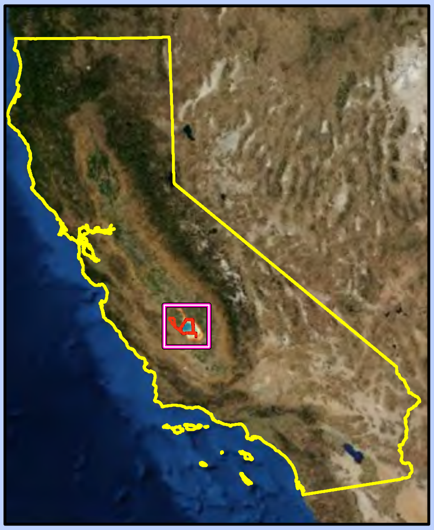

PSSAC 2016 Tulare Lake Field Tour Stops and Elevation Map

1: Utica Avenue - Tulare Lake Edge Soils
2: Sand Ridge at 6th Avenue
3: J.G. Boswell Company, El Rico Ranch, Tule River
4: Quail Avenue High Stand Site (66.5 m / 218 ft)
5: Arroyo Pasajero at California Aqueduct

2016 Professional Soil Scientists Association of California Annual Meeting in the San Joaquin Valley studies hydrology, geomorphology, soils, stratigraphy, and archaeology in the Tulare Lake Basin

April 9, 2016

PSSAC Tour Participants along the Tule River at El Rico Ranch and 10th Avenue. Photo by David McEuen, courtesy of Irfan Ainuddin.

2016 Professional Soil Scientists Association of California Annual Meeting - Harris Ranch

Theme: Hydrology, Geomorphology, Soils, Stratigraphy, and Archaeology in the Southern San Joaquin Valley: Focusing on Buena Vista and Tulare Lake Basins

Meeting Organizers: Kerry Arroues and Phil Smith

Executive Secretary: Mary Reed

Executive Council: Meghan Hynes**, President;** Margaret Bornyasz**, Past-President;** David Kelley**, President-Elect**

Board of Directors: Members of the Executive Council, and John Munn**, Northern Area Director;** Kerry Arroues**, Central Area Director; and** Roy Shlemon**, Southern Area Director**

Presenters:

Rob Hansen, Consultant and Professor, Ecology, Zoology, and General Biological Sciences at College of the Sequoias, Visalia, CA

Jack Meyer, Principal Geoarchaeologist, Far Western Anthropological Research Group, Inc.

John Austin, Retired from National Park Service, author of *Floods and Droughts in the Tulare Lake Basin*

Junhua "Adam" Guo, Department of Geological Sciences, California State University, Bakersfield

Robert Negrini, Department of Geological Sciences, California State University, Bakersfield

Roy J. Shlemon, Consultant, Newport Beach, CA

Robin M. Roberts, USDA-NRCS, Earth Team Volunteer, Hanford, CA

Kerry D. Arroues, Retired USDA-NRCS Soil Scientist, Hanford, CA

Philip D. Smith, USDA-NRCS Soil Scientist, Hanford, CA

2016 Professional Soil Scientists Association of California Annual Meeting - Harris Ranch

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7:00 – 8:30 am: Registration and Continental Breakfast in Foyer of Garden Ballroom

8:30 – 8:45 am: Welcome from PSSAC officers and meeting organizers

8:45 – 9:30 am: Tulare Valley "Sense of Place" through a Naturalist's Eyes –Flora and Fauna of the Fragments Presenter: Rob Hansen, Consultant and Professor, Ecology, Zoology, and General Biological Sciences at College of the Sequoias, Visalia, CA

9:30 – 10:00 am: Prehistoric People and Landscape Changes in the Tulare Lake Basin. Presenter: Jack Meyer, Principal Geoarchaeologist, Far Western Anthropological Research Group, Inc.

10:00 – 10:15 am: Break

10:15 – 11:30 am: Brief History of Water in Tulare Lake Presenter: John Austin, Retired from National Park Service, author of *Floods and Droughts in the Tulare Lake Basin*

11:30 am – Noon: Sediment provenance and paleoenvironmental change since 35 ka in the western North America: Constrained by the mineral evolution in the Tulare Lake, California Presenter: **Junhua "Adam" Guo**, Robert Negrini, Department of Geological Sciences, California State University, Bakersfield

Noon – 1:30 pm: Lunch on your own

1:30 – 2:15 pm: Late Quaternary "Tulare Lake Beds" in the San Joaquin Valley, California: Estimated Age and Influence on Land Subsidence. Presenter: Roy J. Shlemon, Consultant, Newport Beach, CA

2:15 – 3:00 pm: The levels of Tulare Lake for the past ~20,000 years as inferred from the geologic record: Implications for past precipitation in the Sierra Nevada over that time period. Presenter: Robert Negrini, Department of Geological Sciences, California State University, Bakersfield

