51	3.5	OROVILLE AFTERSHOCK
11/ 5/1975	05:37:46.8	39.39	121.50	3.4	OROVILLE AFTERSHOCK

TABLE 2

11/15/1975	03:35:01.9	39.42	121.50	3.8	OROVILLE AFTERSHOCK
1/26/1976	19:40:00.2	39.41	121.55	3.5	SE OF CHICO. OROVILLE.
6/14/1976	23:30:26.5	39.47	121.54	3.8	SE OF CHICO. FELT.
7/ 6/1976	03:55:17.4	39.41	121.52	4.1	S OF OROVILLE.
8/19/1976	08:15:04.7	39.46	121.49	3.0	OROVILLE.
1/ 9/1977	23:24:39.5	39.50	121.64	3.4	5 KM SW OF OROVILLE. FELT IN OROVILLE.
5/ 4/1977	06:59:10.5	39.40	121.50	3.6	15 KM SSE OF OROVILLE. FELT IN OROVILLE.
7/ 9/1977	14:01:01.2	36.86	120.03	3.3	22 KM NW OF FRESNO.
8/ 6/1977	10:35:27.9	39.42	121.55	3.1	10 KM S OF OROVILLE.
12/29/1977	14:09:16.8	36.86	120.02	3.5	22 KM NW OF FRESNO.
5/ 8/1978	01:07:02.4	36.83	120.03	3.3	S OF MADERA, 20 KM W OF FRESNO.
7/23/1978	07:33:35.6	39.40	121.46	3.3	OROVILLE AREA. FELT.
6/17/1979	18:06:37.7	37.34	119.99	3.1	44 KM, E OF MERCED.
10/31/1979	20:06:25.6	39.48	121.45	3.1	OROVILLE.

- END OF LISTING -

TABLE 3 - HISTORICAL SEISMICITY: AUBURN NET
NOVEMBER 1976 THROUGH SEPTEMBER 1980

DATE	ORIGIN TIME (UTC)	LATITUDE DEG-MIN (NORTH)		LONGITUDE DEG-MIN (WEST)	DEPTH (KM)	MAG
76 NOV 19	05:11:12.55	38-54.44		120-55.98	11.26	1.06
76 NOV 28	07:02:29.38	38-47.33	*	121-14.45	14.00	1.12
76 NOV 28	12:35:38.00	38-47.18	*	121-14.50	14.66	1.09
76 DEC 16	12:27:16.53	38-46.72	*	121-14.56	13.51	0.69
76 DEC 31	09:43:04.90	38-47.81	*	121-15.64	14.44	0.46
77 JAN 03	06:23:27.94	38-46.98	*	121-14.38	8.71	0.28
77 JAN 21	17:50:22.67	38-46.02	*	121-14.54	12.54	0.67
77 JAN 22	13:00:31.48	38-46.04	*	121-14.10	12.98	0.70
77 FEB 21	21:37:24.95	38-46.17	*	121-13.91	13.62	1.63
77 MAY 03	08:36:12.36	38-46.10	*	121-14.02	13.04	1.16
77 MAY 07	08:55:36.14	38-45.96	*	121-14.10	13.13	0.57
77 MAY 09	07:58:54.28	38-46.10	*	121-14.08	12.87	1.26
77 MAY 09	07:59:00.77	38-47.43	*	121-13.52	2.21	0.27
77 MAY 14	03:12:30.57	38-46.14	*	121-13.89	13.11	0.50
77 MAY 15	15:28:35.95	38-46.02	*	121-13.82	13.69	1.73
77 MAY 15	15:34:39.80	38-46.17	*	121-13.92	13.13	0.60
77 MAY 15	17:05:32.66	38-46.11	*	121-14.04	13.26	0.81
77 MAY 15	18:44:29.23	38-16.59		121- 5.55	8.32	1.11
77 MAY 16	01:33:11.38	38-46.06	*	121-14.07	13.11	0.30
77 MAY 23	03:22:32.61	38-46.09	*	121-14.04	12.82	0.27
77 JUN 14	17:43:26.85	38-45.08	*	121-13.15	11.80	1.35
77 JUN 18	05:41:58.39	38-45.78	*	121-14.00	11.25	0.45
77 JUN 18	07:57:16.27	38-45.53	*	121-13.35	11.87	0.49
77 JUN 20	10:47:10.22	38-45.04	*	121-13.45	11.57	1.11
77 JUN 21	03:36:17.97	38-45.05	*	121-13.44	11.49	0.65
77 JUL 11	07:48:34.17	38-45.22	*	121-13.54	12.59	0.45
77 AUG 03	08:37:50.89	38-45.44	*	121-13.69	11.71	1.34
77 AUG 03	15:34:32.00	38-45.50	*	121-13.56	12.89	0.77
77 AUG 21	08:08:19.08	38- 7.75		121-27.27	10.02	0.86
77 NOV 01	19:42:27.58	38-45.13	*	121-13.34	10.91	1.26
77 NOV 03	01:07:01.24	38-45.88	*	121-13.91	12.72	1.20
77 NOV 03	10:07:34.25	38-46.06	*	121-12.02	13.19	0.07
77 NOV 03	10:07:49.63	38-46.02	*	121-13.92	12.35	0.81
77 NOV 03	11:55:27.11	38-45.97	*	121-14.05	12.45	0.10
77 NOV 03	11:55:39.57	38-46.06	*	121-13.96	12.60	0.40
77 NOV 03	14:52:54.33	38-46.02	*	121-13.89	12.84	1.15
77 NOV 27	02:52:29.45	38-45.57	*	121-13.51	11.91	1.78
77 NOV 27	02:54:00.82	38-45.08	*	121-13.27	12.33	0.12
77 NOV 27	03:02:27.37	38-45.64	*	121-12.10	12.38	0.09
77 NOV 27	04:02:34.03	38-45.15	*	121-13.15	12.66	0.14
77 NOV 27	20:56:47.29	38-45.99	*	121-13.95	12.77	0.50

TABLE 3 - CONTINUED

DATE	ORIGIN TIME (UTC)	LATITUDE DEG-MIN (NORTH)		LONGITUDE DEG-MIN (WEST)	DEPTH (KM)	MAG
77 NOV 27	23:34:09.34	38-46.14	*	121-11.83	13.14	0.12
77 NOV 28	03:26:16.36	38-46.03	*	121-13.02	12.49	0.14
77 NOV 28	05:26:15.86	38-46.11	*	121-12.49	12.99	0.42
77 DEC 08	22:30:41.52	38-46.12	*	121-13.64	12.89	1.33
77 DEC 12	11:43:21.41	38-44.77	*	121-13.30	10.80	0.41
78 JAN 10	01:02:29.12	38-45.43	*	121-13.48	12.33	1.30
78 JAN 10	01:04:55.28	38-45.34	*	121-13.70	12.51	0.83
78 FEB 05	08:28:35.13	37-48.86		121-14.40	22.90	1.10
78 FEB 16	10:27:44.09	38-53.37	*	121-12.83	6.95	0.89
78 FEB 17	20:09:41.43	38-53.41	*	121-12.97	7.26	1.11
78 MAR 18	14:03:39.99	38-45.52	*	121-13.85	12.94	1.25
78 MAR 19	19:55:47.34	38-28.94		121-10.32	18.15	1.35
78 MAR 21	12:55:47.92	38-42.57		121-28.80	21.28	1.43
78 MAY 30	00:19:54.74	38-45.47	*	121-13.79	11.25	0.98
78 JUN 03	01:38:11.31	39-17.36		121- 6.85	8.93	1.73
78 JUN 03	01:41:23.38	39-17.46		121- 6.47	9.70	1.18
78 JUN 03	01:47:41.12	39-17.25		121- 6.66	11.36	2.15
78 JUN 03	23:28:35.85	39-17.45		121- 6.27	9.94	1.27
78 JUN 05	01:25:41.24	39-17.38		121- 6.37	9.67	1.72
78 JUN 05	17:32:35.56	39-17.34		121- 6.52	11.03	1.57
78 JUN 05	17:55:01.15	39-17.31		121- 6.68	11.77	1.59
78 JUN 05	18:11:46.04	39-17.24		121- 6.06	9.58	1.41
78 JUL 07	17:13:03.25	39-15.83		120-45.48	5.00	1.44
78 JUL 04	23:39:40.13	38-40.75		120-44.51	8.41	1.43
78 JUL 28	18:51:03.52	38-41.17		120-45.12	4.07	2.07
78 AUG 20	17:52:39.93	38-44.92	*	121-13.17	10.45	1.34
78 SEP 11	21:00:43.75	39- 1.92		121- 1.71	5.00	1.30
78 OCT 16	10:54:33.04	38-44.98	*	121-13.27	11.20	0.93
78 NOV 09	05:42:18.71	39-21.69		120-10.18	8.81	2.42
78 NOV 23	17:14:28.33	39-24.68		120-34.11	9.38	2.13
78 NOV 27	00:46:38.14	39-24.15		120-33.23	10.14	1.72
78 NOV 27	02:23:05.23	39-22.77		120-34.99	17.38	1.65
78 NOV 27	04:29:11.02	39-23.08		120-35.79	13.93	1.36
78 DEC 20	23:52:37.05	39-13.29		120-19.77	5.00	1.65
78 DEC 21	04:46:24.96	39-25.33		120-32.76	9.93	2.02
78 DEC 23	22:37:03.17	39-23.38		120- 8.29	7.34	2.06
78 DEC 29	11:36:03.85	39- 0.52		121-30.31	17.48	0.96
78 DEC 30	01:29:22.04	38-41.82		121-35.40	14.06	1.26
79 JAN 15	23:23:52.28	39-25.25		120-34.38	16.56	1.86
79 JAN 25	08:34:29.22	39-23.29		120-15.15	17.62	1.98
79 FEB 13	03:01:03.09	39-26.90		120-16.66	5.00	1.97
79 MAR 04	05:00:01.65	39-10.25		120-26.83	13.05	1.55

