QUATERNARY GEOLOGY OF THE SACRAMENTO AREA

Association of Engineering Geologists, Sacramento Section

Guidebook for Field Trip, 25 March 2000

Leaders

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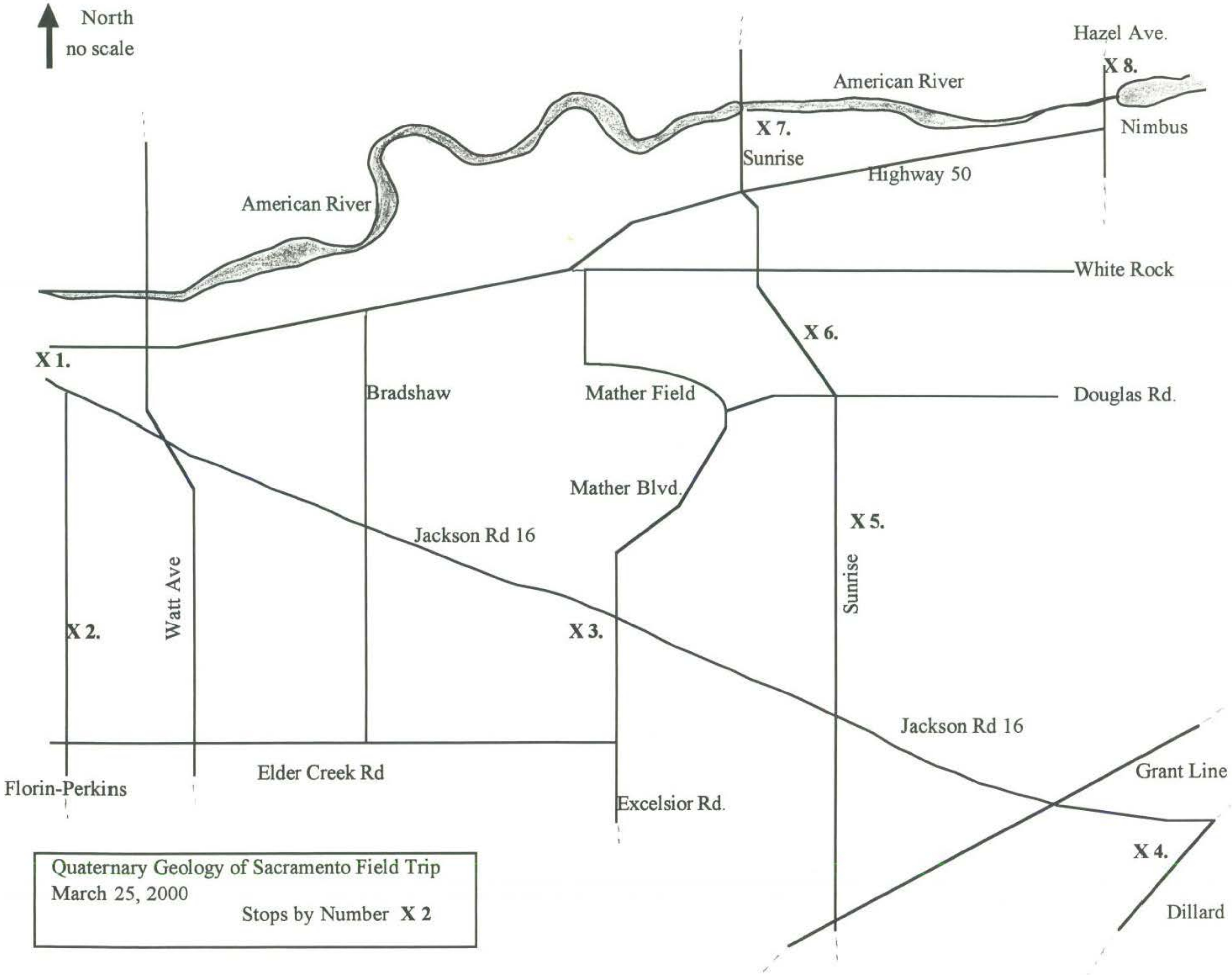

Quaternary Geology of Sacramento Field Trip
March 25, 2000
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Acknowledgments

The Sacramento Section of the Association of Engineering Geologist would like to thank Roy Shlemon, Tim Horner of California State University, Sacramento, and Joan Florsheim of University of California, Davis for agreeing to lead this trip. Additionally, the Section would like to thank Julia Turney for organizing the trip, arranging for transportation, and compiling the field guide; Jay Lucas of Brown and Caldwell for providing parking and financial support for the field trip guide; Tim McCrink of the California Division of Mines and Geology for providing publications to include in the Guidebook; and Bob Sydnor of the California Division of Mines and Geology for helping locate stops for the trip and additional stop information.

Editors Note: This guide is an update of the 1998 March 21 field trip written by Roy Shlemon. Additional information written by Tim Horner and Joan Florsheim has been formatted in the guide by myself. Minor editorial changes to the original text have been made to reflect the change in dates and attachments. - jet

CONTENTS

ATTACHMENTS

1. Shlemon, R.J., 1967, Quaternary geology of northern Sacramento County, California: Annual Field Trip Guidebook of the Geological Society of Sacramento, 67 p., plates

2. Shlemon, R.J., The lower American River Area, California: A model of Pleistocene landscape evolution: Yearbook, Assoc. of Pacific Coast Geographers, v. 34, p. 61-86

3. Shlemon, R.J., 1995, Pleistocene channels of the lower American River, Sacramento County, California: (appended, five page article) in Franks, A., and Moss, G. (leaders), Geology of the Sacramento Area, foothills, and the Sierra Nevada Mountains: Assoc. of Engineering Geologist Field Trip Guide, 1995 Annual Meeting of the Association of Engineering Geologist and Groundwater Resources Association, Sacramento, Ca.

4. Shlemon, R.J., Begg, E.L., and Huntington, G.L., 1973, Fracture Traces: Pacific Discovery, v. XXVI, no. 1, p. 31-32

5. Helly, E.J. and Harwood, D.S., 1985, Geologic Map of the Late Cenozoic Deposits of the Sacramento Valley and Northern Sierran Foothills, California, USGS Map MF-1790 (excerpts)

6. Florsheim, J. L., and J. F. Mount. 1999, Geomorphic and ecological response of the anastomosing lower Cosumnes River, California, to anthropogenic disturbances: implications for restoration. *Geological Society of America, Abstracts With Programs,* 31(7):A-202.

7. Florsheim, J. L. and J. F. Mount, Intentional Levee Breaches as a Floodplain Restoration Tool: Monitoring Floodplain Topography, Cosumnes River, CA. Submitted for Spring AGU Meeting, Washington DC May 30-June 3, 2000.

QUATERNARY GEOLOGY OF THE SACRAMENTO AREA

Association of Engineering Geologists, Sacramento Section

Field Trip, March 25, 2000

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INTRODUCTION

Welcome to the 2000 Field Trip of the Sacramento Section of the Association of Engineering Geologists (AEG). We will emphasize the Quaternary geology of the Sacramento area, and particularly review the major assemblages of sediments, geomorphic surfaces and soils (pedogenic profiles) upon which some of you may reside. To the Quaternary geologist and geormorphologist this is "good stuff;" to the bedrock geologist, alas, this is usually "unconsolidated cover."

Our general route is shown on a road map, part of "Attachment 1. " In essence, we will retrace part of a Trip originally taken in 1967, organized by the Geological Society of Sacramento (Attachment 1). Since that time, some roads have changed, new cuts and subsurface data are available, houses mask many previous exposures, and the sediments are 30-yrs older. Enjoy!

Retrospection

In the early 1 960's, while completing a dissertation at the University of California at Berkeley, I had great hopes of identifying and correlating Quaternary sediments along the east side of the Central Valley, particularly between the Feather River on the north and the Tuolumne River on the south. After three years of emplacing hand-auger borings, digging pits, hand-cleaning roadcut and rivercut exposures, interpreting topographic maps, and plotting literally thousands of well logs, I found that merely correlating sediments and soils across the American River was a sufficient challenge; what a humbling experience! For the new generation of Quaternary, engineering and environmental geologists, the challenge may still be there. I hope that this field trip might therefore stir up discussion, propose alternative hypotheses, and contribute new ideas and data from which we all continuously learn.

The early 1960's were halcyon years in Central Valley Quaternary geology. Rod Arkley, in the Soils Department at Berkeley (one of my mentors), had completed his Soil Survey of Eastern Stanislaus County, and showed a systematic relationship of soils and landforms. The late Clyde Wahrhaftig, also at Berkeley, had induced Dick Janda (now deceased) to map Quaternary sediments and soils along the lower San Joaquin River and correlate these with glacial events in the Sierra Nevada. And Ed Helley was assigned (more or less) to reconstruct the Quaternary history of the unglaciated Chowchilla River. 1, foolishly, decided to tackle the lower American River area, mainly because it was an urban area sufficiently full of roadcuts and water wells, which, I had hoped, would make it relatively easy to correlate sediments regionally. Little did I recognize how neotectonics, regional subsidence and glacio-eustatic sea level change, extending headward from the Sacramento-San Joaquin Delta, impacted the Quaternary geology of the Sacramento area, particularly the depth and course of ancient American River channels. Also, I was not a gung-ho, "Sierra Nevada type" who enjoyed leaping from moraine to moraine, hanging on to precariously perched boulders in order to bang on same with a rock hammer and thereby assess relative weathering. Rather, I then preferred, and still do, taking an afternoon break during a hot Sacramento summer, and indulging in a beer, so readily available in the urban environment.

The Berkeley dissertations essentially confirmed the conclusions, albeit in more detail, of the many soil scientists from Berkeley and Davis who long before had recognized and mapped subtle Central Valley soil-landform relationships during their back-breaking soil surveys. Our contribution was merely to "wed" soils, geomorphic surfaces, and the underlying deposits. In this regard, we recognized that many soils were endemic to specific geomorphic surfaces; that regional climatic change, both in the Sierra Nevada and in the Valley proper, was the dominant agent of sedimentation and ultimately landform development; and that the glacial history of the Sierra Nevada was not recorded in the mountains where successive glaciations generally eroded evidence of previous events, but was preserved in the Central Valley by the myriad of gravel-filled terrace deposits and buried channels, often capped or stratigraphically separated by relict or buried paleosols, respectively. The soils proved to be valuable stratigraphic markers indicative of interglacial or interstadial epochs of non-deposition.

The Grey Literature

Since the early 60's, other Quaternary investigations have confirmed our precarious Sierra Nevada and Central Valley correlations. Additionally, radiocarbon dates are now available for the younger sediments, and numeric dating of relative soil profile development provides minimal ages for the older Quaternary deposits. Also, many Quaternary deposits are now dated by association with the world-wide, marine isotope stage chronology. Much of this information, however, has not been formally published, but remains in the "grey literature," such as this Guidebook. Accordingly, thanks to the generosity of the Sacramento Section of the AEG, some of the "archaic" references to the Quaternary geology of the Sacramento area, in whole or part, have been reproduced, and attached to this document; namely:

Attachment 1:
Shlemon, R. J., 1967, Quaternary geology of northern Sacramento County, California: Annual Field Trip Guidebook of the Geological Society of Sacramento, 67 p., plates.

Attachment 2:
Shlemon, R. J., 1972, The lower American River area, California: a model of Pleistocene landscape evolution: Yearbook, Association of Pacific Coast Geographers, v. 34, p. 61-86.

Attachment 3:
Shlemon, R. J., 1995, Pleistocene channels of the lower American River, Sacramento County, California: (appended, five-page article) in Franks, A., and Moss, G. (leaders), Geology of the Sacramento area, foothills, and the Sierra Nevada mountains: Association of Engineering Geologists Field Trip Guide, 1995 Annual Meeting of the Association of Engineering Geologists and Groundwater Resources Association, Sacramento, CA.

Attachment 4:
Shlemon, R. J., Begg, E. L., and Huntington, G. L., 1973, Fracture traces: Pacific Discovery, v. XXVI, no. 1, p. 31-32.

QUATERNARY CHANNELS: ECONOMIC IMPLICATIONS

Pre-Quaternary channels of the American and other Sierra Nevada drainage underlie much of the superficially appearing "featureless plains" of Sacramento County. These, however, usually have no outcrops, and are identified mainly by interpretation of drillers' logs. In contrast, the Pleistocene channels of the lower American River are expressed as geomorphic terraces, albeit of low relief; and they are of particular interest owing to their economic potential. Originally, where exposed at or near the surface, they were subject to gold mining. Hydraulic mining and dredging left tailing piles still conspicuous on the landscape today. Eventually, early Sacramento-area urbanization utilized the channels as sources of near-surface domestic water. Later urbanization led to increased demand for high-quality aggregate; and the younger Quaternary channels were soon exploited, often giving rise to 1 5-m deep quarry exposures, major "outcrops" in this low-relief terrain. Now, channel delineation is again in vogue, for some channels may well serve as contaminant pathways. Interest in these channels therefore never seems to cease: just live long enough to see it "come around again."

Even reworked channel deposits impact the contemporary landscape. For example, many "leveled" dredge tailings are highly unsuitable for urban construction. Typically, overbank silt and "slickens" within the channels are often covered by gravel during grading, giving rise to differential settlement and thus to potential structural distress. This phenomenon now provides investigative opportunities for the engineering geologist, as well as continued "full employment" for the legal profession.

THE QUATERNARY STRATIGRAPHIC SETTING

Four major Quaternary formations are recognized in the Sacramento area: the Modesto (youngest), the Riverbank, the Fair Oaks/Turlock Lake/Laguna complex, and the Arroyo Seco and older gravel (summarized in Attachment 1, Table 2). The dominant older unit, cropping out near Sloughhouse and Folsom, is the Plio- Pleistocene Mehrten formation, a term applied to any unit generally bearing andesitic sediments, whether reworked or not, and often regardless of age.

The Modesto and Riverbank formations were correlated with their type localities along the Tuolumne and Stanislaus rivers, respectively, in Stanislaus County (Davis and Hall, 1959); and the Arroyo Seco, Laguna and Mehrten formations were originally described in adjacent San Joaquin and Amador counties (Piper and Gale, 1939). The Fair Oaks formation was informally named from bluff exposures on the north side of the American

River (Sunrise Boulevard area) between Fair Oaks and Folsom (Attachment 1, Table 2; Attachment 3, Fig. 3).

Each of the Sacramento area Quaternary formations is expressed geomorphically by nested, fluvial-fill terraces, ancient channels of the American or Cosumnes rivers; and by increasingly dissected (with age) overbank and piedmont fan deposits. The various channels are correlated with major glaciations in the Sierra Nevada; their subsurface depth (up to 20-m below present sea level) in the Sacramento area was also likely affected by glacio-eustatic lowering of sea level.

As elsewhere in the Central Valley, the Sacramento Quaternary formations are distinguished and dated by geomorphic expression, by relative development of capping soil profiles, by radiocarbon and other numeric dating methods, by magnetostratigraphy, and by association with Sierra Nevada glacial events and the oxygen-isotope stage chronology (Attachment 1, Table 2; see also summary and references in Attachment 3). The soils, in particular, are excellent stratigraphic markers, for many strongly developed profiles (with duripan) reflect long periods of weathering during interglacial or interstadial epochs. These soils are often traceable, by means of well-logs, into the subsurface where they separate "late glacial" overbank deposits of the respective formations (Attachment 2).

PLEISTOCENE CHANNELS OF THE LOWER AMERICAN AND COSUMNES RIVERS

The American River channels dominate the Pleistocene hydrology of the Sacramento area; by comparison, the Cosumnes River channels are indeed small (Attachment 3, Fig. 2). These channels, many now buried, apparently were cut during early stages of Sierra Nevada glaciation, abetted by glacio-eustatic lowering of sea level. Ostensibly, during full glacial events, hydraulic competence was greatly increased, and gravel-laden, braided stream deposits filled the channels. With onset of deglaciation, vast quantities of overbank sand and silt were carried far downstream, eventually burying the channels and spilling outward along distributaries to build up broad, coalescing alluvial fans. Interglacial and interstadial epochs were times of relative landscape stability, allowing soils to form on low-gradient terrace and fan deposits (Attachment 2). This sequence of channel cutting and filling was apparently repeated during each successive glaciation, a phenomenon documented elsewhere in the Central Valley (see references in Attachment 3).

Six Pleistocene channels of the lower American River are recognized in the Sacramento area: one of Modesto age (youngest), two of Riverbank age, two of Fair Oaks age, and one of Arroyo Seco age (Attachment 3, Figs. 1 and 2). Other, smaller channels may well exist, particularly those of "Fair Oaks" age. But their terrace expression upstream has largely been destroyed by dredging; and their subsurface expression downstream is uncertain owing to a dearth of well logs (1 960's) in the Elk Grove and Florin areas.

The Modesto-age channel essentially underlies the modern American River. As identified in bridge borings and well logs, the channel gravels are up to about 1 0-m thick, and extend westward to at least the confluence with the modern Sacramento River. An earlier Modesto-age channel is identified by slightly elevated terrace deposits on the south side of the American River at Rancho Cordova. But the extent of these deposits, long modified by dredging, is unknown; and a distinct channel is therefore not mapped (Attachment 1, Fig. 2; Attachment 3; Figs. 1 and 2). Based on correlation of soil profile development with similar deposits numerically dated elsewhere in the Central Valley, the Modesto-age channels are judged to be about 15 - 20 ka and 60-70 ka old, respectively (isotope stages 2 and 4).

The two Riverbank-age channels merge upstream near Mather AFB (Attachment 2). Downstream, they are covered by an increasing thickness of overbank sand and silt, but are traceable in well logs to depths about 20 m below present sea level. The Riverbank-age channels are thought to be about 150 and 250 ka old, respectively (isotope stages 6 and 8).

The Fair Oaks-age channels are expressed upstream as dissected, gravel-filled terraces deposits. Downstream, from about the Highway 16 (Jackson Road) and Excelsior Road junction, they are identified in the subsurface trending southwest toward and under the town of Elk Grove (Attachment 2 and 3; Figs. 1 and 3). Their age is estimated to be about 400 to 700 ka, based on stratigraphic position, on inferred correlation to buried paleosols, and on magneto-stratigraphic dating of overbank deposits exposed at the type locality of the Fair Oaks formation on the north bank of the America River (Attachment 3, Figs. 1 and 2).

The Arroyo Seco channel has little geomorphic expression. It is identified as remnants of high-level fluvial gravel that cap the drainage divide between the American and Cosumnes rivers near Sloughhouse (Attachment 3, Fig. 1). It may well have a subsurface equivalent, for several other ancient channel gravel occur beneath the Pleistocene courses of the lower American River; but such correlation has not yet been made.

The gradients of the American River channels, where expressed geomorphically as fluvial terraces, increase with age. The older channels thus extend to depths greater than the younger channels. This "hinge-line" phenomenon may be caused by continual subsidence in the Sacramento-San Joaquin Delta area, an impact similar to that affecting Pleistocene channels of the lower Mokelumne River in San Joaquin County (Shlemon and others, 1975).

The early Pleistocene American River flowed almost due south from an apex in the Sierran foothills at Folsom. The terraces and buried gravel that identify the Fair Oaks channels extend southward to Elk Grove. Later river courses episodically "migrated" northward to the present position of the American River, leaving behind a

25-km wide band of incised, subsurface gravel-filled channels. The modern American River is now at its northernmost position and, prior to anthropic modification, eroded overbank deposits and local channels that form the bluffs at Fair Oaks (Attachment 1, Fig. 2).

The cause of this northward migration of the lower American River has long been the subject of speculation, and working hypotheses abound; namely: differential subsidence, coriolis force, and sheer coincidence. Whatever the cause, northward movement of the American River during the Pleistocene has preserved a gravel-filled legacy of Sierra Nevada glaciations and a chronology generally unmatched elsewhere in the Central Valley.

The great distance between the ancient north and south banks of the American River poses the major challenge to correlate regional sediments and landforms. However, the stratigraphic relations are quite clear along the far-smaller Cosumnes River. As shown in Attachment 3, Fig. 2, an entire sequence of Quaternary formations and landforms borders much of the Cosumnes drainage, particularly near Sloughhouse. From the floodplain, one can readily see the adjacent fill-terrace deposits, some likely more than about 500 ka old. In contrast, the modern floodplain and Pleistocene terrace sequence of the lower American River, between approximately Fair Oaks and Sloughhouse, is over 20 km wide (Attachment 3, Fig. 2).

INVERSIONS OF TOPOGRAPHY

The Sacramento area also displays classic inversions of topography. Though perhaps not as dramatic as the volcanic flows that produce the Oroville and Jamestown Table Mountains in the Sierran Foothills, the boulder-strewn channels and tuff-breccia flows mark Mehrten-age channels in northeastern Sacramento and adjacent Placer counties. These deposits, obviously laid down in valleys, ultimately proved to be more resistant than the underlying granitic terrain; and channel remnants are now preserved as linear topographic "highs" up to 30 rn above the surrounding, undulating granitic plain. The inversions are particularly well displayed near the Nimbus Dam Overlook (north side of the American River at Hazel Avenue), and as "pediment" remnants traceable from approximately Auburn on the northeast to Roseville on the southwest (Attachment 1, Fig. 13). Granitic rocks (Rocklin Pluton) that underlie the "Roseville Surface" merge almost imperceptibly into fluvially derived granitic sediments of the Fair Oaks formation in the Rocklin/Roseville area, one of the few places in the Sierra Nevada where folded Foothill metamorphic rocks are "breached." This rising plain thus formed a natural "gangplank" for early roads and railroads to ascend from the Sacramento Valley into the high mountains. Water wells within the Fair Oaks formation, some more than 50-m deep and located only a few meters from granitic outcrops, bottom in fluvial sediments. The contact between Roseville surface granitic rocks (Rocklin pluton) and the alluvium may thus be fault controlled, a hypothesis proposed years ago (Shlemon, 1967), but still untested.

FRACTURE TRACES

Sacramento and adjacent Placer counties host yet another geologic feature of interest: fracture traces. Almost undetectable from the ground, the fractures occur within Mehrten formation tuff breccia. From roadcut exposures (Douglas and Sierra College boulevards), the fractures do not extend into underlying Mehrten gravel or granitic terrain. A fault origin is thus precluded. At the surface, and best viewed from the air, the fractures form extensive lineaments, heightened in appearance by the presence of gopher-occupied "mima" mounds (Attachment 4). Deep soils have formed on and within the fractures, which are clearly conduits for gravitational movement of water.

The origin of the fractures, lineaments and mounds is yet conjectural; 25 years ago we hypothesized that such striking topography may have been caused by differential cooling of the tuff breccia (Attachment 4). Now, unfortunately, the fracture-trace topography is aerially diminishing, owing to increasing urbanization. Ironically, this fascinating terrain and its striking interplay of geology, soils, water, vegetation and animals is only minutes from downtown Sacramento, so apparent from the air, yet almost invisible from the ground.

FIELD TRIP POINTS OF INTEREST

The 2000 field trip will entail much driving, lengthy en-route discussion and, given the proposed length, but few stops. Leaving California State University, Sacramento, the trip will initially proceed eastward along Jackson Road (Highway 16) to the Sloughhouse area. The on-going discussion will focus on geomorphic expression of the American and Cosumnes River channels, and their exposures in various gravel quarries.

Depending on condition of roadcuts, we will see soil profiles with increasing relative development that cap various Riverbank, Fair Oaks and Arroyo Seco terraces. At Sloughhouse, we will observe cuts along Dillard Road that expose the so-called "Mehrten-Laguna transition zone" (Attachment 1), and two buried paleosols that may be the Cosumnes River equivalent of Fair Oaks-age paleosols north of the American River.

The trip will then take Sunrise Boulevard north across the American River to view, on the way, the geomorphic expression of American River terrace deposits, mima-mound topography, dredge-tailing terrain, and buried paleosols exposed in the bluffs at Fair Oaks. Proceeding to the Nimbus Dam overlook, (Hazel Avenue) we will be standing on an inversion of topography from which we can readily see the several Pleistocene channels of the lower American River and their upstream confluence (apex) at Folsom. Continuing essentially east along the Folsom-Auburn Road, we will turn south onto Douglas Boulevard, eventually to ascend onto Mooney Ridge, a classic Mehrten-age, inversion of topography that forms the north side of Folsom Reservoir. Finally, time permitting, we will return to Douglas Boulevard and to Sierra College Boulevard where, if conditions are right, we will view the surface expression of fracture traces.

1. **Perkins area**: At Perkins, near the Jackson Road - Highway 50 intersection, several old gravel quarries expose 10 to 20-m thick gravel deposited in a "late Riverbank age" channel of the lower American River. The gravels are of glacial origin, probably laid down during isotope stage 6, about 150 ka ago ("Donner Lake" glaciation of the Sierra Nevada; "Illinoian" in Midwest terminology). These channels rise to the surface toward the east, underlying Mather AFB, and are eventually expressed as terrace deposits. To the west, the channels are buried by an increasing thickness of overbank sands and silts that give rise to grossly, climatically controlled, fining-upward sedimentary sequences capped by a strongly developed buried paleosol. A typical capping soil is the San Joaquin series, with an iron-silica duripan (Abruptic Durixeralf) and now particularly famous since its recent designation as the official California state soil. As shown in Attachment 3, Fig. 1, at least two Riverbank-age channels are present, these diverging downstream. The younger channel is an estimated 150 ka old (stage 6); the older, from stratigraphic position, may be about 250 ka (stage 8). These deposits generally fine down-gradient into interbedded lenses of coarse sand, which ostensibly debouched into a now-buried confluence with an ancestral Sacramento River.

Immediately west of Jackson Road, where crossed by high-power lines, the Teichert Quarry exposed overbank sediments stratigraphically above the channel gravel but below the San Joaquin soil. These sediments yielded vertebrate fossils, including Camelops, Mammuthus and Equus, dated by uranium-series methods as being about 100 ka old (see summary in Attachment 3). Accordingly, the San Joaquin series most likely formed during isotope stage 5 ("Sangamon"), the last major interglacial, and a time of regional landscape stability in the Central Valley.

2. **Highway 16 - Elk Grove-Florin Road area:** Turning right (south) from Jackson Road (Highway 16) onto the Elk Grove-Florin Road, we cross over now-filled 15 to 20m deep gravel quarries that exploited both the early and late Riverbank-age channels. The old quarries are now used for farming. However, when active, the quarry walls exposed ancient meander loops, usually a few meters above braided-stream gravel. Many meanders were filled with compacted and stratified organic material, including logs of Sycamore, Cottonwood and Redwood trees, a mixture derived from ancient, upstream riparian sources. The wood, as expected, yielded "beyond the range" (ca. 35 ka bp) radiocarbon dates; but, when dried, burned nicely in a fireplace.

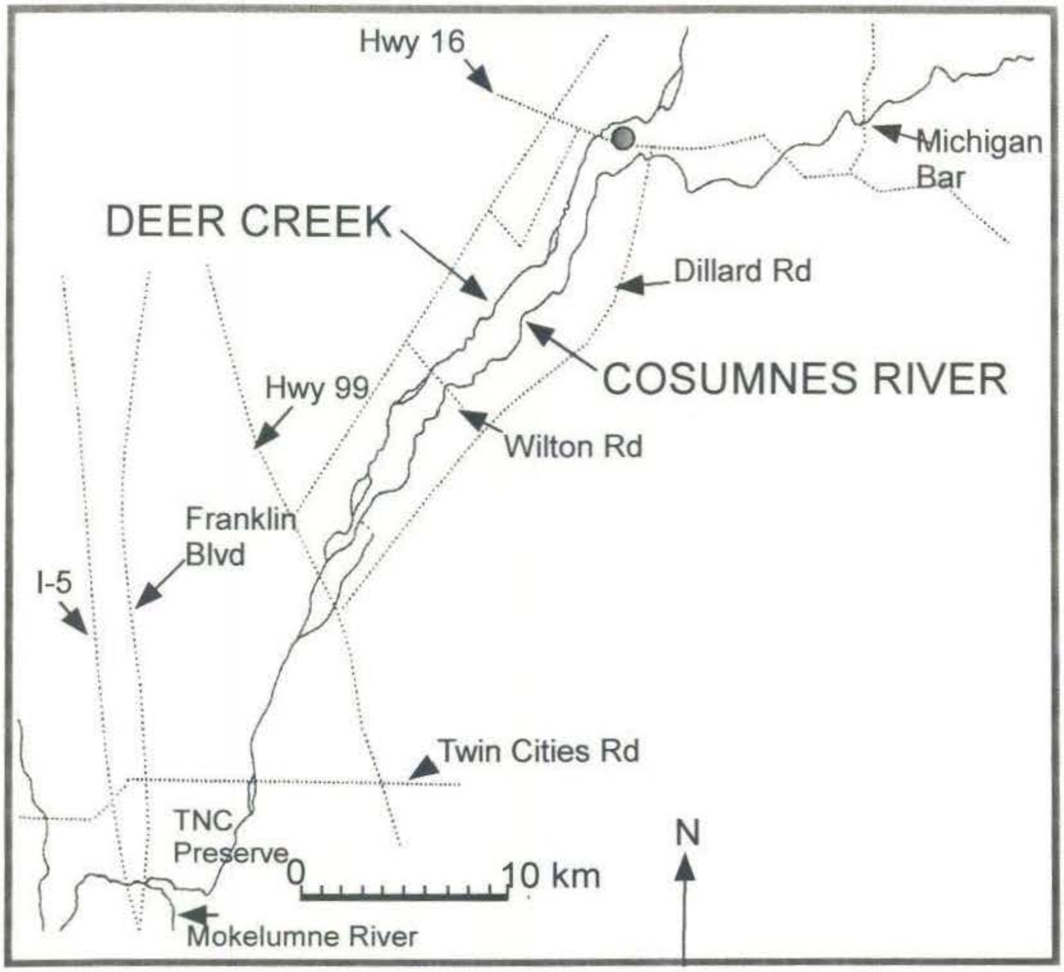
3. **Highway 16 - Excelsior Road area:** We have now ascended several minor escarpments, each marking the back edge of a gravel-filled fluvial terrace, and the trace of an ancient American River channel. This terrain, slightly higher than the Riverbank-age surfaces, is more dissected, and capped by typical reddish-brown relict paleosols. These are channels of Fair Oaks age. As shown in Attachment 3, Fig. 1, two Fair Oaks channels are traced from their terrace positions at this locality into the subsurface toward the town of Elk Grove where the younger channel incises and cuts across the older deposits. This has given rise to the "Elk Grove Outlier," a north-south trending, gravel-filled ridge rising to about 10 m above the surrounding plain (Shlemon, 1967).

The flights of Fair Oaks and Riverbank-age terraces and post-formation soils are also well exposed in cuts along Excelsior Road, north of Highway 16, toward Mather AFB.

4. **Sloughhouse area:** Eastward of Sunrise Avenue, Highway 16 ascends onto and crosses the drainage divide between the American and Cosumnes rivers (Attachment 3, Fig. 2). The old gravel surface here is moderately dissected, and capped by the very strongly developed "Redding soil." These are remnants of one and possibly more "Arroyo Seco channels," which, from stratigraphic position, are probably at least a million years old. Other remnant gravelly surfaces abound; however, most are too limited to be identified as distinct channels. Previous mapping (Piper and Gale, 1939) deemed these gravels as the "Arroyo Seco pediment" (Attachment 1, Table 2).

Dropping down into the Cosumnes River floodplain we cross almost the entire sequence of Quaternary geologic units presently recognized in Sacramento County, including at least three nested fill-terraces; two of which, based on stratigraphic position and relative soil profile development, are judged to be pre-Modesto in age. Hops are still grown on

Late Quaternary River and Floodplain Geomorphology



● Sloughhouse Field Trip Stop

Anthropogenic change, fluvial processes, and restoration activities.

the relatively fertile Modesto-age and Holocene sediments that underlie the Cosumnes floodplain; the soils are typically "undeveloped" (A/C profiles).

A few hundred meters east of Highway 16, cuts made in the early 1 960's for the then-new Dillard Road, exposed a noteworthy sequence of basal, cross-bedded andesitic sands, overlain by interbedded granitic-derived sand and silts, which, in turn, are generally covered by granitic fluvial deposits. These cuts are the type locality for the "Laguna-Mehrten transition zone" (Attachment 1, Table 2; Attachment 2, Fig. 2). Well logs show that the frequency of andesitic sediments increases with depth. Such sediments, by virtue of their general lithology, are usually deemed the "Mehrten formation" regardless of age. In contrast, the overlying granitic-derived sediments are traditionally correlated with the Laguna formation of Piper and Gale (11939). The fact that the two units are stratigraphically interbedded, as exposed in the Dillard Road cuts, suggests that in Laguna-Mehrten transition time, some local streams still headed in Mehrten andesitic tuff breccias, but others had cut through these sediments and were tapping underlying granitic rocks. If this hypothesis be correct, then the first appearance of many so-called Mehrten sediments, as deduced from well-log interpretation, are reworked Mehrten deposits, and may be about 400 or 500 ka old, or even younger, and not millions of years old as heretofore generally postulated.

The Dillard Road cuts also expose two buried paleosols above the LagunaMehrten transition zone. These soils are not classically "red" as many other well developed paleosols; but are readily identified by remnants of blocky structure, illuvial clay films, and root and worm casts (Shlemon, 1967). These paleosols occur at the same stratigraphic position as two, comparably developed buried paleosols exposed north of the American River near the Sunrise Boulevard Bridge. If correlative, the Dillard paleosols would similarly mark epochs of regional landscape stability (interglacial ?) that ostensibly occurred between about 400 to 700 ka ago.

LATE QUATERNARY GEOMORPHOLOGY OF THE LOWER COSUMNES RIVER AND FLOODPLAIN

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The diverse range of geomorphic processes active during the Quaternary Period account for the complex landscape that was present in the on the Lower Cosumnes River floodplain prior to European settlement and anthropogenic change. Geomorphic processes responded to tectonic change (the recent uplift of the Sierra), climate change (glacial and interglacial periods, sea level change), and erosion and sedimentation patterns resulting from glacial cycles. The upper portion of the Cosumnes basin is formed by three main tributaries – the North Fork, the Middle Fork, and the South Fork – that drain Iron Mountain Ridge in El Dorado National Forest. The Cosumnes River flows southwest toward the Great Valley and is a tributary to the Mokelumne River – and is near sea level and tidally influenced at the confluence. Both the Mokelumne River to the south, and the American River to the north share a similar regional geomorphic history with the Cosumnes River.

The lower Cosumnes River is the reach of channel that extends downstream of Michigan Bar to the confluence with the Mokelumne River. Deer Creek drains the foothills and joins the Cosumnes River floodplain near Sloughhouse. The two rivers occupy opposite sides of the same floodplain and flow relatively parallel to each other for almost 25 km before they join upstream of their confluence near Highway 99. The confluence of the Cosumnes River and the Mokelumne River is just upstream of the Franklin Blvd. Bridge. Prior to levee construction and reclamation of the Delta Islands in the late 1800's, the lower portions of the Cosumnes and Mokelumne (downstream of Highway 99) were mapped as "swamp and overflow land" along the margin of the Sacramento-San Joaquin River Delta.

Prior to European settlement, the Cosumnes River floodplain ecosystem was an anastomosing system, with numerous channel branches. Downstream of Highway 99, the multiple channel floodplain system contained hydrologically connected lagunitas (perennial lakes) and seasonal floodplain marshes, while upstream of Highway 99, the floodplain system contained numerous densely vegetated islands between the dominant and secondary channels of the Cosumnes River-Deer Creek fluvial system. Floodplain evolution in the anastomosing system took place by processes including avulsion, where breaches in natural levees initiated new channels, and sediment splays vertically accreted the floodplain. Over time, the entire floodplain width evolved into a complex system with dominant, secondary, and abandoned channels, and levees, splays and wetlands. The nature of geomorphic change during avulsion was episodic – causing erosion and deposition disturbance required for succession within the dynamic riparian ecosystem that existed prior to European settlement.

5. Sunrise Boulevard Roadcuts, Highway 16 to the American River: The Folsom South Canal is on the left (west). Exposures during canal construction revealed the presence of even older American River channels (Attachment 3, Fig 2). The terrain here is entirely relict; that is, it has been little dissected and essentially received no sedimentation since "abandonment" (northern migration) by the American River during "Arroyo Seco time," an estimated 1 my ago.

Road cuts, albeit few, show the deep weathering that characterizes the postArroyo Seco soils. Typically, the relict argillic horizons are almost 2-m thick, and Munsell colors are usually dark reddish brown (2.5YR 3/3-34). Also readily observable are numerous krotovinas (sediment filled rodent burrows), an expression of high bioturbation. Mima mounds are also present. The origin of this microrelief is still the subject of very vigorous debate; hypotheses range from causation by Pleistocene gophers to paleoseismic events!

Northward, Sunrise Boulevard descends across the 3-m high terraces that define the back edge of ancient American River channels. Relative soil profile development decreases as the terraces "young" to the north. Near and underlying the modern American River are sediments and channels of older and younger Modesto-age, dated regionally as about 15-20 ka 60-70 ka old, respectively (isotope stage 2 and 4).

Crossing Morrison Creek we encounter dredge tailings associated with Pleistocene channels of Riverbank age. Yuba-type, bucket-line dredges worked these grounds for over 70 years, progressing from Folsom downstream to what is now the eastern boundary of Mather AFB. By WW 1, some tailings had been used for agriculture in the Folsom area; most, however, were later either leveled for industrial development or exploited as road metal for highway construction.

6. **Sunrise Boulevard - Mechanics Road area:** Cuts along Luyung Road, near the Sunrise Avenue- Mechanics Road junction, exposed Fair Oaks and River-age terrace gravel and dredge tailings. Deeply weathered relict paleosols were once exposed; and, if still preserved, warrant a short stop for inspection and discussion.

7. **(Two Parts) Sunrise Boulevard Bridge across the American River**: north bluff exposures and type locality of the Fair Oaks formation. The bluffs forming the north bank of the American River between the old and new Sunrise bridges expose two clearly visible buried paleosols (Attachment 3, Fig. 2). These soils occur near the top of the cut and both are moderately to strongly developed and mark distinct epochs of relative landscape stability, ostensibly interglacial epochs. The underlying parent material and capping sediments are mainly lenses of interbedded, granitic-derived sand and silt. Local carbonate zones and possible ash beds abound. This is the type locality of the "Fair Oaks Formation," an informal name applied to sediments north of the American River that occur stratigraphically below the Riverbank formation and above the Arroyo Seco gravel and Mehrten andesitic sediments (Attachment 1, Table 1).