3:00-3:15 pm: Break

3:15 – 4:00 pm: The Mussel Slough Tragedy: Creating an Historical Context for Soil Study in California's Southern San Joaquin Valley
Presenter: Robin M. Roberts, Ph.D., USDA-NRCS, Earth Team Volunteer, Hanford, CA

4:00 – 4:45 pm: Soils of the Southern San Joaquin Valley: From Buena Vista Lake to Fresno Slough Presenter: **Kerry D. Arroues**, Retired USDA-NRCS Soil Scientist, Philip D. Smith, USDA-NRCS Soil Scientist, Hanford, CA

4:45 – 5:00 pm: Presentation wrap and organization for field trip that will commence on Saturday, April 9, 2016.

5:00 – 6:00 pm: Break

6:00 – 7:00 pm: Cocktail hour, no-host bar with cheeses garnished with Harris Ranch almonds and assorted crackers in Foyer of Garden Ballroom

7:00 – 9:00 pm: Dinner Banquet in Garden Ballroom. Dinner speakers Kerry Arroues and Robin Roberts will present: The Sage of Garza Creek and His Ship of Life: A Case Study at the Intersection of Earth Sciences and History.

Schedule and Abstracts for Friday, April 8, 2016 Professional Soil Scientists Association of California Annual Meeting

Garden Ballroom - Harris Ranch

Theme: Hydrology, Geomorphology, Soils, Stratigraphy, and Archaeology in the Southern San Joaquin Valley: Focusing on Buena Vista and Tulare Lake Basins

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8:45 – 9:30 am: Tulare Valley "Sense of Place" through a Naturalist's Eyes –Flora and Fauna of the Fragments

Tulare Valley "Sense of Place" through a Naturalist's Eyes –

Flora and Fauna of the Fragments

Rob Hansen, Consultant and Professor, Ecology, Zoology, and General Biological Sciences at College of the Sequoias, Visalia, CA

The Sacramento and San Joaquin rivers flow to the sea, yet no natural lakes are found in either valley. But the rivers in the Tulare Valley — the Kings, Kaweah, Tule and Kern — historically flowed to 5 inland lakes, including Tulare Lake. If you are not familiar with the Tulare Valley … if you don't know where it is, read on. Most of you live there but you probably grew up, as I did, calling it the southern San Joaquin Valley.

Tulare Lake was the largest of five named lakes in the Tulare Valley, all connected by a system of shallow, slow-moving tule-lined sloughs. The southernmost lake, fed by the waters of the Kern River was Kern Lake, south and west of Bakersfield. Kern Lake, about 6 miles by 3 miles in size, was nestled at the toe of the San Emigdio Range at an elevation of 290 feet (the southern end of the Tulare Valley is higher because of the geologically recent uplift of the Transverse Ranges). The Kern River continued west into Buena Vista Lake, just east of Taft. Buena Vista Lake, measuring 9 miles by 6 miles, was situated at the same elevation as Kern Lake and had only a narrow natural levee separating its exit channel from its entrance. Water from Kern and Buena Vista Lakes flowed north (downhill) in Buena Vista Slough and the northern terminus of Kern River through about 80 miles of slough country. Just east of these poorly known and difficult-to-navigate channels lies Jerry Slough, which flows to Goose Lake (elevation 250 feet), a long (up to 20 miles), narrow (1 to 4 miles wide) body of shallow water. During high flow events (with the Kern River as its ultimate source), all this water from the southern Tulare Basin would cross the Sand Ridge (between Alpaugh and Dudley Ridge) and enter the south end of Tulare Lake. Tulare Lake water would flow north through tiny Summit Lake (west of Lemoore), the smallest and northernmost of the five lakes, and ultimately discharge into the San Joaquin River. The actual outlet for the

Tulare Lake system was a narrow opening through the barrier ridge which contained the lake waters. Located a few miles southeast of present-day Mendota, this natural bottleneck was called Sanjon de San Jose.

The Tulare Basin historically supported a complex of wetland and upland habitats unique in the world. This largely flat and arid region served as the floodplain for several Sierra watersheds to the east and small intermittent arroyos flowing east from the Coast Ranges and north from the Transverse Ranges. Oak woodlands and riparian forests, sustained by snowmelt, formed green corridors across the broad prairie on the eastern edge of the Basin. Saltbush was the dominant shrub in the desert scrub communities found in the southern reaches and along the western edge of the basin. Freshwater tule marshes (los tulares) and alkaline wetlands adorned the slow-moving sloughs and shallow margins of Kern Lake, Buena Vista Lake, Goose Lake, Tulare Lake, and Summit Lake in the lowest trough of the Basin. Emergent marsh vegetation (tules, cattails, rushes, and spikerush) grew in permanent standing water at the shallow edges of freshwater wetlands. Such intermittently flooded habitats included alkali grasslands (dominated by saltgrass and alkali bunchgrass).