TABLE 3 - CONTINUED

DATE	ORIGIN TIME (UTC)	LATITUDE DEG-MIN (NORTH)	LONGITUDE DEG-MIN (WEST)	DEPTH (KM)	MAG
79 MAR 19	17:59:05.40	38-42.67	120-57.48	7.18	1.06
79 MAR 25	05:20:39.21	39-25.11	120-12.71	7.60	2.11
79 MAR 25	17:00:33.08	39-24.38	120-12.74	19.47	1.73
79 MAR 29	13:06:56.22	39-17.40	121- 5.95	10.11	1.33
79 MAY 21	01:49:02.46	39-24.46	120-11.68	10.18	2.38
79 JUN 30	02:38:12.25	39-24.01	120-33.03	6.96	1.74
79 JUL 04	03:13:25.75	39-17.78	120-21.80	10.64	2.61
79 JUL 09	01:34:02.73	38-46.30 *	121-13.70	13.14	1.38
79 JUL 26	18:36:10.71	39-24.00	120- 6.23	7.62	2.23
79 AUG 11	13:48:51.92	39-24.71	120-11.66	7.95	2.18
79 AUG 15	19:48:28.89	39- 8.36	120-27.87	14.22	1.58
79 AUG 22	16:12:28.73	39-12.81	120-25.33	5.00	1.85
79 AUG 24	13:49:06.91	38-31.53	120-55.80	13.77	1.17
79 SEP 13	08:15:01.09	38-49.90	120- 2.82	15.96	2.15
79 SEP 22	13:46:51.19	39-18.01	120-21.56	5.85	2.13
79 SEP 26	11:36:18.35	38-55.11 *	121-19.19	8.34	1.13
79 SEP 26	11:42:24.30	38-54.83 *	121-19.84	7.68	1.03
79 NOV 27	05:04:57.48	39-32.90	120-27.97	30.09	2.30
80 JAN 15	12:09:24.55	38-46.18 *	121-14.07	12.63	1.00
80 FEB 14	08:20:51.07	39-23.74	120- 9.71	14.99	1.65
80 FEB 14	10:35:31.69	39- 9.07	121-27.53	13.56	1.15
80 FEB 15	12:40:07.44	39-26.84	120-17.36	15.20	2.53
80 FEB 18	06:59:19.38	39-15.02	120- 6.87	17.25	2.41
80 FEB 21	12:57:50.74	39- 8.93	121-26.77	14.80	1.76
80 FEB 25	04:02:22.11	39-24.16	120-11.21	11.86	1.76
80 FEB 29	08:45:24.93	39-27.21	120-17.42	7.51	2.13
80 MAR 02	11:15:28.50	39-42.42	120-44.05	18.93	1.80
80 MAR 03	19:31:25.77	39-24.39	121-29.61	4.88	1.22
80 MAR 06	02:05:56.07	39- 9.01	121-27.37	13.20	0.94
80 MAR 06	09:14:47.56	39-24.80	120-13.04	11.60	1.95
80 MAR 13	01:03:48.22	39-30.04	121-12.96	18.31	1.57
80 MAR 21	08:26:33.82	39- 9.10	121-28.17	12.15	1.26
80 APR 03	18:29:50.07	39-24.24	120-10.52	5.00	1.29
80 APR 04	08:16:26.20	39-17.50	121- 6.31	10.40	0.92
80 APR 08	03:26:40.05	39-12.90	120-22.06	18.39	1.76
80 APR 09	23:32:53.12	39- 2.76	120-35.49	0.22	1.56
80 APR 18	11:39:14.24	38-45.49 *	121-13.96	11.79	1.30
80 APR 24	01:51:25.95	39-25.69	121-13.01	16.64	1.38
80 APR 24	15:04:18.16	39-16.40	120-10.84	18.01	1.60
80 MAY 05	09:33:10.22	39-26.04	120-23.13	16.30	1.30
80 MAY 06	16:00:53.01	38-46.10 *	121-13.57	13.48	1.54
80 MAY 16	10:10:51.73	39-24.68	121-10.04	7.68	1.04

TABLE 3 - CONTINUED

DATE	ORIGIN TIME (UTC)	LATITUDE DEG-MIN (NORTH)	LONGITUDE DEG-MIN (WEST)	DEPTH (KM)	MAG
80 MAY 17	07:11:42.40	39- 9.87	120-56.74	42.76	1.38
80 JUN 19	02:57:47.34	38-45.12 *	121-13.40	11.03	0.68
80 JUN 21	08:28:57.46	39-23.03	121-15.92	16.79	1.72
80 JUN 24	20:21:20.88	38-45.18 *	121-13.32	11.43	1.37
80 JUL 07	10:28:59.23	38-45.41 *	121-13.11	10.02	0.80
80 JUL 10	13:53:19.27	39-19.56	121-20.57	5.50	0.75
80 JUL 15	12:25:42.53	39-28.15	120- 8.05	9.69	1.83
80 JUL 17	08:29:09.16	39-10.13	120- 3.19	9.06	1.84
80 JUL 21	10:12:22.25	39-17.56	120- 8.65	7.81	2.75
80 JUL 30	07:01:42.62	38-45.74 *	121-12.97	9.68	0.96
80 AUG 04	15:22:12.92	39-13.08	120-28.36	17.19	1.60
80 AUG 22	13:09:40.25	39-16.56	120- 7.94	3.38	2.47
80 AUG 22	13:11:26.82	39-15.71	120- 9.23	12.47	1.86
80 AUG 22	14:17:08.23	39-16.21	120- 8.87	10.20	2.32
80 AUG 30	02:09:57.92	39-12.09	120-24.98	1.28	2.55
80 SEP 04	09:02:06.24	39-15.47	120- 9.65	5.00	1.60
80 SEP 18	11:00:12.77	38-45.78 *	121-13.20	10.77	1.09
80 SEP 20	01:31:44.98	39-12.45	120-24.47	2.05	1.67
80 SEP 21	14:17:24.32	38-45.93 *	121-12.90	11.16	1.39
80 SEP 25	14:04:05.26	38-45.74 *	121-13.39	11.95	1.64
80 SEP 25	18:11:34.65	39- 8.14	120-45.72	1.47	1.32
80 SEP 26	05:24:02.28	39-23.90	121-30.14	7.58	1.62
80 SEP 26	06:26:45.64	39-21.64	121-22.16	0.53	0.67
80 SEP 26	09:38:52.41	39-21.76	121-21.90	0.33	1.65