At the type locality, at the base of the bluffs and observable only when river level is extremely low, are remnants of two other buried paleosols. A paleomagnetic reversal occurs in sediments between the two soils (unpublished data). This is assumed to mark the Brunhes/Matuyama boundary, a magnetic reversal occurring about 760 ka ago. Accordingly, the Fair Oaks formation, with its four buried paleosols, may well record up to five discrete glacial events in the Sierra Nevada; these giving rise to the Fair Oaks-age channel gravel south of the American River, and to extensive overbank sedimentation now preserved in the bluffs at Fair Oaks.

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Introduction and Acknowledgements

This portion of the field trip guide is intended to provide new information and interpretations about the composition and depositional environments of Cenozoic sediments in the Sacramento area. We have focused on the Mehrten, Fair Oaks and Arroyo Seco sedimentary units because they are well-exposed at two outcrops that we will visit during the field trip. Other sedimentary units (Valley Springs, Laguna and Riverbank Formations) are not discussed in detail in this section because they are covered on other field trip stops or lie outside of our field trip area. We would like to give special credit to Roy Shlemon and other previous workers who provided the framework for our discussion. Roy's mapping and interpretation of this very complex area are the benchmark that we used for our project, and we appreciate his willingness to provide background information, generously share his insight, and give feedback about alternate theories. This project was partially funded by CSU Research and Creative Activities Grant #100562 titled *Cenozoic sedimentation in the Sacramento area*.

Stop 7: Old Fair Oaks Bridge Stop

Directions From Interstate 50:

- Drive 1.5 miles north on Sunrise Blvd. Watch for a small brown sign on the right that points to American River Parkway access.

- Turn right (east) at Bridge Street. This poorly marked corner is 0.3 km (0.2 miles) south of the American River. A firewood sales yard and rafting company bus storage lot are located on the northeast corner of the Bridge Street intersection.
- Drive 0.5 km (0.3 miles) east to park entrance. Bridge street bends to the north at the park entrance.
- Pay fee and enter park. Drive 0.1 km (100 yds) north, turn right at the stop sign, and park.
- Stand on the south side of the river at the Fair Oaks footbridge, and look north across the river to the high bluff.

Purpose:

The "Old Fair Oaks Bridge" stop described below is a brief addition at the end of Roy Shlemon's more detailed description of the Fair Oaks and associated type section. This discussion may provide alternate views about the units exposed east of the Sunrise Bridge locality. It will also set the stage for later interpretations about deposition in an alluvial fan system, and will point out a lithologic contact between the Mehrten Formation and Fair Oaks unit that will examined in detail at the Nimbus Dam stop. Discussion by Horner and Giorgis will be limited if Dr. Shlemon covers similar points. At this stop we will:

- View the contact between the Mehrten Formation and Fair Oaks unit.
- Discuss the position and size of the alluvial fan during deposition of Mehrten and Fair Oaks sediments.

Lithologies and depositional environments:

The 35 meter high cliff on the north side of the American River is about 100 meters east of the proposed type section for the lower Fair Oaks formation (Shlemon, 1967a). Petrographic evidence suggests that two units are exposed on this cliff. The upper two thirds of the outcrop consists of unconsolidated sand and silt that belong to the Pliocene/Pleistocene lower Fair Oaks unit, and the lower third of the outcrop is composed of cross-bedded medium and coarse sand from the Miocene/Pliocene Mehrten Formation. Both units are abruptly truncated because of downcutting from the modern American River, resulting in the excellent exposures that we see today.

The contact between the Mehrten Formation and the lower Fair Oaks unit can be identified from this distance by a color change and permeability difference. These differences are related to petrographic distinctions and changes in depositional environments between the two units. The Fair Oaks unit has a plutonic source, while the Mehrten Formation has a volcanic source. Petrographic differences and paleoenvironmental significance of these sediments are discussed below.

East of the Fair Oaks bridge the Mehrten Formation occupies the basal one third of the outcrop, with a contact that is identified by the darker purplish-gray color and seeps that form in the coarser, more permeable sediment. Mehrten sands are medium- to coarse-grained and moderately- to moderately-well sorted, with detrital grains composed almost entirely of well-rounded andesite particles (Plate 1). When interpreted in a broader paleoenvironmental framework, these trough cross-bedded sands are thought to represent deposition in the distal portion of an alluvial fan (Fig 1).

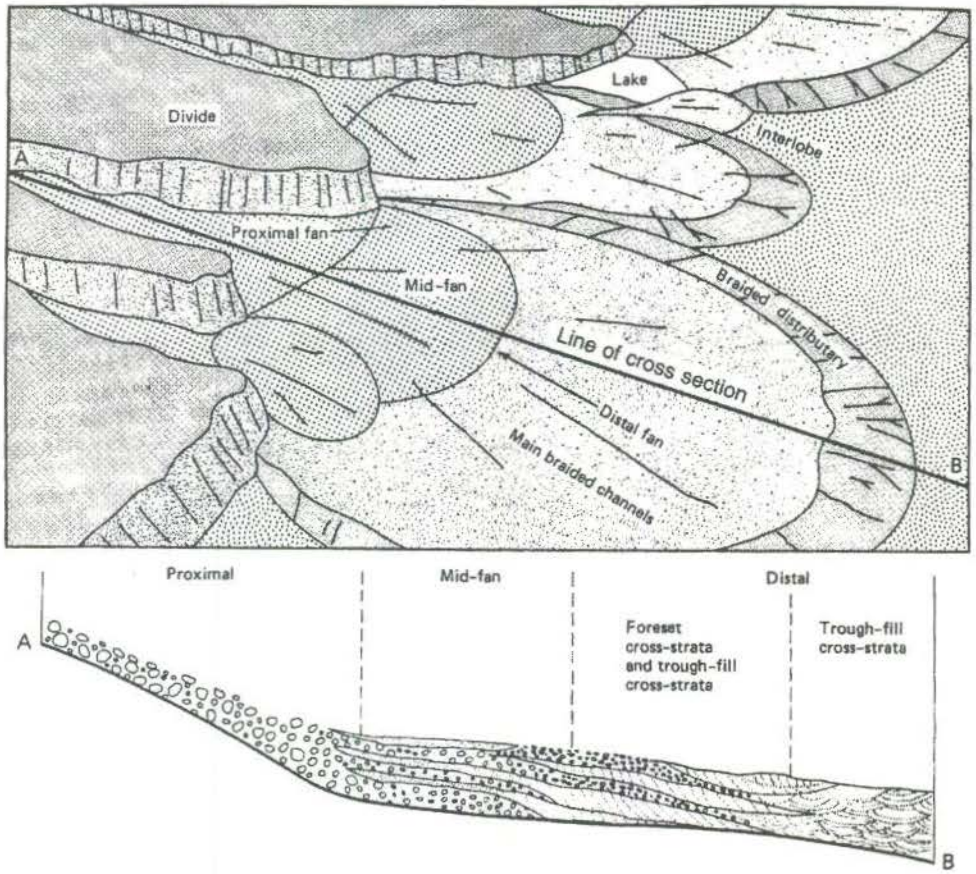

Figure1: Facies and sedimentary structures in the Van Horn Sandstone, Texas. From Boggs (1995), modified from McGowan and Groat (1971). Alluvial fan facies are described as proximal, mid-fan and distal, and have characteristic grain size, thickness patterns and sedimentary structures. At some point deposition on the distal fan grades into fluvial deposition.

The Fair Oaks unit at the Old Fair Oaks Bridge is slightly finer than the Mehrten Formation, with fine to medium-grained trough cross-bedded sand, silty sand, and minor clay. This represents the outermost braided distributary region of an alluvial fan, and includes associated overbank and interchannel deposits. Deposition on an alluvial fan grades distally into fluvial deposition, and fluvial sedimentologists (Mial, 1974) might also refer to this as a Donjek-type braided stream deposit (Figure 2).

Additional evidence from a Fair Oaks exposure at Sunrise and Winding Way:

These environmental interpretations for the Fair Oaks unit are supported by a nearby exposure that was exhumed during construction of the Post Office Distribution Center, located at the southwest corner of Sunrise Blvd. and Winding Way. Most of the outcrop has since been covered by a large retaining wall, but photographs and descriptions collected during construction document important details of Fair Oaks deposition. The south and west excavation walls at this site exposed portions of at least three and possibly four fining upward sequences, with individual fining upward sequences ranging from 70 cm to 4 m in thickness.

The base of each fining-upward sequence consists of trough cross-bedded and rippled sands with erosional lower bounding surfaces. Scoured relief on the base of sandy beds exceds 1.2 m in height, and scours are filled by stacked, low angle trough-cross beds up to 40 cm high. Ripples are common toward the top of sandy intervals. Sandy beds grade upward into massive or rippled siltstone, and carbonized plant fragments are abundant.

Silty intervals in turn grade upward to silty clay. Well-developed blocky ped structures are common toward the top of each fining upward sequence, and iron staining is a common feature on vertical ped surfaces. Silty clay intervals may be up to 1 meter thick. Silty clay beds are 7.5 YR 4/6 (strong brown) to 5YR 4/6 (yellowish red) and are heavily rooted. Rootlets are 2-10 cm long, with well-developed tap roots and branching structure. Blue-gray mottling 20-40 cm thick is present at the top of some of the uppermost (finest) silty clay intervals.

These clay-rich and silty clay beds are interpreted to be weakly to moderately developed soil horizons, with the exception of a 1 meter thick blue-gray clay at the base of the outcrop. The rooted blue-gray clay may be a swampy or lacustrine deposit. Blue-gray mottling at the top of

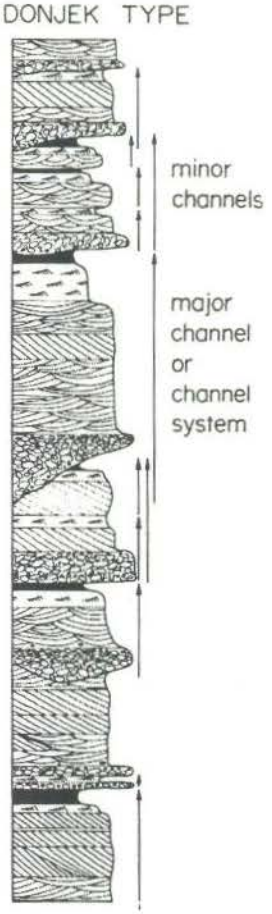

Figure 2: Donjek-type braided stream from Mial (1974) has grain sizes that range from coarse sand to clay, and show repeated fining upward cycles. Finer-grained floodplain sediment is a common component of these braided stream systems. The construction site at Sunrise and Winding Way (refer to Plate 1) has many similarities to the Donjek-type stream model, although Fair Oaks sediments may be slightly finer-grained (lower energy) than this standard fluvial model.

paleosols also suggests humid conditions or standing water. Finer intervals probably represent relatively low rates of deposition on a floodplain with low relief.

Lithostratigraphy and regional fan model:

The Mehrten/Fair Oaks contact can be projected to a known outcrop at Nimbus Dam, located 5.0 km (3.1 miles) to the east. A profile from Sunrise Blvd. to Hazel Ave. reveals that the contact rises approximately 24 meters (75 ft) over the lateral run of 5,000 meters (17,000 ft), or about 5 meters per km (25 ft/mile). This results in an estimated regional dip of approximately 0.25° to the west for the contact between the Mehrten Formation and Fair Oaks unit. Subsurface mapping and cross-sections produced by the Department of Water Resources (DWR, 1974) reveal similar results, with dips of a few degrees or less in this part of the basin.

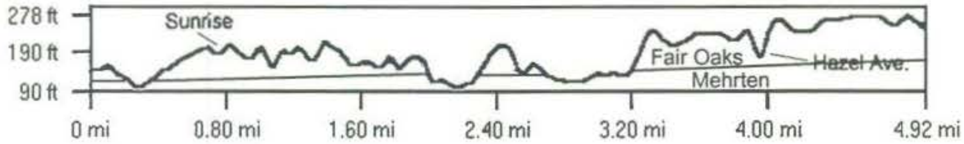

Figure 3: Profile from Sunrise Blvd. to Hazel Ave. The Mehrten Formation outcrops below the projected line and the Fair Oaks unit outcrops above the line. The contact between the two units dips westward at a rate of 5 m/km. Arroyo Seco cap is not shown on this diagram.

A regional view of depositional patterns and grain size relations supports the fan model described above. Mehrten deposits are generally coarser and may be thicker to the north and east, suggesting that the apex of the fan lay east of Rocklin and Penryn. High gradient streams from the Sierra Nevada emptied onto the floor of the Central Valley, and fan lobes formed as sediment left the incised channels of the proximal fan and midfan. Examples of coarse, imbricated cobble conglomerate and debris flows from the proximal and midfan facies of the Mehrten Formation can be seen 4.8 to 8.0 km (three to five miles) north of Interstate 80 along Sierra College Blvd and at Nimbus Dam (see below). Sedimentary structures at coarser outcrops show paleoflow directions toward the south, again supporting the theory of a northern or northeasterly source. Northern outcrops of coarser Mehrten deposits would be typical of a midfan or channelized proximal fan, while the Mehrten sands described at the Old Fair Oaks Bridge represent deposition on an outer fan lobe, with environments that grade into braided stream deposits.

The Fair Oaks unit shows similar large-scale proximal/distal relationships, although it is generally finer-grained than the underlying Mehrten Formation. A coarser, conglomeratic facies of the Fair Oaks unit is exposed in low road cuts along Sunrise Blvd. south of Interstate 80. These conglomeratic intervals probably correspond to deposition in the channelized proximal or midfan region of an alluvial fan, and have features similar to the fan model described for the Van Horn Sandstone, West Texas (Figure 1). Fining upward Fair Oaks sediments that were deposited at the Old Fair Oaks Bridge stop represent the most distal fan fringe and associated floodplain environments.

Stop 8: Nimbus Dam Stop

Directions From Interstate 50:

- Drive 0.5 km (0.3 miles) north from Interstate 50 and cross the American River.
- Continue 0.3 km (100 yds) up the bluff on the north side of the river, slowing down as you near the top of the hill.
- Turn right into the steep drive, park, and pay the day use fee. Drive up to the top of the hill that overlooks Nimbus Dam and Lake Natoma.

Purpose:

This stop will be used to demonstrate differences in composition and depositional environment between the Mehrten Formation, Fair Oaks unit and Arroyo Seco Gravels. Bring your hand lens and field trip notes; we will discuss macroscopic and microscopic features of each unit as we hike around the hill that forms the northern shore of Lake Natoma and Nimbus Dam. Our objectives are to:

- Observe grain size and facies relationships in the Mehrten Formation, Fair Oaks unit and Arroyo Seco Gravel.
- Discuss depositional environments of these units in the context of an alluvial fan environment.
- Interpret paleoclimate or energy levels based on the sedimentology of the units.

Activity:

We will take a clockwise hike around the hill and will be away from the vehicles for about one hour. The path down to the bike trail is narrow and may be muddy, so shoes with some ankle support and tread are recommended. We will walk slowly, but this hike may not be appropriate for people who do not wish to leave the paved path or cannot climb a moderate slope.

The view from the top:

As you look south from the upper parking area you will see Nimbus Dam directly below you. A broad, stepped braid plain extends south toward Jackson Highway (Rt. 16), and on a clear day you can see the slight rise ten miles to the south that forms the modern drainage divide with the Cosumnes River. This surface was initially formed by

Pleistocene to Recent migration of the American River, but gold dredging has also disturbed the sediment to a depth of up to 90 feet in many places. The Natomas Company operated 15 dredges along the American River between Folsom and Mather field, and over a 60 year period this company is estimated to have moved over one billion cubic yards of material in the 26 square mile area. Many smaller dredging companies also operated south of the modern American River. Primary targets for dredging operations were the sand and gravel terraces formed by migration of the American River, so the sediments that we are see to the south are highly disturbed. Dredge design and depth of penetration varied, with larger bucket units capable of digging 100 feet below the land surface (Farina and Carpenter, 1973).

Pliocene/Pleistocene geologic history of the area is equally complex. Shlemon (1967a, 1967b, 1974, 1998) documented the northward migration of the ancestral American River across this surface. Progressively younger channels moved northward and cut deeper into the underlying sediment, producing a series of stepped terraces. Because of these geologic and anthropomorphic forces, Quaternary sediments south of the modern American River have a different history than sediments to the north.

Walking tour of lithologies and depositional environments:

The Arroyo Seco Gravels, Fair Oaks and Mehrten Formation are exposed on the hillside that overlooks Nimbus Dam. Walk to the footpath at the northeast corner of the upper parking area, and note the soil color. As we descend the footpath you will see a subtle color change in the soil. The top of the hill is capped by light orange-brown soil that forms on the Arroyo Seco Gravels, while the middle of the hill has soil cover with a lighter brown to tan color that overlies the Fair Oaks unit. You will also notice a decrease in quartzite lag clasts as we descend the hill. When the footpath meets the old jeep trail, you may see fine-grained sediment of the Fair Oaks unit in some of the deeper erosional cuts. The middle and upper parts of the hill are subject to creep and slumping in many places. We will see better exposures of these units as we walk around the hill in a clockwise direction.

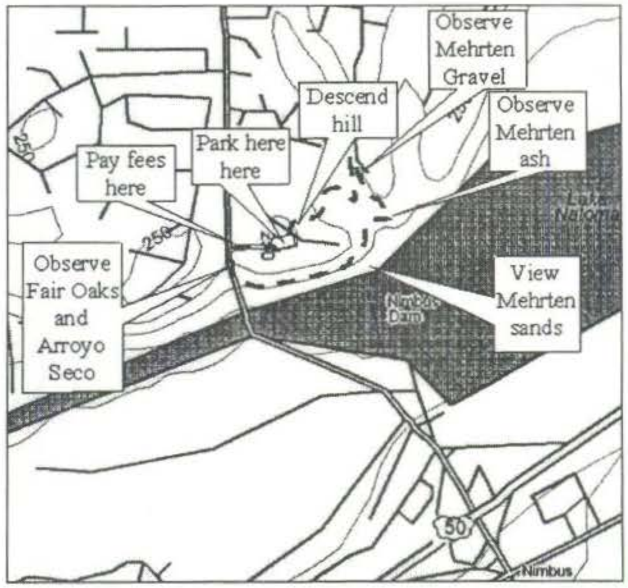

Figure 4: Walking route and points of geologic interest for the Nimbus Dam field trip stop.

Mehrten Formation:

When you have descended the footpath to the level of the bike trail, look north into the ravine at the base of the hill. This north/south trending ravine is an excellent place to observe typical lithologies and sedimentary structures of the Mehrten Formation. At least 26 meters of Mehrten Formation are exposed here, extending from the water level (below the dam) to about one third of the way up the overlook hill.

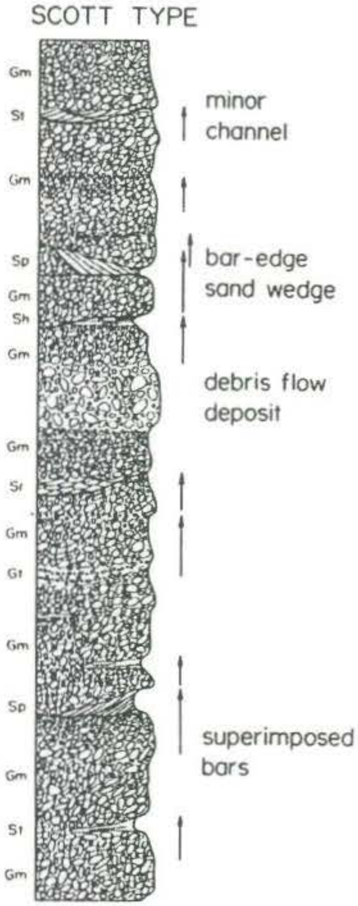

Figure 5: Scott-type braided stream deposit (from Mial, 1974) is similar to the high energy, bed load channels that formed in the incised proximal and midfan regions of the fan during Mehrten time.

The lowest third of the hill has prominent exposures of cobble conglomerate that were deposited by an incised channel of the Mehrten Formation. This channel trends toward the south or southwest, and is not exposed in neighboring ravines. Three- to five- meter high outcrops of imbricated, weakly- bedded conglomerate form resistant cliffs in the ravine at the base of the hill. Grains are 80-90% well-rounded andesite cobbles ranging from 5 cm to 30 cm in diameter, and minor amounts of rhyolite, basalt and metamorphic clasts are also present. Coarse sandy matrix makes up 10-20% of these thick conglomeratic beds, and rare sandy lenses are intercalated with the coarser cobbles. Conglomerates are weakly bedded with preserved foreset cross strata and trough cross beds up to 3 meters high. Scoured surfaces are common. These beds are interpreted as very high energy channelized flow deposits, and probably represent incised channels in the proximal mid fan region. Flow velocities and sediment supply were extremely high, and a fluvial sedimentologist would refer to this as a Scott-type braided stream deposit (Figure 5).

This exposure of the Mehrten Formation also has abundant sandy beds that make up 40-60% of the total formation thickness. Sandy beds and associated sedimentary structures are well-exposed at the bend in the bike trail (at the top of the dam) and on the scoured cliff below the dam and below the level of the bike trail. The majority of this sandy material is medium to coarse-grained and moderately sorted, with trough cross-beds up to 50 cm high, abundant cut and fill structures, and ripple cross lamination in finer sandy intervals. Gravel lenses are common, and courser intervals are weakly bedded.

Close examination with a hand lens will reveal 80-90% gray to purple andesite clasts with traces of basalt, feldspar, ferromagnesian minerals and magnetite. This purplish-gray color and presence of magnetite are distinctive features of the Mehrten Formation. It is also important to note the *absence* of detrital quartz (Giorgis, 1997). The Mehrten Formation is essentially devoid of sand-sized quartz.

At least one ash-rich horizon is present in this section, and impermeable, silty, ash-rich intervals make up at least 10% of the total unit thickness in this outcrop. A thin, relatively pure ash is exposed about 0.5 meter above the bike trail at the southeastern end of the ravine. Follow this interval as we walk around the bend in the bike trail to the west, past the dam and across the level bike trail on the south side (front) of the hill. The finer-grained silty sediment at the level of the bike trail is very ash-rich, and probably represents fluvial reworking of an air fall volcanic event.

Debris flow and mudflow deposits are a common feature in other exposures of the Mehrten Formation (Curtis, 1955), but these features are not found at the Nimbus Dam and Old Fair Oaks Bridge localities. An ash-rich mudflow deposit in the upper Mehrten Formation is exposed west of the Sunrise Bridge at Sailor bar (5.6 km west of this field trip stop), but the lateral extent of this feature is unknown. Debris flow deposits are also common north of interstate 80 along Sierra College Blvd. and south of Rt. 50 along Grant line Rd. near the intersection with Kiefer Rd. These mudflow and debris flow intervals are a reminder of the volcanic source for the Mehrten Formation, although material that we will examine on this trip is reworked by fluvial processes and deposition on an alluvial fan.

Fair Oaks unit:

Continue walking westward along the bike path, but take the uphill fork toward the top of the Hazel bridge rather than following the bike trail under the bridge. The Mehrten/Fair Oaks contact occurs near the north end of the Hazel Ave. bridge, approximately 1 meter below road level. This contact is covered by vegetation on the south side of the hill. The Fair Oaks unit has thinned since we saw it near the Old Fair Oaks Bridge. Total thickness of the Fair Oaks unit at Nimbus Dam is approximately 8 m (25 ft), but this is variable due to the erosional nature of the overlying Arroyo Seco Gravels.

Grain composition is a distinguishing feature of the Fair Oaks unit. Fair Oaks sand layers are composed of 20-30% subangular to angular clear quartz grains, 30-40% white or subrounded feldspar, 20-30% mottled plutonic rock fragments and up to 20% brassy euhedral biotite mica (Plate 3). Low angle trough cross beds and ripples are common in sandy intervals, and finer intervals may have carbonized rootlets. At this outcrop finer silty and clay– rich material is dominant, and represents approximately 60-70% of the total unit thickness. Fining upward cycles and paleosols aren't as evident here as they were at the Sunrise Blvd. outcrop or Winding Way construction site, but the grain composition and lithologies are distinctive of the Fair Oaks unit.

Environmental interpretations for this exposure are similar to environmental interpretations discussed for Fair Oaks outcrops to the west; braided streams and associated floodplain deposits formed this sandy, silty and clay-rich interval. Ancient soils are weakly to moderately developed in finer-grained intervals, and soil formation was probably inhibited by moderately high rates of deposition and frequent switching of the braided stream channel.

Arroyo Seco Gravels:

The term Arroyo Seco Gravels is used in this report to be consistent with the terminology of Shlemon (1967a). Arroyo Seco gravel was originally defined to describe a thin veneer of material on the Arroyo Seco pediment (Piper et al., 1939), but this was a weathered surface eleven feet thick rather than a depositional unit, and the original term had very broad geographic use. Arroyo Seco Gravels in this report are Pliocene/Pleistocene deposits that form fluvial terraces south of the American River, with the exception of a few isolated pockets that border the American River near Nimbus Dam and Sailor Bar. The thickness of these gravels above Nimbus Dam is greater than 20 meters. This is more than three times the thickness of the original pediment cap defined by Piper et al. (1939), and the origin of these sediments as a depositional unit rather than a lag deposit is very clear.

Arroyo Seco Gravels have an erosional lower contact with the underlying Fair Oaks unit. Relief on this contact exceeds two meters at Nimbus Dam, and a similar contact with more than three meters of relief can be seen along Illinois Ave. 0.5 km north of Sailor Bar (approximately 6.4 km west of Nimbus Dam). Scoured surfaces at the contact are interpreted as channel deposits, and have cut and fill structure with poorly sorted sandy fill. Typical Arroyo Seco sediments consist of 60-70% pebble to cobble conglomerate with 30-40% poorly to moderately sorted silty clay matrix. This unit has a characteristic brick-red color (5YR 3/3 dark reddish brown to 5YR 5/6 yellowish red) that includes a spectrum of weathering and iron cementation. Clasts range from 0.5 to 15 cm in diameter, and are dominated by well-rounded quartzite, greenstone and igneous grains. Volcanic and plutonic (granitic) grains are so highly weathered that they are frequently absent or barely recognizable in outcrop. Matrix consists of clay, silt and sand in subequal proportions. Sand grains in the matrix have a plutonic source, with quartz, feldspar and biotite mica common as matrix components (Plate 4).

Most Arroyo Seco Gravels are poorly bedded to massive, and may show one or two episodes of weathering and paleosol development (Shlemon, 1967a, 1967b). Paleosols have not been described at Nimbus Dam, but the distinctive color, composition, sorting and bedding of the sediment allows identification of the Arroyo Seco Gravels. Gravels are weakly bedded to massive, with rare sandy lenses. Sheets of material interfinger laterally with slightly finer or slightly coarser sandy and pebbly beds. The section at Nimbus Dam also has an atypical clay bed that is almost two meters thick. This is interpreted as a lacustrine (pond) deposit, and is not representative of the unit at other localities.

Features described for the Arroyo Seco Gravels at Nimbus Dam are consistent with sedimentation on a midfan or distal fan surface, where runoff events caused sheet flow as high flow events over-topped the incised distributary channels. The source for the granitic matrix was erosion of the Rocklin/Penryn pluton and/or reworking of the underlying granitic debris from the Fair Oaks unit. Resistant metamorphic clasts were derived from the metamorphic belt in the foothills of the Sierra. The Arroyo Seco Gravels mark the first significant input from this metamorphic source area, and the abundance of metamorphic clasts is used to distinguish this unit from other conglomeratic intervals. South of Nimbus Dam, interfingering and sheet flow are not as evident. Periods of weathering, low rates of sediment accumulation and moderate to well-developed soils are characteristic of Arroyo Seco Gravels as river terrace deposits stepped progressively northward and deeper into the underlying sediment (Shlemon; 1967a, 1967b, 1974).

Stratigraphy:

The stratigraphic sequence that we have observed is used to interpret the depositional history north of the river. Work by Roy Shlemon (1967a, 1967b) has provided complimentary evidence south of the river. In the following discussion these histories are merged to give a summary of deposition on the Sacramento fan.

Lithostratigraphy of the older (widespread) fan surface:

From a geologic perspective, we are now standing on the upper surface of the large composite alluvial fan that was discussed at the Fair Oaks Bridge stop. Sediment eroded from the Sierra Nevada was delivered to the edge of the Central Valley by ancestral channels of the American River (Lindgren, 1911, Jenkins, 1932), then dumped in huge, poorly sorted fan-shaped sheets that extend outward into the valley. A large-scale geologic map of the area (CDMG 1:250,000 Sacramento sheet) shows a series of fan-shaped wedges that originate in the Auburn area and step outward into the Central Valley. Older units are dissected by younger channels and partially covered by younger units, but the general fan shape is preserved with remarkable symmetry, especially on the north side of the American River.

We propose to name this composite feature the Sacramento Fan. Source areas and sediment composition of the fan material changed as material was contributed by events that included Sierran volcanism, unroofing of the Rocklin/Penryn pluton, breaches in the metamorphic belt, shifting of the major river system, and reworking of older fan sediments (Table 1). Climatic variability and uplift of the Sierra were also significant events in the history of the Sacramento Fan. DWR (1974) and Shlemon (1998) point out that successively younger units were deposited on an increasingly steep gradient caused by uplift of the Sierra Nevada. This results in an "offlap" pattern, where younger units cover the outer edges of older units that are now buried beneath the valley floor. This pattern of deposition may have started as early as Miocene time with deposition of the

Valley Springs Formation, and continued through deposition of the Riverbank Formation in Pleistocene time (Table 1).

This model of deposition on an alluvial fan is complicated by several factors. Uplift of the Sierra Nevada resulted in downcutting of the ancestral river, and in Late Pliocene to Pleistocene time the river eroded into the underlying Rocklin/Penryn pluton. This resulted in a significant change in source area and clast composition for sediment that was delivered to the alluvial fan. Older units (Valley Springs and Mehrten Formations) have a volcanic source, but later units (lower Fair Oaks and Arroyo Seco Formation) contain abundant quartz, feldspar and mica clasts that were derived from the pluton. Downcutting eventually breached the top of the Jurassic/Cretaceous metamorphic belt, and Arroyo Seco Gravels contain abundant rounded metamorphic clasts in a matrix of eroded granitic material (quartz, feldspar and mica) (see Table 1).

Erosion to the level of the pluton eventually had an effect on the course of the ancestral American River. Continued uplift of the Sierra Nevada resulted in topographic instability over the Rocklin/Penryn Pluton, where resistant crystalline rocks prevented further downcutting. Passage to the south was blocked by the Pine Hill intrusive complex, so the path of lesser resistance was a route through Folsom.

At this point the discussion becomes speculative; did the river move south in incremental stages, led by the South Fork of the ancestral American River as it entered the Folsom area from the east? Or was stream capture responsible for wholesale, catastrophic southerly avulsion (shifting) of the American River, resulting in a more sudden cutoff of sediment supply for the larger fan surface to the north? It is likely that the river moved to the south when the required base level of the ancestral American River dropped below the elevation of the Rocklin/Penryn pluton. This created instability on the older fan surface to the north, and deposition north of the modern American River ceased until Pleistocene (Riverbank) time.

Deposits from the upper Fair Oaks unit and most of the Arroyo Seco Gravels are missing on the northern fan surface, implying that the northern fan surface was less active or inactive for parts of Pliocene to Pleistocene time. Weak drainage systems may have existed if the American River moved incrementally southward, or the northern fan surface may have been completely abandoned if southward shifting of the American River was more sudden. Isolated Arroyo Seco Gravels are preserved on a few ridges near the present American River (Nimbus Dam and Sailor Bar localities), but these are probably part of a new more southerly fan deposit that formed at mid-to-lower elevations by the redirected, south-flowing river system. Stream migration and terrace deposition continued to the south during this inactive period on the northern fan surface,.

Deposition on the edge of the northern fan surface resumed with emplacement of the Pleistocene Riverbank Formation. Riverbank deposits are found as an apron of sediment that offlap the fan surface and completely surround the fan on the northern, western and southern edges. Once again the mode of emplacement is problematic. Did a fork or forks of the American River escape the southerly capture and resume deposition across the northern fan surface? Was a northern fork of the American River still present but less active until Riverbank time? These questions will be the focus of further research.

In either case, sediment bypassed the elevated northern fan surface, and Riverbank deposits are found as a fringe of material that extends into the subsurface of the Central Valley (DWR, 1974). Pleistocene Riverbank sediments are the youngest sedimentary unit that can be described as fan deposits on the Sacramento fan surface. Erosion, incision and weathering are currently modifying the fan surface, but significant deposition in the form of fan-shaped sheet deposits is lacking.

Lithostratigraphy of the younger (southern) fan surface:

Construction, destruction and preservation are key issues in this discussion of fan morphology. The older (northern) fan surface was constructional, and extended southward at least to the modern Cosumnes River. Remnants of the Mehrten Formation are preserved in the south-facing bluffs that overlook the Cosumnes River Divide, and these surface exposures demonstrate a minimum southward extent of the old constructional fan surface. Subsurface correlation of fan sediments (DWR, 1974) confirms the lateral extent of constructional fan deposits at depth in the Central Valley.

After shifting southward, the ancestral American River system began a destructional phase. The Folsom area acted like a pivot point, and the river has rotated northward (clockwise) around this point since Pleistocene time. Pleistocene interglacial events may have been a factor in altering sediment supply to the system, and there was also a complex interplay between channel length and uplift in the Sierra that affected stream competence (ability to transport clastic material). Whatever the cause, the river began migrating northward (back toward the pivot point), removing the edge of the old fan as the channel shifted and cut deeper. Accumulation during this younger (and overall destructional phase) is limited to shallow, highly weathered stepped terraces of Shelemon's (1967a) Upper Fair Oaks unit, Arroyo Seco and Riverbank. These surfaces were cut and filled during northward migration of the river channel. The net effect was to remove large volumes of fan material from the southern flank of the older fan system.

Shlemon (1967a, 1967b, 1974, 1998) provides a very accurate description of the terraces and channels that formed during this northward migration. A potential source of confusion with these younger deposits is the variety of names that have been used by geologists who mapped the Sacramento area. Equivalent names include "Gravels underlying Arroyo Seco surface" and "upper Fair Oaks" (Shlemon, 1967), "Gravel of uncertain age" (Piper et al., 1939), "fanglomerate" and "Red Bluff Formation" (Olmsted and Davis, 1961), "Arroyo Seco Gravels", "Gravels of uncertain age" and "South Fork Gravels" (Ford, 1972; DWR, 1974) and "Laguna Formation" (CDMG, 1984). All of these names have been used to refer to essentially the same material, although the usage is not always consistent between authors or even within studies.

In general, Late Pliocene to Pleistocene gravels south of the modern American river are composed of pebble to cobble-sized metamorphic and highly weathered igneous clasts in a poorly sorted, clay-rich matrix that contains quartz and feldspar grains and abundant iron cement. Several soils with well-developed B_T horizons formed during periods of low sediment accumulation and intense weathering, and the units are distinguished mainly on the basis of superposition and relative terrace levels. Each erosional event cut slightly lower into the older and underling fan apron. This resulted in mixing of older fan material with clastic sediment delivered by the younger river system, and produced the stepped terraces and inverted topography described by Shlemon (1967a, 1967b, 1974, 1998).

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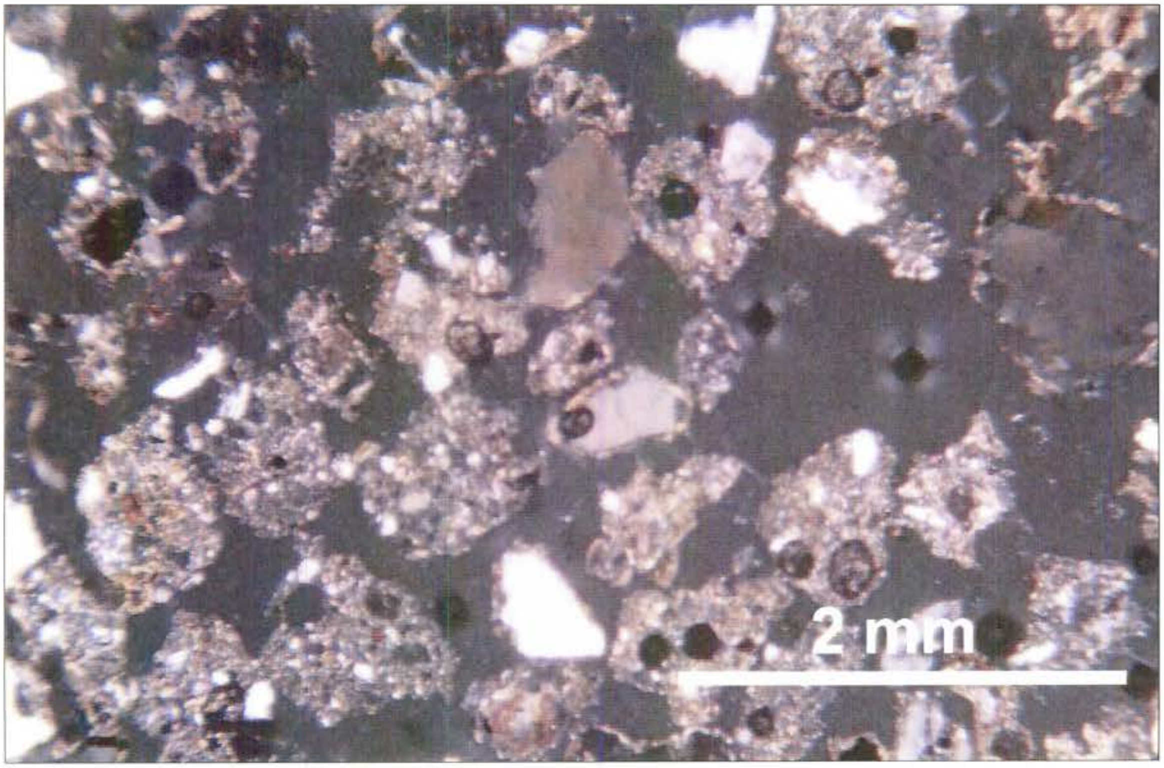


Plate 1: Thin section shows volcanic sand of intermediate composition (andesitic) collected 5 meters below the Old Fair Oaks Bridge. Gray and white grains are orthoclase feldspar. Cross-polarized light.