Not only is the Tulare Basin hydrologically distinct from the more well-watered, more mesic San Joaquin Basin to the north; but the Tulare Basin embraces a biodiversity that includes more desert- and alkali-adapted species. The aridity and high evaporation rates of the Tulare Basin, coupled with

the nearly flat terrain and its poor drainage, created wetlands with a range of salinity from nearly pure snowmelt in the deepest fast-flowing parts of the large Sierra streams to shallow alkaline pools adjacent to marshes and sloughs. The flatness of this saucer-like basin had a significant impact on the type and extent of wetlands, especially along the alkali shores of the lakes and sloughs.

While Salmonids seldom ventured into the too-warm waters of this intriguing inland fish province (since Sierra Rivers south of the San Joaquin River are not perennial streams, they are unsuitable for maintaining anadromous fishes), populations of endemic lake-adapted fishes were so abundant because of the highly productive nature of this shallow system that white pelicans nested by the thousands on islands in Tulare Lake and Buena Vista Lake. Historically significant numbers of resident and migratory waterbirds including grebes, pelicans, cormorants, herons, egrets, ibises, geese, swans, ducks, rails, Sandhill Cranes, plovers, stilts, avocets, sandpipers, phalaropes, gulls, and terns were attracted to these extensive (covering tens of thousands of acres) aquatic habitats.

While scattered remnants of the original wetland and upland habitats remain (where you can observe and enjoy the “flora and fauna of the fragments”), the pristine landscape has been extensively modified by two centuries of European settlement. Aquatic habitats in this area today are chiefly managed wetlands which are operated either: 1) to attract waterbirds during the winter waterfowl season (U.S. Fish and Wildlife Service’s

Kern and Pixley National Wildlife Refuges and private duck club lands in the Kern-Wasco area); 2) for breeding (USDA Natural Resource Conservation Service's Wetland Reserve Program lands near Alpaugh); 3) agricultural reservoirs and settling basins managed for the storage, conveyance, and percolation of surface irrigation water (Corcoran Irrigation District and Alpaugh Irrigation District Reservoirs, Creighton Ranch, Hacienda Ranch/South Wilbur Flood Area, and numerous basins within the boundaries of Kaweah Delta Water Conservation District and Lower Tule River Irrigation District); 4), water banks managed for groundwater recharge (like Kern Water Bank managed by the Kern Water Bank Authority); and 5) evaporation basins and compensation habitat managed for the disposal of subsurface irrigation tailwater (ponds operated by Tulare Lake Drainage District, Westlake Farms, and other operators in southwestern Fresno County, northern and western Kern County, and Kings County).

While the range of salinity in these managed wetlands is probably similar to those in the pre-settlement Tulare Basin, the acreages and ratios of freshwater wetlands and alkali wetlands have changed and a new category of aquatic habitat (saline wetlands) is now present at evaporation basins. Most of the same species of resident and migratory waterbirds that once inhabited the mosaic of natural wetlands in the historic Tulare Basin, today depend on the managed wetlands described above. Even though these manmade saline wetlands can have high salt concentrations, they are also extremely productive biologically. While species richness among microorganisms, invertebrate and vertebrate members of saline aquatic communities is lower than in systems with lower salt concentrations (some "osmotically-challenged" species lack specialized adaptations for dealing with higher salinity), populations of those halophytes that can thrive here (certain species of bacteria, algae, rotifers, *Daphnia*, water boatmen, backswimmers, brine flies, midges, and beetles) are often staggering. High nutrient levels are often associated with high salinity and this may reflect the natural situation under historical conditions in the Tulare Basin.

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We tend to treat a place in ways that reflect how we think about the place. I have a sense that many residents of the Tulare Valley (what most of us know today as the "southern San Joaquin Valley") consider this place … our place … where we live … to be somehow "less than" those parts of California with more scenic grandeur or more cultural offerings. An example of what I mean can be summed up by asking ourselves why this area is thought of by the rest of California as a dumping ground for humans (so many prisons), hazardous waste (in the Kettleman Hills), and treated sewage (much "night soil" from southern California is trucked to be spread on farmland along the west side).