NOTE -
1 - ORIGIN TIME = UTC
2 - MAG = LOCAL MAGNITUDE
3 - * = IN VICINITY OF ROCKLIN/PENRYN PLUTON

TABLE 4 - RELOCATED HYPOCENTERS: ROCKLIN/PENRYN PLUTON AND VICINITY

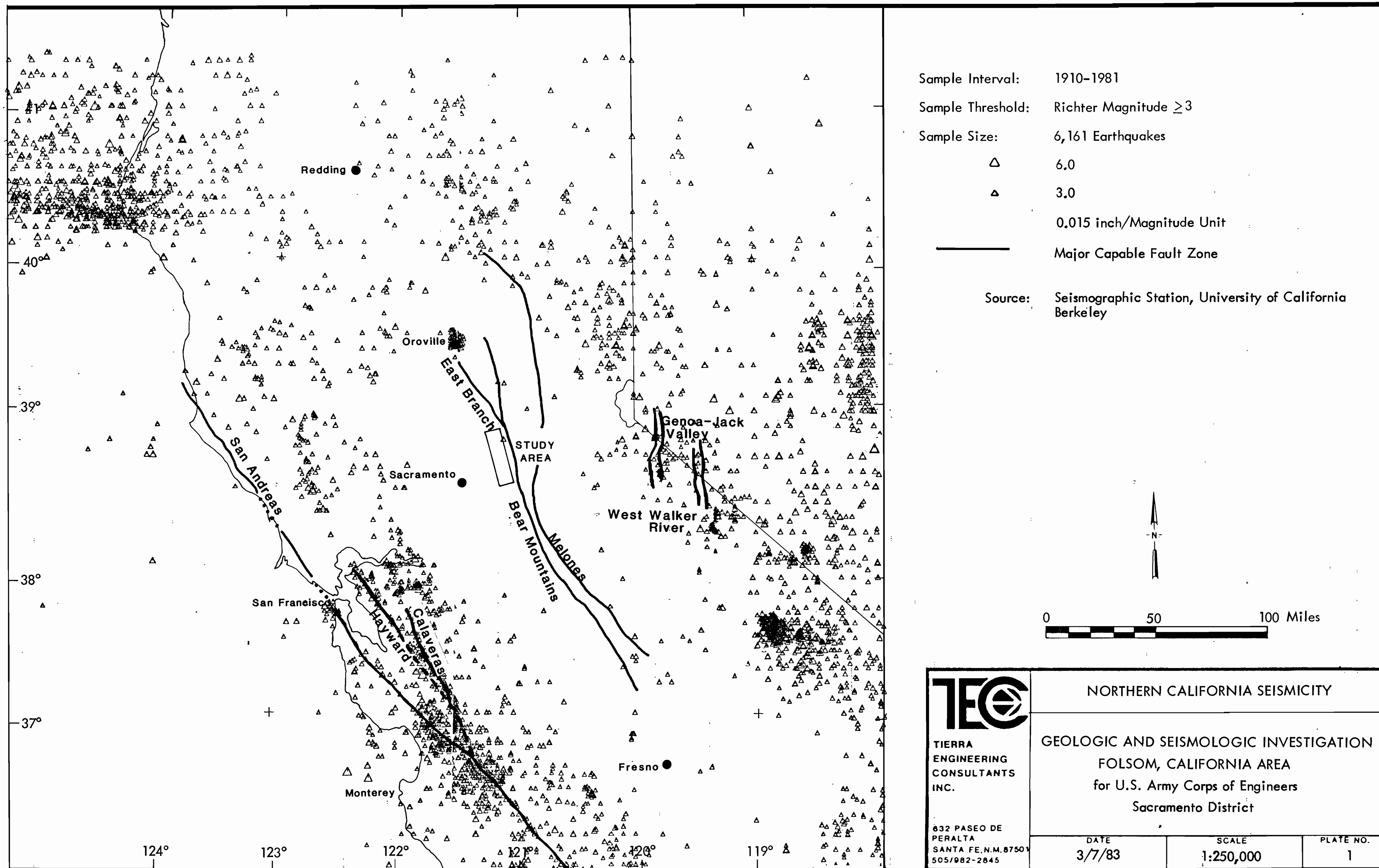
DATE	ORIGIN TIME (UTC)	+/- (SEC)	LATITUDE DEG-MIN (NORTH)	+/- (KM)	LONGITUDE DEG-MIN (WEST)	+/- (KM)	DEPTH (KM)	+/- (KM)	MAG	GROUP
77 JUN 14	17:43:27.03	0.016	38-45.59	0.06	121-13.28	0.07	12.70	0.12	1.35	S
77 JUN 20	10:47:10.42	0.015	38-45.69	0.06	121-13.33	0.07	12.80	0.10	1.11	S
77 AUG 03	08:37:51.06	0.021	38-45.66	0.09	121-13.14	0.10	12.60	0.14	1.34	S
77 SEP 03	15:34:32.20	0.031	38-45.62	0.19	121-13.35	0.16	12.70	0.31	0.77	S
77 NOV 01	19:42:27.72	0.017	38-45.44	0.06	121-12.77	0.08	12.20	0.14	1.26	S
77 NOV 03	01:07:01.45	0.016	38-46.44	0.05	121-13.49	0.06	13.50	0.11	1.20	S
77 NOV 27	02:52:29.59	0.036	38-45.72	0.16	121-13.35	0.17	12.60	0.21	1.78	S
77 DEC 08	22:30:41.71	0.017	38-46.45	0.06	121-13.28	0.08	13.30	0.15	1.33	S
78 JAN 10	01:02:29.27	0.025	38-45.71	0.08	121-13.31	0.12	13.10	0.22	1.30	S
78 JAN 10	01:04:55.42	0.026	38-45.72	0.09	121-13.42	0.12	13.60	0.17	0.83	S
78 FEB 16	10:27:44.31	0.030	38-53.86	0.11	121-12.49	0.13	5.90	0.24	0.89	N
78 FEB 17	20:09:41.68	0.142	38-54.38	0.48	121-12.74	0.73	5.80	1.36	1.11	N
78 MAR 18	14:03:40.19	0.019	38-45.86	0.07	121-13.50	0.09	13.40	0.18	1.25	S
78 MAY 30	00:19:54.85	0.024	38-45.74	0.08	121-13.47	0.11	12.60	0.18	0.98	S
79 JUL 09	01:34:02.94	0.025	38-46.70	0.07	121-13.24	0.10	13.60	0.22	1.38	S
79 SEP 26	11:36:18.70	0.075	38-55.36	0.24	121-18.98	0.42	6.10	0.80	1.13	NW
79 SEP 26	11:42:24.68	0.092	38-55.23	0.30	121-19.95	0.47	4.90	1.24	1.03	NW
80 JAN 15	12:09:24.69	0.029	38-46.63	0.10	121-13.52	0.16	13.80	0.17	1.00	S
80 APR 18	11:39:14.49	0.024	38-45.72	0.07	121-13.40	0.08	12.00	0.20	1.30	S
80 MAY 06	16:00:53.26	0.007	38-46.28	0.03	121-13.30	0.04	13.60	0.05	1.54	S
80 JUN 24	20:21:21.08	0.029	38-45.65	0.12	121-12.92	0.15	12.10	0.30	1.37	S
80 JUL 07	10:28:59.32	0.022	38-45.57	0.09	121-12.90	0.11	11.30	0.17	0.80	S
80 JUL 30	07:01:42.69	0.017	38-45.65	0.08	121-12.93	0.09	11.20	0.13	0.96	S
80 SEP 18	11:00:12.97	0.029	38-45.88	0.13	121-12.80	0.13	11.10	0.18	1.09	S
80 SEP 21	14:17:24.48	0.033	38-46.06	0.15	121-12.58	0.15	11.80	0.19	1.39	S
80 SEP 25	14:04:05.47	0.023	38-45.75	0.10	121-13.09	0.08	12.10	0.18	1.64	S

NOTES -
1 - MAG = LOCAL MAGNITUDE
2 - +/- = STANDARD ERROR

TABLE 5 - STATION COORDINATES AND ADJUSTMENTS

Station	Latitude	Longitude	P-adj* (sec)	S-adj* (sec)
AFR	38° 47.53'N	121° 20.90'N	0.07	0.16
ADW	38° 26.34'N	120° 50.88'N	0.20	0.40
AHD	39° 2.89'N	121° 4.58'N	-0.03	0.22
AVR	39° 1.48'N	121° 16.07'N	-0.09	0.07
ARW	38° 57.37'N	121° 9.72'N	-0.09	0.04
AFD	38° 56.68'N	120° 58.09'	0.04	0.37
APR	38° 52.61'N	121° 13.02'N	-0.08	0.06
AMR	38° 51.25'N	121° 4.22'N	-0.11	--
AGI	38° 50.67'N	120° 58.87'N	-0.06	-0.41
ABR	38° 45.91'N	121° 10.30'N	-0.10	-0.06
ABJ	39° 9.89'N	121° 11.46'N	-0.17	0.04
ALN	38° 55.77'N	121° 17.26'N	-0.04	0.13
ARJ	38° 41.18'N	120° 57.37'N	-0.12	0.04
ALA	38° 33.99'N	120° 57.36'N	-0.10	0.04

* Adjustments are to added to calculated travel times.



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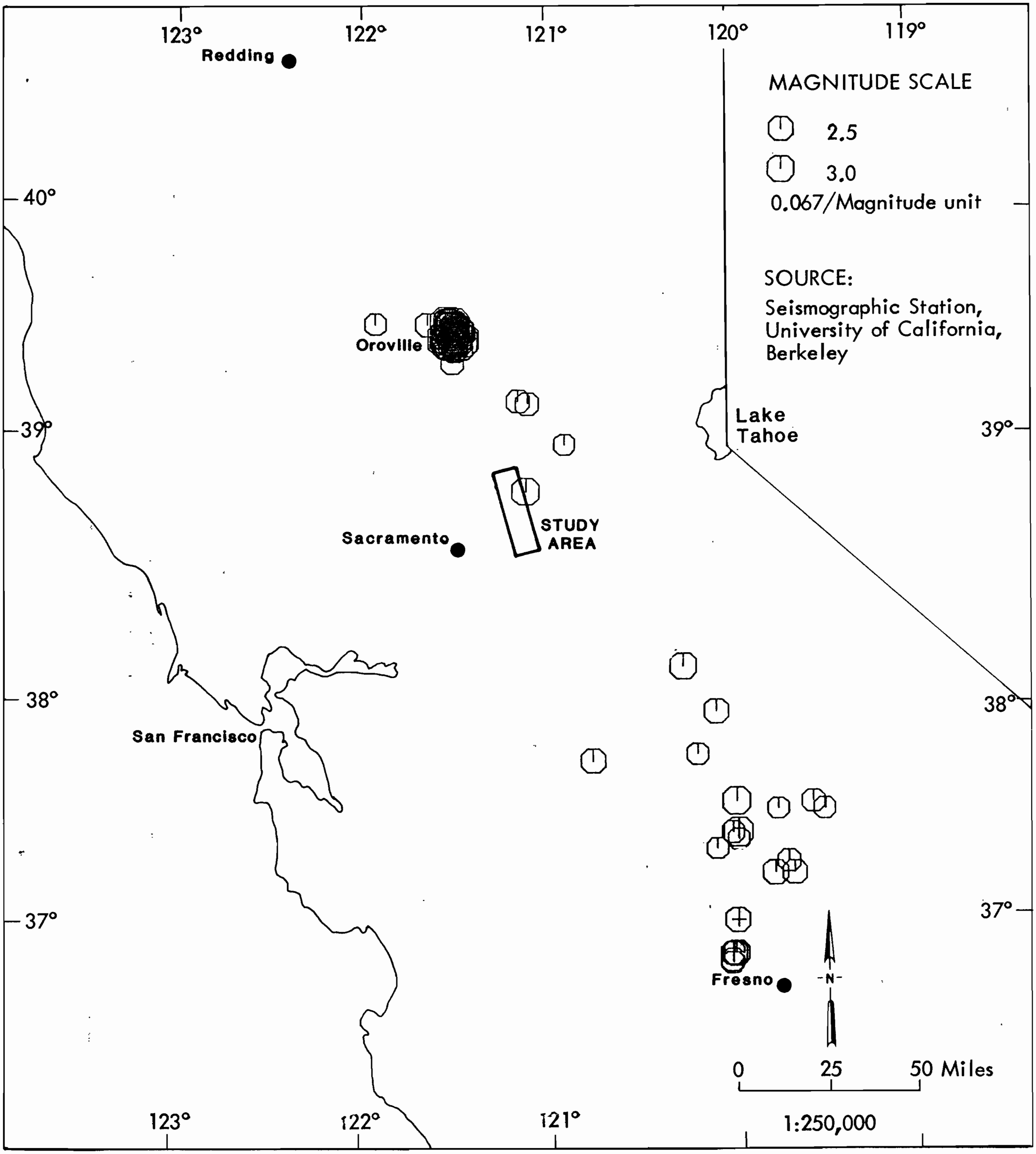
NORTHERN CALIFORNIA SEISMICITY