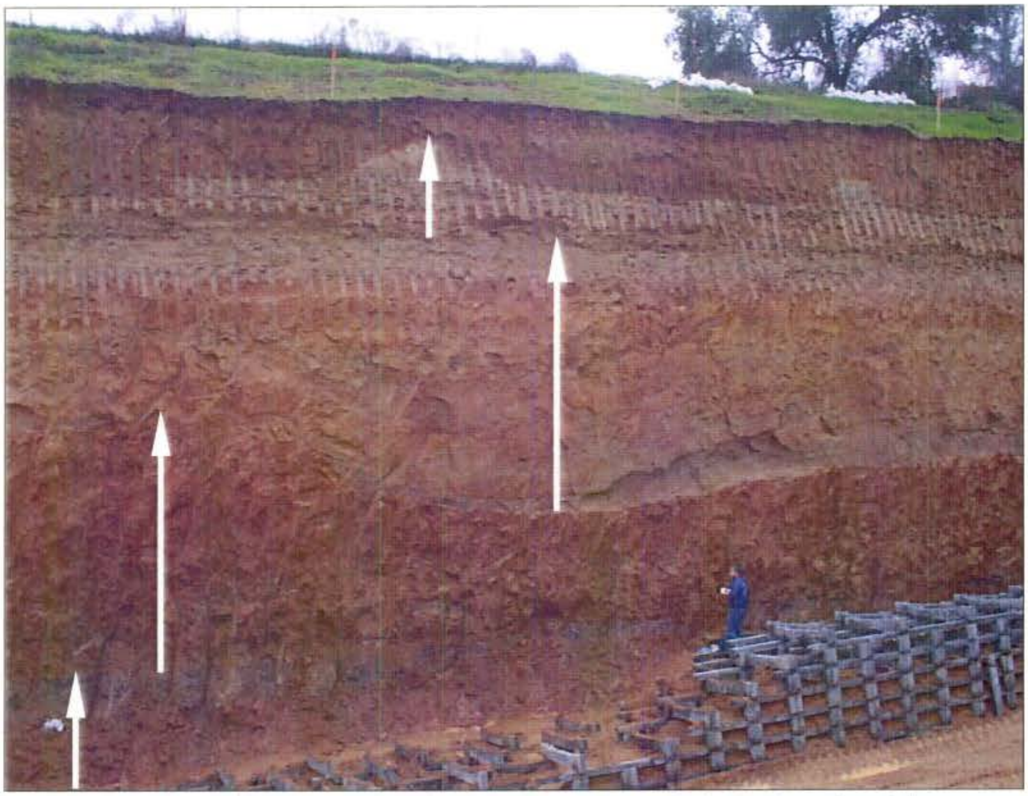


Plate 2: Construction site at Sunrise and Winding Way shows Fair Oaks unit with composite fining upward cycles. Thicker sandy beds have scoured lower bounding surfaces and are trough-crossbedded. Cycles fine upward to rooted, red or blue-gray mottled clay. Soil development probably occurred in a humid environment.

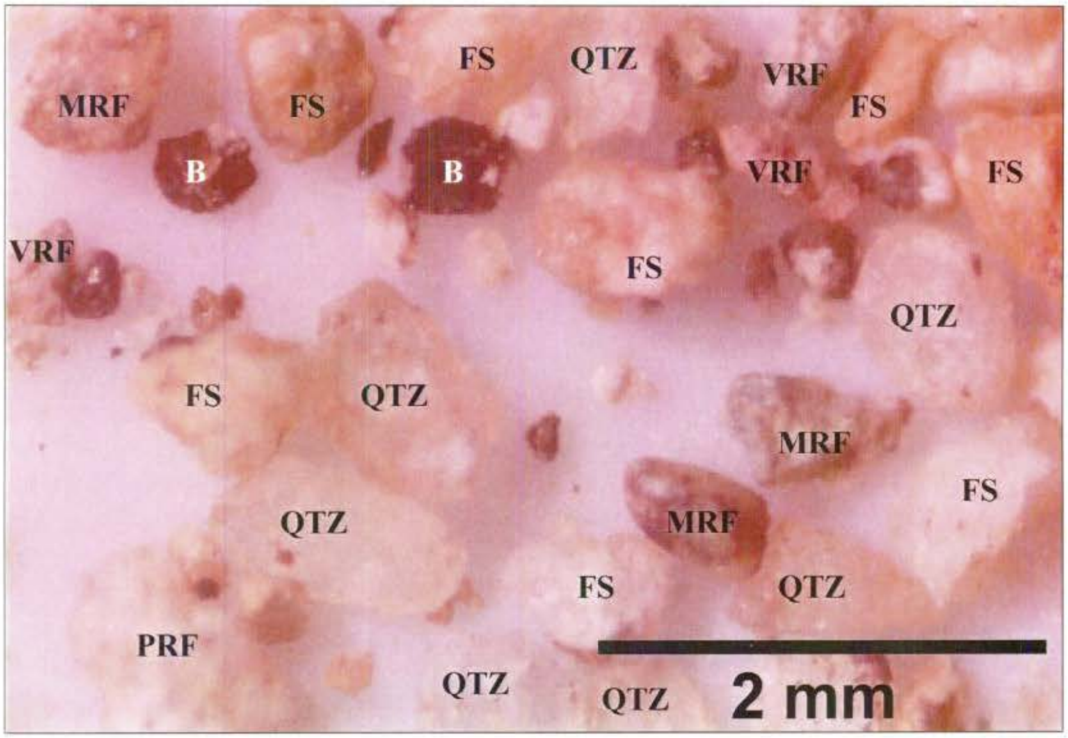


Plate 3: Unconsolidated sand from Fair Oaks unit at Nimbus Dam. QTZ = quartz, FS = feldspar (predominantly orthoclase), B = biotite, VRF = volcanic rock fragment, MRF = metamorphic rock fragment, PRF = plutonic rock fragment. The high proportion of quartz, feldspar and mica suggest a granitic source, with minor mixing from metamorphic and volcanic source areas

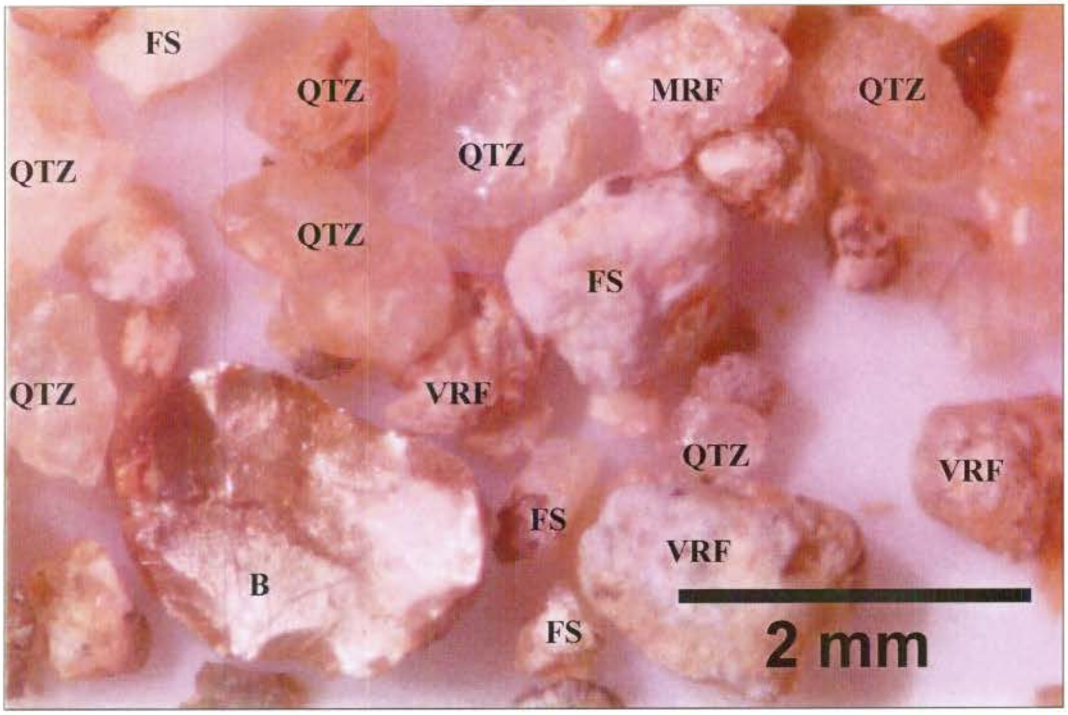


Plate 4: Unconsolidated sandy matrix from Arroyo Seco Gravels at Nimbus Dam has a marked similarity to Fair Oaks sand. See Plate 3 for key. The source for matrix from both units was the Rocklin/Penryn pluton. Coarser metamorphic clasts and reddish iron stain are used to distinguish Arroyo Seco Gravels..

Table 1: Informal Summary of Geologic History of Sacramento and the Surrounding Area:

Geologic Time (ma)	Geologic Events in the Middle California Area (taken from text of Howard, 1979)	Units Deposited (Howard, 1979)	Description and Location of Resulting Deposit	Activity Relevant to Sacramento Fan Structure (preliminary findings & speculations by Horner & Giorgis)
Middle to Late Paleozoic (230 to 400 ma)	Time of Pangea. California lies beneath the sea.	Thick assemblage of marine shale, siltstone, limestone, and volcanic rocks are deposited over the location of modern Sierra Nevada.		
Close of Paleozoic to early Mesozoic (150 to 230 ma)	Subduction begins and compression causes crumpling and metamorphism of sea floor sediments. Ancestral Sierra Nevada form.	Sediments are metamorphosed to slate, phylite, quartzite, marble, schist, and gneiss, then invaded by granitic magamas during Triassic time (ending at 205 with the Calavaras Formation).	Metamorphic rocks, including highly folded quartzite and chert are prominently exposed in Sierra Nevada foothills along California 140 near Briceburg and Merced Rivers. (Howard, 1979).	
Mesozoic Late Jurassic to Early Cretaceous (100 to 150 ma)	Nevadan Orogeny: subduction resumes and accentuates mountain-building forces and additional granitic magmas invade the crust. Deformation reaches a climax in late Jurassic time. Igneous precursors of serpentine are implanted into the metamorphic complex. Older subduction zone and associated trench shift 80 miles seaward to the present site of the Coast Ranges, and a new trench forms offshore. Buckling at the edge of the new continent creates a forearc basin. The Coast Ranges begin to form as a submarine ridge. By early Cretaceous time the descending oceanic plate reaches sufficient depth to cause melting. Sierra Nevada become a volcanic arc.	Triassic and Jurassic sea floor sediments (and volcanic rocks from the offshore island arc) are accreted onto the ancient coast. A second series of metamorphic rocks is compressed against the older Calavaras rocks to the east. A widespread product of this deformation is the Mariposa Slate. The submerged forearc basin begins to fill with volcanic debris from the Sierra Nevada. Deposition of the Great Valley Sequence begins.	Highway 50 crosses the eastern boundary of these formations west of Placerville. Remains of metamorphic units can be observed on foothill slopes as tilted tombstones. (Howard, 1979)	Rocklin/Penryn Pluton is implaced at approximately 128 mya.
Cretaceous (65 to 100 ma)	By Late Cretaceous time the volcanic cap of the Sierra is uplifted and eroded, exposing older metamorphic rocks and Cretaceous granitic plutons. West side of the Great Valley and Coast Ranges is underplated by accretionary wedges. Stockton Arch appears between two valleys, but is still submarine. Subduction of the Kula Plate may have resulted in an ancient San Andreas Fault system (strike-slip motion) until subduction of the Fallon Plate was initiated.	Considerable granitic debris was added to sediments in the offshore basin. In the trench, the accumulating sediments were crumpled, sheared and in some cases forced under the Coast Range Thrust. Extended period of erosion at close of Cretaceous time.	Chico: Exposure of the Chico Formation along the American River near Folsom and resting on the Rocklin Pluton. (Durrell, 1987). The Chico Formation consists of mostly marine sandstones, with lesser amounts of clay, silt and gravel.	Removal of some of the country rock covering the Rocklin/Penryn Pluton. Chico Formation is deposited in late Cretaceous time (Durrell, 1987). It appears to have been unconformably deposited onto parts of the exposed pluton *and* in the Sacramento area prior to initiation of deposition on the fan.
Cenozoic Tertiary Paleocene (55 to 63 ma)	Wide fluctuations in Early Tertiary sea level affect deposition in the Great Valley. Large gorges and submarine canyons develop on the Sacramento Valley floor (Meganos, Markley, and Princetonn Gorges). An inland sea in the Sacramento Valley is connected to the Pacific Ocean through the Markley Strait (near the current Bay area). Stockton Arch emerges and becomes prominant.	No deposition of any preserved units on the valley floor (Sacramento Area).		

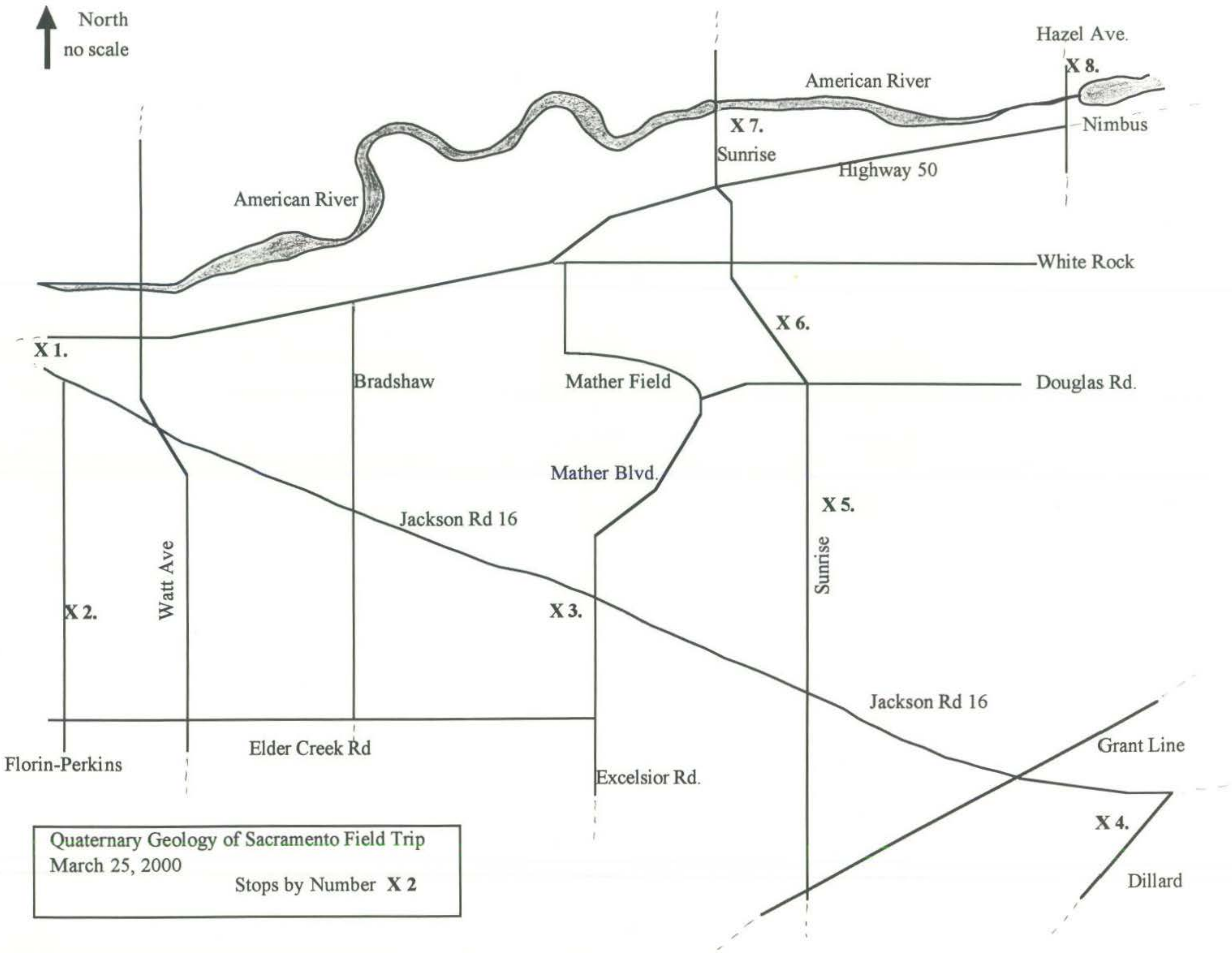
Geologic Time (ma)			Geologic Events in the Middle California Area (taken from text of Howard, 1979)	Units Deposited (Howard, 1979)	Description and Location of Resulting Deposit	Activity Relevant to Sacramento Fan Structure (preliminary findings & speculations by Horner & Giorgis)
Cenozoic	Tertiary	Eocene (38 to 55 ma)	Deep valleys are eroded in the Sierra Nevada foothills and later widened. Foothill valleys are filled with coarse gravel. Fine placer gold is eroded into streams and remains as a lag deposit, while clastic sediment is flushed to the edge of the foothills.	Ione Formation is deposited at the edge of an inland sea that occupies the Great Valley.	The Ione Formation has various phases that include quartzose sands with flakes of white anauxite, and occasionally abundant quartzite pebbles. A clay member is also common.	CDMG[1] map shows Ione Formation remnants near Citrus Heights and Lincoln. These deposits lie disconformably over small areas of the Rocklin/Penryn pluton. The Ione Formation is also frequently preserved south of the Consumnes River.
		Oligocene (24 to 38 ma)	Rhyolitic volcanic eruptions begin on a large scale north of the Merced River at 33 ma. The Sierra Nevada are covered with a volcanic blanket of light colored lavas, ash, and lahars. Volcanic-rich alluvium flows westward into the Sacramento Valley, and is no longer channeled by the previous trellis-type drainage system Climatic cooling that began at end of Eocene time continues, resulting in polar glaciation and lowering of sea level. There is a resulting increase in erosion, which may explain the lack of marine sediments except for deposits in some isolated valley gorges, which were still underwater. Terrestrial sediments become more common. At 29 ma, the westward-moving North American continent begins to override the East Pacific Rise, and the Fallon Plate undergoes complete subduction. The edge of the North American continent creeps westward onto the northwestward-moving Pacific Plate. A shear zone develops in Southern California and gradually shifts eastward, reaching Middle California at 21 ma.	No remnants of any Sacramento area (surface) units.		
		Miocene (5 to 24 ma)	Intense volcanic activity that began in Oligocene time continues intermittently with ash falls contributing to deposition in the Sacramento Valley. This activity terminates at 16 ma and deep erosion of Sierra Nevada begins.	RhyoliticValley Springs Formation deposited as volcanic sediment blanket on Sierra Nevada north of Merced River. (Howard, 1979)	Valley Springs: Mostly tuffaceous rhyolitic beds of light colored sand and ash.	Little evidence of Valley Springs significantly contributing to fan. American River system may have began fan deposition from Auburn apex during latter Miocene.
			Earlier rhyolitic volcanic activity is followed by another intense period of volcanism, burying the Sierra Nevada with the andesitic Mehrten volcanics. Volcanic deposition is less intense in the Sierran foothills. A westward drainage systems is initiated again from the Sierran slopes. Volcanism stops, and deep valleys are eroded through both Mehrten and Valley Springs volcanic sediments. Lava flows pour down Sierran valleys starting at 9 ma. The west slope of the Sierra Nevada remains a smooth, sloping plane. Late Miocene uplift starts at 9 my. The inland sea regresses from the Sacramento Valley and the Sierra Nevada are uplifted and tilted westward, causing increased streamflow and rates of erosion. Sea level rises, but the Sacramento Valley stays above water with the exception of some minor transgressions into the southwestern portion of the valley. Coast Ranges are deformed by imbricate faults associated with the San Andres Fault system. Subduction of the Fallon Plate is completed near San Francisco at 5 ma.	Eruptions associated with Mehrten volcanism bury the Sierra Nevada with a blanket of volcanic debris, former drainages fill, producing a mountain range with less local relief. Stream paths tend to straighten down-gradient toward the valley. Again, the southern boundary of the volcanic deposition is the Merced River. (Howard, 1979) Deposition of the Mehrten Formation in the Great Valley begins in late Miocene and continues through early Pliocene time. Shlemon (1967) notes that the Mehrten-Laguna transition is evident south of the American River in early Pliocene time.	Mehrten : Near the fan Apex: gravelly andesitic deposits that include lahars and earthflows give rise to andesitic tuff breccias; some are welded, dark colored conglomerates with generally well rounded clasts. Tuffaceous matrix of tuff breccias is often pinkish tan. Distal from the Fan Apex: Later deposits tend to be dark andesitic sands with noticeable magnetite content, occasional conglomerate lenses and reworked ash beds.	Overburden appears to have been unroofed from much of the Penryn Pluton. Mehrten deposits form the first sedimentary apron near the apex of the fan (see CDMG[1] map). Evidence indicates that all three branches of the American River are flowing into Auburn/Roseville area. This appears to be the beginning of the Sacramento fan.
		Pliocene (1.8 to 5 ma)	Uplift and tilting of the Sierra Nevada causes heavy sediment influx into the Sacramento Valley, and sediments spread onto alluvial fans. As fans increase in size they merge onto the old Laguna alluvial plain. There were no lowland water passages from the Sacramento Valley to the ocean through the Northern Coast Ranges, but there may have been an outlet through the San Joaquin Valley south of the Bay Area. This accelerates sediment accumulation in the valley.	The Laguna Formation is deposited according to CDMG (1981)[1], DWR (1976), and Shlemon (1967)	Laguna sedimentary deposits are tan to brown and volcanic-rich, with grain sizes ranging from clay to silt and sand; minor granitic and metamorphic input.	Sediments of derived from the Rocklin/Penryn Plutons are deposited on the fan as the lower Fair Oaks Formation.

Geologic Time (mya)			Geologic Events in the Broader Middle California Area (taken from text of Howard, 1979)	Depositions and Formations				Description and Location of Resulting Deposit	Activity Relevant to Sacramento Fan Structure (preliminary findings & speculations by Horner & Giorgis)
				DWR (1976)	CDMG (1981)[1]	Shlemon (1967)			
						North of River	South of River		
Cenozoic	Tertiary	Pliocene/Pleistocene	Uplift and tilting of the Sierra Nevada continues, causing heavy sediment flow into the Sacramento Valley, with sedimentary deposits the form alluvial fans. As the fans increase in size, they merge and form the Laguna Alluvial Plain. Outlets to the ocean are cut off from the Northern Coast Ranges to the Sacramento Valley and south to the current Bay Area. This accelerates sediment accumulation in the valley. Sutter Butes begin to emerge.	Laguna	North Merced Gravel (Equiv. to Arroyo Seco Gravels)	Lower Fair Oaks	Arroyo Seco Gravels	North Merced Gravel: A thin pediment veneer forms on top of the Laguna Formation. This is generally absent in the Sacramento area. Fair Oaks or Turlock Lake: Light brown, granitic sands rich in quartz and biotite are deposited. This unit also includes some silt and clay. Arroyo Seco Gravels: Rounded gravels with red matrix derived from granite. Clasts are largely metamorphic and andesitic pebbles and cobbles. The unit forms a caprock where found in the Sacramento area.	The Fair Oaks Formation continues to be deposited on the fan. The drainage shadow of the Pine Hill Complex allows the fan to expand southward.
	Quaternary		Continued uplift and tilting of the Sierra Nevada causes trenching of Laguna Alluvial Plain, making it an erosional surface. The Arroyo Seco pediment (not the Arroyo Seco Gravels), which is found on alluvial fans south of the Sacramento Area, forms from the weathered top of the remaining Laguna erosional surface. Streams from the Sierra Nevada begin to downcut due to an increase in slope caused by uplift of the Sierra Nevada. Beginning of Pleistocene Ice Age.	Fair Oaks					The American River (south Fork?) swings southward and begins flow over southern portion of the fan. Initial deposits are Arroyo Seco Gravels that later cap ridge summits between the current American and Consumnes River Channels.
		Pleistocene (0.01 to 1.8 ma)	The Sierra Nevada are subjected to cycles of glaciation and deglaciation. Sea level cycles in a corresponding manner. Deglaciation results in results in floods of debris that spread into the Sacramento Valley. A direct river outlet to the ocean develops in the Bay Area. Former openings in the Southern Coast Ranges are closed due to increased elevation of the coast Ranges. Volcanic activity is increasingly evident at Clear Lake.	Arroyo Seco Gravels …………… South Fork Gravels	Turlock Lake (Equiv. to Fair Oaks) River-bank	River-bank	Upper Fair Oaks Riverbank	Upper Fair Oaks: Rounded pebble to cobble gravels with granitic red matrix. Clasts largely of metamorphic with less component andesitic clasts. Largely equivalent to South Fork Gravels of DWR (1976). Riverbank: Gray, unconsolidated gravel, sand, silt, and clay from a granitic source. Victor: Unconsolidated gravel, sand, silt and clay derived from a granitic source.	Deposition of the Riverbank Formation continues. Initiation of Riverbank fan deposits may extend back into late Pliocene time. Clast composition of well cores indicates Riverbank deposits extend 210 feet below land surface under the CSUS campus. Increased competence of the American River allows it to cut incrementally northward into the dead fan.
			Continued uplift and tilting of the Sierra Nevada during Pleistocene time causes entrenchment of the Arroyo Seco and underlying units. Sediments forms alluvial fans on the lower Sacramento Valley floor. A depositional plain, (the Victor Alluvial Plain), develops as fans coalesce. Glacial periods are associated with sea levels changes. Volcanic activity at mount Konocti near Clear Lake.	Victor	Modesto	Modesto	Modesto	Modesto: Unconsolidated gravel, sand, silt, and clay from a granitic source is deposited, largely near stream channels.	The Sacramento Fan is no longer fed at the apex. All branches of the American River use the current channel, and the . Fan drains inward from the Fair Oaks cliffs. The American River continues to cut northward into the south flank of fan.
		Holocene (0.01 to pres.)	After the last deglaciation, stream flows drop and streams become undersized compared to their valleys.	Alluvium				Unconsolidated gravel, sand, silt, and clay are deposited along stream channels.	

ATTACHMENT 1

Selected figures and tables from:

Shlemon, R. J., 1967, Quaternary geology of northern Sacramento County, California: Annual Field Trip Guidebook of the Geological Society of Sacramento, 67 p., plates.



Quaternary Geology of Sacramento Field Trip
March 25, 2000
Stops by Number **X 2**

TABLE 2

CORRELATION OF CENOZOIC FORMATIONS ALONG THE EAST SIDE OF THE GREAT VALLEY

(ASSOCIATED SOILS INDICATED FOR SACRAMENTO COUNTY SECTION)

EPOCHS	SACRAMENTO COUNTY (THIS REPORT)		SOUTHEASTERN SACRAMENTO VALLEY	LOWER MOKELUMNE RIVER AREA	LOWER TUOLUMNE RIVER AREA	LOWER MERCED RIVER AREA
	North Of American River	South Of American River	OLMSTED AND DAVIS, 1961	(PIPER ETAL, 1939)	DAVIS AND HALL, 1959	ARKLEY, 1962; HUDSON, 1960
RECENT	*Columbia, Sacramento, and Freeport Soils* Alluvium and Basin Deposits	*Columbia, Sacramento, and Freeport Soils* Alluvium and Basin Deposits	Alluvium and Basin Deposits	Alluvium	Alluvium and Eolian Sand	Alluvium
PLEISTOCENE	Modesto Formation: *Hanford Soil* Upper Member *Chualar Soil* Lower Member *San Joaquin and Alamo Soil* Riverbank Formation Fair Oaks Formation: *Whitney Soil* Upper Member *Upper Buried Soil* *Lower Buried Soil*	Modesto Formation: *Hanford Soil* Upper Member *Honcut and Bear Creek Soils* Lower Member *San Joaquin Soil* Riverbank Formation *Corning Soil* Fair Oaks Formation Upper Member Gravels Underlying Lower Arroyo Seco Surface	Victor Formation Arroyo Seco Gravel	Victor Formation Arroyo Seco Gr. and Gravel Of Uncertain Age	Modesto Formation Riverbank Formation Turlock Lake Formation ?-?-?	Modesto Formation Riverbank Formation Turlork Lake Formation North Merced Gravel
PLIOCENE (?) AND PLEISTOCENE (?)	Fair Oaks Formation: *Redding Soil* Lower Member ?-?-?-?	Gravels Underlying Upper Arroyo Seco Surface Laguna Formation *Whitney Soil* Laguna-Mehrten Transition Mehrten Formation	Laguna Formation Mehrten Formation	Laguna Formation Mehrten Formation	?-?-? Mehrten Formation	China Hat Gravel Mehrten Formation
MIOCENE	Mehrten Formation ?-?-?-?	?-?-?-?-?-? Valley Springs Formation ?-?-?-?-?-?	Valley Springs Formation	Valley Springs Formation	Valley Springs Formation	Valley Springs Formation
OLIGOCENE						
EOCENE		Ione Formation	Ione Formation	Ione Formation (unnamed)	Ione Formation	Ione Formation

/////////// Surface Soil

\\\\\\\\\\\\ Buried Soil

〰〰〰 Unconformity

— — — — — Inferred Position in Stratigraphic Sequence

–?–?–?– Inferred Correlation

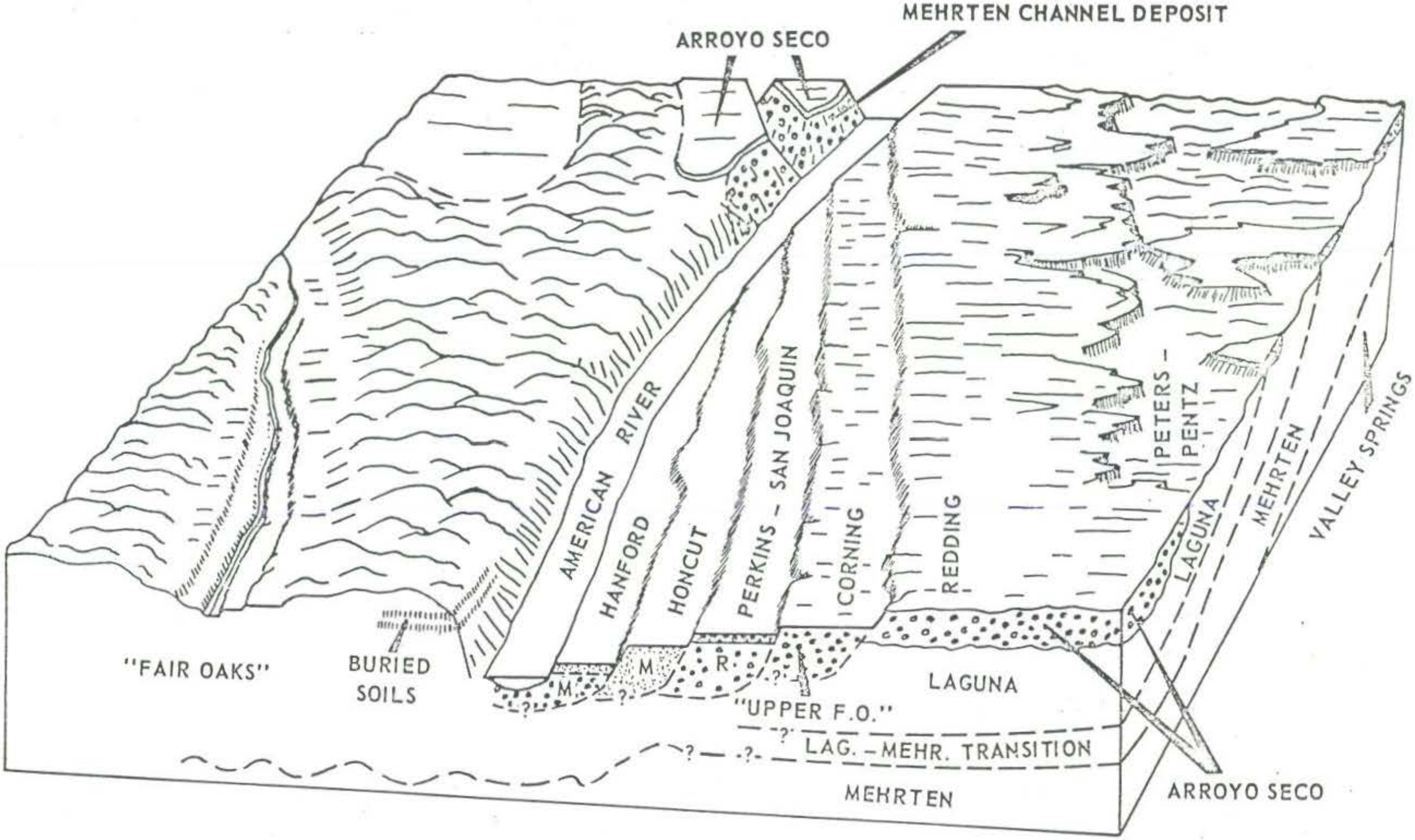
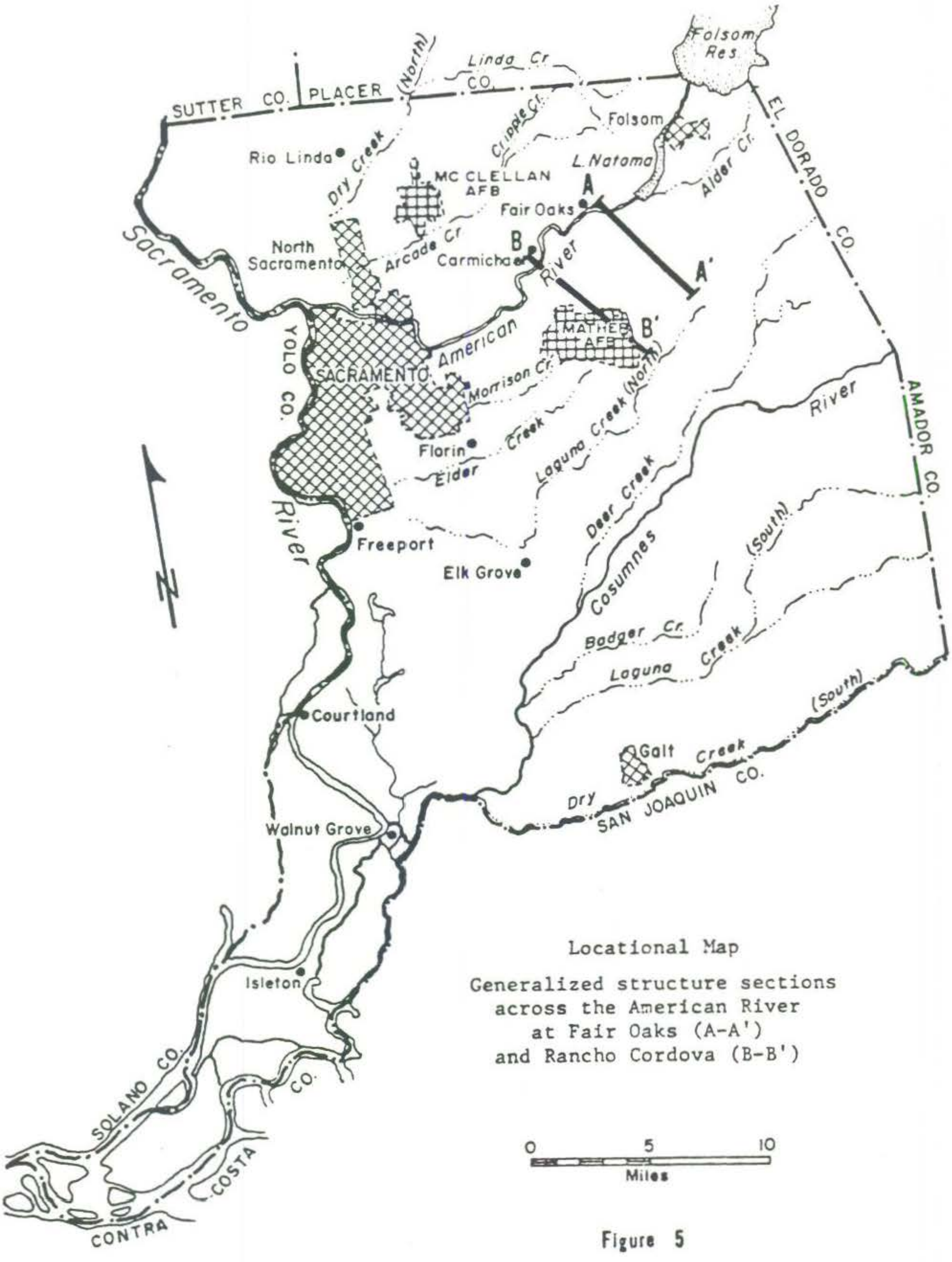


Figure 2 –Block diagram showing the general association of major landforms and soils along the lower American River. Characteristic soil series indicated on landform surface; geologic unit identified below surface: M = Modesto Formation, R = Riverbank Formation, F.O. = Fair Oaks Formation, A. S. = Arroyo Seco Gravel, Lag. = Laguna Formation, Mehr. = Mehrten Formation.