There might be merit in revisiting the name "Tulare Valley" as a way of celebrating unique aspects of this part of California in much the way that many of us equate a certain cachet with place name "brands" like "Napa Valley" and "Silicon Valley". Just as the single word "sequoia" conjures up imagery of the giant trees in "our" portion of the Sierra Nevada, so might "Tulare" Valley come to suggest, to visitors from around the world, this special part of Central California … the only "hydrological basin" in the

Central Valley where extensive tule marshes historically surrounded fresh water lakes set amidst the San Joaquin Desert. In case you didn't know that Visalia, Hanford, Bakersfield, and Fresno are located in … or near … one of five recognized deserts in North America, treat yourself to the pdf version of this 2011 article about our own San Joaquin Desert by Germano et al at this link: http://www.bioone.org/doi/abs/10.3375/043.031.0206?journalCode=naar . Just like the other 4 North American Deserts (the Mojave, Great Basin, Sonoran, and Chihuahuan Deserts), the San Joaquin Desert is classified based on characteristic climate, soils, vegetation, and wildlife. The kind of biodiversity that evolved in this land of dramatic ecological contrast (where white pelicans nested on islands in lakes surrounded by burrowing owls, horned lizards, and kangaroo rats) still persists here, even in the midst of this millennial drought year. As climate change shifts our regional winter weather pattern to one where snowpack is less reliable and we get more of our precipitation as rain, water districts and irrigators are beginning to look at the Tulare Valley's historic lakebeds (Tulare Lake, Kern Lake, Buena Vista Lake, Goose Lake, and Summit Lake) as places to capture and hold large volumes of storm water runoff in order to minimize urban flood damage during the rainy season while maximizing our ability to retain water for agriculture and wildlife in our region … water that moves through our area so quickly during storm events that there is no way to percolate all of it into regional aquifers before it flows to the Delta. Designated portions of those historic lakebeds may be an ideal place to park large volumes of storm water runoff until the water can be directed to farmland or groundwater bank recharge basins.

I try to familiarize my students with the unique hydrology of our Tulare Lake Basin. Most of my students (even if their former high school is on the bank of the St. Johns River or Mill Creek) do not know where their water comes from (or whether these waterways provide reliable flows each year adequate to meet the "needs" of urban, agricultural, and environmental water consumers). As a college biology and ecology professor (and as President of Tulare Basin Wildlife Partners) I try to encourage students and other audiences to become more familiar with the Sierra watersheds of our local rivers, creeks and sloughs, and the floodplains on the floor of the Tulare Valley where that water spreads out, I hope some of them will be the creative thinkers and entrepreneurs in a future when we are more aware, creative, and considerate about:

- where we site developments (in order to keep valuable structures and permanent crops out of floodplains so that the waterways and storm water flows have room to meander without causing economic hardship and increasing flood insurance costs),
- how to accommodate habitat and wildlife wherever we store and convey irrigation water, and,
- ways that all of our communities … large and small … can explore conjunctive use solutions that allow our limited water supply to provide for landscape, wildlife, scenic, and recreational values while helping to maintain and grow our agricultural economy.

I don't mean to be too Pollyanna-ish by imagining that millions of tourism dollars will flow into the Tulare Valley tomorrow as out-of-towners suddenly "flock" here to see desert-dwelling burrowing owls and wintering sandhill cranes at Pixley NWR but visitors ***are already*** being attracted to the wide-open spaces where desert and wetland species live. There is value in wild places and dollars will be spent by local residents and tourists alike when they travel to the dozens of "fragments where local biodiversity still persists for us to observe and enjoy. Whether they are managed by federal or State agencies, water districts, conservation-minded non-government organizations (NGOs), or private landowners, all of these destinations attract travelers in search of solitude and recreation … people who take walks (and buy outdoor clothing and sporting goods), have hungry children (for whom they buy food and drinks), drive along tour routes (and fill their tanks with gasoline), look at birds and butterflies (and rent motel and hotel rooms), and take nature photographs (and buy meals at restaurants).

It just seems to me that many of the smaller communities (and some of the larger towns) in the Tulare Valley would benefit by working together to get the word out that there are remarkable things to see and do in the wildlands (ecotourism) and farmlands (agritourism) of this singularly remarkable part of California … the Tulare Valley. If I sound like a "booster" for the place I live, I am. While I am not a member of any Chamber of Commerce I do believe that when we help our children, our students, residents, and visitors to become aware of these local "treasures", that we can help engender an ethic of stewardship that can grow to help more residents of the Tulare Valley to have a positive "sense of place" … one that can then be appreciated and celebrated by ever more travelers and tourists from other parts of California and from around the world. If you aren't already familiar with Tulare County Treasures (visit their website at this link http://www.tularecountytreasures.org/treasure-tales.html), their mission …

> to celebrate, educate, and inspire by telling the stories of the wonderfully diverse places that have been conserved in Tulare county, and of the visionary people who have worked to protect and steward them ...

captures the essence of why I love to be out in the field trying to better understand connections between the geology, soils, hydrology, flora, and fauna of the Tulare Valley, an area with a colorful human history and a unique and intriguing natural history.

9:30 – 10:00 am: Prehistoric People and Landscape Changes in the Tulare Lake Basin.

Prehistoric People and Landscape Changes in the Tulare Lake Basin

Jack Meyer, Principal Geoarchaeologist, Far Western Anthropological Research Group, Inc.