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:250,000	1

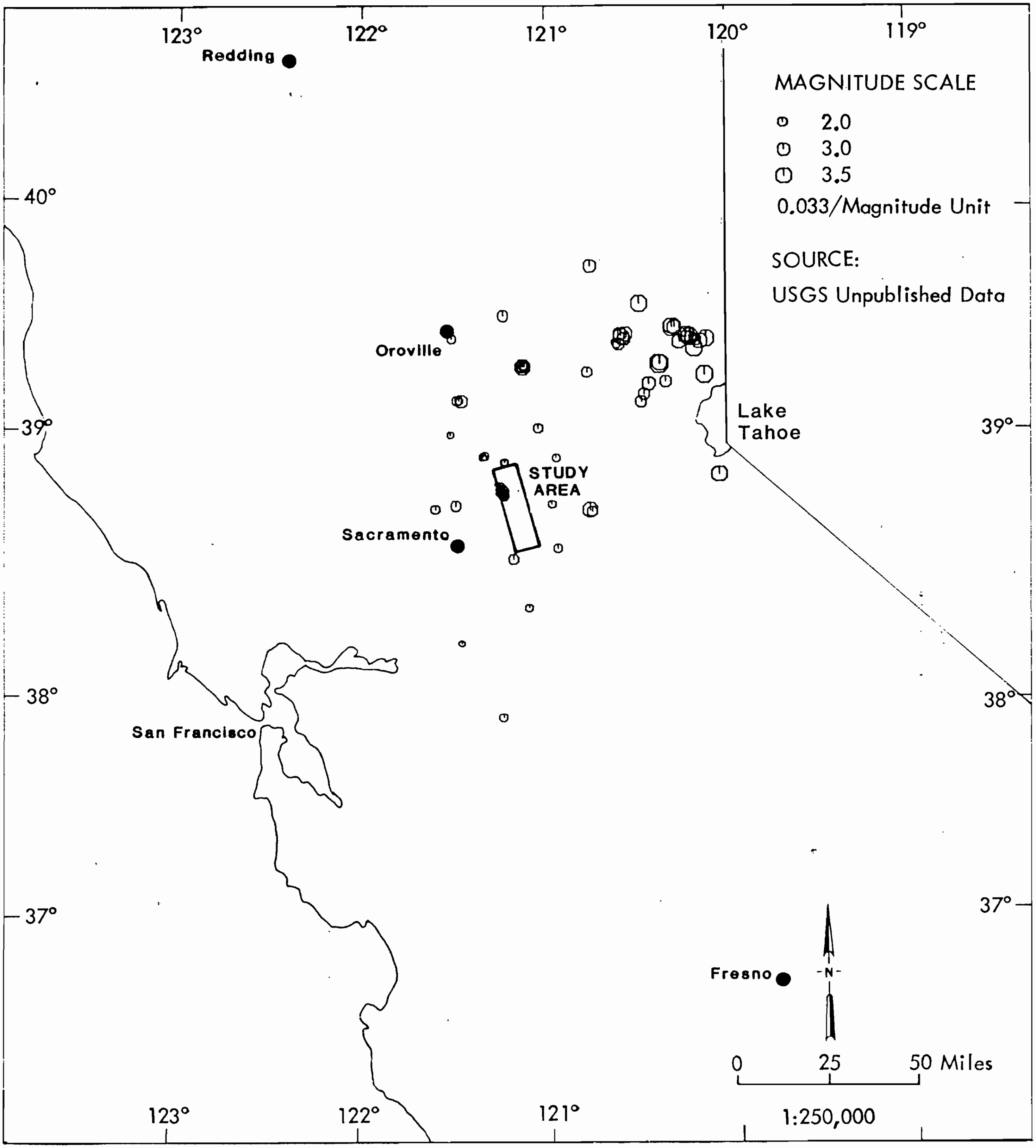


TIERRA ENGINEERING CONSULTANTS

SIERRA FOOTHILLS SEISMICITY 1937-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 2

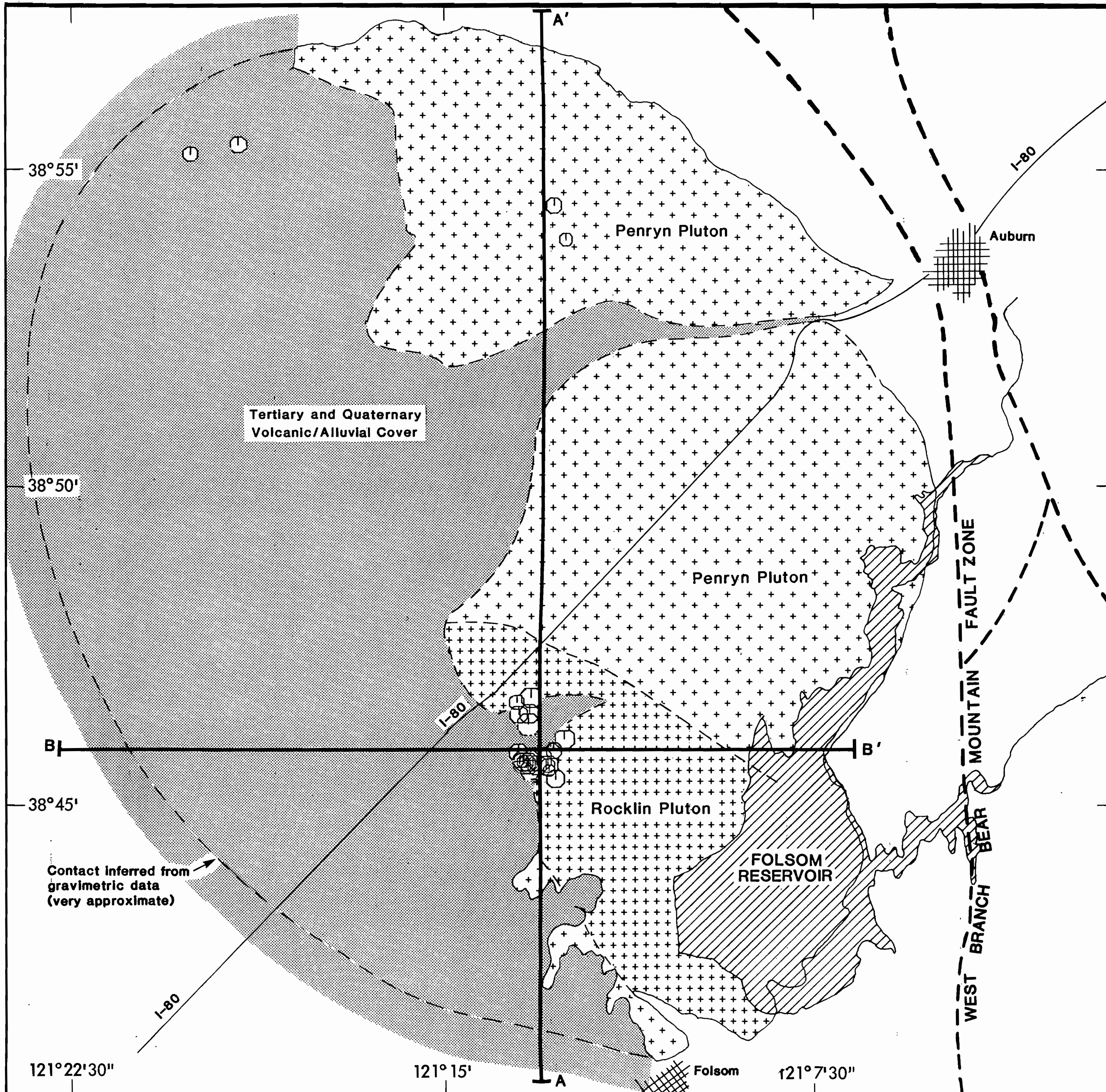


TIERRA ENGINEERING CONSULTANTS

AUBURN NET SEISMICITY 1977-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 3



EXPLANATION

1.0

2.0

Epicenter
(Scale 0.125"/unit Richter Magnitude)

Cenozoic surficial deposits

Mesozoic Rocklin pluton (granodiorite)

Mesozoic Penryn pluton (quartz diorite)

B B' Location of cross section
(See Plate 7-5)

Sample Interval: 1977-1980

Source: USGS Auburn Net

N

0 1 2 3 4 Miles

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INC.