Locational Map

Generalized structure sections across the American River at Fair Oaks (A-A') and Rancho Cordova (B-B')

Figure 5

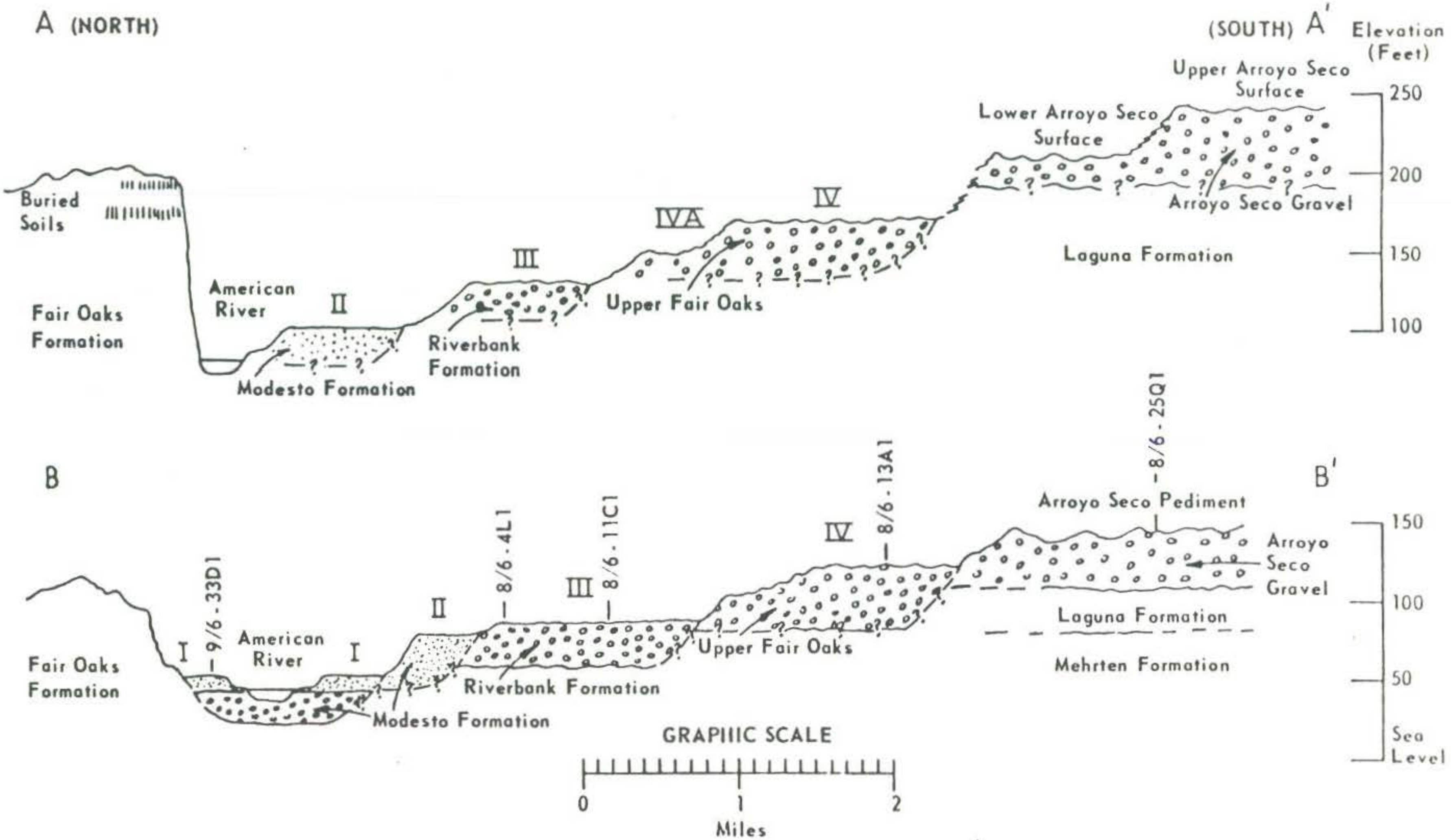


Figure 6 – Generalized structure sections across the American River at Fair Oaks (A-A') and downstream near the Rancho Cordova District (B-B'). American River terraces designated by Roman numerals; subsurface contacts along section B-B' based on well log control as indicated e.g., 9/6 - 33D1, 8/6 - 4L1 etc.

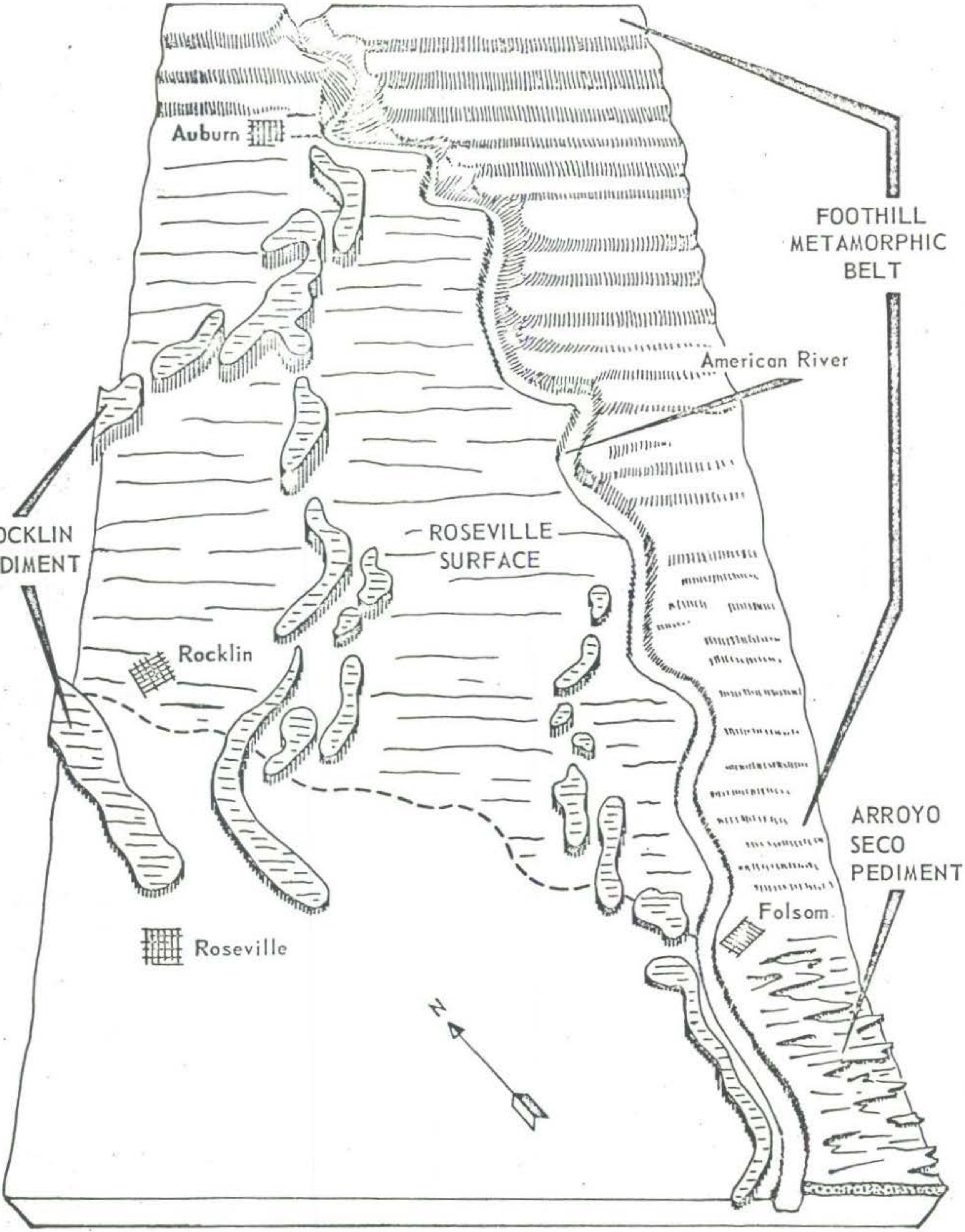


Figure 13 – Generalized diagram illustrating the topographic relationship of the Arroyo Seco Pediment, Rocklin Pediment, and Roseville Surface in northeastern Sacramento and southwestern Placer counties. The American River forms the northern boundary of northwestward trending ridges of the foothill metamorphic belt. Granitic rocks of the Roseville Surface merge imperceptibly into the dissected alluvial plains (Fair Oaks Formation) near Roseville.

ATTACHMENT 2

Shlemon, R. J., The lower American River area, California: a model of Pleistocene landscape evolution: Yearbook, Association of Pacific Coast Geographers, v. 34, p. 61-86.

The Lower American River Area, California: A Model of Pleistocene Landscape Evolution

Roy J. Shlemon[*]

GEOMORPHOLOGISTS AND STRATIGRAPHERS long have been concerned with the form and magnitude of valley development and landscape evolution during the Pleistocene Epoch. In middle latitudes especially, many workers believe that degradation probably occurred during glacial periods; conversely, others believe that aggradation dominated during these times with streams cutting primarily during interglacial stages. The differences of opinion generally concern phases of cutting and filling; whether each occurred in glacial, interglacial, or some transitional period. Almost all agree that landscapes more than several thousand years old were subject to Pleistocene climatic change and thus experienced cycles of aggradation and degradation.[1] Of increasing significance is the growing realization that certain epochs of landscape evolution were characterized by relative stability in which great areas were neither significantly eroded nor aggraded.

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[*] Dr. Shlemon is an associate professor in the Center for Wetland Resources, Louisiana State University, Baton Rouge, 70803. This interpretation of the American River Quaternary stratigraphy to a great degree is based on unpublished subsurface engineering and geologic data made available over the last several years by the U. S. Bureau of Reclamation, U. S. Geological Survey, California Department of Water Resources, and California Division of Highways. A. Teichert and Son, operators of several gravel quarries in the Sacramento area, kindly authorized collecting of the vertebrate bones and wood used for radiometric dating. David S. McArthur read the manuscript and made valuable suggestions for improvement.

[1] The literature abounds with hypotheses concerning Pleistocene climatic or man-induced cycles of landscape evolution. For a general treatment of regional cutting and filling in varying climates see Karl W. Butzer, *Environment and Archeology*, (Chicago: Aldine Publishing Company, 1966), 524 pp. A

Many models have been proposed attempting to simplify the complexities of landscape evolution in different morphogenetic regions. Some models have evaluated areas only where the major drainages originated in either glacial or in non-glacial terrain; others have assessed the relative effects of sea-level change.[2] Only a few models, however, especially of North American landscapes, have considered areas in which trunk streams passed through all these environments, having headed in glacial terrain, traversed non-glacial topography, and finally debouched into a glacio-eustatically fluctuating sea. In part this is due simply to scale. As a classic example, continental glacial deposits in the upper Mississippi River Valley are at least 500 miles from the downstream eustatically-affected alluvial terrace and deltaic section. Thus whereas alluviation in the lower Mississippi River Valley is attributed to rising sea level during interglaciation, deposition upstream is believed to have occurred in glacial time.[3] Typically the stratigraphy of the intervening area is extremely complex and not well understood. Quite unique, therefore, is the landscape in which the major fluvial system affected both by sea-level fluctuation and headwater glaciation records in its sediments an almost complete Pleistocene history of cutting, filling, and stability. Such a landscape occurs along the lower American River, California.

The Lower American River

Draining the high Sierra west of Lake Tahoe, the American River enters the Sacramento Valley near the town of Folsom (Figure 1). Though traversing an area with an interior Mediterranean climatic regime, discharges of the lower American River and other westward flowing trunk streams are controlled primarily by precipitation and snow melt in the adjacent mountains. In this low lying alluvial zone between the foothills and the Valley trough the modern American River is incised into Pleistocene alluvium and terraces. The confluence with the Sacramento River, only 20 feet above sea level, is subject to tidal fluctuation although more than 100 miles north of the Golden Gate and San Francisco Bay (Figure 1).

Underlying terraces and piedmont alluvial fans are several distinct gravel-filled channels laid down by ancestors of the present American River during Pleistocene time. Some of the channels occur more than 60 feet below present sea-level, apparently graded to glacio-eustatically lowered base levels. For reasons yet unknown the American River migrated northward in "jumps" with each successive Pleistocene glaciation thus fortuitously preserving older sediments.[4]

In contrast to most Pleistocene alluvial sections, abundant subsurface lithologic data are available in the lower American River area. This fortunate occurrence is due to many reasons, the foremost of which is that in this urbanized area thousands of water wells have been drilled into the alluvium, some penetrating more than 200 feet. The logs of these wells containing lithologic, color, and texture data

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model and review of arroyo development in the southwestern United States is given by Yi-Fu Tuan, "New Mexican Gullies: A Critical Review and Some Recent Observations," *Annals, Association of American Geographers*, Vol. 56 (1966), pp. 573-597. Examples of periodic landscape change based primarily on environmental interpretation of paleosols are discussed by B. E. Butler, "Soil Periodicity in Relationship to Landform Development in Southeastern Australia," in J. N. Jennings, and J. A. Mabbutt (eds.), *Landform Studies From Australia and New Guinea*, (London, Cambridge University Press, 1967), pp. 231-255; and by Robert B. Ruhe, *Quaternary Landscapes in Iowa*, (Ames: Iowa State University Press, 1969), 255 pp.

[2] The numerous European landscape models are frequently based on paleoenvironmental interpretations of climatic terraces. For a synthesis see F. E. Zeuner, *The Pleistocene Period*, (London: Hutchinson and Company, 1959), 447 pp. Many North American models are reviewed by S. A. Schumm, "Quaternary Paleohydrology," in H. E. Wright and D. G. Frey (eds.), *The Quaternary of the United States* (Princeton: Princeton University Press, 1965), pp. 783-794.

[3] Glacio-eustatic control of alluviation in the lower Mississippi River has been expounded primarily by H. N. Fisk, "Loess and Quaternary Geology of the Lower Mississippi Valley," *Journal of Geology*, Vol. 59 (1952), pp. 333-356; and R. J. Russell, "Duration of the Quaternary and its Subdivisions," *Proceedings, National Academy of Sciences*, Vol. 52 (1964), pp. 790-796. Objections to the interglacial alluviation interpretation have been raised by C. O. Durham, C. H. Moore, and Brian Parsons, "An Agnostic View of the Terraces: Natchez to New Orleans," *Lower Mississippi Alluvial Valley and Terraces, Field Trip Guidebook*, (New Orleans: Geological Society of America, 1967), pp. E1-E22. Midcontinental glacio-fluvial deposition is documented in numerous studies; see, for example, J. C. Frye and H. B. Willman, "Continental Glaciation in Relation to McFarlan's Sea-Level Curves for Louisiana," *Geological Society of America Bulletin*, Vol. 72 (1961), pp. 991-992.

[4] R. J. Shlemon, "Quaternary Geology of Northern Sacramento County, California,' '*Annual Field Trip Guidebook* (Sacramento: Geological Society of Sacramento, 1967), 60 pp.

have been filed and are readily available for analysis.[5] Also in recent years many new bridges have been built across the American and Sacramento rivers. Engineering boring logs for each bridge similarly yield excellent subsurface data.[6] Further, many new road alignments in the Sacramento suburban area cut into undulating terrain underlain by older Pleistocene sediments thus frequently exposing stream gravels and buried soils. Finally, gravel quarries and canal excavations have opened very large cuts, some more than a mile long, often revealing the contact between ancestral channel deposits and confining sediments. From these man-made exposures some wood and vertebrate fossils have been collected and radiometrically dated. The ages obtained provide a chronologic framework into which can be fitted the stratigraphic record of the lower American River area. This combination of sediment preservation and surface and subsurface data thus makes the lower American River area stratigraphically unique and an excellent region for documenting landscape change throughout Pleistocene time.

THE STRATIGRAPHIC FRAMEWORK

A model of landscape change deduced from the sedimentary record can be formulated only when the sediments themselves are adequately delimited, areally and chronologically. The general Pleistocene geology of the lower American River area has been described earlier but is briefly reviewed here.[7] New data concerning the older Pleistocene channels are presented for the first time.

At least five separate Plio-Pleistocene formations are recognized in the lower American River area. Surface form and subsurface stratigraphy show that each was laid down as a distinct fill in the Sacramento Valley. The younger formations were entrenched and

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[5] The logs of all water wells drilled in California are required by law to be filed with the State Department of Water Resources. Although notoriously diverse in description and accuracy, many logs are useful for identifying major lithologic units beneath the surface, especially if these have surficial expression, such as gravel-filled terraces.

[6] Most bridge boring logs were provided by the California Division of Highways, Bridge Department (Sacramento). Others were made available by local engineering firms that built the bridges under contract with the State.

[7] Shlemon, *op. cit.*, footnote 4.

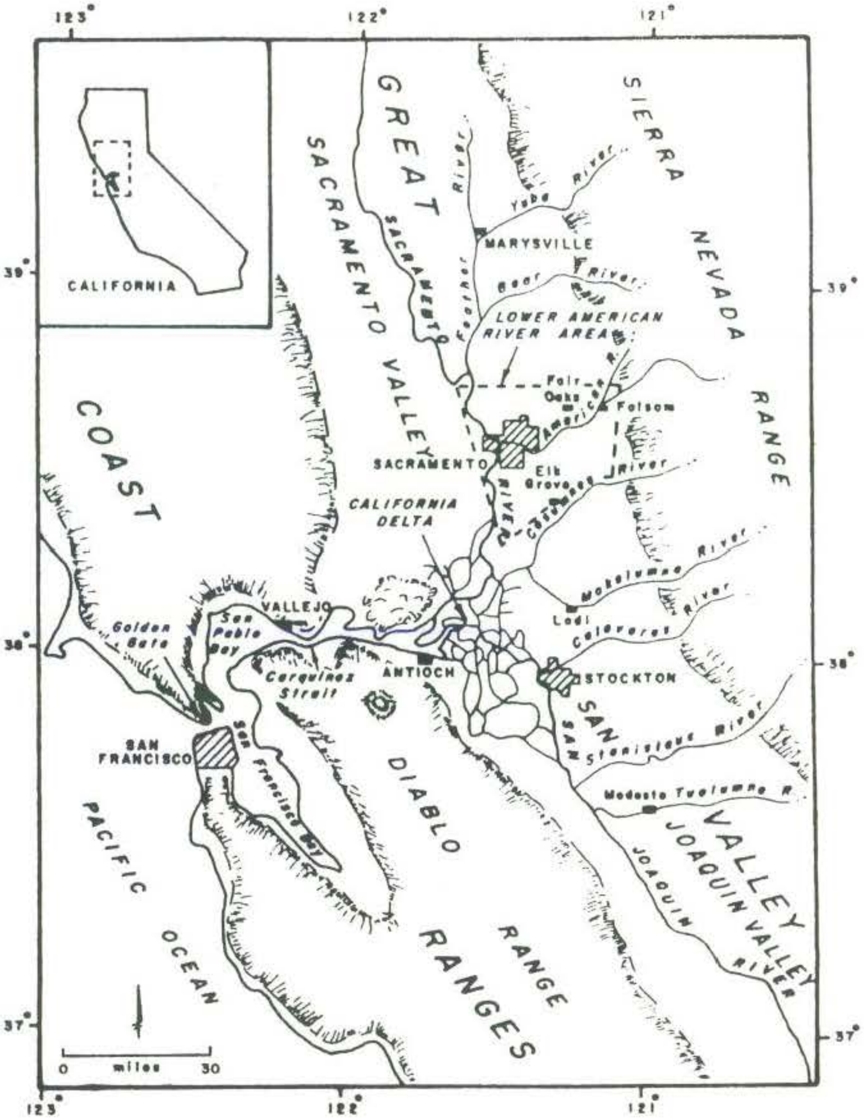

Figure 1. Lower American River Area, California.

nested into older fan deposits but were deposited progressively westward toward the Valley trough. From older to younger these formations are called the Laguna, Arroyo Seco Gravel, Fair Oaks, Riverbank, and Modesto respectively. Within each formation are one or more distinct gravel-filled channels, ancestral American rivers, some of which can be traced downstream from fill terraces into the subsurface 50 to 60 feet below present sea level (Figure 2). Burying each channel and spreading out as alluvial fans are fine-grained sands and silts. These in turn are capped by distinctive paleosols that formed during times of regional landscape stability. Most of the stratigraphically significant paleosols are preserved either on the surface as relict soils or in the subsurface as buried soils.

The Laguna Formation

Consisting mainly of fluvial granitic sand and silt, the Laguna Formation locally crops out in the form of haystack hills 25 to 50 feet above modern floodplains in southeastern Sacramento County. Thought to be of early Pleistocene age, the formation was laid down when streams draining the western slope of the Sierra Nevada cut through andesitic detritus (Mehrten Formation) and tapped underlying granitic bedrock. Transported to the Sacramento Valley, Laguna deposits now conformably overlie and locally intermix with Mehrten andesitic sediments. Boring logs of the Folsom-South Canal in eastern Sacramento County show that there is a distinctive continuous 25-foot thick gravel within the upper part of the Laguna Formation (Figure 3).[8] Although exposed only briefly during excavation of the canal cut, the location, thickness, and gradient of this gravel suggest it too may have filled an ancestral channel of the American River. Whether or not the gravel is glacial outwash is still conjectural. If so, based on stratigraphic position, it would be filling the oldest glacial channel yet recognized in California.[9]

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[8] Engineering subsurface data for the Folsom-South Canal were provided by David Carpenter, U. S. Bureau of Reclamation (Sacramento). The stratigraphic interpretation of these data, however, is solely that of the writer.

[9] Direct correlation of most Sierra glacial deposits and Central Valley alluvium is not yet possible owing to extensive erosion in the intervening canyons. Inferred correlation, however, is made through comparative soil and geologic stratigraphy, and radiometric control. Moraine, perhaps 3 million years old, has now been discovered in the central Sierra Nevada: see R. R. Curry, "Glaciation About 3,000,000 Years Ago in the Sierra Nevada," *Science*, Vol. 154 (1966), pp. 770-771. Equivalent age outwash in the Central Valley is unknown although conceivably the inferred Laguna gravels may be correlative.

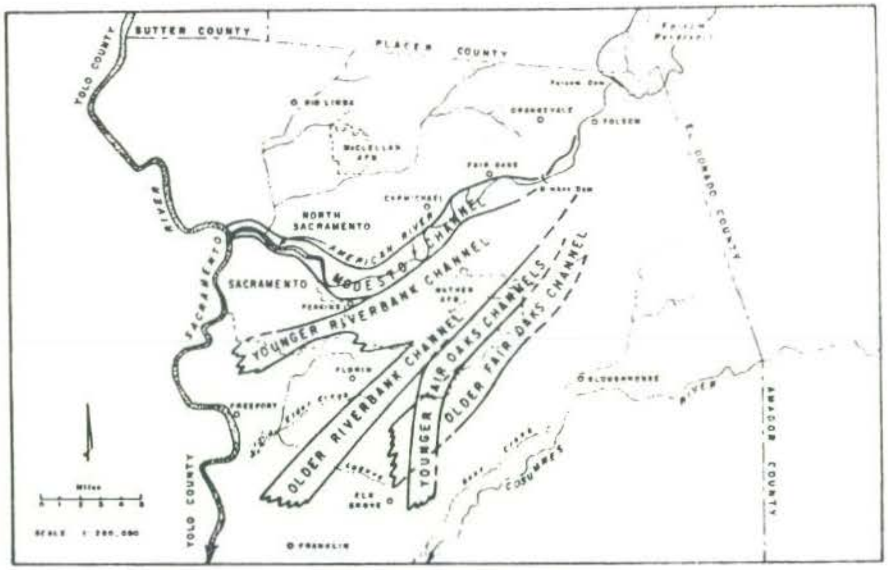

Figure 2. Pleistocene Channels of the Lower American River.

Arroyo Seco Gravel

The Arroyo Seco Gravel was originally mapped as a pediment fill covering the Laguna and older formations along the east side of the lower Sacramento Valley.[10] New cuts, however, now show that the gravel, at least in the lower American River area, was deposited in two or more epochs, each separated by a distinct weathering interval.[11] The oldest gravel, now the restricted "Arroyo Seco Gravel," is preserved only on the highest drainage divide between the American and Cosumnes rivers; its form is poorly preserved and only a few wells penetrate it. Therefore, at present, it is unknown if this gravel were laid down as a distinct channel fill, perhaps of glacial origin, or as a broad pediment sheet as originally defined.

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[10] A. M. Piper, H. S. Gale, H. E. Thomas, and T. W. Robinson, "Geology and Ground-Water Hydrology of the Mokelumne Area, California," *U. S. Geological Survey Water-Supply Paper* 780 (1939), 230 pp.

[11] Shlemon, *op. cit.*, footnote 4, p. 27.

The Fair Oaks Formation

Informally described as the stratigraphic interval north of the American River between the underlying Mehrten Formation and the overlying Riverbank Formation, gravels of Fair Oaks age also occur as continuous channel-fills south of the American River (Figure 3). The older and topographically higher channel has a surface expression at least 10 miles long and 2 miles wide. Capped by a strongly developed soil with hardpan (Redding series), the gravelly surface now has about 5 feet of undulating local relief. Canal cuts and well borings show that the gravel thickness is about 20 feet, thinning slightly downstream. These gravels, as all ancestral American River channel deposits, are generally metamorphic, primarily composed of quartzite and amphibolite cobbles and boulders in a granitic sand matrix.[12]

The southwestern downstream end of the older Fair Oaks channel was apparently truncated by younger Fair Oaks-age streams; and now the westernmost edge of the older gravels is preserved only in an erosional outlier near the town of Elk Grove (Figure 2). Here the base of the old Fair Oaks gravels is about 55 feet above sea level. Most likely these gravels once continued farther westward, perhaps below present sea level, but they have since been eroded by younger channels of the American River.

The younger Fair Oaks channels are internally differentiated by topographic form and elevation. Generally separated by less than 5 feet vertically, the two channels trend essentially parallel from gravel-fill terraces near Mather Air Force Base southward into the subsurface east of Elk Grove (Figure 2). Here they can be traced to at least 45 feet below sea level. Presumably these channels once extended farther south, but since have been eroded by still younger courses of the Cosumnes River. At this point, southeast of Elk Grove, gravels of the younger Fair Oaks channels are about 12 miles from the present Sacramento-American River confluence (Figure 2).

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[12] The older Fair Oaks channel was originally defined as the "lower Arroyo Seco surface" for it was not known if the surface were cut or filled; Shlemon, *op. cit.*, footnote 4 ,p. 25. Now owing to new exposures in canal and road cuts, its distinctive channel-fill is apparent.

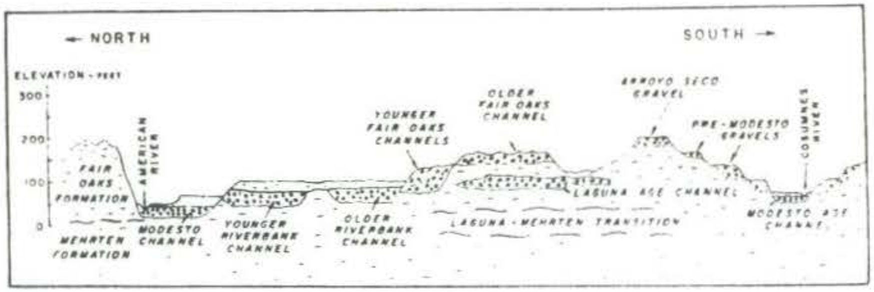

Figure 3. Generalized composite structure section from the American River near Fair Oaks to the Cosumnes River showing Quaternary formations and the surface and buried channels. Vertical scale exaggerated.

The absolute age of the Fair Oaks channels is unknown; however, the younger channels occur within the same stratigraphic interval as sediments in the San Joaquin Valley radiometrically dated as approximately 600,000 years old.[13] Thus because of stratigraphic position the older Fair Oaks, Arroyo Seco, and Laguna channels, respectively, are progressively older than 600,000 years. If, as seems likely, these ancestral American River channels were cut and filled during major glaciations, then they are probably correlative to several ancient glacial deposits now recognized in the adjacent Sierra Nevada.[14] However, direct correlation of Valley alluvium to specific Sierran moraines at present is still conjectural.

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[13] The age is based on potassium-argon dating of pumice east of Fresno, California: see R. J. Janda, "Quaternary Alluvium Near Friant, California," in *Northern Great Basin and California*, Guidebook for Field Conference I, International Association for Quaternary Research (Lincoln: Nebraska Academy of Sciences, 1965), pp. 127-133. Petrologically the dated ash is similar to the "Bishop Ash," a 0.7 million year old stratigraphic marker found extensively east of the Sierra Nevada: see G. A. Izett, R. E. Wilcox, H. A. Powers, and G. A. Desborough, "The Bishop Ash Bed, a Pleistocene Marker Bed in the Western United States," *Quaternary Research*, Vol. 1, No. 1 (1970), pp. 121-132. White clay beds megascopically similar to the Bishop Ash occur in the Fair Oaks Formation, a chronologically correlative unit north of the American River (Robert S. Ford, California Department of Water Resources, personal communication, 1970).

[14] Curry, *op. cit.*, footnote 9; and R. P. Sharp, "Sherwin Till-Bishop Tuff Geological Relationships, Sierra Nevada, California," *Geological Society of America Bulletin*, Vol. 79 (1968), pp. 351-364.

Riverbank Formation

As originally defined along the lower American River, the Riverbank Formation was thought to consist of one basal channel gravel and overlying fan deposits.[15] Now, however, new subsurface data show that there are at least two distinct ancestral American River channels within the Riverbank Formation. Overlying each are fine-grained overbank and fan deposits and distinctive soils, buried and relict.

Of all Pleistocene formations in the American River area, the Riverbank is best known with respect to its lithology, thickness, and facies changes. Numerous quarry exposures and abundant subsurface data make it possible to trace with great accuracy the buried gravel-filled channels within the formation.

As shown in Figure 2, the older Riverbank channel trends from terrace deposits near Mather Air Force Base southwestwardly to a depth of 60 feet below sea level near the town of Franklin. The channel ranges in width from about one and one-half miles to two miles and is filled with metamorphic gravels and granitic sand, generally decreasing in size downstream. Logs of many closely spaced water wells show that the gravels are often 40 feet thick yet completely absent a few yards away from the channel edge. This relative sharpness of the channel boundaries is also borne out by observation in gravel quarries at Perkins, immediately east of Sacramento.[16] Here the trend, thickness, and depth of the gravels suggest that they were deposited in relatively steep-walled "canyons," cut at least 40 feet into older alluvium and later covered by fine-grained sand and silt outwash.

The age of the older Riverbank channel is unknown; however, it occurs within a stratigraphic interval bounded by sediments radiometrically dated approximately 100,000 and 600,000 years old, respectively.[17] The channel form, trend, and its close areal proximity

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[15] Shlemon, *op. cit.*, footnote 4, p. 7.

[16] Best exposures are in gravel quarries of A. Teichert and Son (NW 1/4, sec. 24, T. 8 N., R. 5 E., Mt. Diablo).

[17] R. J. Shlemon and R. O. Hansen, "Radiometric and Faunal Dating of Quaternary Alluvium in the Sacramento Area, California," (Abs.), *Geologic Society of America, Cordilleran Section, Part 3* (Eugene, Oregon, 1969), pp. 61-62.

to younger dated deposits suggest that the older Riverbank channel may possibly be about 270,000 years old, perhaps correlative to glaciations recognized locally in the Sierra Nevada and world-wide in deep sea cores.[18]

The younger Riverbank age channel similarly is clearly defined in well logs and gravel quarries. As in other ancestral American River channels, the filling deposits are mostly metamorphic cobbles and boulders and coarse-grained granitic sands. Present also are a few granitic rocks now weathered to grus. Cross-bedding and a crude imbricate structure suggest that deposition occurred in a stream flowing southwestward, a trend also supported by well log data (Figure 2). Overlying the gravels in abrupt but conformable contact are sands and silts. A few water-worn gravel lenses show, however, that the younger deposits are primarily fluvial although some loess may be present.

The base of the younger Riverbank age gravels is traced to about 60 feet below sea level or about 80 feet below the land surface in the "south area" of the city of Sacramento. Where exposed in gravel quarries near Perkins, sediments immediately above the gravels contain a rich assemblage of vertebrate fauna including camel (*Camelops hesternus*), mammoth (*Mammuthus*), and horse (*Equus*). Uranium

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[18] Based on comparative weathering of alluvial formations in the San Joaquin Valley, the Riverbank Formation is probably less than 300,000 years old and perhaps equivalent to the Hobart glaciation in the Sierra Nevada; R. J. Janda and M. G. Croft, "The Stratigraphic Significance of a Sequence of Noncalcic Brown Soils Formed on the Quaternary Alluvium of the Northeastern San Joaquin Valley, California," in R. B. Morrison and H. E. Wright (eds.), *Quaternary Soils*, Proceedings, Vol. 9, VII Congress, International Association for Quaternary Research (Reno: University of Nevada, Desert Research Institute, 1967), pp. 157-190; P. W. Birkeland, "Pleistocene Glaciation of the Northern Sierra Nevada North of Lake Tahoe, California," *Journal of Geology*, Vol. 72, (1964), pp. 810-825. According to deep sea temperature curves of Emiliani, major world-wide cooling (glaciation) occurred about 110, 180, and 275 thousand years ago. Chronologically, the older Riverbank age channel may be correlative with one of the earlier cold epochs but which is at present unknown; C. Emiliani, "Cenozoic Climatic Changes as Indicated by the Stratigraphy and Chronology of Deep-Sea Cores of Globerigina-Ooze Facies," in R. W. Fairbridge (ed.), *Solar Variations, Climatic Change, and Related Geophysical Problems, Annals of the New York Academy of Sciences*, Vol. 95, (1961), pp. 521-536.

and actinium series dating of these bones yield an average age of 103,000 ± 6,000 years.[19] This age and dating technique is also supported by a finite radiocarbon date of greater than 38,000 years for willow and sycamore wood preserved in sediments stratigraphically adjacent to the bone-bearing units.[20]

There is no disconformity or buried soil separating the channel gravels from the overlying radiometrically dated sediments. Because of this close stratigraphic proximity, inferentially, the gravels were laid down by an ancestral American River, perhaps 110,000 years ago, a time of world-wide cooling as deduced from deep sea cores.[21]

Capping much of the Riverbank Formation are fine-grained sands and silts. The silts especially have weathered giving rise to a regionally extensive well-developed soil, the San Joaquin series (Abruptic Durixeralf).[22] This soil is locally dissected but on the lower edges of Riverbank-age fans is buried by sediments of the Modesto Formation. Yet in the subsurface where now exposed in quarries and road cuts, this post-Riverbank soil is megascopically similar in profile development to the modern surface San Joaquin soil. The same stratigraphic relationship occurs widely along the east side of the Sacramento and San Joaquin valleys, thus indicating that the San Joaquin soil reached its strong degree of profile development before burial in Modesto time. Further, it implies that the landscape (top of the Riverbank Formation alluvium) must have been relatively stable during the interval between deposition of the Riverbank and Modesto formations, allowing soil development to proceed without interference from active degradation or aggradation.

Modesto Formation

Along the lower American River from Nimbus Dam westward to the confluence of the Sacramento River the Modesto Formation was laid down in a one-mile wide "trench" cut into Riverbank age and older alluvium. The modern American River is confined to this trench with Holocene floodplain sediments covering much of the Modesto Formation, especially downstream in the city of Sacramento.

Two distinct fills of Modesto age are recognized in the lower American River area (Figure 3). The oldest is a basal gravel fill, lithologically similar to older ancestral channel deposits of the American River. Traced in numerous bridge borings and well logs, the base of the gravel occurs about 50 feet below sea level at the Sacramento River confluence. Gravel thickness and coarseness suggest that the Modesto age channel continued westward and deeper in the subsurface, but subsequent eastward migration of the Sacramento River has eroded many American River deposits. Also the longitudinal profile of the gravel fill, as indicated in bridge borings, is concave upward and has no unusual "knicks." Thus, apparently there has been no significant downwarping in this portion of the Valley trough at least since Modesto time.

The younger Modesto age fill, primarily coarse- to medium-grained granitic sand, underlies a terrace on the south side of the modern American River (Figure 3). The terrace increases in elevation from a few feet above the floodplain near Perkins to slightly over 20 feet about 10 miles upstream near Nimbus Dam. These younger sediments merge downstream into Holocene floodplain and natural levee deposits of the Sacramento River.

The absolute age of the Modesto Formation is unknown. However preliminary uranium-thorium dating of vertebrate bones outside of the lower American River area but in stratigraphically contiguous sediments yielded an approximate date of 27,000 years.[23] Probably more than 100 feet of Modesto age sediments underlie the dated bones, suggesting that the start of deposition occurred much earlier but certainly after deposition of the 103,000 year old radiometrically dated sediments of upper Riverbank Formation. Although not precisely dated, topographic expression and relative profile development of capping soils suggest that Modesto-age deposits were laid down during the last major glaciation in the Sierra Nevada, prob-

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[19] R. O. Hansen, and E. L. Begg, "Age of Quaternary Sediments and Soils in the Sacramento Area, California by Uranium and Actinum Series Dating of Vertebrate Fossils," *Earth and Planetary Science Letters*, Vol. 8, (1970), pp. 411-419.

[20] Shlemon and Hansen, *op. cit.*, footnote 17.

[21] Emiliani, *op. cit.*, footnote 18, p. 530.

[22] R. C. Cole, L. K. Stromberg, O. F. Bartholomew, and J. L. Retzer, "Soil Survey of the Sacramento Area, California," *U. S. Department of Agriculture, Soil Conservation Service, series 1941*, No. 11 (1954), 101 pp.

[23] Dennis Garber, University of California, Davis (personal communication, 1970).

ably the Tahoe and Tioga advances, respectively.[24] The Sierran deposits in turn are believed correlative with Wisconsinian stage outwash in the Midcontinent.[25]

LANDSCAPE EVOLUTION DURING RIVERBANK TIME

The Riverbank Formation records best the typical cycle of Pleistocene landscape cutting, filling, and stability in the lower American River area. The soil and rock stratigraphic units that make up the Formation are well exposed in numerous gravel quarries and road cuts; and thousands of water wells penetrate the Riverbank Formation. From well logs one can readily plot the subsurface course, thickness, and depth of several ancient channels. Hence, from the Riverbank-age stratigraphy is deduced a chronology of changing, climatically-controlled paleoenvironments. Together with some assumptions regarding local tectonism and landscape stability, this chronology is discussed below and shown in Figure 4a-d.