The Tulare Lake basin contains some of the earliest evidence of human occupation yet identified in California. Hundreds of fluted or concave-base projectile points recovered from the basin suggest prehistoric people arrived here more than 11,600 years ago during terminal late Pleistocene, and a few intact archaeological deposits have produced radiocarbon dates that exceed 8,000 years cal BP. Over this time the basin has undergone a series of significant landscape changes that undoubtedly influenced the location and intensity of prehistoric human settlement. When considered together, the archaeological and geological datasets provide information about the nature and timing of large-scale landscape changes, and the paleoenvironmental conditions faced by early people within the basin.

10:15 – 11:30 am: Brief History of Water in Tulare Lake Presenter: John Austin, Retired from National Park Service, author of *Floods and Droughts in the Tulare Lake Basin.*
The full-featured (and free) pdf version of the second edition of John Austin's book is posted online at the Tulare Basin Watershed Initiative's (TBWI) website:
http://www.tularebasinwatershed.org/sites/default/files/sites/all/default/files/pdf/Floods%20and%20Droughts%20in%20Tulare%20Lake%20%20Basin_SecondEdition.pdf

Brief History of Water in Tulare Lake
John Austin
Revised March 30, 2016

Description of Tulare Lake. Tulare Lake is fed by the Kings, Kaweah, Tule, and Kern Rivers as well as many smaller streams. The maximum elevation of the lake was controlled by a sill (like a window sill or a broad saddle) on the north near present-day Lemoore. This sill has an elevation of 207 feet, and was formed by the meeting of two huge deltas. The bigger delta was formed by the west-flowing Kings River coming out of the Sierra. It met the smaller east-flowing delta formed by the Arroyo Pasajero coming out of the Coast Ranges.

In very wet years, Tulare Lake overflowed this delta sill and connected through the Fresno Slough to the San Joaquin River. From there, the water flowed on to San Francisco Bay. The lowest part of the lakebed was 179 feet elevation. Tulare Lake was a shallow lake. Except during flood periods, the lake had a maximum depth of about 28 feet at its deepest point (elevation 207 - 179 feet). There could be as much as nine feet of water flowing over the delta sill during the spring in big runoff years. At such high stands, the lake had a maximum elevation of 216 feet and was about 37 feet deep at the deepest point (elevation 216 - 179 feet).

Tulare Lake fluctuated in size depending largely on the amount of runoff coming from the Sierra. In very wet years, it could grow to at least 790 square miles. That is over four times larger than Lake Tahoe, easily qualifying it as the largest freshwater lake west of the Great Lakes.

Tulare Lake was the largest of the five valley lakes that existed at the time of Euro-American settlement in the early 1850s. These lakes were the anchors of a wetland complex of over

400,000 acres. That complex constituted the largest single wetland in California. This wetland complex connected with the wetlands that fringed the San Joaquin River, making a continuous wetland all the way to the Sacramento–San Joaquin Delta.

These five lakes supported an extensive fringing tule marsh. The tules (also known as bulrushes) grew in very dense stands. The plants were up to 16 feet tall and the stems were 1–2 inches in diameter.

Precipitation and runoff in the Tulare Lake Basin are extremely variable; we seldom have "normal." Likewise, the elevation of Tulare Lake was extremely variable. Little of the water soaked into the lakebed. Under natural conditions, the elevation of the lake was controlled largely by the interplay of runoff and evaporation.

The five lakes and the wetland complex were sustained largely by runoff from the Sierra. This wetland complex was located in the middle of a very arid area that has been described as the San Joaquin Valley Desert. Tulare Lake functioned somewhat like a water hole on the Serengeti, just much, much bigger. The floods kept this system going through the dry periods.

Decline of Tulare Lake. There was a wide strip of sparsely vegetated land between the foothills and the wetlands. Beginning in about 1855, the early settlers tapped the rivers where they came out of the foothills, and used this water to convert the arid land into irrigated fields and orchards. This enabled the San Joaquin Valley to become one of the world's most productive agricultural regions. By 1900, the Kings River — historically Tulare Lake's most important source of water — was irrigating over a million acres, more land than any other stream in the world except the Nile and Indus Rivers.

The construction of that network of canals in the late 1800s was the primary reason that Tulare Lake declined from full-pool in 1878 to bone-dry in 1898. As the inflow of water to the lakebed was reduced, it became feasible to farm the rich lakebed soils. Because of the highly variable runoff in our basin, lakebed farmers are faced with the dual challenge of dealing with the partial return of the lake in high-water years, and finding enough water in normal and low-runoff years.

There was one more big change in water supply. At the time of settlement, the Kings River flowed on the south side of its delta fan, directly into Tulare Lake. In 1916, the river completed the switch to the north side of its fan. After this switch, the lakebed farmers were left without sufficient water to irrigate the reclaimed grain land, forcing them to sink deep wells for their irrigation water.