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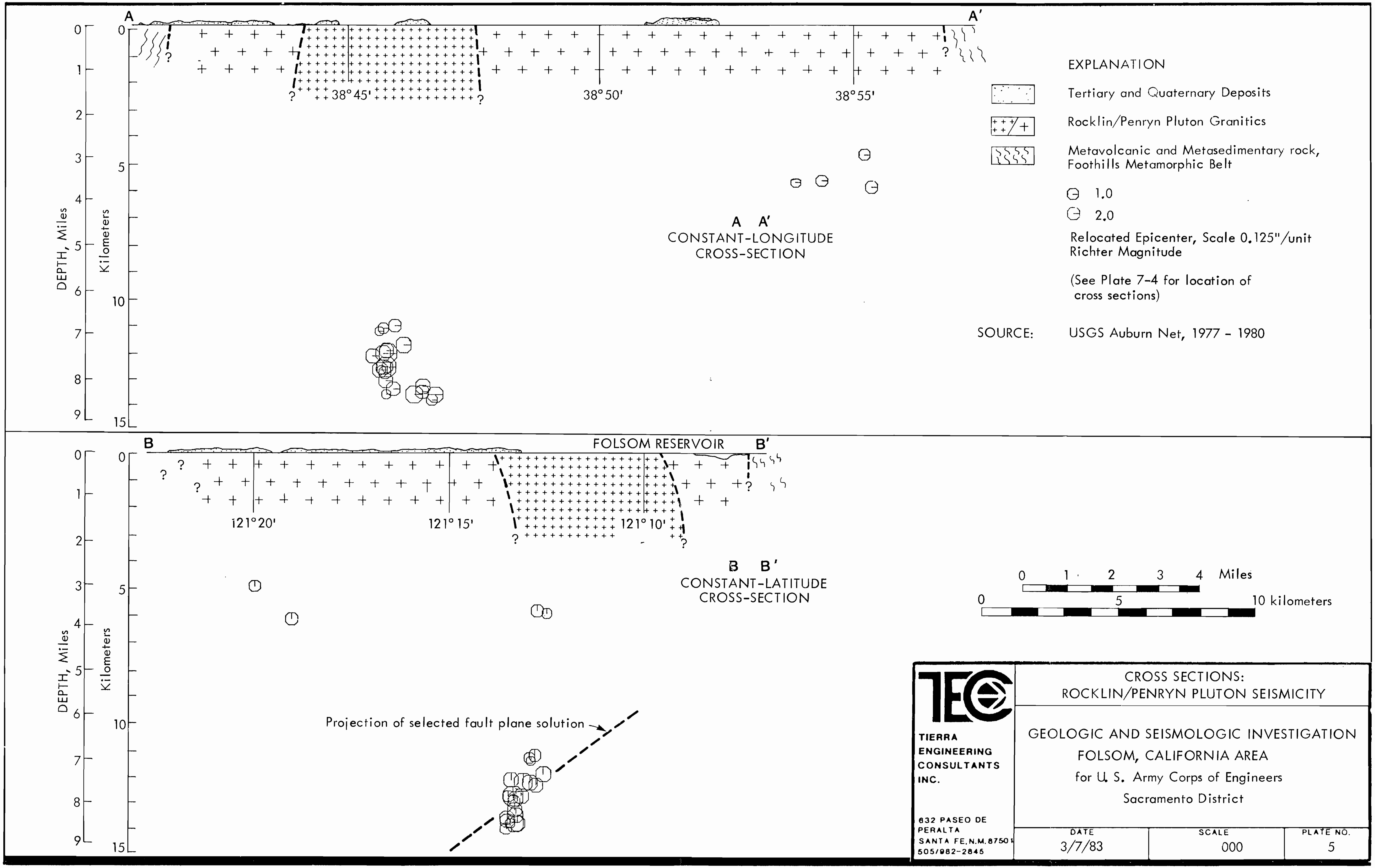
PERALTA
SANTA FE, N.M. 87501
505/982-2845

ROCKLIN/PENRYN PLUTON-
RELOCATED EPICENTERS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

DATE	SCALE	PLATE NO.
3/7/83	1:125,000	4


A
A′
38° 45′
38° 50′
38° 55′
DEPTH, Miles
Kilometers
A A′
CONSTANT-LONGITUDE
CROSS-SECTION
EXPLANATION
Tertiary and Quaternary Deposits
Rocklin/Penryn Pluton Granitics
Metavolcanic and Metasedimentary rock,
Foothills Metamorphic Belt
1.0
2.0
Relocated Epicenter, Scale 0.125"/unit
Richter Magnitude
(See Plate 7-4 for location of
cross sections)
SOURCE:
USGS Auburn Net, 1977 - 1980
B
FOLSOM RESERVOIR
B′
121° 20′
121° 15′
121° 10′
B B′
CONSTANT-LATITUDE
CROSS-SECTION
Miles
10 kilometers
Projection of selected fault plane solution
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SANTA FE, N.M. 87501
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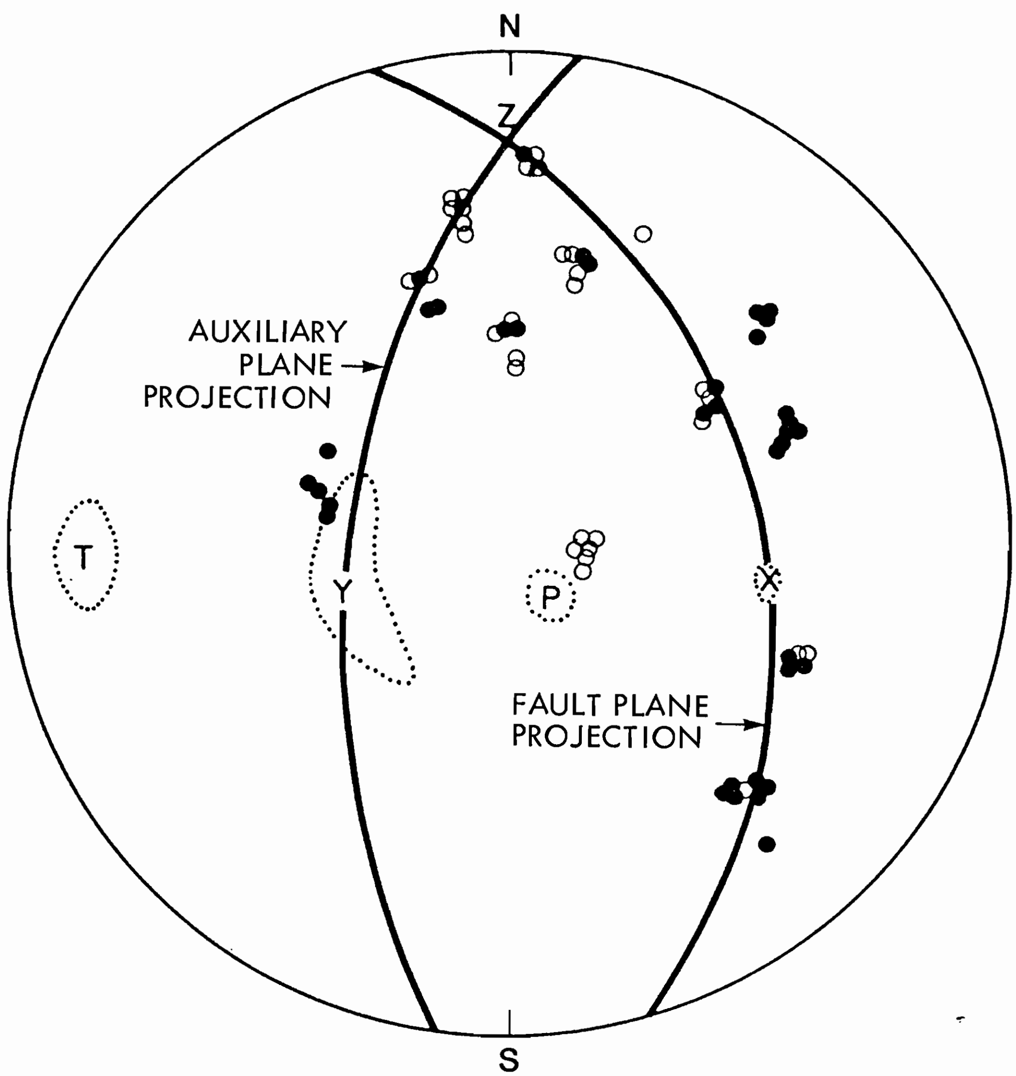
CROSS SECTIONS:
ROCKLIN/PENRYN PLUTON SEISMICITY
GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U. S. Army Corps of Engineers
Sacramento District
DATE
3/7/83
SCALE
000
PLATE NO.
5



UPPER HEMISPHERE PLOT

	FAULT PLANE	AUXILIARY PLANE
Strike	344° ± 21	188° ± 2
Dip	37° ± 4	55° ± 1
Slip	71° ± 15	76° ± 12