In the lower American River area gravel-filled channels of the Riverbank Formation extend to about 60 feet below sea level. This depth may be due to post-depositional subsidence of the Valley trough, glacio-eustatic fluctuations of local base level, or a combination of both. Quaternary tectonism may have affected the Riverbank-age channels, for regional downwarping of the Great Valley has been well-documented.[26] Yet there is also evidence suggesting that the depths of the Riverbank channels were controlled more by major glacio-eustatic changes of base level than by tectonism. For example, the Modesto Formation, the youngest Pleistocene unit in the area, contains a basal gravel-filled channel also traceable to at least 50 feet below present sea level. Stratigraphic position and preliminary radiometric dating indicate that the Modesto-age channel is probably not more than 50 or 60 thousand years old, and perhaps much younger.[27] It seems unlikely—and there is no field evidence to the contrary—that channel depth is due to local subsidence of 50 feet or more in latest Pleistocene or Holocene time. Further, during the last glaciation the regional drainage, the Sacramento River, cut a bedrock canyon increasing in depth from about 120 feet below present sea level in the Carquinez Strait to minus 380 feet "downstream" at the Golden Gate.[28] Upstream incision of approximately 60 feet by the lower American River in response to glacio-eustatic lowering of sea level is therefore quite plausible.[29] Thus although possibly affected by regional downwarping, their depth, gradient, and age suggest that the Riverbank and other Pleistocene American River channels repeatedly incised older alluvium when sea level was low-

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[24] Shlemon, *op. cit.*, footnote 4, p. 10; P. W. Birkeland, "Correlation of Soils of Stratigraphic Importance in Western Nevada and California, and Their Relative Rates of Profile Development," in R. B. Morrison and H. E. Wright (eds.), *Quaternary Soils*, Proceedings, Vol. 9, VII Congress, International Association of Quaternary Research (Reno: University of Nevada, Desert Research Institute, 1967), pp. 70-91; and Janda and Croft, *op. cit.*, footnote 18, p. 173.

[25] R. P. Sharp, and J. H. Birman, "Additions to the Classical Sequence of Pleistocene Glaciations, Sierra Nevada, California," *Geological Society of America Bulletin*, Vol. 74 (1963), pp. 1079-1086; and R. B. Morrison, "Quaternary Geology of the Great Basin," in H. E. Wright and D. G. Frey (eds.), *The Quaternary of the United States* (Princeton: Princeton University Press, 1965), pp. 265-285.

[26] Most noticeably in the San Joaquin Valley where lacustrine deposits have been identified more than 400 feet below present sea level. See G. H. Davis, J. H. Green, F. H. Olmstead, and D. W. Brown, "Ground-Water Conditions and Storage Capacity in the San Joaquin Valley, California," *U. S. Geological Survey Water-Supply Paper 1469* (1959), 287 pp.; R. J. Arkley, "The Geology, Geomorphology, and Soils of the San Joaquin Valley in the Vicinity of the Merced River, California," *Geologic Guide to the Merced Canyon and Yosemite Valley*, Bulletin 182 (1962), California Division of Mines and Geology, pp. 25-32; and M. G. Croft, "Geology and Radiocarbon Ages of Late Pleistocene Lacustrine Clay Deposits, Southern Part of San Joaquin Valley, California," *U. S. Geological Survey Professional Paper 600-B* (1968), pp. B151-B156.

[27] Based on inferred correlation with Tahoe and Tioga glacial advances in the Sierra Nevada.

[28] Subsurface bedrock channels under San Francisco Bay were mapped by P. R. Carlson, R. R. Alpha, and D. S. McCullogh, "The Floor of Central San Francisco Bay," *Mineral Information Service*, California Division of Mines and Geology, Vol. 23 (1970), pp. 97-107. Ancestral Sacramento River bedrock elevation through the intervening Carquinez Strait, as interpreted from bridge borings, decreases from about 120 feet below sea level near Antioch (Sherman Island) on the east to −130 feet near Vallejo (Carquinez Bridge) on the west.

[29] Discontinuous remnants of gravel-filled ancestral channels of the Mokelumne River, debouching directly into the California Delta, are identified more than 125 feet below present sea level. This depth for the most part was probably glacio-eustatically controlled although some post-depositional downwarping has occurred: R. J. Shlemon, "The Quaternary Deltaic and Channel System in the Central Great Valley, California," *Annals, Association of American Geographers*, Vol. 61, (1971), pp. 427-440.

ered during glacial epochs. In the lower American River area, at least, climatic-eustatic changes were superimposed upon possible regional tectonism and were the most important factors influencing local landscape evolution.

Landscape stability, as used in this study, is a relative term referring to transitional periods or stages between major glaciations and interglaciations when the hydrologic variables of the local trunk stream, the American River, were so adjusted that over the long-run adjacent terraces and interfluves were neither significantly eroded or aggraded. Stability is thus viewed as a transitory stage in landscape evolution controlled mainly by changes in regional climatic-hydrologic regimes. In areas of high tectonic activity adjacent to the lower American River, such as the Sierra Nevada or possibly the center of the Valley trough, there was probably never long-term landscape stability during Quaternary time.

Well-log lithologic and thickness data show that initially each ancestral American River in general and those of Riverbank age in particular cut canyon-like steep-walled channels approximately 1 mile wide and 40 to 60 feet deep (Figure 4a). Shortly thereafter, small side-stream tributaries of the lower American and adjacent trunk streams responded to the new base level by cutting downward and extending their drainage nets into older alluvium (Figure 4b; Figure 5).[30]

Shortly after entrenchment, the Riverbank-age American River channels were filled with metamorphic gravels and granitic sand (Figure 4c). The size and extent of channel fill suggest that the ancestral main streams had much greater competence than the present rivers in order to transport their gravel load almost to the center of the Sacramento Valley trough. Increased competence probably resulted from a combination of factors affecting the hydraulic regime of the lower American River during glacial times; primarily increased gradient caused by sea level lowering and greater water availability owing to glaciation in the Sierra Nevada.

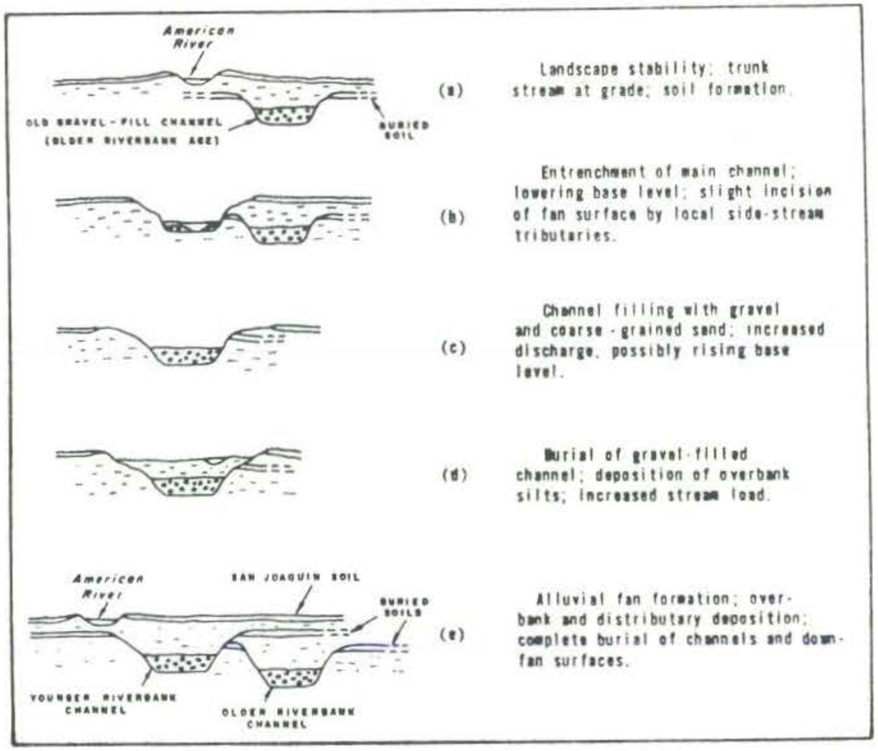

Figure 4. Landscape evolution during younger Riverbank time.

Deposition of gravel in the Riverbank age channels apparently ceased quite rapidly (Figure 4d). This is shown in numerous gravel quarries by the very sharp contact between basal gravels and overlying sand and silt. At this boundary, exposed more than a mile in some quarries, there is no disconformity or buried soil suggesting a hiatus in deposition. Apparently discharge of the trunk stream abruptly decreased so that few if any gravels were being transported far downstream; however stream load apparently increased as fine-grained sand and silt (glacial flour) buried the gravels in the entrenched channels eventually spreading outward and downstream as overbank and levee deposits to cover existing topography and finally to form extensive alluvial fans (Figure 4e). Small gravel lenses and current bedding within the silt indicate that fluvial deposition predominated, but a few zones of unreworked homogeneous

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[30] This is best illustrated in the Sacramento area along the Cosumnes River where large-scale topographic maps show that 35-foot deep gullies cut into Riverbank-age fans during glacial time have been dammed by younger main-channel fill (Modesto Formation). See, for example, the Elk Grove, California Quadrangle; sections 2, 3, 10, and 11, T. 6 N., R. 6 E., Mt. Diablo.

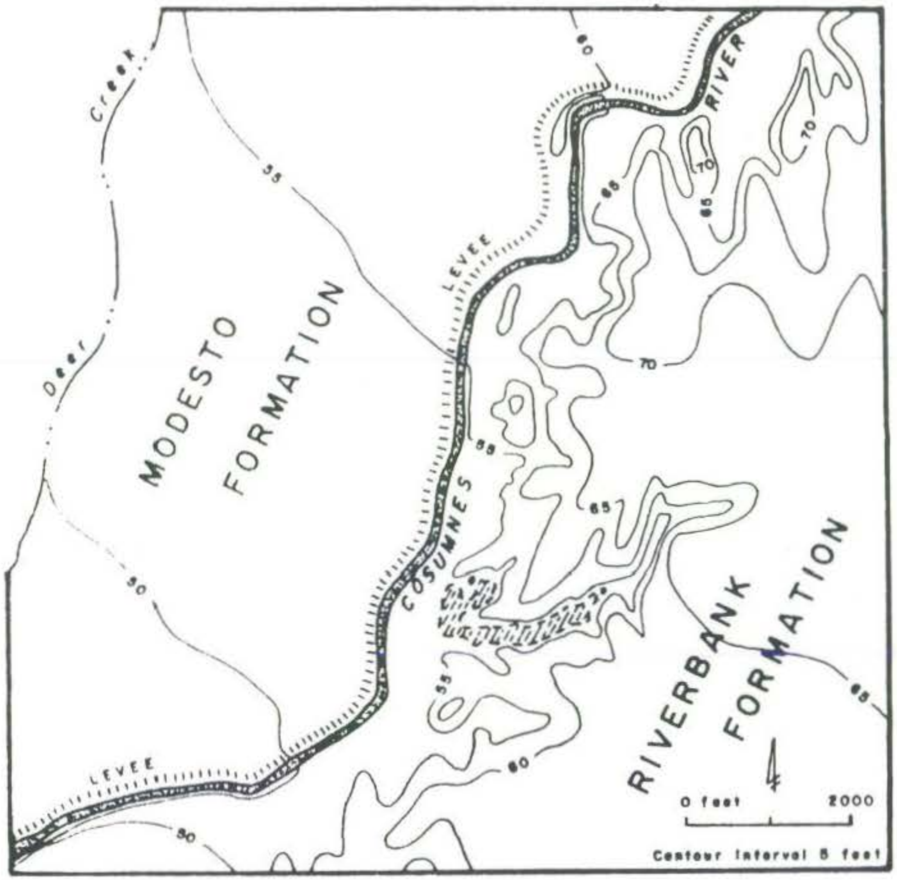

Figure 5. Typical sidestream tributary cut into older alluvium of the Riverbank Formation during early glacial time and later "dammed" by late-glacial main-channel fill. This tributary graded to a Modesto-age Cosumnes River gravel-filled channel approximately 35 feet below the present floodplain. (Topography from the Elk Grove, California Quadrangle; Sections 2, 3, 10, and 11, T. 6 N., R. 6 E., Mt. Diablo.)

silt suggest that some locally-derived loess may have been incorporated into the covering sediments.

Preserved also in the Riverbank age section is the typical downstream thickening wedge of alluvium. This suggests that the postglacial rising sea level was also reducing the trunk stream gradient (lower American River) at the same time stream load was approaching grade. Therefore, at that time, there was little if any erosion or deposition in the interfluves between the westward flowing main

streams, and the regional landscape approached stability. As today, active degradation probably occurred upstream in the Sierra Nevada and foothill canyons, and deposition of fine-grained sediments continued unabated downstream near the Valley trough. On these stable surfaces during interglacial time the post-Riverbank soils developed (e.g. San Joaquin series), some remaining uneroded during the next climatically-induced cycle of cutting and filling and thus becoming relict, others cut or buried by younger channels or alluvium, respectively. Whether the post-Riverbank soils attained their particular degree of profile development in one interval of landscape stability (interglacial/interstadial) or are the product of continuous weathering through time is debatable.[31] However, soils on sediments laid down since the last major Sierran glaciation at best have developed only an incipient textural B horizon and thus are thought to be in weathering "harmony" with the present climate.[32]

LANDSCAPE EVOLUTION: A STRATIGRAPHIC MODEL

The abundance of surface and subsurface data in the lower American River area offers a unique opportunity to interpret the effect of changing Pleistocene climates on the regional landscape. Here the various stratigraphic units record a systematic sequence of landscape cutting, filling, and stability related to glacial advances and recessions in the Sierra Nevada and to glacio-eustatic fluctuations of sea level. So well preserved are Pleistocene soil and rock stratigraphic units that it now seems possible to propose a model of landscape evolution for this area of low relief; one which qualitatively assesses changing discharge-load relationships of a trunk stream (American River), oscillations of base level, and the general climatic regime (Table 1).

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[31] Accelerated episodic soil development thought to be due to increased interglacial and interstadial temperature or precipitation or both is postulated by many stratigraphers, *e.g.*, G. M. Richmond, "Quaternary Stratigraphy of the La Sal Mountains, Utah," *U. S. Geological Survey Professional Paper 324*, (1962), 135 pp., and R. B. Morrison, "Principles of Quaternary Soil Stratigraphy," in R. B. Morrison and H. E. Wright (eds.), *Quaternary Soils*, Proceedings, Vol. 9, VII Congress, International Association for Quaternary Research (Reno: University of Nevada, Desert Research Institute, 1967), pp. 1-69.

[32] Janda and Croft, *op. cit.*, footnote 18, p. 184.

Starting with an epoch of regional landscape stability, probably similar to the present, five transitional stages of aggradation and degradation are identified from the stratigraphic record. Along the lower American River there is sufficient evidence to show that the region has passed through at least four five-stage cycles of landscape change within the last 600,000 years. Remnants of gravel-filled channels and discontinuous buried soils suggest also there were at least three older cycles. The model, however, is based primarily on environmental interpretation of sediments and facies changes within the younger, better-documented Pleistocene units.

STAGE 1—*Landscape Stability*

The natural climatic-hydrologic regime that gave rise to landscape stability in the past is similar to that affecting the landscape today. Before hydraulic mining, dam and reservoir construction, deforestation, and other activities of man, the long-term degradational-aggradational regime of the lower American River and adjacent landsurface apparently was quite stable. In the unmodified environment, aggradational processes dominated in the Valley trough as natural levee and basin sediments were laid down in periodic floods. Degradation continued upstream in the Sierra Nevada as high energy fluvial systems constantly expanded. In the intervening low elevation transition zone, however, between the Valley trough and the foothills, the Pleistocene alluvial fans and river terraces were seemingly little affected by erosion or deposition. Controlled by the contemporary combination of climate, relative development of Sierran glaciers, and position of sea level, the pristine fluvial environment of the lower river area was one of landscape stability.

The stable environment occurred periodically in the past. Then as now the lower American River, the regional trunk stream, was probably at grade with most of its load eventually transported into the Sacramento River.[38] Discharge was controlled primarily by winter cyclonic rain and snow in the headwaters with few or no cirque glaciers present to affect the hydraulic regime. Sea level was probably

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[38] "Grade" is here used in the sense of stream quasi-equilibrium over a long period of time, in the order of thousands of years.

Table 1. FIVE-STAGE CYCLE OF LANDSCAPE EVOLUTION—LOWER AMERICAN RIVER, CALIFORNIA

General climatic regime	Landscape evolution; General physical processes	Hydrologic properties of the lower American River		Relative development of sierran glaciers	Relative position of sea-level (Regional base)	Stage in erosional-depositional cycle
		Discharge	Load			
Interglacial	Landscape stability; soil formation	Stream at grade	Balanced load	None or few cirque glaciers	Approximately at present sea-level	1
Latest glacial-earliest interglacial	Regional aggradation; overbank and distributary deposition; alluvial fan formation	Approaching grade	Increased	Restricted cirque glaciers	Approaching present level	5
Late glacial	Local aggradation; burial of main stream gravels; cessation of side-stream dissection; downstream silt deposition; transitional to stage 5	Decreasing	Highly increased	General recession of ice fronts; decreasing meltwater; increasing glacial flour	Rising sea-level	4
Full glacial	Filling of trunk stream channel with gravels and coarse-grained outwash	Highly increased	Increased	Fluctuating or receding of ice front from maximum advance; increased meltwater	Sea-level fluctuating near maximum low levels	3
Onset of glaciation	Regional degradation entrenchment of trunk stream channel; incision of sidestream tributaries; main valley widening	Increased	No change or reduced	Onset to maximum advance of ice	Rapidly lowering sea-level	2
Interglacial	Landscape stability; soil formation	Stream at grade	Balanced load	None or few cirque glaciers	Approximately at present sea-level	1

at or close to its present elevation. Each degradational-aggradational cycle in the lower American River area, therefore, apparently was preceded by an epoch of landscape stability controlled by base level and trunk stream discharge, similar to the present.

STAGE 2—*Regional Degradation*

Because detailed subsurface data show that each ancestral American River incised a deep canyon into older alluvium, inferentially the onset of regional degradation occurred quite rapidly, at least along the trunk streams. Cutting well below the present surface, the old streams apparently graded to a lowered sea level. Since major changes in Pleistocene sea levels are intimately controlled by world-wide glaciation, presumably alpine glaciers in the Sierra Nevada were advancing, perhaps to their maximum down-valley position. Possible increased precipitation in the Sacramento Valley during glacial times apparently had little effect on discharge of the lower American River, at least compared with meltwater coming from active glaciers in the Sierra Nevada. Reduced sedimentation owing to changing local vegetation likewise seems insignificant. At least such is not obvious in the stratigraphic record. Combined with regression of the sea and an inferred increase in discharge, the trunk streams cut deep courses to the new eustatically-lowered base. Local sidestreams were also affected by the change of base level, cutting headward into older alluvium. Onset of glaciation, therefore, produced a period of active regional degradation.

STAGE 3—*Filling of Trunk Stream Channels*

During maximum glaciation the glacial and periglacial terrain of the high Sierra Nevada apparently supplied by frost action and mass-movement an inordinant amount of debris to the American River. With increased competence stemming from glacial meltwater, the American River transported large cobbles and boulders far out into the Valley trough. These braided stream deposits, characterized by abundant transverse and longitudinal bars, slowly filled the entrenched trunk stream channels. Far downstream in the lower Sacramento River and California Delta the fine-grained suspended load was laid down as the post-glacial sea began to rise.

STAGE 4—*Burial of Trunk Stream Gravels*

With the general recession of glacial fronts in the Sierra Nevada the discharge of the lower American River probably still remained high. Now, however, sediment load was apparently greatly increased for the stream was highly charged with glacial flour. Carried to the lower course as fine-grained sands and silts, these sediments completely filled the entrenched channels, burying the basal gravels. Presumably some of the silts were reworked by wind shortly after deposition in the Valley for thin-bedded homogeneous silt, superficially similar to loess, occurs in the covering sediments. However, local gravel lenses suggest that fluvial rather than eolian processes continued to dominate the aggradational regime.

The mouths of many sidestreams, tributary to the lower American River and adjacent trunk streams, were now dammed owing to filling of the main valleys. Additionally with climatic amelioration local precipitation may have decreased thus reducing headward extension of small drainage nets into older alluvial fan topography. During this stage, therefore, the incised main channels were filled and local relief was reduced, perhaps close to present level.

STAGE 5—*Regional Aggradation*

As Sierran glaciers continued to retreat, the sea presumably was rising to its present level. However, "late glacial" fine-grained sediments were still carried out into the Valley trough, laid down as distributary and overbank deposits radiating outward from the apex of alluvial fans. Downstream the fans coalesced and distributaries of adjacent trunk streams comingled before flowing into the Sacramento River or the California Delta. High stream load and a rising glacio-eustatic base level combined giving rise to general landscape filling. Many downstream sections of alluvial fans, terraces, and natural levees undissected throughout glacial time were now covered and their capping soils buried. Thus by latest glacial or earliest interglacial time regional aggradation prevailed.

STAGE 1—*Return to Landscape Stability*

Completion of the landscape cycle and a return to relative stability of landforms between the Valley trough and the foothills occurred with the almost complete melting of Sierran glaciers and a rise of the sea to about the present level. As today, dissection continued in the foothills and in the high Sierra and filling took place downstream in the floodplains. On the intervening fans, especially along the interfluves between trunk streams, stable surfaces weathered and soil formed on the newly deposited alluvium. Average temperatures may have been the same as today or possibly somewhat higher. But with glacial recession and a high stand of sea level the interglacial or interstadial climatic-hydrologic regime led to landscape stability.

The cycle of landscape evolution was now complete, having passed through five stages: trunk stream incision in earliest glacial time followed by short-term headward extension of side-stream tributaries; channel filling during maximum glaciations; channel burial in a late glacial stage; alluvial fan formation and regional aggradation during late glacial and earliest interglacial time, the individual phases of which were controlled by changing base level and discharge-load relationships; and relative landscape stability during interglaciation.

THE LOWER AMERICAN RIVER MODEL—DISCUSSION

The model of landscape evolution proposed for the lower American River area is primarily an environmental interpretation of Pleistocene stratigraphy. It incorporates a sequential history of degradation, aggradation, and stability as recorded in the local alluvial sequence. Controlling landscape development were regional forces that operated periodically in time and intensity. In the lower American River area these forces probably were Pleistocene tectonism, climatic change, or a combination of both.

Although California is certainly a tectonically active region, that portion of the lower American River between the Sierra Nevada foothills and the Valley trough seemingly was little affected during the time span encompassed by the model. Tectonism is often shown by downstream convergence of terraces usually indicating either uplift in headwaters or subsidence downvalley. Terraces adjacent to the lower American River do converge downstream; however stratigraphic superposition and facies changes show that terrace convergence is more apparent than real. Alluvial fan and terrace deposits were laid down at their present elevation. With each succeeding cycle of erosion, deposition, and stability, younger sediments

were carried progressively farther downstream into the structural trough of the Sacramento Valley. Gradients of older terraces computed along lines normal to the modern river successively increase and when plotted in profile appear to converge downstream. However this is not necessarily indicative of uplift in the headwaters but rather of a climatically-controlled periodic extension of the longitudinal profile of the American River.

It also seems unlikely that the four or more cycles of cutting and filling recorded in the American River sediments are due mainly to downwarping of the Valley trough. Local subsidence in the Central Valley of California is well-known but not evident in the American River stratigraphy.

Therefore the most likely cause of local landscape change was the indirect effect of Pleistocene climatic change, possibly superimposed on sediments deposited into a slowly subsiding basin. The effect of climatic change on landscapes is well-documented and has been included as a basic tenet in several other models.[34] In the lower American River area it thus seems clear that climatically-controlled sea-level change caused periodic entrenchment of main channels. And similarly, advances and recessions of Sierra Nevada glaciers brought about episodic sedimentation downstream. Sediments in the lower American River area, preserved as a repeated sequence of coarse-grained deposits (channel gravel) overlain by fine-grained outwash, are thus best explained as a product of major oscillations of climate during the Pleistocene Epoch.

The American River landscape model records yet another phenomenon worthy of further study—specifically the apparent "sudden" sea-level control of main stream entrenchment and the abrupt change in sedimentation from channel gravel to overlying sand and

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[34] Schumm, *op. cit.*, footnote 2; J. C. Frye, and A. B. Leonard, "Pleistocene Geology of the Red River Basin in Texas." *University of Texas, Bureau of Economic Geology Report 49,* (1963), 48 pp.; L. H. Gile, J. W. Hawley, and R. B. Grossman, "Distribution and Genesis of Soils and Geomorphic Surfaces in a Desert Region of Southern New Mexico," *Guidebook, Soil-Geomorphology Field Conference, Soil Science Society of America,* (August 1970), 156 pp; R. T. Saucier, and A. R. Fleetwood, "Origin and Chronologic Significance of Late Quaternary Terraces, Ouachita River, Arkansas and Louisiana," *Geological Society of America Bulletin,* Vol. 81, (1970), pp. 869-890

silt. These stratigraphic characteristics repeated throughout the Pleistocene section seem to support the notion that glacial to interglacial climatic change was probably quite rapid.[35] What is unclear is the length of time between long-term meteorologic change and the effect of this change as recorded in the sediments. Perhaps rapidly cooling or warming temperatures preceding and following glaciation may be more the rule than the exception.

The American River landscape model agrees with many others in which degradation and aggradation are linked to Pleistocene climatic shifts. It most resembles models of landscape change in arid regions, differing only slightly in the time of cutting and filling.[36] Because it is based on interpretation of the lower American River stratigraphy, the model can be extended out of the region only with great care. Nevertheless in contrast to many models it evaluates the combined environmental effect of climatically-controlled changing base levels and main-stream discharge and load. The American River landscape model is therefore offered as a working hypothesis to be tested against Pleistocene stratigraphic and paleohydrologic records elsewhere.

Reprinted from Volume 34 (1972)
YEARBOOK of Association of Pacific Coast Geographers

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[35] R. A. Bryson, "The Character of Climatic Change, and the End of the Pleistocene." *Abstracts, American Quaternary Association*, 1st Meeting (Bozeman, Montana, 1970), p .20.

[36] Gile, Hawley, and Grossman, *op. cit.*, footnote 34.

ATTACHMENT 3

Shlemon, R. J., 1995, Pleistocene channels of the lower American River, Sacramento County, California: (appended, five-page article) *in* Franks, A., and Moss, G. (leaders), Geology of the Sacramento area, foothills, and the Sierra Nevada mountains: Association of Engineering Geologists Field Trip Guide, 1995 Annual Meeting of the Association of Engineering Geologists and Groundwater Resources Association, Sacramento, CA.

PLEISTOCENE CHANNELS OF THE LOWER AMERICAN RIVER, SACRAMENTO COUNTY, CALIFORNIA

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INTRODUCTION

At casual glance, the Sacramento area appears to be geomorphically rather benign. Indeed, prior to urbanization, the only obvious landforms were the approximately 10 foot high natural levees that border the lower Sacramento River, and the almost 50 foot high bluffs that mark the north side of the American River at the town of Fair Oaks. Only a few other minor landforms broke this apparent flat topography; namely, 5 to 10 foot "escarpments" south of the American River where crossed by Jackson Road (Highway 16) between Perkins and the Cosumnes River (Figure 1). These escarpments are significant, however, for they prove to be fluvial terraces, geomorphic expressions of several Pleistocene–age gravel–filled channels of the lower American River that, when traced into the subsurface by water well logs, extend to depths of 60 feet below sea level. Underneath Sacramento, therefore, from the modern American River on the north to almost the town of Franklin some 20 miles to the south (Fig. 1), is a buried topography with up to 75 feet of local relief that marks several epochs of channel cutting and filling and records major Pleistocene changes of climate, hydrology and sedimentation in the adjacent Sierra Nevada mountains.

The ancient American River deposits are mainly basal boulders and cobbles progressively overlain by fining–upward sands and silts which, in turn, are capped by buried paleosols. These deposits have long had economic and engineering geologic significance: (1) the gravels were first exploited for gold, particularly during the late 19th and early 20th centuries when Yuba–type bucket–line dredges plied the modern channel and adjacent terraces from Folsom downstream to Mather Air Force Base; (2) the gravels and overlying sands are still quarried for high–quality aggregate and road metal ; and (3) the gravels are highly permeable and, though once a primarily source for domestic water, are now, unfortunately, excellent pathways for downstream contaminant movement.

QUATERNARY FRAMEWORK

Four major Quaternary formations are recognized in the Sacramento area: the Modesto (youngest), the Riverbank, the Fair Oaks/Turlock Lake/Laguna complex, and the Arroyo Seco and older gravels (Shlemon, 1967, 1972; Helley and Harwood, 1985). Also present near the foothills, and particularly south of the American River, is the Plio– Pleistocene Mehrten formation (Gale and others, 1939), a term now generally applied to any sediments dominantly andesitic in lithology. The Modesto, Riverbank and Turlock Lake formations have been "extrapolated" from type localities in Stanislaus County (Davis and Hall, 1959); the Arroyo Seco, Laguna and Mehrten formations were described in adjacent San Joaquin and Amador counties (Gale and others, 1939); and the Fair Oaks formation was informally designated from bluff exposures on the north side of the American River between Fair Oaks and Folsom (Fig. 1; Shlemon, 1967).

As elsewhere in the Central Valley of California, the Sacramento Quaternary formations are distinguished and dated by geomorphic expression, by relative development of capping soil profiles, by radiocarbon and uranium–series dates, by magneto–stratigraphy and by association with

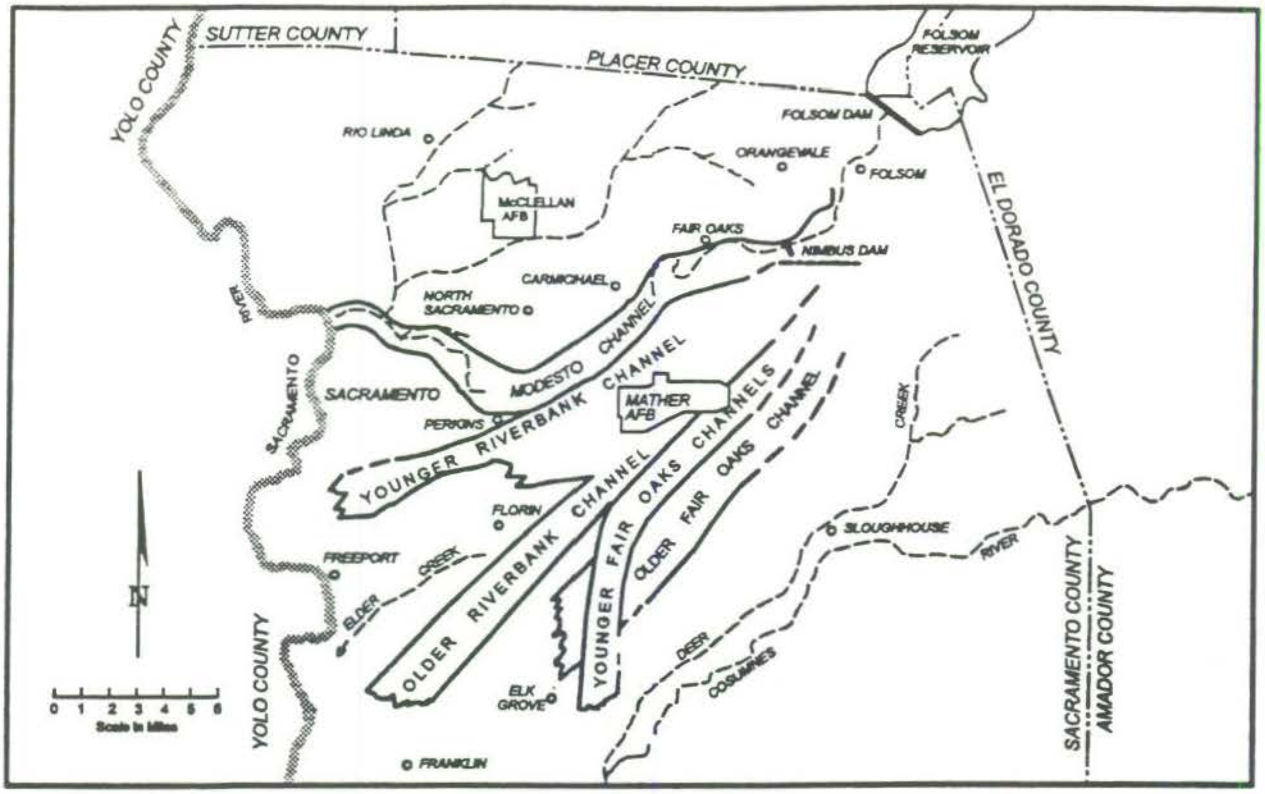

Fig. 1: Pleistocene channels of the lower American River (after Shlemon, 1972).

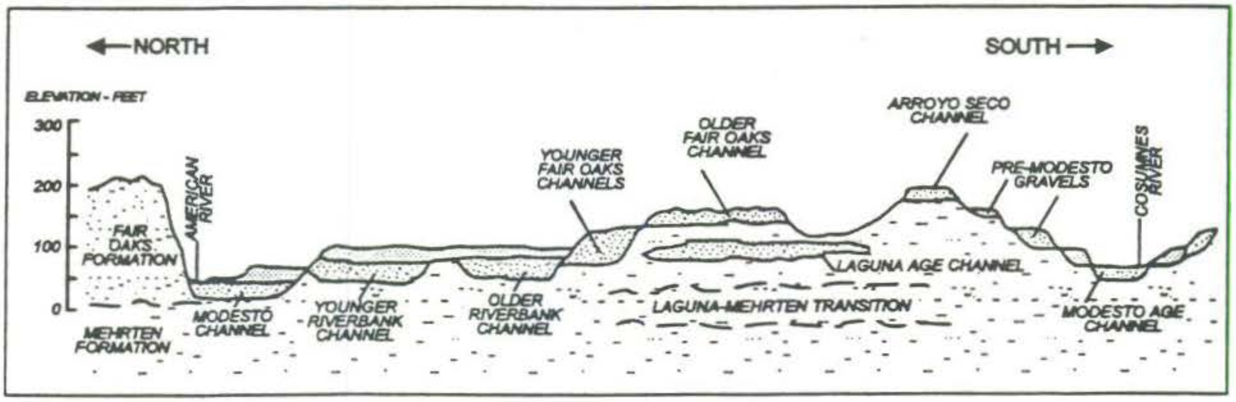

Fig. 2: Generalized composite cross section from the American River near Fair Oaks to the Cosumnes River showing Quaternary formations and the surface and buried channels. Vertical scale exaggerated (after Shlemon, 1972).

Sierra Nevada glacial events and the marine oxygen– isotope stage chronology (Janda and Croft, 1967; Shlemon, 1967, 1972; Hansen and Begg, 1970; Harden and Marchand, 1977; Marchand and Allwardt, 1981; Cherven, 1984; Helley and Harwood, 1985; Busacca and others, 1989). Each Sacramento–area formation is characterized by two or more basal gravel–filled channels. As shown on a schematic cross–section (Fig. 2), the channels have "migrated" northward throughout Pleistocene time from their "apex" near Folsom. The modern American River and underlying gravel of "late Modesto age," are now about 15 miles northwest of "early Fair Oaks" deposits (Figs. 1 and 2). The reason for this progressive northward movement is unknown; but may relate to differential subsidence in this portion of the Sacramento Valley (Shlemon, 1967).

PLEISTOCENE CHANNELS

Modesto–Age Channels

A younger Modesto–age channel underlies the modern American River from Folsom downstream to the Sacramento River confluence (Fig. 1). The basal gravel–filled channel, approximately 3,000 feet wide and up to 30 feet thick, was laid down during the last major Sierra Nevada glaciation (Tioga; isotope stage 2) about 12,000 to 20,000 yrs ago. Terrace remnants of an earlier Modesto channel (Tahoe ?; stage 4) were once apparent south of the American River at Rancho Cordova, but most have since been obliterated by dredging and urbanization.

Riverbank–Age Channels

Two distinct Riverbank–age channels are recognized in the Sacramento area: a younger terrace gravel, now dredged between Folsom and Mather Air Force Base, that is traced to 50 feet from Perkins to below the Sacramento Municipal Airport in South Sacramento; and an older gravel of similar thickness and depth identified in the subsurface almost to the town of Franklin in southwestern Sacramento County (Fig. 1).

The Riverbank–age channels are an estimated 150,000 and 250,000–yrs old respectively (isotope stages 6 and 8), and inferentially correlated to the Donner Lake and older glaciations in the Sierra Nevada. Soils capping Riverbank–age sediments are relict paleosols, and range in relative development from "strong" where preserved on permeable terrace gravels, to "very strong" with distinct argillic and silcrete horizons (Abruptic Durixeralf) where formed on overbank silts. A minimum age for the younger Riverbank deposits is about 100,000 years, as deduced by uranium–series dates (Hansen and Begg, 1970) on vertebrate fossils (camelops, mammuthus, equus) exposed in gravel quarries near Perkins (Fig. 1). Nearby quarry– exposed fossil redwood, sycamore and willow logs yielded expected radiocarbon dates greater than about 35,000 years (Shlemon, 1972).

The Riverbank–age channels have long extensively exploited for gold (Weatherbe, 1907; Winston and Janin, 1910). The last bucket–line dredge ceased operation adjacent to Mather AFB in 1964. The channels today are still economically important sources of high–quality aggregate as obtained from 50 feet deep gravel quarries in the Perkins area (Fig. 1).

Fair Oaks Channels

The informal type locality for the Fair Oaks formation is bluff exposures on the north bank of the American River adjacent to the Sunrise Avenue Bridge (Shlemon, 1967). Exposed here, near the top of the bluffs, are two, reddish–brown, strongly–developed buried paleosols, each capping overbank sands and silts. The paleosols are judged to have formed during interglacial epochs of regional landscape stability (Shlemon, 1967, 1972). Two less–distinct buried paleosols are exposed lower in the section, but can be observed only during times of low water. A magnetic reversal between the two paleosols is interpreted to mark the approximately 790,000–yr old Brunhes–Matuyama boundary. Accordingly, based on stratigraphic position between the younger Riverbank and the older Mehrten deposits, the Fair Oaks formation is probably equivalent in part to the Laguna formation mapped in southern Sacramento County (Gale and others, 1939), and to the Turlock Lake formation in Stanislaus County (Davis and Hall, 1959; Arkley, 1962).

The "glacial" channels of the Fair Oaks formation all lie south of the present American River (Figs. 1 and 2). Two and possibly three channels are present, each expressed geomorphically by low escarpments south of Mather AFB, and by gravels traced in the subsurface to more than 50 feet below land surface southward near Florin (Fig. 1). Most Fair Oaks deposits are sufficiently dissected such that the capping soil profiles are, at best, only moderately developed, forming on the modern micro–relief.