Salinity conditions at the time of settlement. Precipitation was fairly steady from before 1600 A.D. to the mid-1980s. Rainwater contains no salt, so that precipitation added no salt to the environment. The majority of the precipitation evaporated in the upper watersheds and went over the Sierra.

Roughly a quarter of the precipitation ran off into rivers and streams. A large portion of the soluble salts and sodium in soils originates in the decomposition of soil minerals and rocks by weathering. Runoff transports many of these soluble salts and sodium from the higher elevations of the basin to the wetlands in the valley floor.

Most of the water in the valley wetlands evaporated or was transpired from plants; little soaked into the ground except in the sandy sloughs that meandered through the alluvial fans. The water and soils in this area became naturally alkaline and salty. Salts concentrated in the soils around the outside perimeter of the lakes and wetlands due to this evaporation and capillary action within the soils. Periodic high-water years flushed some of the salts out of the Tulare Lake system. We assume the system was in rough equilibrium; the water and soils were not getting significantly saltier.

Change in salinity that occurred 1878–1898. Tulare Lake declined from full-pool in 1878 to bone-dry in 1898, due primarily to the canals. The Tulare Lake system stopped flushing in 1878 and began dropping in elevation. As the lakes shrank, the alkalinity and salinity rose. The ecosystem started to go into a tailspin in 1888. The fishing (or seining) was apparently terrific that year as the ecosystem crashed. Over 133,600 pounds of fish from Tulare Lake were shipped to San Francisco in one ten-week period in the fall of 1888. By the end of 1888, the catfish, lake trout, pond turtles, and mussels had reportedly died out of all three lakes (Tulare, Kern, and Buena Vista) due to the increasing alkalinity and salinity.

The various lakebeds and surrounding wetlands were naturally salty. This higher salinity is illustrated while driving on Highway 41 from Stratford to Kettleman City. The north side of the road along the perimeter of the Tulare Lakebed generally has higher salinity than the clayey soils south of the Blakeley Canal in the lakebed. Various saline-sodic tolerant crops have been grown over the years in the very diverse saline-sodic soils with textures that range from sand to clay along the rim of the lakebed, but the farming inputs necessary to make a profit are significant.

Change in salinity and drainage since 1898. For decades, approximately half a million tons of salt annually have accumulated in the San Joaquin River and Tulare Lake Basins. The problem of soil salinization is especially severe in the Tulare Lake Basin because we have functioned largely as a closed basin since 1878 without a regular outlet to the ocean. Water comes in, but it seldom flows out. The Tulare Lake Basin retains almost all the salt that enters the basin.

Soluble salts and sodium in soils can be traced to several sources. These sources of salts historically accumulated in predictable landform positions such as fan skirts, basin floors and floodplains. Some soils have less salts than they had before irrigation while other soils are rapidly increasing in salt content. Most areas in the San Joaquin Valley are experiencing increasing salt content and many of these areas are on landform positions, such as alluvial fans that historically had relatively low levels of salinity. This change in the equilibrium of salts in the San Joaquin Valley is a predictable outcome based on the following:

- In order to create a productive agricultural region in an arid desert, we import additional river water into our basin, far more than the total water from all our local streams combined. That water brings in significant additional salt.
- Using nearly as much groundwater as all our surface water (local and imported), combined. Not all irrigation water is the same quality. When there isn't enough high-quality freshwater to meet our demand (the amount of water we choose to apply), farmers often turn to saltier water to irrigate their crops. This practice directly adds salt to the soil where crops are being grown. In a portion of Kings and western parts of Fresno County, farmers are pumping water from great depths. This water

is often 3–4 times saltier than the water in the California Aqueduct. The water contains a mixture of salts that vary depending on the aquifer source. It is much easier to put salty water on the land than to remove it later.

In the south part of the San Joaquin Valley, where the amount of rainfall is low and the evaporation rate is high, soluble salts remain within the soil profile and may accumulate sufficiently to restrict the growth of plants. In addition, some areas receive salt-charged runoff or groundwater. The perimeter of Buena Vista Lake Basin and much of the Tulare Lakebed has a high water table at a depth of 4 to 6 feet (122 to 183 centimeters) from March through August. Water rises in the soil as irrigation begins and as runoff from surrounding mountains drains toward the basin floor. As evaporation proceeds during the hot summer, dissolved salts are deposited near the surface of the soil. The salts remain as moisture evaporates. This cycle is especially prevalent along the rim of the Tulare Lakebed.

Stratification of the soils, seasonal wetting and drying and capillary action from the high water table has resulted in strongly saline-sodic conditions in most areas of soils that surround basin floor landforms in the San Joaquin Valley. Percolating water from seasonal rainfall modifies the location and amount of salts that accumulate within the soil, but it does not remove salts from the soil. Over time, productivity is seriously impacted.