SOURCE: 1977-1980 Relocated Epicenters, USGS Auburn Net

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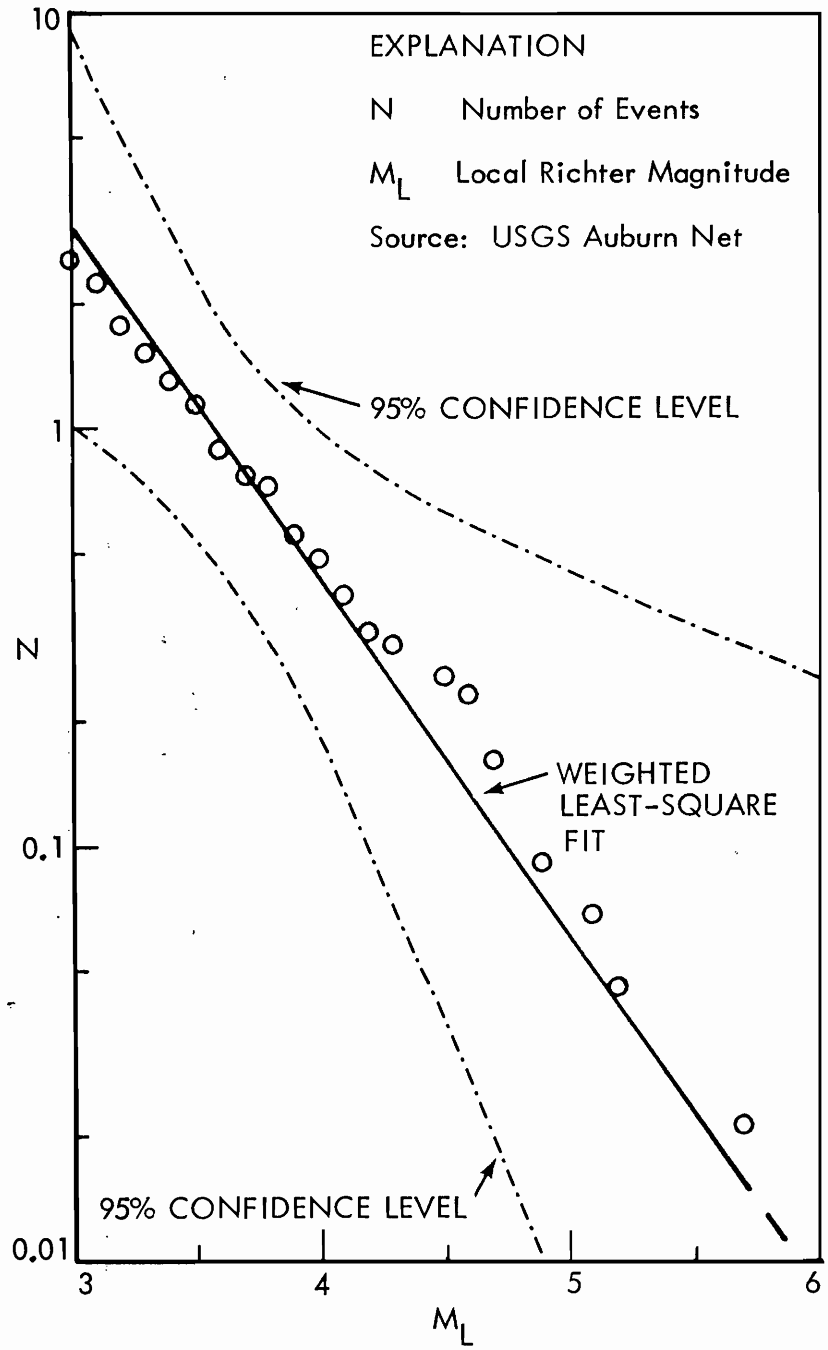
FAULT PLANE SOLUTIONS: ROCKLIN/PENRYN PLUTON

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 6



RATE OF SEISMICITY, NORTHERN CALIFORNIA 1937-1980

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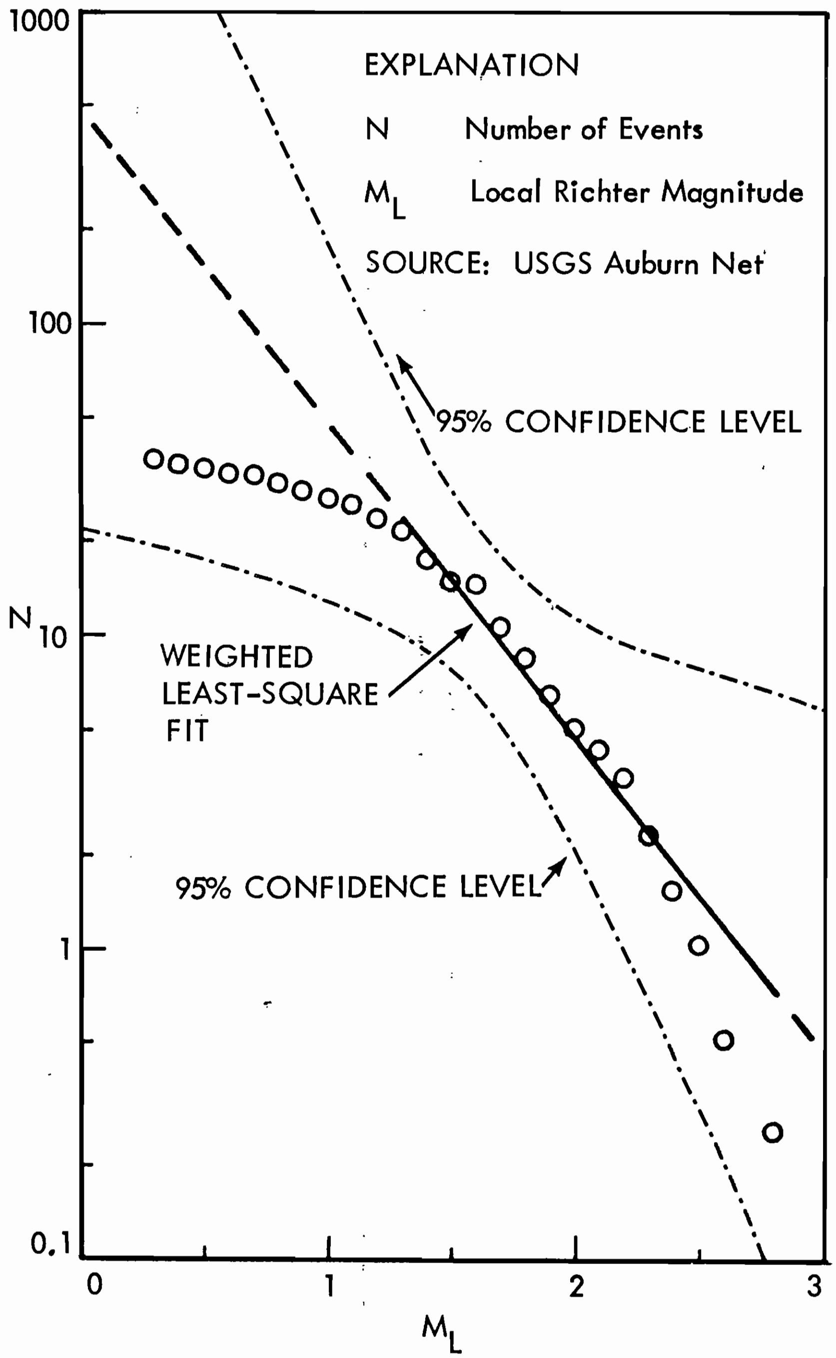
GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 7



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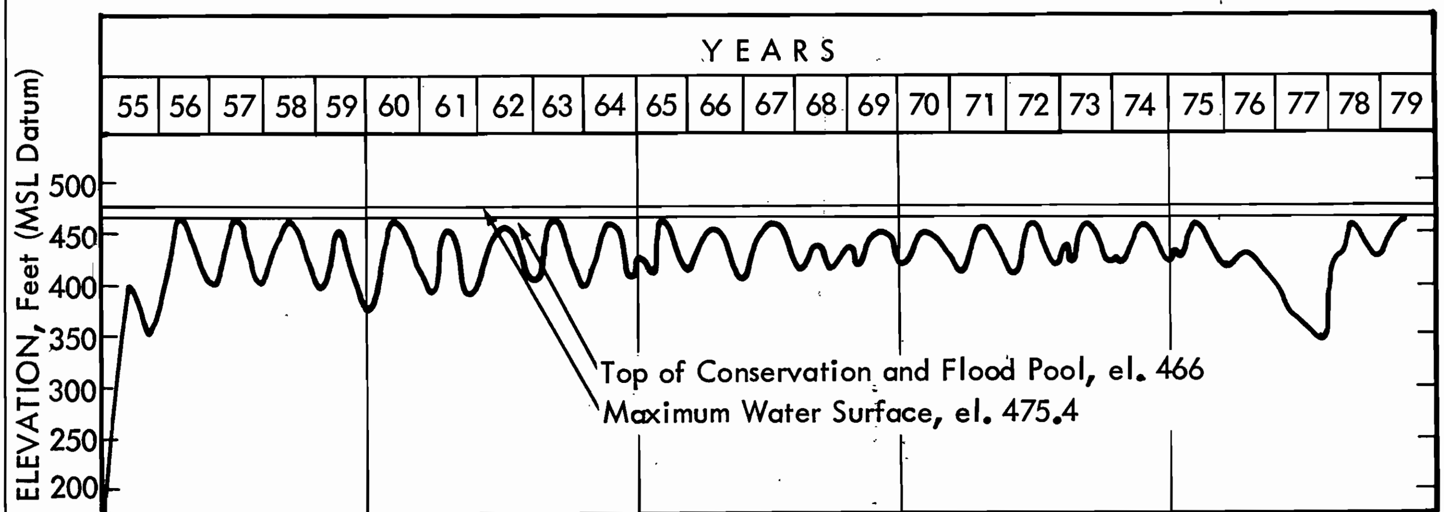
RATE OF SEISMICITY, AUBURN NET 1976-1980

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 8



Time Period: Initial Filling to July, 1979

Source: U.S. Army Corps of Engineers,
Sacramento District

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FOLSOM RESERVOIR LEVEL FLUCTUATIONS

GEOLOGIC AND SEISMOLOGIC INVESTIGATION
FOLSOM, CALIFORNIA AREA
for U.S. Army Corps of Engineers
Sacramento District

Plate No. 9

Appendix C

SOIL-STRATIGRAPHIC AGE ASSESSMENTS, WEST BRANCH BEAR MOUNTAINS AND MORMON ISLAND FAULT ZONES, FOLSOM DAM AREA, CALIFORNIA

by

Roy J. Shlemon

for

Tierra Engineering Consultants, Inc.

on behalf of the U.S. Army Corps of Engineers

February 1983

Roy J. Shlemon & Assoc., Inc.
P.O. Box 3066
Newport Beach, CA 92663

CONTENTS

SOIL-STRATIGRAPHIC AGE ASSESSMENTS,
WEST BRANCH BEAR MOUNTAINS AND MORMON ISLAND FAULT ZONES
FOLSOM DAM AREA, CALIFORNIA

INTRODUCTION

This report summarizes the results of field investigations near Folsom Dam in Sacramento, El Dorado and Placer counties, California. It focuses mainly on the presence and age of soil-stratigraphic markers useful to assess possible late Quaternary faulting in the area. This study supports other investigations concerned with the seismotectonic setting of Folsom Dam, carried out by Tierra Engineering Consultants, Inc. (TEC) and Converse Consultants, Inc. (CC) on behalf of the U.S. Army Corps of Engineers. The conclusions herein stem from field observations and measurements, and from interpretation of aerial photography, geological mapping, and trench logs provided by TEC and CC.