Numeric ages for the Fair Oaks channels and related overbank deposits are presently lacking; however, based primarily on stratigraphic position, on associated paleosols, and on magneto– stratigraphy, the formation probably reflects climatically controlled, periodic deposition and soil formation between about 450,000 and 800,000–yrs ago.

The Arroyo Seco and Older Gravels

The Arroyo Seco gravels were originally defined as broad pediment deposits that covered the Laguna and older formations (Gale and others, 1939). However, more recent investigations show that many Arroyo Seco gravels are remnant fluvial channels preserved on the highest– level drainage divides separating major west–flowing streams debouching from the Sierra Nevada (Arkley, 1962; Shlemon, 1967; Harden and Marchand, 1977; Marchand and Allwardt, 1981; Busacca and others, 1989). In the Sacramento area, the Arroyo Seco gravels are best preserved on the divide between the American and the Cosumnes River (Fig. 2). Soil profiles are typically very strongly developed (Palexeralfs), and locally a duripan (silcrete) is present. The age of the Arroyo Seco is unknown, but from stratigraphic position, it is likely to be at least a million years old.

Remnants of still older gravel channels, presumably deposited by ancestral American or Cosumnes Rivers, underlie the Arroyo Seco gravels. Most have no surface expression and are identified mainly in well logs and in road or canal–cut exposures, particularly apparent during the late 1960's construction of the Folsom South Canal (near the intersection of Jackson Road and Sunrise Avenue; Fig. 2).

SUMMARY

Each of the several Pleistocene channels of the lower American River area was cut during a major glaciation in the Sierra Nevada. Many now–buried channels are traceable eastward almost to the Sacramento River and to depths well below present sea level. The channel depth was also controlled by glacio– eustatic sea level lowering that affected the Sacramento, the Mokelumne, and other rivers that combine to form the Sacramento–San Joaquin Delta (Shlemon, 1971; Shlemon and Begg, 1975). For reasons yet unknown, the lower American River channels "migrated" northward throughout much of Pleistocene time; the present confluence with the Sacramento River was probably established in late Modesto time, about 12,000 to 20,000 years ago.

With periodic, climatically controlled fluctuation in discharge and rising sea level, the gravel– filled channels were eventually filled with overbank deposits and ultimately completely buried by distributary fan sediments. Most covering deposits were then subject to epochs of general landscape stability which permitted formation of strongly developed soil profiles.

Downstream channel reaches and covering soils were eventually incised and buried during the next epoch of regional climatic change as recorded by the distinctive subsurface gravels and buried paleosols. Upstream channel segments are geomorphically preserved as fluvial terrace gravels. The capping soils, particularly on Riverbank–age and older deposits, are generally strongly developed relict paleosols.

The lower American River channels and capping soils thus record at least a million years of changes in Pleistocene climatic, hydrology and sedimentation. In contrast to the high Sierra Nevada where successive glaciations tend to destroy evidence of earlier advances, the Sacramento area records major depositional epochs (channel gravels) as well as interglacial periods of relative landscape stability (soil formation). And most of this million–yr old stratigraphy is preserved less than 100 feet below the city and suburban streets of Sacramento.

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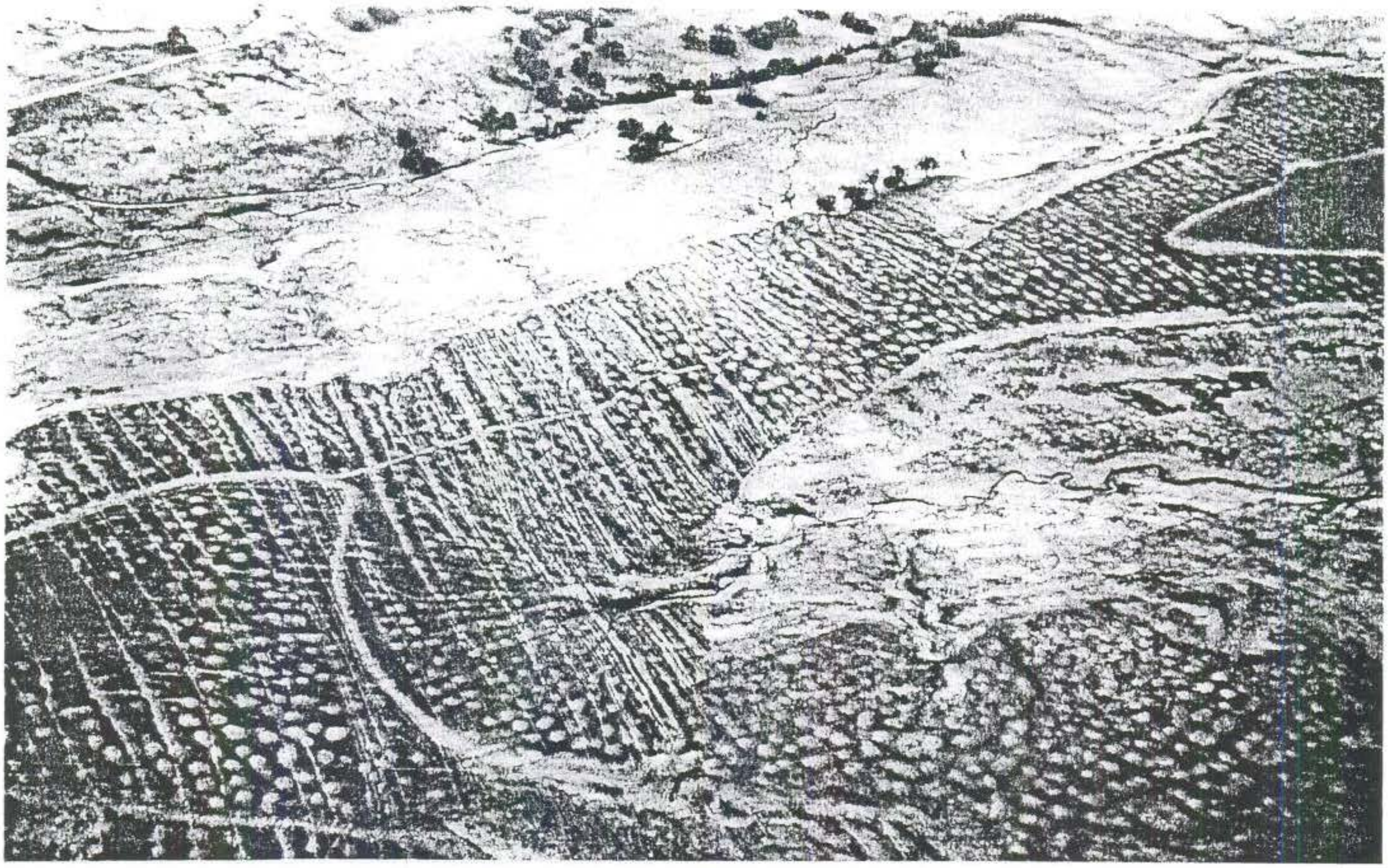


FRACTURE TRACES

Roy J. Shlemon, Eugene L. Begg, and Gordon L. Huntington

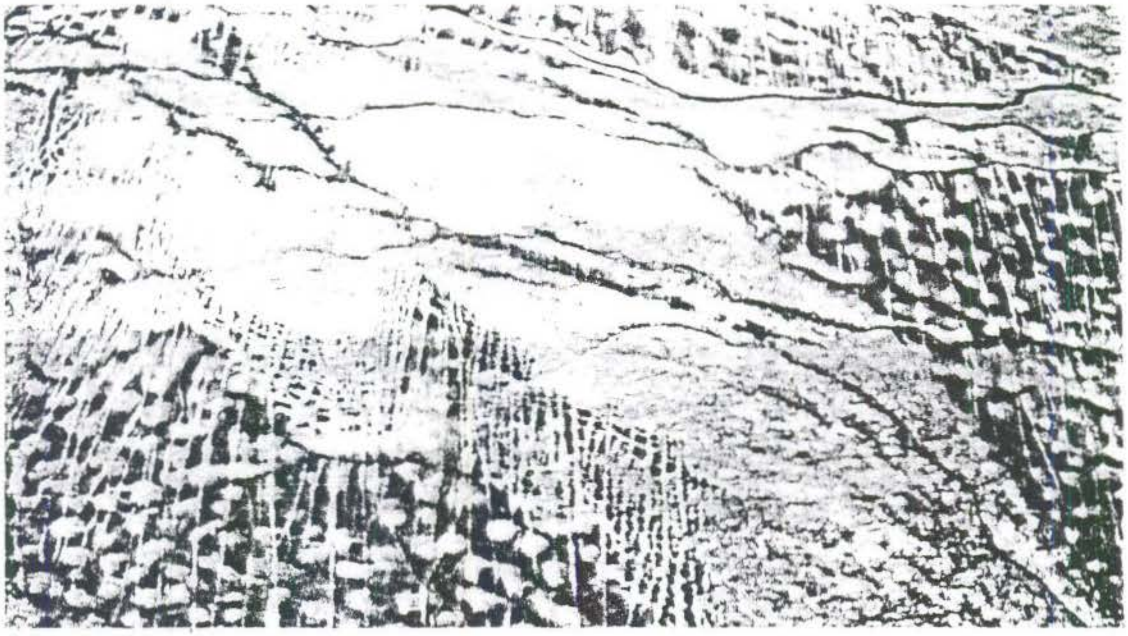
Photographs by the authors

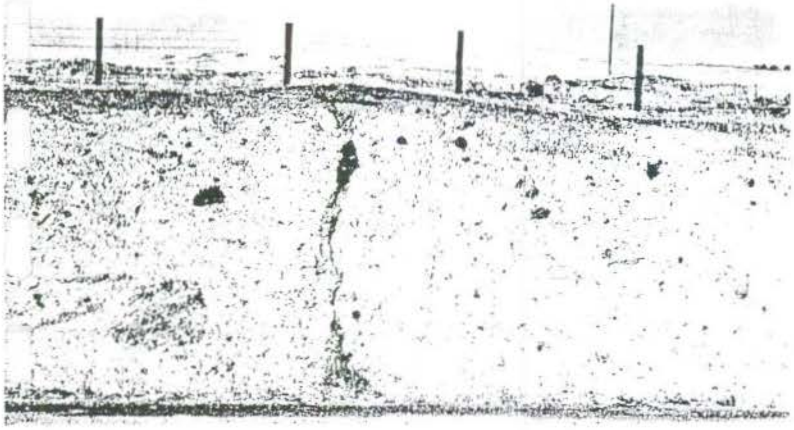
EVERY day thousands of people drive along Interstate Highway 80 between Sacramento and Auburn, for the most part not realizing that this route takes them but a few minutes from a patterned landscape of subparallel lines and dots superficially resembling the pre-Columbian agricultural ridged fields in Latin America, or the striking man-made terraces in Southeast Asia. Indeed, upon cursory aerial inspection, our first impulse was to ascribe the pattern to cattle grazing, or perhaps even to some form of early-day hydraulic or dredge mining, activities of man which cast seemingly indestructible imprints on the landscape. Was this linear terrain, covering some 17,000 acres in Placer County, the handiwork of man, the result of Pleistocene periglacial activity, or some other unknown process, either natural or man-induced? Possible answers to these questions, of course, could be obtained only by ground search.

Building new highways certainly disturbs the natural landscape. But for us, however, such construction was fortunate, for Placer County had recently completed a new road alignment (Sierra College Boulevard) across the linearly patterned ground. Exposed in the fresh roadcuts was the entire sequence of the Mehrten Formation, some 20 feet of andesitic gravel overlain by about 25 to 40 feet of tuff-breccia, apparently remnants of volcanic fluvial and mudflow deposits which swept down across the western slope of the Sierra Nevada some 5 to 12 million years ago. The tuff-breccia forms relatively flat-topped and nearly treeless plains, across which we could see the faint outlines of what proved to be the striking subparallel lines observed from the air. The "lines" were subtle ridges, about a foot high and 2 feet wide; and the "dots" were mounds, the largest about 25 feet in diameter and 3 feet high.

On this high topography grows light-colored tarweed *(Holocarpha virgata),* fescue grasses *(Festuca* spp.), soft chess *(Bromos mollus),* and ripgut *(B. rigidus).* Contrasting sharply in color with the ridge and mound vegetation are dark green forbs, foothill filaree *(Erodium obtusiplicatum)* and redstem filaree *(E. cicutarium)* which, just after the first winter rain, carpet the inter-ridge and mound areas. Cattle intensively graze the patterned ground, yet the linearity of vegetation is not de-

Above, part of the 17,000-acre dots-and-lines pattern near Highway 80 between Sacramento and Auburn.





Right, the varied patterns of rocks and soil, mounds and the fracture traces form a beautifully abstract pattern. Below, cross-section of a fracture trace in a road cut.

stroyed. Locally an incipient dendritic drainage is forming, but often the lineations cross even this pattern. Large blocks of breccia dot the surface, seemingly not concentrated in either ridge or swale area. There is, however, a noticeable alignment of mounds along the ridges, as if laid out by design.

Clearly, pocket gophers *(Geomys breviceps)* occupy the higher terrain of ridge and mound, for their fresh spoil and burrow holes are everywhere apparent. But whether the gophers made the mounds or simply occupied them is a moot question. It seems likely, and we find no evidence to the contrary, that the linear pattern was not man-induced, but rather is a natural phenomenon. But what natural agency could have given rise to the ridges and mounds, their alignment and vegetation, and striking northwest-southeast trend across the landscape? Fortunately some evidence appears in the roadcuts.

Extending vertically through the tuff-breccia, from the surface to the underlying gravels, are steeply-dipping parallel fractures, generally 20 to 40 feet apart. Toward the surface these fractures become V-shaped, as much as five feet wide. In these regions a loamy soil develops (Toomes series). On the fracture-zone soil, deeper and somewhat better drained than that in the inter-ridge and inter-mound swales, pocket gophers continually stir the earth, in essence acting as micro-plows. The better drainage, greater depth, and higher water holding capacity of the fracture-zone soil supports tarweed and summer annual grasses for one to four months longer than does the soil in the adjacent swales. The fractures occur only in the tuff-breccia; they do not pass into the underlying andesitic gravels nor into adjacent granitic or alluvial terrain.

The fractures may have originated during cooling or dessication of the avalanche and mud-flow deposits that gave rise to the breccia; or less likely they formed following gentle tilting of the region. Regardless of their genesis, the fracture traces are seemingly of great antiquity, yet still preserved on the landscape. Along the fractures moderately deep soils have developed; these soils, in turn, are continually reworked by gophers to form low mounds. And on the better-drained ridge and mound micro-topography grows a suite of natural and introduced weeds and grasses patently different from those in the adjoining shallow swales. This complicated interplay of geology, soils, water, vegetation, and animals has given rise to a striking natural patterned landscape within five minutes flight from Sacramento, so apparent from the air, yet almost invisible from the ground.

ATTACHMENT 5

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DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TO ACCOMPANY MAP MF-1790

GEOLOGIC MAP OF THE LATE CENOZOIC DEPOSITS OF THE SACRAMENTO VALLEY AND NORTHERN SIERRAN FOOTHILLS, CALIFORNIA

By

Edward J. Helley and David S. Harwood

INTRODUCTION

Sheet 1

The southernmost (sheet 1) of five map sheets depicts the late Cenozoic geology of the Sacramento Valley. This map area extends from the northern part of the Sacramento-San Joaquin delta north to about the latitude of Cache Creek, 16 km north of Sacramento. The foothills of the Sierra Nevada form the east margin; the low foothills of the Coast Ranges form the west margin. The western part of the map area is underlain by the Pliocene Tehama Formation, which also underlies the Dunnigan Hills in the northwestern part of the mapped area. Along much of the west margin of the valley, the Tehama lies unconformably on Cretaceous sedimentary rocks and is uncomformably overlain by the Pleistocene Red Bluff Formation and younger alluvium. Farther east, however, lower Tertiary rocks occur between the Cretaceous and Pliocene rocks. West of the Sacramento River, all the post-Red Bluff alluvium is deposited at a level below or in channels cut into the Tehama and Red Bluff Formations. These younger deposits, which include primarily the Modesto Formation and Holocene alluvium, form broad alluvial fans, the most prominent of which emanate from Cache and Putah Creeks.

The valley in the central part of the map area is formed mainly by Holocene basin deposits (Qb) that were laid down by the Sacramento River and its two major local tributaries, Putah and Cache Creeks. In the southern part of the map area these deposits grade basinward into peat-rich muds of the Sacramento River delta.

East of the Sacramento River, most of the map area is covered by large alluvial fans of the Riverbank Formation that appear to bury older alluvial fans of the Turlock Lake, Laguna, and Mehrten Formations. The flood plain and central part of the Sacramento Valley are formed mainly by Holocene alluvial (Qsc, Qa) and basin deposits (Qb).

Sheet 2

The south-central part of the valley (sheet 2) extends from the confluence of the Sacramento and Feather Rivers northward to include about three-fourths of the Sutter Buttes. It extends in an east-west direction from the Coast Ranges foothills to the Sierran foothills east of Marysville and Yuba City.

The most salient geologic feature of this area is the Sutter Buttes, which rise abruptly about 700 m above the valley floor. Their sharp, jagged peaks stand in marked contrast to the relatively flat alluvial fill of the valley.

The western foothills are underlain by the Tehama Formation, which is sporadically capped by the Red Bluff Formation. Younger sediments are incised into the Tehama and Red Bluff; these sediments also form broad fans spilling into the Colusa Basin. A few scattered remnants of alluvial fans of Riverbank age are found along the foothill front in the northwest corner of the map area. Riverbank-age alluvial fans are also found on the western side of the Sutter Buttes. Holocene alluvial and flood-basin deposits of the Sacramento River are actively burying the fans there.

The eastern side of the valley is covered by deposits of the Feather River and smaller streams of the western Sierra Nevada. The broad alluvial fan of Riverbank age, located east of Sacramento, underlies most of the eastern part of this map area in an outcrop belt that narrows northward toward Marysville. Eroded remnants of the Turlock Lake, Laguna, and Mehrten Formations are buried with the Riverbank alluvium and all are presently being dissected by Holocene stream channels.

Sheet 3

The central part of the valley (sheet 3), extends north from the northern one-fourth of the Sutter Buttes to the latitude of Chico and extends in an east-west direction from the Coast Ranges foothills to the Sierran foothills and Chico monocline.

The Tehama Formation is not exposed in the southwestern two-thirds of this map area, but it does underlie the foothills south of the Orland Buttes at the extreme northwest corner of the map area. Where the Tehama is absent, Cretaceous marine rocks are dissected by Holocene streams that carry debris to the flood basins. The Red Bluff caps the Tehama in the northwestern part of the map area, and it also caps the Cretaceous marine rocks to the south and west. The fan of Stony Creek dominates the north-central part of the map area. Its large distributary channels form an anastomosing network of linear deposits that range from early Riverbank age to Holocene. The large sediment load supplied to the Sacramento River by Stony Creek is probably responsible for the large levee deposits along the Sacramento River below Stony Creek.

The northeastern part of the map area is underlain by the Pliocene Tuscan Formation which unconformably overlies rocks of Miocene, Eocene, and Cretaceous age.

The conspicuous geomorphic landmark at Oroville, the north and south Oroville Table Mountains, is composed of dense, black Lovejoy Basalt. The Lovejoy Basalt also caps the Orland Buttes.

South of Oroville the Laguna Formation is dissected and backfilled with deposits of Turlock Lake age. Several thin cappings of the Red Bluff unconformably overlie these deposits. Alluvial deposits of Riverbank age form cut-and-fill channel deposits in all older units. Younger deposits of Modesto and Holocene age flank the Feather River and occupy most of the area east of the Sutter Buttes and west of the Sierran basement.

Sheet 4

The north-central part of the valley (sheet 4), extends from the Orland Buttes to the south to just north of Red Bluff and the Iron Canyon section of the Sacramento River. It is bounded on the west by the Coast Ranges foothills and on the east by the Chico monocline.

The Coast Ranges foothills are underlain by the Tehama Formation, which unconformably overlies more steeply dipping Cretaceous marine strata. The Tehama also unconformably overlies the Miocene Lovejoy Basalt on the east flank of the Orland Buttes. Excellent exposures of the Nomlaki Tuff Member are found within the Tehama Formation near its base in stream cuts all along the western side of the valley. In the southern half of the western foothills the Nomlaki dips 15-17° E. whereas in the northern half of the western foothills it is nearly flat lying. The dip changes across the projection of the Cold Fork and Elder Creek faults. The Nomlaki also occurs at the base of the Tuscan Formation along the Chico monocline where the tuff is exposed in the bottom of deeply incised stream channels along the monoclinal flexure.

Of all the published maps that cover the Sacramento Valley, this one displays the best developed and most widely preserved areas of the Red Bluff pediment. The Red Bluff truncates and caps the Tehama on the west and truncates and forms fans on the older gravels derived from the Tuscan on the east. The Red Bluff is deformed in a series of folds along the central and western parts of the map area. Bryan (1923) first noted the domes at Corning, but others exist at Hooker (west of Red Bluff and north of Blossom) and also southwest of Red Bluff between Red Bank and Oat Creeks. An exposure of the Tehama in the channel of Stony Creek due south of the Corning Dome suggests that more doming may exist south of Corning.

All the younger deposits, which include the Riverbank Formation, Modesto Formation and Holocene alluvium, are cut and back filled in a series of nested terraces and fans topographically below the Tehama, Tuscan, and Red Bluff Formations. Younger deposits are basinward and topographically lower then Tehama, Tuscan, and Red Bluff Formations.

Sheet 5

The northernmost (sheet 5) of the five maps in this study depict the northern geology of the Sacramento Valley. Its south boundary is near Bend on the incised meander loops of the Sacramento River and extends northward almost to Shasta Dam. Its west boundary is the foothills of the Klamath Mountains and Coast Ranges, and the east border is marked by the various volcanic rocks derived from the Lassen Peak area. The western part of the valley floor is underlain by the Tehama Formation while its temporal equivalent, the Tuscan Formation, underlies the eastern part. In the area of this map, the Tehama unconformably overlies primarily plutonic and metamorphic rocks of the Klamath Mountains, and the Tuscan either overlies the alluvial deposits of the Eocene Montgomery Creek Formation or the Cretaceous Chico Formation. The Tehama and Tuscan Formation interfinger near the present center of the Sacramento Valley, and we have arbitrarily chosen to use the channel of the Sacramento River as the Tehama-Tuscan contact. The Nomlaki Tuff Member (3.4 m.y.) occurs locally near the bases of the Tehama and Tuscan Formations.

These Pliocene rocks are beveled and capped by the thin Red Bluff pediment. Some of the best examples of the Red Bluff pediment can be seen in the river bluffs near the city of Redding. On the western side of the Sacramento River, the Red Bluff Formation forms the highest part of the landscape, but east of the river younger volcanic flows extend westward over part of the Red Bluff. These younger volcanic rocks, as well as the underlying Pliocene rocks, have been deeply eroded by west-flowing streams that locally expose the Cretaceous and Eocene rocks along their canyon walls. The Chico Formation is highly susceptible to landsliding.

The Battle Creek fault zone is one of the most prominent structural features in northern California. It crosses the southeastern part of the map area and strikes about N. 75° E. East of the Sacramento River, the Battle Creek fault zone forms a prominent escarpment rising to the northeast that is buried by late Quaternary flows from the Lassen Peak area. The sense of motion on the dominantly normal Battle Creek fault zone is north-side up. The basaltic cinder cone of Black Butte sits atop the escarpment and displays little erosion. Westward, the Battle Creek fault zone probably controls the orientation of Cottonwood Creek valley. Linear geomorphic features that may be related to faulting extend westward along the South Fork of Cottonwood Creek, Mitchel Gulch, Colyear's Spring, Sour Grass Gulch, and finally into the Coast Ranges (Helley and others, 1981). Along the tributaries of Cottonwood Creek, Quaternary terraces of Riverbank age display features such as vegetation lines and linear depressions. Good examples of linear features may be seen near the confluences of Red Bank Gulch, Sour Grass Gulch, and Wild Hide Gulch with the South Fork of Cottonwood Creek. This area is just west of the Inks Creek fold system and may be affected by these structures. A few kilometers north of, and parallel to, the Battle Creek fault zone the Bear Creek fault also shows north-side up displacement, although on a much smaller scale than that of the Battle Creek fault zone.

A large area underlain by the Red Bluff south and east of Redding is dissected by very straight northwest-trending stream channels. These channels may be structurally controlled.

PREVIOUS WORK

Since the turn of the century, most geologic studies of the area have concentrated on the oil and gas potential of the older, pre-Pliocene rocks. Diller (1894) described the rocks surrounding and underlying the Sacramento Valley. He also described and named the Red Bluff Formation and noted that these Pleistocene gravels were involved in the deformation of the Coast Ranges. Bryan (1923) described the ground-water resource and the valley physiography when natural artesian flow conditions existed. He subdivided the valley into five natural provinces (1923, p. 9): the redlands, the low plains, the river lands, the flood basins, and the island country. Bryan also recognized, that the Red Bluff Formation was more widespread than Diller had previously recognized, but more importantly he noted that it was deformed at Corning, along the Chico monocline, and at Dunnigan Hills. Olmsted and Davis (1961) described the regional ground-water hydrology, and they were the first to use stratigraphic nomenclature in order to rank geologic units in terms of their water yield. They also recognized the widespread distribution of the Red Bluff Formation and that these gravels truncated and beveled a surface of low relief across the Tehama and Tuscan Formations. They also noted that the hardpans that developed on the Red Bluff soils act as aquicludes to prevent percolation of surface water (Olmsted and Davis, 1961, p. 35). Safanov (1968) and Redwine (1972) summarized the geologic framework of the oil and gas potential for this area.

On August 1, 1975, residents of the Sacramento Valley and adjacent Sierra Nevada foothills were startled by a moderate-size earthquake ($\underline{M_s} = 5.6$) centered near Oroville. Previously, this region was considered to be tectonically stable, but this earth tremor sparked new interest in the seismogenic potential of the valley. The tectonic activity in the Sacramento Valley and foothills and the possibility of active faulting have been assessed for selected areas by studies of structural history (Woodward Clyde Consultants, 1977; Harwood and others, 1981; Helley and others, 1981; and Harwood and Helley, 1982).

The maps presented here provide a greater subdivision of the late Cenozoic deposits (65 map units). Limits are placed in a time-stratigraphic context based on absolute ages of ash beds and volcanic rocks that are interbedded with the alluvial deposits. The deposits and map units are also related to their geomorphic forms, lithologies, and post-depositional soil profiles.

GEOLOGIC MAPPING TECHNIQUES

One way to assess the recency of tectonic activity in any area is to differentiate and map the youngest deposits and then evaluate their origin. In the Sacramento Valley such deposits include fluvial, paludal, lacustrine, estuarine, and volcanic materials that comprise a broad, largely featureless physiographic plain within the Coast Ranges to the west, the Sierra Nevada to the east, and the Klamath Mountains to the north (fig. 1). In our mapping we attempted to relate the deposits to the processes responsible for their deposition. By such association, any deviation from an expected geomorphic form of a given depositional process might be caused by tectonism and thus warrant closer scrutiny.

The alluvial and volcanic units of this series of maps were differentiated by various geologic criteria including age, lithology, induration, compaction, texture, depositional environment, geomorphic expression, and soil-profile development. The alluvial deposits were mapped on the basis of their topographic expressions, which were determined, in part, by interpretation of aerial photographs and partly from geologic interpretation of published and unpublished soils-series maps. The quality, vintage, and type of aerial photography available varies considerably over the area. Some areas are covered by standard black and white photos, whereas other areas are covered by special photos, such as false-color infrared photography.

Some of the mapping was incorporated directly from published sources and some was modified from published and unpublished work (fig. 2). The geologic map for the Whitmore quadrangle, in the northeast corner of sheet 5, is reproduced without modification or field checking from Macdonald and Lydon (1972). We modified slightly the work of Busacca (1982) in the Oroville quadrangle and that of M. P. Doukas (unpub. data, 1981) in the Chico area. We also used the mapping of Williams and Curtis (1977) for the Sutter Buttes area, although we combined some of their units. We used the basal contact of the Tehama Formation drawn by Murphy and others (1969) in the Ono quadrangle and modified that contact in the Colyear Springs quadrangle (Bailey and Jones, 1973) after field checking. Mapping in the Sacramento-San Joaquin delta was taken from Atwater (1982) and Atwater and Marchand (1980). The remaining areas of these five oversized sheets were compiled from our own published and unpublished mapping at scales of 1:24,000 and 1:62,500; base maps used in compilation for each sheet are shown in figures 3 through 7.

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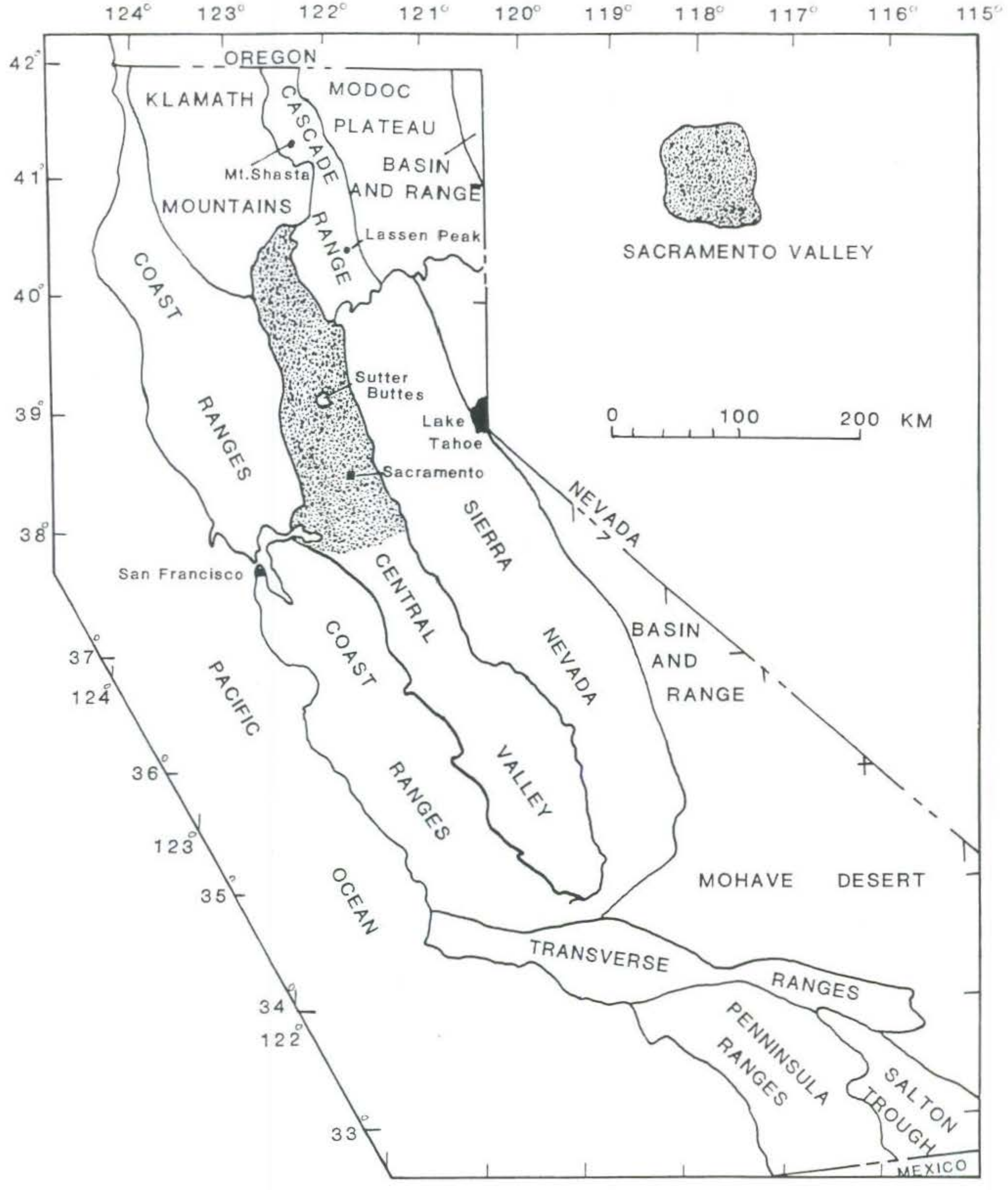


Figure 1.--Location map of the Sacramento Valley, California.

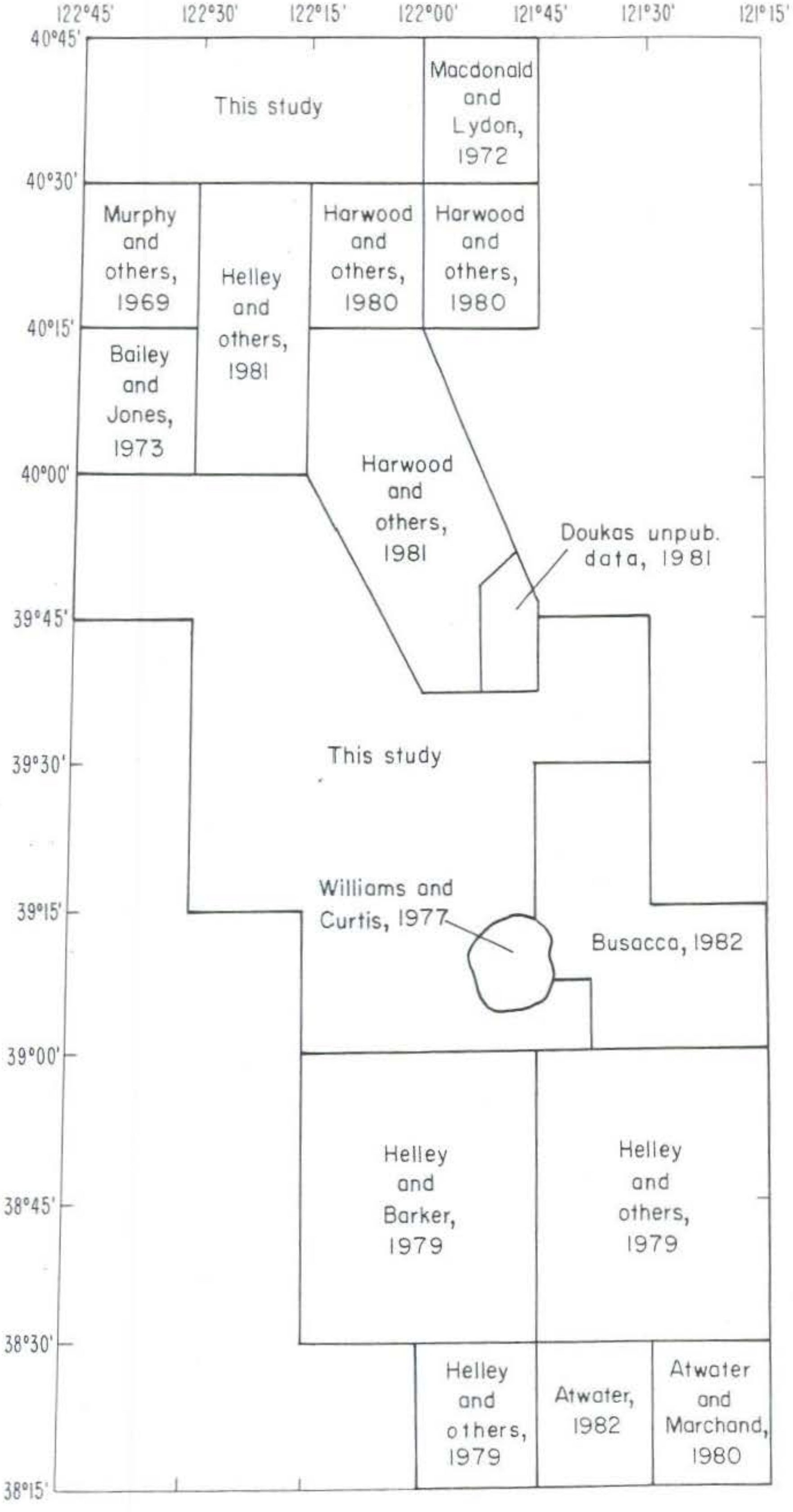


Figure 2.--Sources of data.

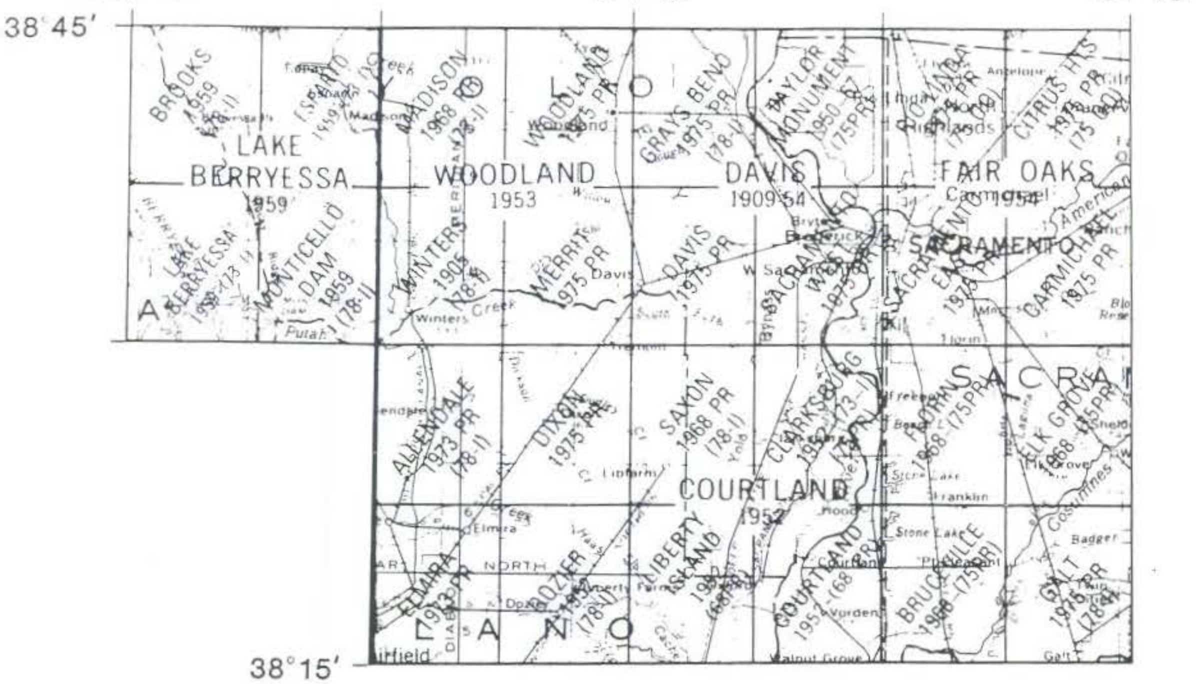


Figure 3.--Index map for the southern Sacramento Valley.