The shallow groundwater at lower elevations becomes saline-sodic because of salts in the soil and evaporation from the surface of the soil. The soluble salts that accumulate in these soils consist of calcium sulfate and sodium sulfate, along with smaller quantities of magnesium sulfate. Smaller amounts of sodium bicarbonate, sodium carbonate, sodium chloride, and calcium chloride also occur in some soils in the San Joaquin Valley.

Saline-sodic soils have enough soluble salts to interfere with the growth of most crops and enough exchangeable sodium to affect physical soil properties and plant growth adversely. The conductivity of the saturation extract is more than 4 decisiemens per meter (at 25 degrees C) and sodium adsorption ratio is more than 13.

Field and laboratory determinations indicate that the amount of soluble salts and sodium can vary considerably in the San Joaquin Valley. Some general guidelines that should be helpful in dealing with saline-sodic soils can be given.

An ample supply of good-quality water is a primary requirement to remove excess salts from the soil. More water than is needed to grow crops should be applied. The additional water is for leaching the salts downward into the lower part of the subsoil or below. This is known as "Leaching Requirement" or "Leaching Fraction." Water in this quantity and quality is often not available, especially in recent years.

Adequate drainage is also necessary to remove excess salts from the soil. Improvement is likely only to that depth in the soil for which adequate drainage can be provided. The better the drainage, the more readily excess salts can be removed. If drainage is not adequate and no measures are taken to improve it, little change is likely.

Many factors affect the downward movement of water through the soil, including texture, bulk density, porosity, structure, and the shrinking and swelling of the soil upon wetting and drying. The more rapid the rate of internal drainage, the more quickly excess salts can be removed and the sooner improvements can be made.

If internal drainage is adequate or is artificially improved, even severely affected saline-sodic soils can be improved by leaching the salts through the soil profile. If a sufficient amount of water is used, the salts will be flushed downward. Removing excess sodium is somewhat more difficult and expensive than removing excess salts. A chemical change must take place in the soils. This is generally brought about by applying gypsum (calcium sulfate). A soil test helps to determine how much gypsum should be applied to obtain the desired results. Gypsum supplies the calcium to replace the excess sodium on the surface of the clay particles. Calcium can also be obtained by applying sulfuric acid in bulk quantities. The acid reacts with the calcium carbonate common in the soils. Both the calcium and hydrogen ions displace the adsorbed sodium. The acid method often achieves quick results, but it is more expensive and extra care is needed in handling the acid. Elemental sulfur can be used instead of gypsum, but sulfur takes longer to react. Before it can act, sulfur must be changed to sulfate. This change is made by microbes living in the soil. About the same result is obtained with any of these materials, but time and cost differences should be considered.

The productive life of much of this area has already been extended by improvements in agricultural water use efficiency (which results in not only less water, but less salt, being applied to the soils), set-asides of some local areas for salt disposal, improved leaching methods, and retirement of some lands with high natural soil salinity. Maintaining a sustainable salt balance in remaining agricultural areas would require further drainage from the basin, reductions in salt loads entering the basin, or further reductions in irrigated area.

The sustainability of irrigated agriculture in many arid and semiarid areas of the world is at risk because of a combination of several interrelated factors, including lack of fresh water, lack of drainage, the presence of high water tables, and salinization of soil and groundwater resources. Nowhere in the United States are these issues more apparent than in the San Joaquin Valley of California.

Current drought. The Tulare Lake Basin entered a long-term precipitation drought in the mid-1980s and a long-term temperature-induced drought (PDSI stress) in the mid-1990s. But our primary long-term drought began in the 1880s.

From a human perspective, drought can best be viewed as when supply (defined as our dedicated and developed water supplies) fails to equal demand (defined as applied water, the amount of water we choose to apply). By that definition, the Tulare Lake Basin has been in a long-term drought for about 130 years. We have been applying more water than our sustainable supply since the 1880s.

This is even after supplementing our water supply with large quantiles of imported river water (average of 3.2 million acre-feet per year), more than the total water from all the streams in the Tulare Lake Basin (average of 2.3 million acre-feet per year).

Use of groundwater. We routinely turn to groundwater to make up for our unmet demand. The Tulare Lake Basin uses more groundwater than any other basin in the state. This has resulted in a significant draining of our groundwater aquifer. The water table began dropping in the 1880s, and it has been dropping for about 130 years. As a general trend, we have been applying more water than our sustainable supply during this entire period.

The Central Valley has lost about 38 cubic miles of groundwater since settlement began, more than the volume of Lake Tahoe. Most of that volume came out of the Tulare Lake Basin.

Groundwater overdraft. In recent years, our basin has been overdrawing the groundwater aquifer by about 1.2 million acre-feet per year. For perspective, that is equal to the average flows of the Kaweah, Tule, and Kern Rivers, combined. Basin-wide, our groundwater aquifer has been going down an average of 2–4 feet per year in recent years. That is not sustainable in the long run. Water users throughout our basin are currently working on plans for how best to achieve sustainable use of our groundwater, ending the long-term groundwater overdraft.