Purpose

The main purpose of this study was to assess the age of sediments and geomorphic features useful to date possible faulting in the Folsom Dam area. Specific tasks were:

1. to reconnoiter the area with TEC and CC geotechnical personnel in order to:

   (a) locate Quaternary stratigraphic sequences amenable to dating; and

   (b) site trenches across lineaments significant to the seismotectonic analysis;

2. to delineate pertinent geomorphic features suggestive of possible late Quaternary tectonism; e.g., truncated spurs, aligned topographic saddles, and structurally-controlled drainages;

3. to inspect trenches emplaced by TEC/CC across the West Branch of the Bear Mountains and the Mormon Island faults, identifying and dating key soil-stratigraphic markers; and

4. to review trench logs and other data provided by TEC and CC, particularly those relevant to possible Quaternary faulting in the area.

This report documents the scope of field investigations, calls attention to soil-stratigraphic techniques applicable to the study area, and summarizes soil data pertaining to last displacement of the West Branch Bear Mountains and the Mormon Island faults.

Scope of Investigation

Accompanied by TEC and CC personnel, field investigations were carried out between August and December 1982. Initially, a reconnaissance was made of large-scale, previously-dated Quaternary geomorphic features and stratigraphic markers in the Folsom Dam area; viz., ancestral channels and terraces of the lower American River (Shlemon, 1967, 1972). Later observations focused on potential trench sites to expose the West Branch, Bear Mountains and the Mormon Island faults. Soil-stratigraphic relationships were observed in trenches excavated by TEC/CC deemed the "Sunset", "Lagoon," "Dunlap Ranch," and "Russell Ranch." The locations of these trenches, associated lineaments and faults, and soil-stratigraphic markers are shown on plates and logs accompanying the main body of the seismotectonic report, and are so referred to in this text. The ages of the key soil-stratigraphic units and their relationship to the seismotectonic history of the Folsom area were previously reviewed with TEC and CC personnel in the field and in the office.

Acknowledgements

Logistical support for this investigation was provided by TEC and CC. Acknowledged with special thanks is the commentary of R. Catanach, A. O'Neill, and M. Shaffer. Particularly appreciated is the field assistance graciously given by engineering geologists G. A. Ford (CC) and M. Pincus (TEC) who obtained pertinent literature, photographs, access to trenching sites, and otherwise aided in identifying and logging soil-stratigraphic markers.

SUMMARY OF CONCLUSIONS

The main conclusions concerning soil-stratigraphic age assessments in the Folsom Dam area may be summarized as follows:

1. Quaternary stratigraphic markers, datable by relative soil profile development and association with the marine isotope stage chronology, were encountered in trenches excavated across the West Branch of the Bear Mountains and the Mormon island faults.

2. The faults are expressed by photographic tonal lineaments, but no geomorphic features of youthful displacement were observed.

3. Last displacement of West Branch, Bear Mountains fault, based mainly on stratigraphy in the Sunset site trenches, took place at least 125,000 years ago, and possibly more than 195,000 years before present (BP).

4. Any displacement of the Mormon Island fault in the Folsom Dam area, based on soil stratigraphy in the Russell Ranch trench, occurred at least 50,000 to 70,000 years ago, and possibly more than about 125,000 years BP.

SOIL STRATIGRAPHIC DATING

Though highly desirable for seismotectonic investigations, materials amenable to unequivocal radiocarbon or uranium-series dating are not often encountered. Such has been the case in the Folsom Dam area. Nevertheless, trenching does show the presence of Quaternary sediments overlying bedrock, and these sediments are susceptible to dating by soil-stratigraphic techniques. Such techniques have been successfully used in geotechnical studies elsewhere in California, particularly to date last displacement and to discern possible recurrence of faulting at and near nuclear plants and large dams (e.g., Shlemon, 1977a, 1977b, 1979, 1980; Shlemon and Hamilton, 1978; Swan and Hanson, 1977; Borchardt and others, 1980).

The techniques of soil-stratigraphic dating have been spelled out elsewhere (e.g., Morrison, 1967, 1968, 1978; Birkeland, 1974) and are not repeated here. However, for context, as applied to the Folsom Dam seismotectonic investigations, two main soil-stratigraphic techniques have been employed: (1) comparison of relative soil development with profiles dated elsewhere in the Central Valley and in the Sierra Nevada foothills; and (2) association with the marine (deep sea) isotope stage chronology. These are briefly described in sections following, but the reader is referred to the cited literature for additional documentation.

Relative Soil Profile Development

The term "soil" is here employed in its pedological sense; that is, as a weathering phenomenon (Jenny, 1941, 1980; Soil Survey Staff, 1951, 1975). In brief, under a given soil climate, and on a relatively stable geomorphic surface, weathering proceeds and a profile begins to form. Initially, an A (organic) horizon develops. Eventually, with oxidation and translocation of sesquioxides and iron-silicate clay, a B horizon (cambic to argillic) transitionally forms. Of interest is the time required for B horizon development. Where calibrated by radiometric dates it is found that about 30,000 years are required for a slight to moderate profile, and some 100,000 years is necessary to form a strong soil on granitic alluvium (parent material) in the eastern Central Valley of California (Arkley, 1962; Janda and Croft, 1967; Shlemon, 1967; Hansen and Begg, 1970; Marchand, 1977). On finer-grained and more mafic sediments, as in the Sierra Nevada foothills, soil formation is faster, and a slightly-developed profile (cambic horizon) may form in about 15,000 years, and a moderately-developed soil in some 35,000 to 45,000 years (Marchand, 1977; Shlemon, 1977a; Swan and Hanson, 1978; Borchardt and others, 1980).

The age of a soil, as determined by its relative development, may also be applied to buried paleosols. Such paleosols, formed under environments of the past (Ruhe, 1965; Yaalon, 1972; Valentine and Dalrymple, 1976), required a finite time to develop before covering by younger sediments, which in turn were subject to later pedogenesis. The presence of multiple buried soils provides particularly useful information to date Quaternary sediments, and hence the last displacement of any associated fault.

Marine Isotope Stage Chronology

In addition to relative profile development, many soil-stratigraphic sequences are datable by association with the Quaternary, marine isotope chronology (Emiliani, 1955; Shackleton and Opdyke, 1973, 1976; Bloom and others, 1974). In brief, during glacio-eustatic lowering of sea level during the Pleistocene, many parts of California with Mediterranean climatic regimes were subject to geomorphic instability whereby sedimentation occured in many interior valleys, and "accelerated" colluviation took place on foothill slopes. In contrast, during relatively high stands of sea level (interstadial and interglacial), relative landscape stability prevailed and many distinctive soil-stratigraphic markers formed (Butler, 1959; Janda and Croft, 1967; Morrison, 1967, 1968; Shlemon, 1972; Swan and Hanson, 1977). Thus alternating sequences of regionally-extensive alluvial and colluvial sections, separated by buried paleosols, often record climatic change during the Quaternary, indirectly datable by association with the marine isotope stage chronology. Such sequences were well exposed in the Folsom area trenches, providing excellent stratigraphic markers to date Quaternary sediments overlying the West Branch, Bear Mountains and the Mormon Island faults.

WEST BRANCH, BEAR MOUNTAINS FAULT ZONE

From literature review, aerial photographic analysis, and geological mapping TEC and CC geotechnical personnel determined that a lineament deemed the "West Branch of the Bear Mountains fault zone" was indeed an expression of tectonic displacement. Two localities, the Lagoon and Sunset sites, were trenched in order to expose the fault and any overlying stratigraphy (Plates 5-1 and 5-3).

Lagoon Site

The Lagoon trench, some 220 feet long, was excavated across a high topographic saddle coincident with a photolineament associated with the Bear Mountains fault. Trenching was initiated to expose bedrock, to determine the relationship of shear zones and clearly-discernible vegetation alignments, and to identify soil-stratigraphic or other Quaternary units useful to date last displacement of the fault.

As shown in trench logs (Plates 5-2a and -2b), several shears and fracture fillings occur in bedrock. Because the trench was located on a divide, only a thin colluvial unit is preserved over bedrock and associated shear zones. This unit, called "1" on trench logs, is derived from adjacent side-slopes and ranges in thickness from several inches to a few feet. The colluvium is unbroken; and typified by a thin but discernible stoneline at its base, particularly observable between stations 8 and 16 (Plate 5-2a).

A soil (pedogenic profile) has formed on this colluvium. Where examined at station 25, the profile has a thin (0.2 foot) A_1-B horizon, and an underlying B_1-B_2 (weak argillic horizon). This soil, by virtue of its topographic position, is now being degraded; and the slightly-developed profile yet remaining can only provide a minimum age for the colluvium.