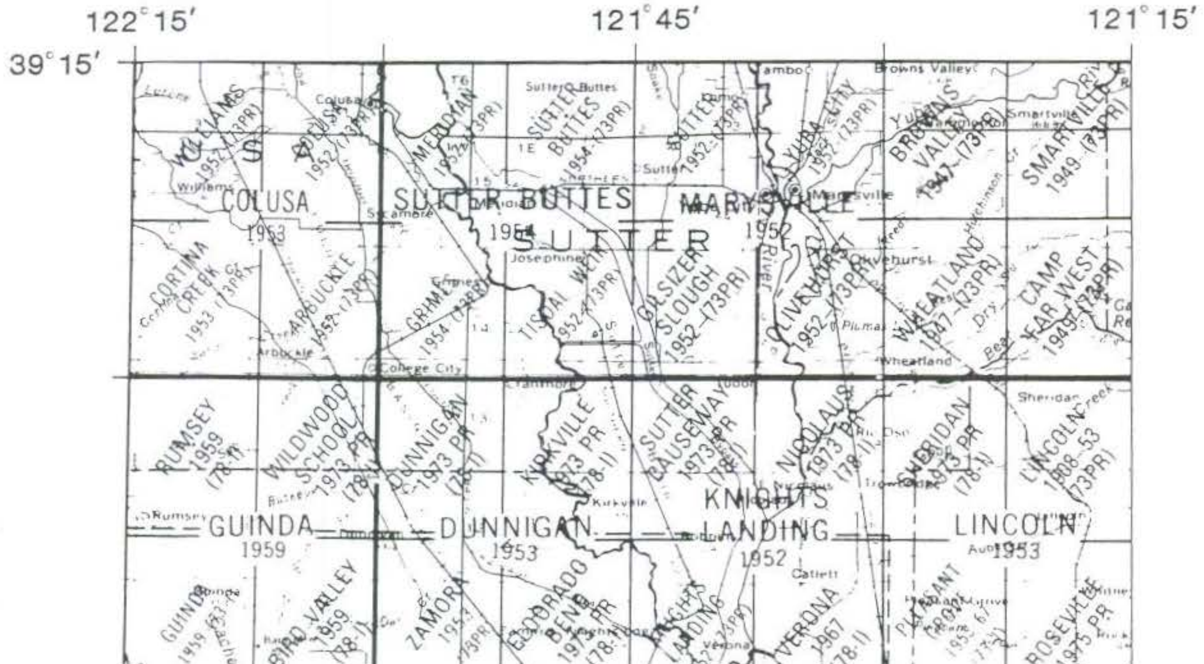


Figure 4.--Index map for the south-central Sacramento Valley.

DESCRIPTION OF MAP UNITS
SURFICIAL DEPOSITS

Alluvial deposits

Qsc STREAM CHANNEL DEPOSITS (HOLOCENE)--Deposits of open, active stream channels without permanent vegetation. These deposits are being transported under modern hydrologic conditions; consequently they are light tan and gray, unweathered, and usually in contact with modern surface waters. Our mapping merely limits the right and left bank boundaries of the active stream channel. Morphology within the deposits is constantly changing. Thickness may reach 25 m on the Sacramento River or be less than a few centimeters in bedrock canyons

Qa ALLUVIUM (Holocene)--Unweathered gravel, sand, and silt deposited by present-day stream and river systems that drain the Coast Ranges, Klamath Mountains, and Sierra Nevada. Differentiated from older stream-channel deposits (Qao and Qal) by position in modern channels. These units lie outboard of unit Qsc but inside the first low terraces flanking modern stream channels. The deposits form levees along the main course of the Sacramento River, and broad alluvial fans of low surface relief along the western and southwestern side of the valley. Because of high organic content the levee deposits are darker gray than the alluvium flanking the channels on smaller streams. Thickness varies from a few centimeters to 10 m

Qo OVERBANK DEPOSITS (HOLOCENE)--Sand, silt, and minor lenses of gravel deposited by floods and during high water stages; form low terraces adjacent to present-day alluvial stream channels; coincident with tan and gray organic-rich sediments (Qm), which generally mark high-water trimlines of historic floodwaters. Probably do not exceed 3 meters in maximum thickness

Qao ALLUVIAL AND OVERBANK DEPOSITS, UNDIVIDED (HOLOCENE)--Consists of units Qma and Qo

Qal ALLUVIAL DEPOSITS, UNDIVIDED (HOLOCENE AND PLEISTOCENE)--Undivided gravel, sand, and silt; this unit generally taken from previous mapping

OLDER ALLUVIUM (PLEISTOCENE)--A general description of the older alluvium applies to the Pleistocene Modesto, Riverbank, Turlock Lake, and Red Bluff Formations. Mainly forms fans and terraces whose distal ends grade to low plains and basins and whose proximal ends grade to colluvium along the foothills surrounding the valley. Consists of tan, brown, gray, black, and red gravels, sands, silts, and clays that lithologically reflect local source areas. The youngest of these deposits are unconsolidated and show minimal weathering, while the oldest display maximal weathering and are semiconsolidated. Soil profiles were used to help differentiate members. The Upper Pleistocene older alluvium is incised into older Quaternary and upper Tertiary deposits. Thickness ranges from zero to as much as 120 m in the central part of the valley. The stream systems that deposited the older alluvium are essentially those that flow today as all deposits border modern streams. The youngest deposits lie only a few meters above present stream channels and may even be overtopped by infrequent flooding. The oldest Pleistocene alluvial surface lies tens of meters above modern flood plains. Consists of:

MODESTO FORMATION--The youngest unit comprising the Pleistocene alluvium consists of distinct alluvial terraces and some alluvial fans and abandoned channel ridges. The unit forms the lowest deposits lying topographically above the Holocene deposits along streams and in valleys. It consists of tan and light-gray gravely sand, silt, and clay except where derived from volcanic rocks of the Tuscan Formation; it then is distinctly red and black with minor brown clasts. The Modesto was deposited by streams still existing today because the deposits, for the most part, border existing streams. An exception is the abandoned channel filled with deposits belonging to the upper member of the Modesto on the south side of the alluvial fan of Stony Creek. Divided into:

Qmu Upper member--Unconsolidated, unweathered gravel, sand, silt, and clay. The upper member forms terraces that are topographically the lowest of the two Modesto terraces. It also forms alluvial fans along the east side of the Sacramento Valley from Red Bluff to Oroville. Soils at the top of the upper member have A/C horizon profiles, but unlike the lower member they lack argillic B horizons. Deposits belonging to the upper member of the Modesto are only a few meters thick and generally form a thin veneer deposited on older alluvial deposits. Original surficial fluvial morphology is usually preserved and gives relief of 1 or 2 m. C^{14} age determinations on plant remains from the upper member at Tulare Lake suggest that the unit is between 12,000 and 26,000 yr old (Brian Atwater, oral commun., 1982). Thus the deposition of the upper member of the Modesto Formation appears to correspond with the Tioga glaciation in the Sierra Nevada (Birkeland and others, 1976)

Qml Lower member--Unconsolidated, slightly weathered gravel, sand, silt, and clay. The lower member forms terraces that are topographically a few meters higher than those of the upper member. It forms alluvial fans along the main channel of the Sacramento River and Feather River and large levees bordering the Sacramento River from Stony Creek to Sutter Buttes. Upstream from Stony Creek the lower member of the Modesto is preserved as scattered terrace remnants. Alluvium of the lower member of the Modesto surrounds the Dunnigan Hills and borders Cache Creek near Esparto. Soils developed on the lower member contain an argillic B horizon, which is marked by a noticeable increase in clay content and a distinct red color. Its surface fluvial morphology is remarkably smooth and displays little relief. The unit is much more extensive than the upper member and probably represents a longer period of deposition. The lower member of the Modesto unit is the youngest deposit from which we have evidence for possible fault displacement. Conspicuous linear-edged terraces composed of the lower member are found just south of Orland Buttes and may be a reflection of the Willow fault zone. The lower member deposited along the northeast fan of the Dunnigan Hills may also reflect fault displacement.

Marchand and Allwardt (1981) gave an age for the lower member as probably Altonean (early and middle Wisconsinan) based on an open-system uranium series minimum age of 29,407±2,027 yr on bone from basin deposits of the lower member of the Modesto. A radiocarbon age on wood from a depth of 15-16 m in basin deposits of the lower member was 42,400±1,000 yr B.P. (Marchand and Allwardt, 1981, p. 57). They speculated that this may be the older age limit of the lower member. Since the dates were from flood-basin deposits where deposition may have continued long after terrace deposition ceased, the ages may be too young

RIVERBANK FORMATION--Weathered reddish gravel, sand, and silt forming clearly recognizable alluvial terraces and fans. Riverbank alluvium is distinctly older than the Modesto and can be differentiated by (1) its geomorphic position in terraces topographically above the terraces of Modesto age and (2) the degree of post-depositional soil-profile development. The Riverbank displays thicker argillic B horizons with a consistent shift in hue from 10 YR to 7.5 YR and even some 5 YR hues (Munsell color notations). We have divided the Riverbank into two informal members in contrast to the northeastern San Joaquin Valley where Marchand and Allwardt (1981, p. 36) recognized three members. Based on soil-profile development, we tentatively correlate the two members of the Riverbank in the Sacramento Valley with the upper two members in the San Joaquin Valley as described by Marchand and Allwardt (1981). The main distinction between the two areas is lithology: the Riverbank of the San Joaquin Valley is predominantly arkosic alluvium while that of the Sacramento Valley contains more mafic igneous rock fragments. Consequently, Riverbank deposits in the Sacramento Valley tend toward stronger soil-profile development for deposits of the same age. Both members of the Riverbank in the Sacramento Valley are lithologically very similar, but the upper member is more widespread and less dissected.

The upper member is prominent in the northwestern part of the Sacramento Valley from Red Bluff to about Willows; it is absent from Willows south toward Winters along the west side of the valley. The upper member is not widespread on the east side of the Sacramento Valley from Red Bluff to Chico, but it does occur around the western half of Sutter Buttes. However, both members form a dominant part of the landscape from Oroville south to the delta along the east side of the valley. Their asymmetrical distribution, widespread extent in the northwest and southeast, and absence in the southwest may reflect broad, slow, and relatively aseismic tectonic movement of the valley. Deposits of both Riverbank members are well preserved on the Stony Creek fan and along Cottonwood Creek and the Sacramento River near Anderson.

The Riverbank alluvium is older than the Modesto alluvium but younger than the Red Bluff Formation. Since the Red Bluff is overlain by the Rockland ash bed (0.45 m.y.), the Riverbank, which is cut and filled below the Red Bluff, can be no older than the ash bed and is probably much younger. Considering the degree of erosional dissection of the Riverbank and strong soil-profile development, it must be at least twice as old as the older Modesto age of about 50,000 yr. Marchand and Allwardt (1981 p. 41) placed the Riverbank of the San Joaquin Valley between 130,000 to 450,000 yr B.P. They used several lines of evidence including uranium-trend dating on soils (Rosholt, 1978), which gave the younger limit, while the older limit was based on stratigraphic evidence. The Riverbank in the San Joaquin Valley occupies the stratigraphic interval between the Modesto above and Turlock Lake Formation below. The upper part of the Turlock Lake contains the Friant Pumice Member (600,000 yr old). The Riverbank in the San Joaquin Valley must be considerably younger since a period of erosion and soil formation occurred between its deposition and that of the Turlock Lake. Divided into:

Qru Upper member--Unconsolidated but compact, dark-brown to red alluvium composed of gravel, sand, silt and with minor clay. Topographically forms the lower of the two Riverbank terraces; forms dissected alluvial fans on the northwest and southeast sides of the Sacramento Valley with distinct and now abandoned distributary channels cut into the lower member and older deposits. The Riverbank members generally are separated vertically by about 3 m, but the lower member of the Modesto may be more than 5 m lower in elevation. The upper member, while smoother than the more dissected lower member, displays more relief than the lower member of the Modesto

Qrl Lower member--Red semiconsolidated gravel, sand, and silt. Comprises the higher of the two Riverbank terraces and remnants of dissected alluvial fans. This terrace is cut and backfilled into the Red Bluff and older alluvial deposits. Its surface is much more dissected than the upper member with several meters of local relief. Where eroded it also displays much stronger, almost maximal soil profiles with hues approaching a maximum 2.5 YR. Like the upper member, the lower member is best preserved in the northwestern and southeastern parts of the valley; the most extensive exposures are in and around the city of Sacramento. Most of the alluvium of the lower member near Sacramento is very arkosic, and it was probably derived from the western slopes of the Sierra Nevada and deposited by the American River. The modern Sacramento River impinges on the alluvial fan comprising the lower member of the Riverbank and appears to be cannibalizing it.

Northwest of the confluence of the Sacramento and American Rivers, numerous small discontinuous outcrops of the lower member are buried partially by Holocene alluvial and basin deposits. The deposits of the lower member in that area probably mark the ancient distal edge of the Riverbank fan. It also appears that the lower member was cut by a south-flowing ancient channel of the Feather River or Bear River, or both. Today, the Feather River departs from its due-south course below its confluence with the Bear and abruptly strikes southwesterly around the numerous outcrops of the lower member of the Riverbank

Qrb RED BLUFF FORMATION--A thin veneer of distinctive, highly weathered bright-red gravels beveling and overlying the Tehama, Tuscan, and Laguna Formations. In this study we interpret the Red Bluff Formation as a sedimentary cover on a pediment surface and therefore suggest that it formed in response to a fixed base level caused by impeded or closed drainages of the Sacramento Valley. The Red Bluff pediment is overlain by the Rockland ash bed (0.45 m.y. old) (Meyer and others, 1980) and in turn overlies the basalt of Deer Creek (1.08±0.16 m.y.). Therefore, the pediment must have formed sometime within that 630,000-yr interval.

The Red Bluff is best preserved in the northern part of the valley from Redding to south of Orland Buttes on the west and south to Chico on the east; it also occurs along the southwest side of the valley where its pediment character is less clear. The scattered cappings of the Arroyo Seco Gravel of Piper and others (1939) and Shlemon (1967) in the Sacramento area and also the half dozen or so scattered gravel remnants south of Woodland between Cache and Putah Creeks may actually be Red Bluff. The Red Bluff is deformed by the Dunnigan Hills anticline, a doubly plunging fold west of Arbuckle, and it unconformably overlies the Tehama on a structural high south of Woodland that may be a continuation of that fold. The Red Bluff also unconformably overlies the Tehama in intermittent patches along the western valley between Winters and the mouth of Cache Creek

Qtl TURLOCK LAKE FORMATION (PLEISTOCENE)-Deeply weathered and dissected arkosic gravels with minor resistant metamorphic rock fragments and quartz pebbles; sand and silt present along the south and east sides of the Sacramento Valley. The Turlock Lake is more widespread in the San Joaquin Valley where Arkley (1954) first recognized this unit, but it was named by Davis and Hall (1959) for arkosic alluvium overlying the Mehrten Formation and underlying the Riverbank Formation in eastern Stanislaus and northern Merced Counties. The Turlock Lake is easily recognized in both valleys by its characteristic arkosic lithology, geomorphic form, and relation to underlying and overlying units. The Turlock Lake stands topographically above the younger fans and terraces commonly displays as much as 30 m of erosional relief. The unit represents eroded alluvial fans derived primarily from the plutonic rocks of the Sierra Nevada to the east.

In the San Joaquin Valley, Arkley (1954) recognized that the Turlock Lake consists of two distinct units separated by a very strongly developed soil on the lower part, while the upper part contained two distinct members, the Corcoran Clay Member and the Friant Pumice Member. Janda (1965) reported a K-Ar age of 0.62±0.02) m.y. for the pumice member. The paleomagnetic data of Verosub (in Marchand and Allwardt, 1981) support this age by showing that the upper part of the Turlock Lake has normal polarity and the lower part has reversed polarity, and thus is greater than 0.7 m.y. old. The upper part of the Turlock Lake is probably correlative with the Red Bluff pediment because there is overlap in the age range of the units. The upper part of the Turlock Lake and the Red Bluff pediment also may be physically related through the Corcoran Clay Member of the Turlock Lake, which represents lacustrine conditions that may have impeded through-flowing drainage from the Sacramento Valley thus favoring the Red Bluff pediment-forming process. The Turlock Lake mapped in the Sacramento Valley probably correlates with the lower part of the Turlock Lake of the San Joaquin Valley since it overlies the Laguna Formation and is truncated by the Red Bluff Formation pediment. The Red Bluff pediment may have developed in the time interval between the deposition of the Corcoran Clay Member about 600,000 yr ago and the deposition of the Rockland ash bed approximately 450,000 yr ago

QTog OLDER GRAVEL DEPOSITS (PLEISTOCENE AND (OR) PLIOCENE)--Moderately well indurated, coarse to very coarse gravel with minor coarse sand resting unconformably on a truncated soil profile developed on the Tuscan Formation that is well-exposed along Hogback Road and in Salt Creek east of Red Bluff. These coarse gravels, derived from the Tuscan Formation, are bright reddish tan (2.5 YR) to yellowish tan, well rounded, and locally deeply weathered. The deposits are expressed geomorphically as very steep-sloping, symmetrical alluvial fans that probably developed during or soon after formation of the Chico monocline

Basin deposits

Qb BASIN DEPOSITS, UNDIVIDED (HOLOCENE)--Fine-grained silt and clay derived from the same sources as modern alluvium. The dark-gray to black deposits are the distal facies of unit Qa. The undivided basin deposits provide rich and valuable farmland especially for rice production in the Sacramento Valley. This unit covers much of the valley in the southern half of map area. Thickness varies from 1 or 2 m along the valley perimeter to as much as 60 m in the center of the valley

Qm MARSH DEPOSITS (HOLOCENE)--Fine-grained, very organic rich marsh deposits; differentiated from the undivided basin deposits (Qb) by generally being under water

Qp PEAT DEPOSITS (HOLOCENE)--Composed of decaying fresh-water plant remains with minor amounts of clay and silt generally deposited below historic high-tide lines. Original presettlement maximum thickness about 25 m

Landslide deposits

Qls LANDSLIDES (HOLOCENE AND PLEISTOCENE)--Slumped, rotated chaotic mixtures of underlying bedrock units and colluvium; particularly abundant and extensive in the Montgomery Creek and Chico Formations. Arrows show direction of movement

VOLCANIC ROCKS INCLUDING MINOR SEDIMENTARY DEPOSITS

BASALTIC ROCKS OF INSKIP HILL VOLCANIC CENTER (PLEISTOCENE)--Divided into:

Qif_3-Qif_1 FLANK FISSURE FLOWS--Several small, blocky basalt flows originating from vents along two parallel, northeast-trending fissures on the north slope of Little Inskip Hill located 29 km northeast of Red Bluff. These flows extend 1 to 2.5 km northward toward Battle Creek. Although the flows appear to be contemporaneous, three separate pulses of lava, which are inferred from their superposition, are labeled from oldest to youngest, Qif_1, Qif_2, and Qif_3. Flows erupted first from the northern fissure and their proximal parts were overlapped by subunit Qif_3 from the northeast end of the upper fissure. Individual thickness of the flows is unknown due to their blocky nature and brushy cover; they probably are less than 5 m in individual thickness

Qic CINDER CONE DEPOSITS--Red and black basaltic cinders forming the prominent cones of Inskip Hill and Little Inskip Hill; four small cinder cones with essentially uneroded morphology are superposed on the larger older cone of Inskip Hill. These smaller cones are crudely alined in a north-south direction across the main mass of Inskip Hill and, thus reflect the north-trending fracture system prominent in the underlying Tuscan Formation. Two satellitic eruptive centers marked by small basaltic lava flows and cinder cones lie southeast of Inskip Hill near the settlement of Paynes Creek and in the upper reaches of Oak Creek near McKenzie Place (southwest corner of the Manton 15' quadrangle)

Qip BASALT FLOWS OF PAYNES CREEK--Thin, black to dark-gray basalt flows that were erupted at Inskip Hill and flowed primarily westward into the drainage of Paynes Creek and reached the Sacramento River at Chinese Rapids near Bend (southwest corner Tuscan Buttes 15' quadrangle). On the flanks of Inskip Hill, the flows are characterized by small lava tubes, pahoehoe texture, and thin scoria layers. Farther from the eruptive center the Paynes Creek flows display scattered yellowish-brown phenocrysts of olivine and glassy-green phenocrysts of clinopyroxene, set in a matrix of fine-grained plagioclase, clinopyroxene, and glass. Northeast of Dales in the Tuscan Buttes 15' quadrangle, the Paynes Creek lava is about 8 m thick; where it crosses the Manton Road northeast of Dales Lake, it is about 2 m thick. The age of the Paynes Creek flows is unknown, but it must be less than 26,000 yr and possibly less than 12,000 yr because the flows overlie the upper member of the Modesto Formation in a tributary of Inks Creek

Qiu UNDIFFERENTIATED BASALT FLOWS OF INSKIP HILL

BASALTIC ROCKS OF BLACK BUTTE VOLCANIC CENTER (PLEISTOCENE)--Divided into:

Qbbb CINDER BLANKET DEPOSITS--Black, well-bedded basaltic cinder deposits forming a dissected ejecta blanket that ranges in thickness from about 10 m just north of Black Butte to about 1.5 m on the south rim of Ash Creek. Beds ranging from 1 to 20 cm thick show normal grading. No major unconformities or buried soil horizons were found in the cinder deposits suggesting rapid accumulation. Total remaining volume of cinder blanket and cone deposits is estimated to be about
6×10^6 m^3

Qbbf BASALT FLOW OF BLACK BUTTE--Dark-gray to black basalt similar in texture and mineralogy to the Paynes Creek flows from Inskip Hill. Olivine and clinopyroxene phenocrysts are scattered in a diktytaxitic matrix of clinopyroxene and plagioclase. Volcanic activity at Black Butte began with the eruption of a small flow of olivine basalt and progressed to the formation of a cinder cone. The flow formed two branches, one part moved about 1 km west of the vent into the upper reaches of Rancherio Creek; the other part cascaded over the Battle Creek fault scarp and formed a bulbous puddle of blocky lava just north of the Darrah Spring Fish Hatchery. The basalt flow of Black Butte, like that of Paynes Creek, is high in aluminum (17.41 percent) and remarkably low in potassium (0.19 percent). The basalt flow of Black Butte is probably no older than the basalt flows of Paynes Creek

Qbbc CINDER CONE DEPOSITS--Thinly layered and loosely aggregated, brick-red and black basaltic cinder deposits containing scattered red and black scoriaceous to glassy bombs of basalt as much as 2 m in length. The vent is marked by a conical depression 15 to 20 m deep and offset slightly to the south of center. The north rim of the cone is a spatter rampart that rises about 25 m above the south rim of the cone

BASALTIC ROCKS OF DIGGER BUTTES VOLCANIC CENTER (PLEISTOCENE)--Divided into:

Qdbc CINDER CONE DEPOSITS--Black and red basaltic cinders forming two small cones atop the east end of the basalt flows of Digger Buttes

Qdb BASALT FLOWS OF DIGGER BUTTES--A series of thin, dark-gray to black, high alumina olivine basalt flows that originated from a vent or vents at Digger Buttes and flowed westward about 4.5 km. Unconformably overlies the Rockland ash bed (0.45 m.y.) and volcanic units as old as the Tuscan Formation. The rock is a fine-grained olivine basalt with trachytic texture that contains scattered olivine phenocrysts in a matrix of clinopyroxene and plagioclase. Total thickness of the flows is unknown but is probably only a few tens of meters

Qtbb BASALT OF TUSCAN BUTTES (PLEISTOCENE)--Gray to reddish-gray and black, fine-grained, porphyritic to glomeroporphyritic basalt and basaltic andesite composed of olivine and clinopyroxene phenocrysts in a matrix of plagioclase microlites and variable amounts of glass. Thin basaltic flows vary in texture from coarsely vesicular in Sevenmile Creek to massive and platy elsewhere. The flows overlie and interfinger with red scoria and breccia on the west slope of the Tuscan Buttes where they form three small isolated, but probably contemporaneous, fissure-vent deposits extending along a nearly north-trending fracture system. Extrusion of the flows postdated folding, uplift, and erosion in the area. They unconformably overlie broadly warped beds of the Tuscan Formation and locally rest on steeply inclined beds of the Upper Cretaceous Chico Formation in Sevenmile Creek

Qvu VOLCANIC ROCKS OF THE WHITMORE, MILLVILLE, AND MANTON QUADRANGLES (PLEISTOCENE)--Dark-gray, moderately diktytaxitic, high-alumina basalt (Al_2O_3 18.4 to 19.1 percent) composed of openwork plagioclase laths, fine-grained clinopyroxene, and magnetite with small scattered phenocrysts of brownish-green olivine. Distribution of these basalt flows in the Whitmore quadrangle is mapped by Macdonald and Lydon (1972)

Qbs_3-Qbs_1 BASALT OF SHINGLETOWN RIDGE (PLEISTOCENE)--Composed of three subunits of dark-gray, fine-grained, diktytaxtic, and locally porphyritic basalt with rounded phenocrysts of brownish-green olivine scattered in an openwork mesh matrix of plagioclase and clinopyroxene. They are high-alumina basalts containing about 47.6 percent SiO_2, 18.09 percent Al_2O_3, and 0.19 percent K_2O. Chemically, mineralogically, and texturally the rocks are very similar to the underlying basalt of Coleman Forebay, and both units may have originated from the same source area at separate, but perhaps not widely spaced, times. The flows of olivine basalt cap Shingletown Ridge north of Manton and extend westward north of Ash Creek to Bear Creek. The flows extend westward from the southern part of the Whitmore quadrangle (Macdonald and Lydon, 1972) and Macdonald (1963) traced them eastward in to the Red Mountain Lake area in the Manzanita Lake quadrangle where they may have originated from a series of vents distributed along a fissure system trending north-northwest from the vicinity of Lassen Peak. The basalt flows overlie the Tuscan Formation and have a total thickness of about 30 m north of Manton, but they are only about 5 m thick near Bear Creek

Qab ANDESITE OF BROKEOFF MOUNTAIN (PLEISTOCENE)--At least two distinct flows of porphyritic hypersthene andesite that contain abundant white plagioclase phenocrysts, minor amounts of hypersthene, and sparse augite phenocyrsts set in a fine-grained matrix of plagioclase microlites and brown glass. The lower part of the andesite sequence contains light-gray cumulate knots of plagioclase and clinopyroxene. These flows spill over the Battle Creek escarpment north of Digger Buttes and follow the Battle Creek fault zone to the southwest for about 35 km. The flows apparently are continuous with the andesite of Brokeoff Mountain mapped by Macdonald and Lyndon (1972) in the adjacent Whitmore quadrangle. On the Battle Creek escarpment, the hypersthene andesite flows rest unconformably on rocks as old as Eocene (Mongtomery Creek Formation), and on the footwall of the fault zone they rest on the Rockland ash bed, which is dated at 0.45 m.y. old (Meyer and others, 1980). North of Manton the total thickness of the andesite flows is about 20 m

Qar ROCKLAND ASH BED (PLEISTOENCE)--Unit is equivalent to the ash of Mount Maidu of Harwood and others (1981) and Helley and others (1981). We here use the name Rockland ash bed for this unit for reasons given by Sarna-Wojcicki and others (written commun., 1982). White loosely aggregated pumice lapilli ash with scattered coarse pumice fragments as large as 20 cm in diameter form a major dacitic to rhyolitic ash-flow tuff deposit between Digger Buttes and the Battle Creek escarpment. One arm of the deposit filled the lowland southeast of Digger Buttes and extends to the north rim of the canyon of the South Fork of Battle Creek. Scattered erosional remnants of the ash bed represent channel deposits north and northwest of Long Ranch. Round Mountain west of Table Mountain in the Bend section of the Sacramento River is made up of this ash deposit. Farther south the ash bed underlies a dozen or so low hills, locally known as the Sand Hills, that rise above alluvial fan deposits derived from the Tuscan Formation. The ash deposit has been dated by fission-track method at 0.45 m.y. (Meyer and others, 1980). The ash bed is also recognized in core samples from a test well near Zamora (T.12 N., R.1 E. SW 1/4 SE 1/4 sec 34) at a depth of 137 m (Page and Bertoldi, 1983), where it was deposited by the ancestral Sacramento River or a major tributary presumably at or near sea level. The position of the ash bed in the well at Zamora gives a local rate of subsidence of 0.3 m/10^3 yr. The ash is predominantly fine grained glass, locally distinctly bedded in the distal exposures and generally massive with scattered large pumiceous fragments in the proximal areas. The pumicious fragments are composed primarily of silky white, wispy, vesicular glass that contains scattered crystals of clear to white plagioclase and sanidine, green hornblende, hypersthene, and minor magnetite. Wilson (1961) determined the refractive index of the glass to be 1.500±.001, indicative of a silica content of about 67 percent, and an overall dacitic composition. The ash flow is at least 60 m thick north of Digger Buttes, but it is generally less than 5 m thick in the scattered patches to the west

Qeb BASALT OF EAGLE CANYON (PLEISTOCENE)--Dark-gray, vesicular, diktytaxitic olivine basalt underlying the broad plain carved by the North Fork of Battle Creek from the vicinity of Ponderosa Way on the east along the toe of Battle Creek escarpment nearly to the Coleman Powerhouse (northeast quarter of the Tuscan Buttes 15' quadrangle). This basalt, along with the underlying conglomerate here mapped as the Red Bluff Formation, and the basalt below the conglomerate were compositely grouped by Wilson (1961, p. 11) in his Long Ranch (basalt) unit. The upper unit of basalt is here designated the (olivine) basalt of Eagle Canyon; the lower basalt, which underlies the Red Bluff Formation, is herein termed the basalt of Coleman Forebay

Qcb BASALT OF COLEMAN FOREBAY (PLEISTOCENE)--Light-rusty-gray-weathering, dark-gray olivine basalt with pronounced diktytaxitic texture and scattered large vesicles and voids that form large rounded pits on the weathered surfaces. This basalt underlies the Red Bluff Formation in several isolated areas extending from Coleman Forebay on the Battle Creek fault escarpment southward to the vicinity of Hog Lake, 17 km northeast of Red Bluff on California Highway 36. The unit is undated but is older than the Red Bluff Formation and has a maximum thickness of about 10 m

Qbd OLIVINE BASALT OF DEVILS HALF ACRE (PLEISTOCENE)--Gray glomeroporphyritic vesicular basalt showing well-developed columnar jointing on the north rim of Antelope Creek. Aggregates of strongly zoned plagioclase as much as 10 mm in diameter and euhedral to anhedral olivine as much as 5 mm in diameter are set in an ophitic matrix of nearly equal amounts of plagioclase microlites and clinopyroxene. Magnetite is scattered throughout the matrix and rutile(?) is included within the plagioclase. Clear to white opal lines some vesicles and also occurs as fracture fillings in some plagioclase phenocrysts. Maximum thickness is 15 m

Qbdc OLIVINE BASALT OF DEER CREEK (PLEISTOCENE)--Dark-gray to greenish-black, sparsely vesicular olivine basalt flows locally exposed on the north and south rims of the canyon of Deer Creek (northeast quarter of the Corning 15' quadrangle). Euhedral to subhedral olivine phenocrysts as much as 3 mm in diameter set in a fine-grained matrix of plagioclase and clinopyroxene. The clinopyroxene is intergranular to plagioclase microlites and which are strongly alined giving a trachitic texture. Olivine and clinopyroxene are slightly altered to iddingsite. Magnetite and ilmenite are present in the intergranular spaces. Plagioclase microlites contain small amounts of black dust-like opaque inclusions of magnetite(?) and light-colored fluid inclusions. The contact between the olivine basalt of Deer Creek and the underlying older gravel deposits is exposed in the older, western part of the quarry at the head of Juniper Gulch. The base of the basalt exposed in the quarry is a scoriaceous layer 0.3 m thick showing westward overturned flow folds outlined by deformed vesicles. A K-Ar age of 1.08±0.16 m.y. (J. Von Essen, written commun., 1978) was obtained on basalt from the quarry; the maximum thickness is 20 m

Qbr BLUE RIDGE RHYOLITE OF COE (1977) (PLEISTOCENE)--Mottled and flow-banded, light- and dark-gray, pink, and lavender glassy rhyolite, variably devitrified; minor perlite, pumice, and pitchstone near base. Contains andesine, oxyhornblende, hypersthene, and rare biotite phenocrysts; potassium-rich glassy matrix devitrified to feldspar and silica-rich spherulites. Wilson (1961, p. 68) gives one complete and four partial chemical analyses for the rhyolite; Gilbert (1968, p. 27) gives K-Ar ages of 1.15±0.07 m.y. on glass and 1.24±0.11 m.y. on plagioclase from the rhyolite

VOLCANIC ROCKS AND LACUSTRINE DEPOSITS OF SUTTER BUTTES (PLEISTOCENE AND PLIOCENE)--The descriptions of the rocks and deposits around Sutter Buttes are shortened versions of those of Williams and Curtis (1977) to whom the reader is referred for greater detail. The K-Ar dates presented on the entire eruptive sequence by Williams and Curtis range in age from 1.9 to 2.4 m.y. (1977, p. 42). Divided into:

QTvl VOLCANIC LAKE BEDS--Well-bedded volcanogenic sediments of mainly lacustrine but partly fluviatile, origin occupying an area measuring 1.6 by 2.7 km in the center of the buttes; (Williams and Curtis, 1977, p. 35)

QTa ANDESITES--Gray and brown, porphyritic, biotite-hornblende andesite that contains variable amounts of biotite, hornblende, and plagioclase phenocrysts set in a dense nonvesicular pilotaxitic matrix; generally located in the central part of Sutter Buttes where the andesite forms a coalescing group of intrusive and extrusive domes (Williams and Curtis, 1977, p. 21-22, 44-45)

QTr RHYOLITE DOMES--Conspicuous white topographic domes composed of light-gray to white porphyritic rhyolite and dacite that contrast sharply with exposures of the darker andesites. Both rhyolite and dacite contain variable amounts of biotite, quartz, plagioclase, and subordinate sanidine phenocrysts in a dense, micro- to crypto-felsitic matrix (Williams and Curtis, 1977, p. 23-27, 46-47)

QTm TUFF BRECCIA--Tuff breccia primarily comprising the peripheral topographic ring surrounding Sutter Buttes; equivalent to the middle unit of the Rampart Beds of William and Curtis (1977, p. 26)

QTmb TUFF BRECCIA OF MINERAL AREA (PLEISTOCENE AND PLIOCENE)--These rocks were mapped and described originally by Wilson (1961, p. 14-16) and an abbreviated description based on his report and our reconnaissance is used here. The tuff breccia consists of layers of angular blocks of basaltic andesite and andesite interbedded locally with andesitic tuff, scoria, and minor andesite flows. The unit is about 240 m thick at the head of Mill Creek Canyon

Ta ANDESITE (PLIOCENE)--Undivided flows of predominantly two pyroxene andesite; commonly platy, medium to light gray, rarely dark gray, locally pink, greenish gray, or mottled; locally overlies hornblende-bearing pyroxene andesite containing abundant plagioclase phenocrysts and less abundant, smaller hornblende phenocrysts. This thick sequence of andesite lava flows with minor interbedded tuff and tuff breccia was mapped in the Whitmore quadrangle by Macdonald and Lydon (1972) and is mapped here without field checking

Tpa PLATY ANDESITE (PLIOCENE)--Light- to dark-gray, bluish-gray, and brick-red, fine-grained, sparsely porphyritic, slabby-weathering to massive, locally streaked and flow-banded platy andesite exposed on the Battle Creek escarpment near Bailey Creek and at the top of Tuscan Buttes. Andesite at these widely separated areas was never part of the same flow and it represents chemically and mineralogically different flows that originated at different, unknown sources. The rocks share only a common platy structure and a similar stratigraphic position unconformably above the Tuscan Formation. The andesite is about 70 m thick at Tuscan Buttes and about 55 m thick at Bailey Creek.

At Tuscan Buttes the unit consists of several flows that are gray through most of their thickness and brick red at their tops. The rock is fine grained, sparsely porphyritic and composed of a matrix of oriented plagioclase microlites rimmed by devitrified glass. Glass contains scattered phenocrysts of reddish-brown basaltic hornblende as much as 3 mm long altered to varying degrees to dust like opaque magnetite particles. Sparse hornblende phenocrysts define a subtle, subhorizontal lineation oriented roughly east-west throughout the flows; the phenocrysts lie parallel to distinct flow banding in the rocks exposed in cliffs on the southwest face of the east butte. Layers in the flow-banded andesite range in thickness from 3 to 10 mm and locally contain angular fragments of porphyritic andesite. The andesite at Tuscan Buttes probably represents the remnants of a channelized flow or flows (Anderson, 1933) that may have originated from a vent or vents now marked by andesite plugs located in and near Antelope Creek to the east.

At Bailey Creek the platy andesite is gray to bluish gray, locally flow banded, and composed predominantly of devitrified glass; phenocrysts of plagioclase, hypersthene, and green hornblende combine to make up generally less than 15 percent of the rock

Tbp OLIVINE BASALT OF PARADISE (PLIOCENE)--Gray, slightly vesicular, glomeroporphyritic olivine basalt with aggregates of plagioclase as much as 15 mm in length that form abundant white knots. Aggregates of olivine as large as 10 mm in diameter form glassy yellowish-green phenocrysts in a gray matrix of plagioclase microlites and intergranular clinopyroxene. Plagioclase phenocrysts have well-developed oscillatory zoning and pronounced sieve texture with abundant inclusions of clinopyroxene in the middle zones. The edges of the plagioclase crystals are resorbed and crowded with black dustlike opaque inclusions and clear fluid inclusions. Magnetite occurs with intergranular clinopyroxene. Maximum thickness in the map area is about 25 m. The most extensive exposures are in and around the village of Paradise just east of Chico with two less extensive exposures on Mill Ridge due north of Paradise. The basalt weathers to a bright-brick-red (5-2.5 YR) soil

Tbc OLIVINE BASALT OF COHASSET RIDGE (PLIOCENE)--Gray vesicular porphyritic basalt flows with olivine phenocrysts as much as 6 mm in diameter set in a diktytaxitic matrix of plagioclase and clinopyroxene. Clinopyroxene as much as 2 mm in length is intergranular to plagioclase microlites. Magnetite and ilmenite occur with clinopyroxene. High-relief, knee-shaped twinned crystals, possibly rutile, occur in the plagioclase. Drusy clear quartz and clear to white opal line many vesicles. A sample taken from the roadcut on the east side of Cohasset Highway at the intersection of Keeler Road gives a K-Ar age of 2.41±0.12 m.y. (J. von Essen, written commun., 1978). Maximum thickness is about 25 m

Tba BASALTIC ANDESITE OF ANTELOPE CREEK (PLIOCENE)--Dark-gray to greenish-gray, massive to highly fractured, fine-grained, sparsely vesicular basaltic andesite exposed in Antelope Creek and to a lesser extent in Salt Creek; locally altered to brick red and reddish gray. Red and reddish-gray scoria layers about 1 m thick alternate with layers of more massive gray basaltic andesite of about equal thickness in the western exposures in Antelope and Salt Creeks, which suggests that these exposures are near the distal end of the flow. Plagioclase laths as much as 2 mm long are strongly aligned and locally swirled around equidimensional to elongate masses of iddingsite(?) and fine-grained magnetite, probably pseudomorphous after olivine. No fresh olivine was seen in this rock type, which was originally described as a basalt (olivine basalt of Antelope Creek) (Harwood and others, 1981), but which is now known to contain 54.7 percent SiO_2 and thus is located on the generally accepted basalt-andesite boundary of 54 percent SiO_2. A K-Ar age of 3.99±0.12 m.y. was obtained on the basaltic andesite of Antelope Creek (J. Von Essen, oral commun., 1979)

SEDIMENTARY ROCKS INCLUDING SOME VOLCANIC ROCKS

Tte TEHAMA FORMATION (PLIOCENE)--Pale-green, gray, and tan sandstone and siltstone with lenses of crossbedded pebble and cobble conglomerate derived from the Coast Ranges and Klamath Mountains; named by Diller (1894) for typical exposures in Tehama County in northwestern Sacramento Valley.

The Tehama rests with marked unconformity on Cretaceous rocks of the Great Valley sequence along the west side of the valley and on plutonic and metamorphic rocks of the Klamath Mountains west of Redding where the Mesozoic sedimentary rocks are missing. The Tehama is unconformably overlain by gravels of the Red Bluff pediment; excellent exposures of this stratigraphic relation are visible a few kilometers south of Red Bluff along Interstate Highway 5 and along the river bluffs at Redding.

North of Red Bluff the Tehama Formation interfingers with the Tuscan Formation in a broad zone extending approximately from Interstate Highway 5 east to the Sacramento River. The clastic debris becomes progressively more andesitic in composition and Tuscan-like in appearance eastward in this area of sediment interfingering. The contact with the Tuscan is gradational and we have arbitrarily chosen the Sacramento River channel as the map contact. Since both the Tehama and Tuscan contain the Nomlaki Tuff Member at or near their stratigraphic bases they are considered coeval. In the southwestern part of the Sacramento Valley, the Tehama also contains the Putah Tuff Member near its base; the Putah is the same age as, but stratigraphically below, the Nomlaki (Sarna-Wojcicki, 1976, p. 18; oral commun., 1982).

The maximum thickness of the Tehama is about 600 m (Olmsted and Davis, 1961). The Tehama is significant because the base of the unit is also the base of fresh ground water in the entire Sacramento Valley. Divided into:

Ttn Nomlaki Tuff Member--See description under the Tuscan Formation

Ttep Putah Tuff Member--Buff to light-gray, poorly to well-sorted, moderately consolidated, hypersthene-hornblende, vitric pumiceous tuff (Sarna-Wojcicki, 1976). The map unit consists of several fluvial tuffs separated by nonvolcanic fluvial sediments and probably represents several closely spaced eruptive events. The tuff beds are massive but generally uncemented. At most exposures the tuffs are conformable with sediments above and below; it occurs at or very near the base of the Tehama Formation. Maximum thickness is about 15 m. Some of the very best exposures are at the type locality, a road cut along California Highway 128 (sec. 36, T. 8 N., R. 2 W.) in Yolo County. The Putah occurs as a nearly continuous outcrop for a distance of about 60 km along the southwest side of the Sacramento Valley from the Capay Hills south to the south end of the English Hills near Vacaville in Solano County. The closest surface exposures of the Putah and Nomlaki Tuff Members are approximately 80 km apart on the west side of Sacramento Valley. The Putah does not extend beyond the northeastern side of Capay Hills and the Nomlaki not beyond about 10 km south of Orland Buttes.

Miller (1966) obtained a K-Ar age of 3.3±0.1 m.y. on glass separated from the tuff. He also stated that although the age is analytically identical to that of the Nomlaki, the two tuffs are petrologically different. Sarna-Wojcicki (1976) agreed with Miller's (1966) conclusions based on differences in refractive indices of glass and differences in mineralogy. The Putah contains apatite and basaltic hornblende that are absent from the Nomlaki, whereas the Nomlaki contains zircon that the Putah does not. The Nomlaki came from a source in the Lassen area while the Putah came from a source near Mount St. Helena in the Sonoma volcanic field. Both tuffs were reported in stratigraphic superposition in a gas well (Johnson, no. 1, Orland Oil Syndicated, Sarna-Wojcicki, oral commun., 1982) where the Nomlaki occurs at 442 m and the Putah 10 m lower

Tt TUSCAN FORMATION (PLIOCENE)--Interbedded lahars, volcanic conglomerate, volcanic sandstone, siltstone, and pumiceous tuff. Divided into:

Ttd Unit D--Predominantly fragmental deposits characterized by large monolithologic masses of gray hornblende andesite, augite-olivine basaltic andesite, black pumice, and smaller fragments of black obsidian and white and gray hornblende-bearing pumice in a grayish-tan pumiceous mudstone matrix; locally in Battle Creek and elsewhere unit contains an unlayered basal deposit of dark-gray andesite tuff with abundant black scoria and less abundant black glass fragments. Size of monolithologic fragments increases to the east toward Mineral, Calif.; highly fractured monolithologic masses 8 to 10 m in diameter are exposed in new road cuts on California Highway 36 on the south slope of Inskip Hill. Unit D probably originated from a major explosive event at its source volcano and consists of directed blast or avalanche deposits, or both, juvenile pyroclastic deposits of andesitic tuff, and lahars derived from the blast deposits. Samples from two monolithologic masses of andesite in the avalanche(?) deposit at Inskip Hill gave K-Ar ages of 2.49±0.08 and 2.43±0.07 m.y. (J. von Essen, written commun., 1982); slightly older than the basalt of Cohasset Ridge. Locally separated from unit C by the tuff of Hogback Road; where tuff is absent, lahars of unit D are distinguished from those of unit C by the presence of monolithologic rock masses, black obsidian fragments, and white and dove-gray dacitic pumice fragments. Unit D lies gradationally above the tuff of Hogback Road and unconformably above unit C where the tuff is missing. The unit ranges in thickness from about 10 to 50 m

Tth Tuff of Hogback Road--Discontinuous thin lapilli tuff, pumiceous sandstone, and conglomerate composed of rounded white hornblende-bearing dacitic pumice fragments as much as 3 cm in diameter and smaller gray and black pumice fragments admixed with varying amounts of andesitic detritus. Unit is commonly thin bedded, locally cross-bedded water-worked dacitic ash deposit that rests unconformably on unit C. Excellent exposures are found on the southwestern slope of Tuscan Buttes and in the broad topographic depression between Tuscan Buttes and Tuscan Springs where the unit is about 15 m thick. The tuff is about 2.5 m thick at the hogback on Hogback Road

Ttc Unit C--Lahars with some interbedded volcanic conglomerate and sandstone locally, north of Antelope Creek, separated from overlying units by partially stripped soil horizon. Along the Chico monocline southeast of Richardson Springs, unit C consists of several lahars 3 to 12 m thick separated from each other by thin layers of volcanic sediments; lahars contain abundant casts of wood fragments and prominent cooling fractures. Along Dye Creek Canyon, unit C consists of interfingering and overlapping discontinuous lahars without significant interbeds of volcanic sediments. At Tuscan Springs and around Tuscan Buttes, unit C consists of indistinctly layered to chaotic lahars with minor scattered volcanic conglomerate and crossbedded sandstone occupying distinct and restricted channels in the volcanic deposits. Unit C is about 50 m thick in Mud Creek Canyon west of Richardson Spring and about 80 m thick near Tuscan Springs

Tti Ishi Tuff Member--White to light-gray, fine-grained, pumiceous air-fall tuff commonly reworked and contaminated with variable amounts of volcanic sandstone and silt. Distinguished by abundant black to bronze biotite flakes about 1 mm in diameter. The Ishi was originally identified along the Chico monocline where it occurs as a 0.03-m-thick ash layer deposited on volcanic conglomerate and silt at the top of unit B. Subsequent mapping identified a white, biotite-bearing tuff near Millville that correlates chemically with the Ishi (A. M. Sarna-Wojcicki, oral commun., 1982). East of Millville the Ishi contains pumice clasts as much as 8 cm in diameter and rests directly on a welded ash-flow tuff identical to that at Bear Creek Falls dated by Evernden and others (1964) at 3.4 m.y. and correlated by Anderson and Russell (1939) with the type Nomlaki Tuff Member (of the Tehama Formation). Biotite, plagioclase, and hornblende, which are separated from the large pumice clasts in the Ishi near Millville, give discordant K-Ar ages; a fission-track age of 2.7 m.y. obtained from zircons separated from the pumice clasts is the best current estimate of the age of the Ishi Tuff Member

Ttb Unit B--Defined along the Chico monocline as interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone similar to unit C, but underlying the Ishi Tuff Member. Lahars and volcaniclastic rocks interbedded in approximately equal proportions give a more regularly layered sequence than in the lahar-rich unit C. Maximum thickness of conglomerate layers about 15 m. Coarse cobble to boulder conglomerate predominant in the eastern and northern parts of mapped unit; crossbedded and channeled volcanic sandstone increases in abundance to the west and south. Unit B is about 130 m thick

Tta Unit A--Interbedded lahars, volcanic conglomerate, volcanic sandstone, and siltstone all containing scattered fragments of metamorphic rocks. Metamorphic rock fragments, as much as 20 cm in diameter, include white vein quartz, green, gray, and black chert, greenstone, greenish-gray slate, and serpentinite. Metamorphic clasts usually make up less than 1 percent of the rock, the remainder is basaltic and basaltic andesite volcanic fragments. The top of the member is defined by the highest lahar or volcanic conglomerate layer that contains metamorphic fragments. Unit A is about 65 m thick along the Chico monocline where it is defined

Ttn Nomlaki Tuff Member--White, light-gray, locally reddish-tan to salmon dacitic pumice tuff and pumice lapilli tuff exposed in widely separated areas at or very near the bases of the Tuscan and Tehama Formations. Pumice fragments as much as 20 cm in diameter are generally white in the lower part of the member and a mixture of white, light gray, and dark gray in the upper part. Member varies from massive nonlayered ash flow at Tuscan Springs, Gas Point, and Antelope Creek to distinctly bedded and crossbedded, reworked pumiceous sediment west of Richardson Springs. Maximum thickness is 25 m at Tuscan Springs, about 20 m at Antelope Creek, 1 m at Richardson Springs and 30 m at Gas Point on the west side of the valley in the Cottonwood Creek drainage. Lahars containing metamorphic rock fragments typical of unit A of the Tuscan occur below the Nomlaki Tuff Member in Rock Creek and at the west end of the exposures of the Lovejoy Basalt in Bidwell Park east of Chico. Evernden and others (1964) obtained a K-Ar age of 3.4 m.y. for a welded ash-flow tuff at Bear Creek Falls, which Anderson and Russell (1939) correlated with the type Nomlaki.

The Nomlaki Tuff Member has been identified from trace-element content of the glass by Sarna-Wojcicki, (written commun., 1982) at eight localities near the base of gravel and sand deposits, mapped as the Laguna Formation (Olmsted and Davis, 1961; Busacca, 1982), around Oroville and points south to the Yuba River and Beale Air Force Base. The presence of the Nomlaki Tuff near the base of the Laguna Formation suggests that the Laguna is coeval with the Tuscan and Tehama

Tla LAGUNA FORMATION (PLIOCENE)--Interbedded alluvial gravel, sand, and silt. Pebbles and cobbles of quartz and metamorphic rock fragments generally dominate the gravels, but the matrix of the gravelly units and finer sediments are invariably arkosic. In the vicinity of Oroville, volcanic rocks may comprise as much as 20 percent of the gravels, but again the finer sediments are dominantly arkosic. The Laguna is lithologically indistinguishable from the Turlock Lake Formation, but the Turlock Lake is more compact at the surface due to a preserved B_2t soil horizon. The Laguna, on the other hand, has had its former soil profiles stripped by erosion. The Turlock Lake and the Laguna can be distinguished by their stratigraphic positions relative to pediment gravels, by the presence or absence of some soil profiles, and by their topographic settings. In the Oroville area the Laguna is easier to distinguish because it contains the Nomlaki Tuff Member near its base (Busacca, 1982, p. 103). We have not found the Nomlaki in the Laguna in the Sacramento area nor anywhere south of Beale Air Force Base.

The Laguna Formation was named by Piper and others (1939) for arkosic alluvial deposits in the vicinity of Laguna Creek, San Joaquin County. These Sierran-derived deposits overlie the Mehrten Formation and are unconformably overlain by gravel of the North Merced pediment. Although the Laguna gravels are not exposed continuously from the type area northward into the Sacramento Valley, similar arkosic sediments overlying the Mehrten and truncated by the Red Bluff pediment occur in the Sacramento Valley and have been correlated with the Laguna (Olmsted and Davis, 1961 and Busacca, 1982). We agree with this correlation. The Laguna displays highly dissected rolling topography with tens of meters of relief. The only exposures are between Oroville and Sacramento on the southeast side of the valley. The Laguna was deposited by the ancestral west-flowing Feather, Yuba, Bear, and American Rivers.

The thickness of the Laguna is difficult to estimate because its base is rarely exposed and its surface has been highly eroded except where preserved beneath the Red Bluff Formation. The Laguna is probably about 60 m thick in the Oroville and thins to about 20 m or so south of Sacramento. Locally divided into:

Nomlaki Tuff Member--See description under the Tuscan Formation

Ts SUTTER FORMATION OF WILLIAMS AND CURTIS (1977) (PLIOCENE, MIOCENE, AND OLIGOCENE)--Williams and Curtis (1977) described these beds in the Sutter Buttes as consisting "almost exclusively of volcanic sediments transported by rivers from the Sierra Nevada to be deposited in deltaic fans and on broad flood plains that occupied most of the Sacramento Valley during Oligocene, Miocene, and Pliocene times" (Williams and Curtis, 1977, p. 13). Unit thickness ranges from 180 m to as much as 300 m

Tc CHANNEL DEPOSITS (PLIOCENE AND (OR) MIOCENE)--Tan, yellowish-tan to reddish-brown interbedded fluvial conglomerate and lesser amounts of sandstone exposed in some of the deeper canyons below the Tuscan Formation; includes the New Era Formation of Creely (1965). Unit is exposed near the New Era Mine in the northeast central part of the map, in Butte Creek, in Mud Creek below the Nomlaki Tuff Member of the Tuscan Formation and west of the Lovejoy Basalt, in the West Fork of Rock Creek below the Nomlaki, and at Tuscan Springs below the Nomlaki. Cobble to pebble conglomerate has rounded, commonly disk-shaped clasts showing variable degrees of imbrication. Clasts include greenstone, gray quartzite, red, green, and black chert, white vein quartz, and lesser amounts of green and gray phyllite. Variable amounts of basalt identical to that in the Tuscan Formation are intermixed with polycycle metamorphic fragments. Maximum thickness is about 20 m

Tm MEHRTEN FORMATION (PLIOCENE AND MIOCENE)--Sandstone, laminated siltstone, conglomerate, and tuff breccia composed almost entirely of andesitic material with only small amounts of igneous and metamorphic rock fragments. The fragments of andesite are almost always dark-gray porphyritic andesite with phenocrysts of hornblende and plagioclase in a microcrystalline to glassy groundmass. The only outcrops of the Mehrten in the map area occur in a few square kilometers of the southeast side of the valley northeast of Roseville along Interstate Highway 80 where the unit rests unconformably on granitic basement. In the San Joaquin Valley the strata that underlie the Laguna Formation and overlie the Valley Springs Formation have been mapped as the Mehrten Formation by Piper and others (1939)

Tl LOVEJOY BASALT (MIOCENE)--Black, dense, hard, microcrystalline to extremely fine grained, equigranular to sparsely porphyritic basalt. Where porphyritic, it contains scattered phenocrysts of plagioclase and lesser amounts of clinopyroxene in an hypocrystalline groundmass of felted plagioclase microlites, intergranular clinopyroxene, olivine and magnetite, and intersertal grayish-green to black, opaque basaltic glass. It is everywhere highly fractured with distinctive conchoidal fracture surfaces.

The Lovejoy comprises the prominent Orland Buttes on the west side of the valley as well as the conspicuous Table Mountain at Oroville on the east side of the valley. The Lovejoy Basalt is also exposed in deep canyons cut through the Tuscan Formation that narrow markedly where the Lovejoy is exposed. In Big and Little Chico Creeks, the Lovejoy is incised in very narrow channels only a few meters wide but as much as 60 m deep. The basalt at Putnam Peak at the south end of the English Hills near Vacaville is also composed of the Lovejoy Basalt (S. Gromme, oral comm., 1981). It is also exposed in the foothills northwest of Winters. The Lovejoy is penetrated by numerous wells in the valley (van den Berge, 1968) where a narrow linear subsurface distribution pattern strongly suggests that the Lovejoy flowed in a channel or channels across the present site of the Sacramento Valley. The outcrop and subcrop pattern (van den Berge, 1968) definitely suggests the Lovejoy flowed down more than one channel.

The maximum thickness in the mapped area is about 20 m (Harwood and others, 1981).

Dalrymple (1964) obtained a K-Ar age of 23.8 m.y. on a thin dacite ash just beneath the Lovejoy at Oroville Table Mountain. The date seems reasonable since the Lovejoy and the dacite ash overlie both the Eocene Ione and the auriferous gravels at Oroville. The Delleker Formation (not mapped in this report), which overlies the Lovejoy elsewhere, has been dated by Evernden and others (1964) at 22.2 m.y. near the type locality of the Lovejoy. Therefore the Lovejoy Basalt is bracketed within the early Miocene

Ts SEDIMENTARY ROCKS IN SUTTER BUTTES AREA (EOCENE)--Consist of what Allen (1925) and Williams and Curtis (1977) variously refer to as their "Capay Shales", "Ione Sands", and "Butte Gravels". At Sutter Buttes the Capay consists of "buff sands locally rich in ferruginous concretions and glauconitic shales rich in foraminifera. Carbonaceous mudstones are occasionally present as are thin seams of low-grade coal especially on the north and east sides of the Buttes" (Williams and Curtis, 1977, p. 12). Maximum thickness is about 1,200 m on the western side of the buttes. The Ione consists of white well-sorted quartz sand with irregular pink, purple, or brown streaks of oxidation with minor amounts of bleached anauxite. Thickness ranges from 30 to 50 m. The Butte Gravels consist of poorly consolidated interbedded gravel and sand with thin lenses of limestone and sandstone. The clasts in the gravel are primarily colorless and milky vein quartz with other minor clasts of quartz porphyry, varigated chert, schist, and hornfels. The Butte Gravels is as much as 400 m thick

Tmc MONTGOMERY CREEK FORMATION (EOCENE)--Gray, yellowish-orange-weathering, arkosic sandstone with conglomerate and shale; crops out on the Battle Creek escarpment along the road between Manton and Shingletown in the upper part of Lack Creek and Ash Creek, and occurs much more extensively in major southwest-trending drainages of the Millville and Whitmore quadrangles. The rock is commonly massive to thick-bedded nonmarine sandstone with scattered lenses of pebble conglomerate and shale. Detrital muscovite and feldspar are common in the sandstone; red, green, and gray chert are the most common clasts in the conglomerate lenses. The unit is about 80 m thick at its south limit and apparently thickens to the north where Anderson and Russell (1939) reported 200 m of the formation exposed in Montgomery Creek.

Anderson and Russell (1939) collected fossil leaves from the Montgomery Creek, which Chaney identified as definitely Eocene in age

Ti IONE FORMATION (EOCENE)--Light-colored, commonly white conglomerate, sandstone, and claystone. Argillaceous sandstone and claystone comprise about 75 percent of the Ione along the southeast side of Sacramento Valley; northward the rest of the unit consists of interbedded siltstone, conglomerate and shale. It should be noted that the map area is far north of the type locality at Ione in Amador County. The Ione is generally soft, deeply eroded, and marked by numerous landslides. Ione sandstones are characterized by fine grains of angular quartz and thin stringers of weathered anauxite. Allen (1929) interpreted the Ione sediments to be similar to modern deltaic deposits. He also correlated the Ione sediments with Sierran auriferous gravels based on a comparison of mineralogy and stratigraphic position. The Ione underlies the Lovejoy Basalt at Oroville Table Mountain and it is present in the Lincoln area. The maximum thickness of the Ione near Table Mountain is 200 m (Creely, 1965)

Kc CHICO FORMATION (CRETACEOUS)--Tan, yellowish-brown to light-gray, fossiliferous marine sandstone with lenticular beds of pebble to fine cobble conglomerate and minor siltstone. Clasts in the conglomerate include rounded to well-rounded, red, green, and black chert, white vein quartz, quartzite, granite, and greenstone. Calcite-cemented concretions and layers of fossil fragments are common. The sandstone is composed of fine to medium, angular to subrounded grains of quartz, plagioclase, alkali feldspar, lithic fragments, and detrital chert. At the type section on Big Chico Creek the unit is about 650 m thick (Taff and others, 1940, p. 1317)

BEDROCK

pKmi METAMORPHIC AND IGNEOUS ROCKS (PRE-CRETACEOUS)--Undivided slate, quartzite, metaconglomerate, marble, metavolcanic rocks, serpentinite, metagabbro, diorite, and monzonite (see Creely, 1965; Hietanen, 1973, 1976)

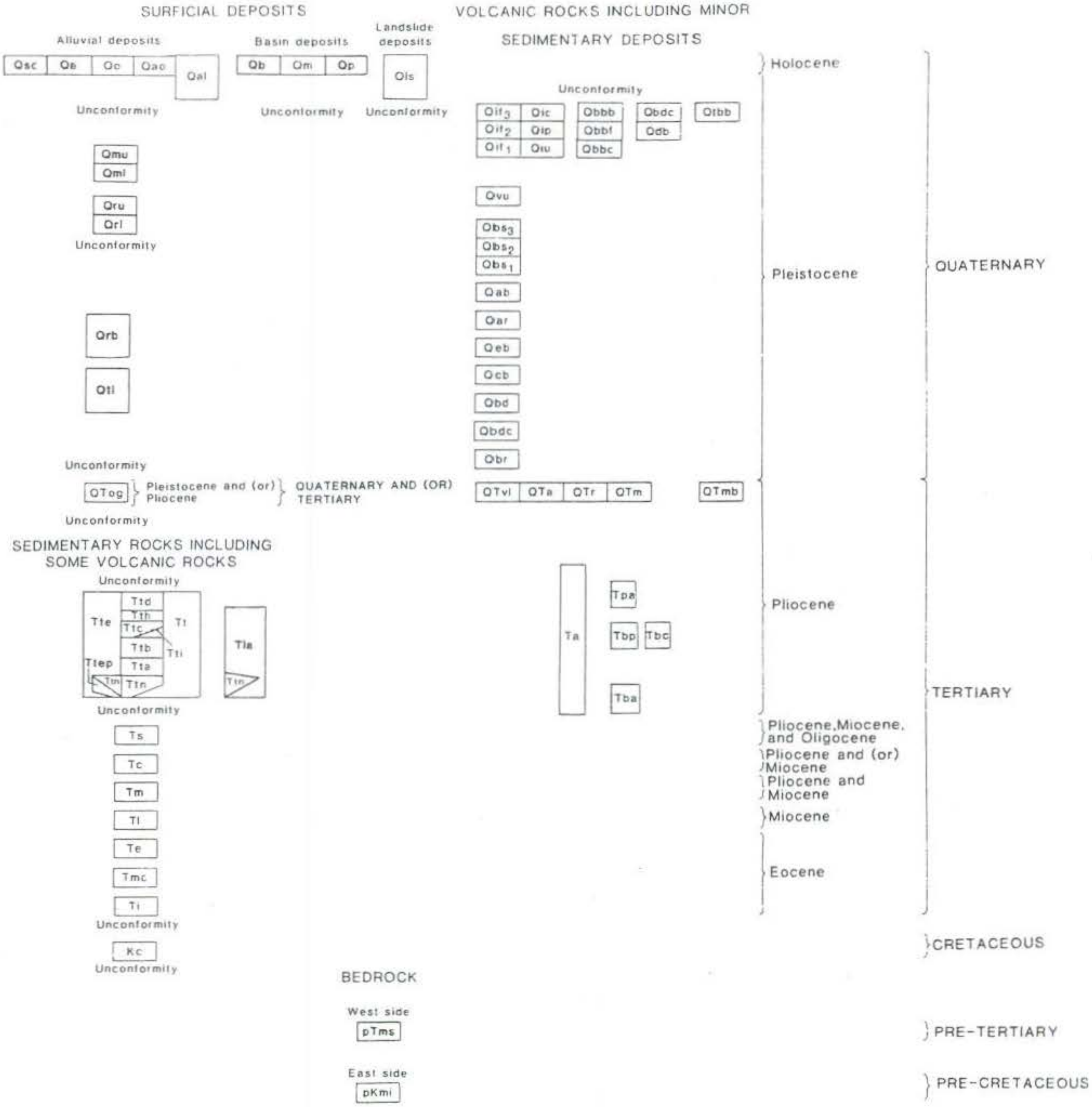
pTms METAMORPHIC, INTRUSIVE, AND SEDIMENTARY ROCKS (PRE-TERTIARY)--Undivided metamorphosed Paleozoic and Mesozoic volcanic and sedimentary rocks intruded by Mesozoic and older granitic rocks in the Klamath Mountains; the Franciscan Complex and the Coast Range ophiolite (discussed in detail by Irwin, 1966, Murphy and others, 1969, and Irwin and others, 1978); and the overlying unmetamorphosed sedimentary rocks of the Great Valley sequence (see Bailey and Jones, 1973)

SOUTHERN SACRAMENTO VALLEY

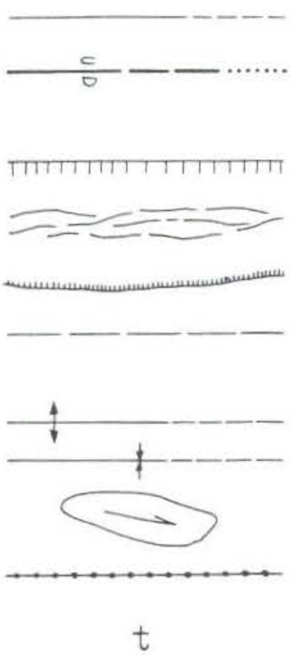
CORRELATION OF MAP UNITS

SHEET 1

(NOTE - Not all map units occur on every sheet; stippling indicates presence on this map sheet)



EXPLANATION



CONTACT-Dashed where approximately located

FAULT - Dashed where approximately located; dotted where concealed;
U, upthrown side; D, downthrown side

FAULT SCARP - Hachures on downthrown side

FRACTURE PATTERN - On Chico Monocline

VOLCANIC FISSURES OF INSKIP HILL

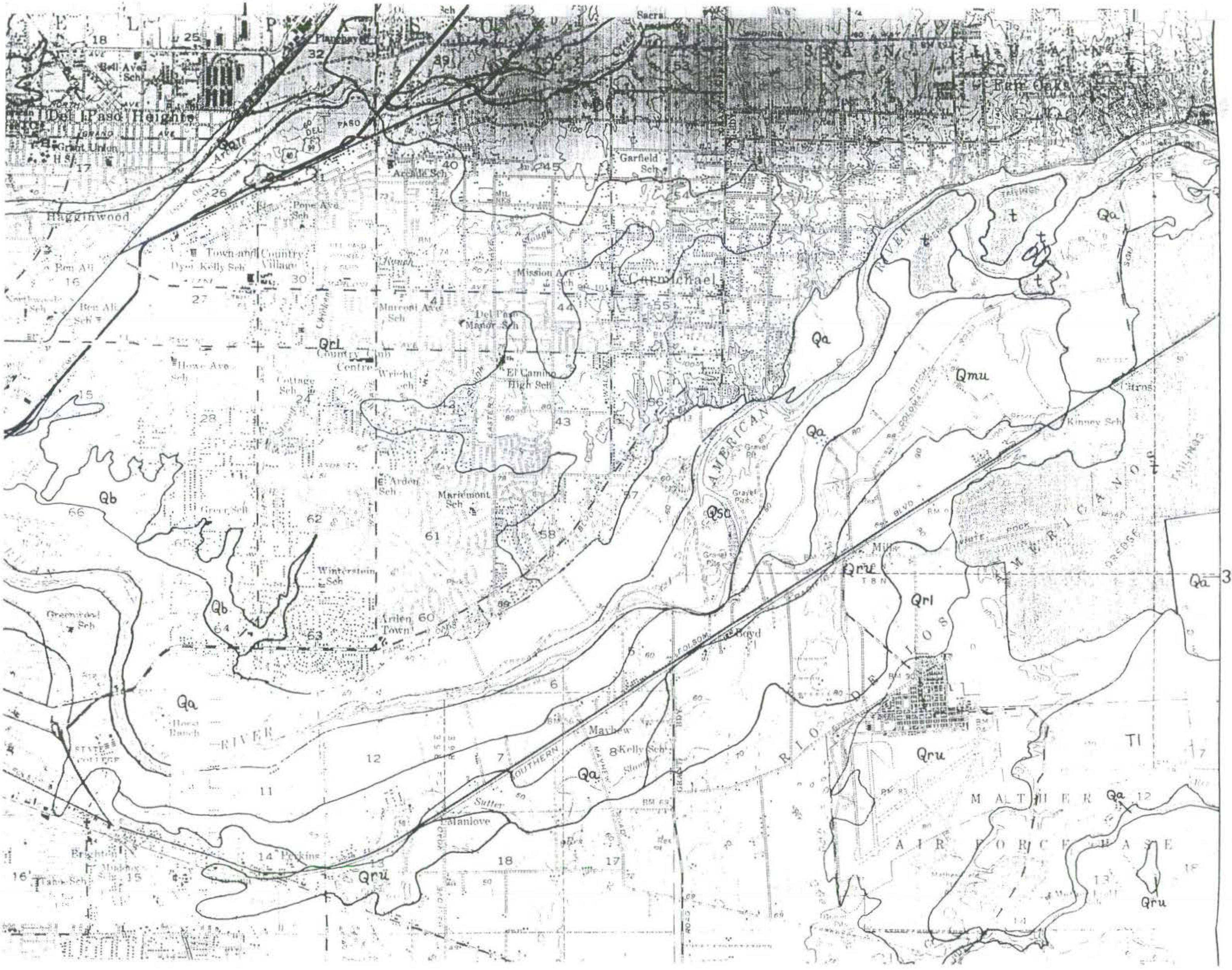
PHOTO LINEAMENT

FOLDS
  Anticline - Dashed where approximately located
  Syncline - Dashed where approximately located

LANDSLIDE - Arrow indicates direction of movement

TUFF BED

MAN MADE MATERIALS - Dredge tailings and other
disturbed ground


Del Paso Heights
Haggin wood
Town and Country Village
Country Club Centre
Carmichael
Fair Oaks
Garfield Sch
Mission Ave Sch
Del Paso Manor Sch
El Camino High Sch
Marconi Ave Sch
Arden Sch
Mariemont Sch
Winterstein Sch
Arden Town
Greer Sch
Howe Ave Sch
Cottage Sch
Greenwood Sch
State College
Brighton
Perkins
Manlove
Sutter
Mayhew
Kelly Sch
Mills
Boyd
Kinney Sch
Citrus
AMERICAN
RIVER
RIO DE LOS AMERICANOS
MATHER AIR FORCE BASE
SOUTHERN PACIFIC
FOLSOM BLVD
COLOMA
WHITE ROCK
Gravel Pit
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Tl
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16′

ATTACHMENTS 6 AND 7

Florsheim, J. L., and J. F. Mount. 1999. Geomorphic and ecological response of the anastomosing lower Cosumnes River, California, to anthropogenic disturbances: implications for restoration. *Geological Society of America, Abstracts With Programs,* 31(7):A-202.

Florsheim, J. L. and J. F. Mount. Intentional Levee Breaches as a Floodplain Restoration Tool: Monitoring Floodplain Topography, Cosumnes River, CA. Submitted for Spring AGU Meeting, Washington DC May 30-June 3, 2000.

GEOMORPHIC AND ECOLOGICAL RESPONSE OF THE ANASTOMOSING LOWER COSUMNES RIVER, CALIFORNIA TO ANTHROPOGENIC DISTURBANCES: IMPLICATIONS FOR RESTORATION

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Prior to anthropogenic disturbance, the lower Cosumnes River, California, was an anastomosing river. Maps and historical data of the lowland river (slope 0.0006) suggest that the upstream portion of the system contained numerous islands with dense riparian forest between the dominant and secondary channels. The downstream reach flowed through seasonal marsh that was periodically inundated by overbank flow from the Sacramento and Mokelumne Rivers. The lowermost Cosumnes floodplain contained multiple channels that were hydrologically connected to the marsh and lagunitas (tributary mouth and floodplain lakes). Anthropogenic changes such as grazing, agricultural clearing of the riparian forest, gold dredging, woody debris removal, logging, aggregate extraction, road and railway construction, and urbanization altered the system. Levee construction, beginning in 1907, had significant geomorphic and ecological effects including concentrating flow from multiple anastomosing channels to one main channel isolated from its floodplain, inducing incision, increasing flood hazards, and reducing ecosystem diversity. Reclamation of the seasonal marsh in the downstream portion of the system began in the mid 1800's and isolated the river from its floodplain marshes and lagunitas. Today, most of the Lower Cosumnes River channel is maintained in place by levees, agriculture dominates the floodplain, and remnants of the original riparian forest remain only in the Cosumnes River Preserve.

In an anastomosing system, floodplain evolution takes place by avulsion, where breaches in natural levees initiate new channel formation or re-occupation of old channels, and development of sediment splays. Geomorphic change during avulsion is episodic, causing natural erosion and deposition disturbance required for riparian vegetation succession. The anastomosing character of the Cosumnes River prior to anthropogenic disturbance has implications for planned restoration strategies because in some locations, the tendency of river morphology may be to evolve by re-forming multiple channels through avulsion. Strategies that limit the fluvial system to a single channel may not be sustainable in the long-term. This may be relevant for other lowland river restoration projects in California's Central Valley.

Florsheim, J. L., and J. F. Mount. 1999. Geomorphic and ecological response of the anastomosing lower Cosumnes River, California, to anthropogenic disturbances: implications for restoration. ***Geological Society of America, Abstracts With Programs,*** **31(7):A-202.**

INTENTIONAL LEVEE BREACHES AS A FLOODPLAIN RESTORATION TOOL: MONITORING FLOODPLAIN TOPOGRAPHY, COSUMNES RIVER, CA

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Restoration includes an attempt to promote geomorphic processes – or the disturbances – that recreate dynamic ecosystem habitat. Accommodation of fundamental processes such as flooding, erosion, transport, and deposition are essential for diversity in floodplain ecology. Critical elements in restoration designs should include identification of the links between basin-scale and reach-scale geomorphic processes, the range in magnitude of processes needed to create the dynamic physical conditions that sustain floodplain ecosystem functions, and the space necessary to accommodate these processes over the long-term. Levees constructed over the past century in the lowland Cosumnes River, Central Valley, CA, have changed floodplain ecology by inhibiting geomorphic processes. Levees concentrated multiple channels into a single channel and isolated the river from its floodplain. Additionally, agricultural draining, leveling, and clearing of riparian vegetation reduced the geomorphic complexity associated with the pre-disturbance anastomosing system (topographically low seasonal marshes, channels, and perennial lakes, and topographically higher splays and levees). As part of a long-term interdisciplinary ecosystem monitoring project, we are investigating two intentional levee breaches constructed to restore floodplain habitat in portions of the Cosumnes River Preserve. Levee breaches at the 'Accidental Forest' (1995) and the 'Corps Breach' (1997) restored connectivity between the main channel and floodplain. Our total station field surveys document the morphology of the resulting sand splays that formed (formerly flat agricultural fields) at the levee breaches. Floodplain sand splay deposition (up to 0.5m) and erosion (up to 0.8m) patterns, progradation of splay channels, and topographic variation resulting from large woody debris recruitment illustrate: 1) the first phase in the evolution of topography needed to restore diversity typical of a floodplain to the former agricultural field (accommodation of geomorphic processes); and 2) the effect of initial grading inside the breach (inhibition of geomorphic processes). Monitoring intentional levee breaches as a floodplain restoration tool will provide further information to help define a scientific basis for floodplain river restoration.

Florsheim, J. L. and J. F. Mount. Intentional Levee Breaches as a Floodplain Restoration Tool: Monitoring Floodplain Topography, Cosumnes River, CA. Submitted for Spring AGU Meeting, Washington DC May 30-June 3, 2000.