Comparison of relative development with similar profiles dated in adjacent areas suggests that this soil is somewhat older than about 12,000 or 13,000 years. This age is in accord with that of the colluvium and stoneline judged to have been laid down during a previous epoch of relative geomorphic instability, about 17,000 to 20,000 years ago (maximum of isotope stage 2; Shackleton and Opdyke, 1973, 1976).

In sum, only one soil-stratigraphic marker is present at the Lagoon site. This marker is unbroken. Soil development indicates that the colluvium on which it formed is probably somewhat less than about 20,000 years old; and hence provides a minimum age for last displacement of the West Branch, Bear Mountains fault in this area.

Sunset Site

Two trenches were excavated at the Sunset site, across a weak vegetation alignment and an adjacent degraded escarpment coincident with the West Branch of the Bear Mountains fault (Plate 5-3). These trenches, called the "Sunset North" and the "Sunset South," respectively, each exposed three distinct colluvial units and intercalated buried paleosols overlying bedrock shears and filled fractures (Plates 5-4a, -4b and 5-5a, -5b).

Representative of the soil-stratigraphy in this area is a section measured at station 4 on the north wall of the Sunset North trench. Here, each of the three colluvial units is capped by a soil; the upper colluvium (unit 1) bears a slightly-developed surface profile with cambic B horizon; the middle colluvium (unit 2) gives rise to a truncated but still visible, moderately-developed paleosol with weak argillic horizon; and the lower colluvium (unit 3) is characterized by a very strongly-developed buried paleosol with an argillic horizon in excess of 3 feet thick.

The Quaternary soil stratigraphy in the Sunset site trenches is remarkably complete, recording three epochs of regional geomorphic instability (colluviation) separated by periods of landscape stability (soil formation). As shown on trench logs (Plate Series 5-4 and 5-5), each colluvium is characterized by a discontinuous but recognizable basal stoneline generally comparable to the colluvial unit exposed at the Lagoon site.

The internal stratigraphy and the relative soil profile development of Sunset colluvium 1 (SILTY CLAY) (brown - 7.5YR 5/4; fine silty loam; moderate, medium subangular blocky structure) is consistent with an age of about 12,000 to 20,000 years (late isotope stage 2). Colluvium 2 (SILTY GRAVELLY CLAY) bears a soil (yellowish red - 5YR 5/6; gravelly clay loam; moderate, medium angular blocky structure; common, moderately-thick clay films on ped faces) typical of those formed about 35,000-45,000 years ago (stage 3) on sediments laid down during a preceding epoch of deposition some 50,000 to 70,000 years BP (stage 4). And the lower colluvium (SILTY GRAVELLY CLAY) gives rise to a strongly-developed soil (red - 2.5YR 4/8; gravelly clay loam; moderate, coarse angular blocky to prismatic structure; many, thick clay films lining ped faces and tubular pores) representative of those about 80,000-125,000 years old (stage 5). This oldest colluvium, accordingly, was laid down earlier, judged to be about 125,000-195,000 years ago (stage 6). The detailed logs of the Sunset trenches (Plate Series 5-4 and 5-5) show no shears or other apparent vertical displacement of the overlying soil and colluvial units. Therefore, from this soil-stratigraphic evidence last displacement of the West Branch of the Bear Mountains fault in this area took place at least 125,000 years ago, and possibly more than about 195,000 years BP.

MORMON ISLAND FAULT ZONE

Photographic analysis indicates the presence of a general, northwest-trending lineament projecting through the east abutment of the Mormon Island Dam. This lineament, later discerned to be the bedrock expression of faulting, was trenched at two locations, the Dunlap Ranch and the Russell Ranch sites (Plate 4-6 and 5-6).

Dunlap Ranch Site

The Dunlap Ranch site was selected for trenching because of its position on fluvial terrace deposits adjacent to Deer Creek, the largest drainage with a potentially datable stratigraphy across the Mormon Island fault. Initial test pits revealed the presence of overbank sands and silts capped by a slightly-developed soil profile. These, in turn, overlay fluvial terrance gravels several feet above the present flood plain. The gravels, based on their stratigraphic position, would have been laid down during a previous epoch of sedimentation, in the order of 15,000 to 20,000 years ago (isotope stage 2).

Based on the test pit data, a trench some 78 feet long was excavated immediately north of Deer Creek across the projection of the Mormon Island fault (Plate 5-8). Numerous bedrock shears were encountered attesting to the presence of the fault. However, the overlying alluvial deposits were found to be highly disturbed. The original A and B_1 horizons had been locally removed and incorporated into adjacent, poorly-sorted fill. This disturbance apparently stems from early dredging and associated mining activities, the evidence for which is readily visible in the adjacent Deer Creek flood plain. In essence, the Quaternary stratigraphy of the Dunlap Ranch site was too altered for adequate dating; and an age for last displacement of the Mormon Island fault was ultimately based on exposures in the Russell Ranch trench.

Russell Ranch Site

The Russell Ranch site is particularly important because of its proximity (less than one mile) to the Mormon Island Dam, and because of its photographic expression of possible seismotectonic structures (vegetation alignment and a subparallel degraded escarpment). Accordingly, a trench almost 550 feet long was excavated in order to cross all geomorphic features indicative of possible faults, and to expose a Quaternary colluvial stratigraphy extending from eroding hillslopes to an adjacent, aggrading stream valley (Plate 5-6).

Several topographic "steps" and shear zones were encountered in the bedrock; but in every case were covered by at least one and usually two distinct colluvial units. The Russell Ranch trench was particularly instructive, for sidecuts every

50 feet afforded a three-dimensional view of the Quaternary soil stratigraphy and its relationship to underlying bedrock. Both colluvial units were typified by a weak, but still recognizable basal stoneline, comparable to colluvial sections exposed elsewhere in the study area. From observations and measurements near station 90, the upper colluvium (SANDY SILTY CLAY), some 2.2 feet thick, bears a moderately-developed profile with weak argillic horizon (yellowish red-5YR 5/6; silty clay loam; weak, medium subangular blocky structure; and common, thin illuvial clay films on ped faces and lining interstitial pores). Such profile development characterizes sediments in this area at least 15,000 to 20,000 years old (isotope stage 2).

The underlying colluvium (SILTY SANDY CLAY), likewise more than about 2 feet thick, bears a moderately- to strongly-developed buried paleosol, the upper part of which has been eroded. This paleosol is well expressed by its argillic horizon (dark grayish brown-2.5Y 4/2; clay; strong, very coarse prismatic structure; few to common, thin, yellowish-red 5YR 4/6 clay films on ped faces near base). Numerous slickensides (pressure faces) also characterize the paleosol argillic horizon; these expressive of an expansive, smectitic clay mineralogy. The relative development of this buried soil, based on the horizons still preserved, indicates formation at least 35,000 to 45,000 years ago (stage 3), and possibly 80,000 to 125,000 years ago (stage 5). At a minimum, therefore, the age of the lower colluvium on which the paleosol has formed is judged to be about 50,000 to 70,000 years old, laid down during an epoch of regional geomorphic stability (stage 4).

Several bedrock steps with 1 to 2 feet of vertical relief occur between stations 30 and 45 (Plate 5-7a), but no shears extend into or otherwise vertically displace the overlying colluvial units. Of interest also was the presence of standing water, coincident with a vegetation alignment between stations 110 and 120 (Plate 5-7a). Here the colluvial units similarly extended unbroken across this zone. In sum, the soil-stratigraphic markers and related colluvial deposits in the Russell Ranch trench are continuous throughout, indicating that any displacement of the Mormon Island fault in this area took place at least 50,000 to 70,000 years, and possibly more than about 125,000 years ago.

SUMMARY AND CONCLUSIONS

Soil-stratigraphic age assessments, conducted as part of a seismotectonic study for Folsom Dam, were carried out in order to date sediments exposed in trenches excavated across the West Branch Bear Mountains and the Mormon Island faults. In the absence of materials suitable for radiocarbon and uranium-series assay, the age of Quaternary sediments was determined by comparison of soil development with profiles dated radiometrically elsewhere in the Central Valley and Sierra Nevada foothills; and by association with the marine isotope stage chronology.

Trenches were emplaced across the West Branch of the Bear Mountains fault at the Lagoon and Sunset sites. A colluvium, dated as slightly less than about 20,000 years, lies unbroken across bedrock shears and fracture fillings at the Lagoon site. A more complete stratigraphy, typified by three colluvial units with basal stoneline and capping soils (surface soil and buried paleosois), occurs at the Sunset site. The soil-stratigraphic markers record alternating epochs of relative geomorphic instability (colluviation) separated by periods of landscape stabilty (soil formation). From soil development and association with the isotope stage chronology, the Quaternary stratigraphy here encompasses a section from a Holocene surface soil to a basal colluvium in excess of about 125,000 years old. None of the Quaternary sediments are displaced. Therefore, last movement of the West Branch of the Bear Mountains fault in this area occurred at least 125,000 years ago, and possibly more than about 195,000 years BP.

The Mormon Island fault was trenched adjacent to Deer Creek (Dunlap Ranch site) and within one mile of Mormon Island Dam (Russell Ranch site). The Dunlap Ranch excavation was inconclusive, owing to probable mining-induced disturbance of Quaternary sediments useful for dating. In contrast, the Russell Ranch trenches exposed two colluvial units and a related surface soil and buried paleosol. The stratigraphy is unbroken, crossing bedrock "steps," shear zones, vegetation alignments and other expressions of possible Quaternary faulting. Soil profile development indicates the basal colluvium is probably at least 50,000 to 70,000 years old, and possibly in excess of 125,000 years. Accordingly, any displacement of the Mormon Island fault in this area took place before about 50,000 to 70,000 years ago.

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