Land subsidence. As a result of our groundwater overdraft, the San Joaquin Valley has the greatest land subsidence in the world. Over 5,200 square miles in area (one-half the entire valley floor) and a maximum of over 28 vertical feet. Those measurements were as of 1970. There has been considerable subsidence since then. Some areas are currently dropping at a rate of over one foot per year.

11:30 am – Noon: Sediment provenance and paleoenvironmental change since 35 ka in the western North America: Constrained by the mineral evolution in the Tulare Lake, California

Presenter: **Junhua "Adam" Guo**, Robert Negrini, Department of Geological Sciences, California State University, Bakersfield

Sediment provenance and paleoenvironmental change since 35 ka in the western North America: Constrained by the mineral evolution in the Tulare Lake, California

Junhua Guo, Robert Negrini
Department of Geological Sciences, California State University Bakersfield

The Tulare Lake is a natural laboratory for the study of late Quaternary paleoclimate change in the western North America. In this study we reconstructed the evolution of mineral assemblages of the bulk and clay-size fraction in Cores TL05-4A and TL05-1B retrieved from the Tulare Lake. Composite clay is the dominant composition in the bulk fraction with average contents of ~ 48% followed by quartz, feldspar, and calcite. Smectite dominates the clay mineral compositions, with average contents above ~ 60%. Mineral assemblages since 35 ka are related to changes in sediment provenance and paleoenvironment. Abrupt increase in clay and illite+chlorite content occurred about 14,500 cal BP, which correlates to the end of of the last glacial maximum in California (i.e., the Tioga). Clay content and illite+chlorite increased during post-glaciation whereas quartz+feldspars and smectite decreased. During post-glaciation, melted glaciers increased water supply and sediment discharge to the Tulare Lake. Increase of water supply raised the lake level leading to transgression so that relatively more fine clays deposited in the post-glaciation strata. More illite+chlorite-rich sediments from the Sierra Nevada Mountains diluted the smectite-rich sediments supplied from the near local area to the Tulare Lake. The content ratio fluctuation of smectite versus illite+chlorite during post-glaciation may be useful as a proxy for the precipitation in the Sierra Nevada Mountains.

1:30 – 2:15 pm: Late Quaternary “Tulare Lake Beds” in the San Joaquin Valley, California: Estimated Age and Influence on Land Subsidence.

Late Quaternary “Tulare Lake Beds” in the San Joaquin Valley, California: Estimated Age and Influence on Land Subsidence.

Roy J. Shlemon, Consultant, Newport Beach, CA

The historical Tulare (and southerly Buena Vista and Kern) lake beds are but shrunken remnants of once-extensive, generally fine-grained (lacustrine) deposits that underlie the central and southern San Joaquin Valley. The stratigraphically most extensive is the Corcoran Clay (“E-clay”). The Corcoran is typically 50-60-ft thick and, as encountered in thousands of wells, ranges in depth from ~50 to 75-ft below ground surface. Near Wasco, 100+ m deep cores taken from a proposed nuclear power-plant site, recovered Corcoran beds containing the Bishop Tuff. Paleomagnetic analysis showed that Corcoran beds ~3-4 m below the Tuff, recorded the ~0.80 ka Brunhes-Matuyama reversal. The beds are reportedly overlain by the ~ 0.48 ka Friant Ash, thus yielding a wide age range for Corcoran deposits.

Overlying the “Tulare Lake beds” are many, less extensive clayey and silty clayey sediments similarly interpreted to be lacustrine in origin, though many may well be local backswamp deposits. The major clayey units are informally designated, from youngest to oldest, the “A, B, C and D” beds, respectively. Although paleo-environmental interpretations of pollen and micro-fossil data may be contentious, the more extensive ancestral lakes are assumed to owe their origin to pluvial environments, ostensibly associated with successive Sierra Nevada glaciations.

Clayey and silty-clay facies within the old lake beds often form local aquitards, which, with intervening coarser-grained sediments, historically provided sustainable groundwater resources. However, since ~1940, increasing groundwater overdraft has given rise to regional land subsidence, locally exceeding 50 ft. Although some subsidence is (or was) caused by surficial hydrocompaction, most subsidence stems from deep-well exploitation of old lake-bed and swamp facies giving rise to non-reversible, “aquifer collapse.” Such major, deep-water extraction inherently increases effective stresses on the aquifer system resulting in pore-space collapse and ultimately in surface subsidence.

The ancient Tulare Lake and nearshore deposits are thus of particular interest owing to their recordation of paleo-environments, their innate groundwater resources and their influence on contemporary subsidence and related landuse.

2:15 – 3:00 pm: The levels of Tulare Lake for the past ~20,000 years as inferred from the geologic record: Implications for past precipitation in the Sierra Nevada over that time period.

The levels of Tulare Lake for the past ~20,000 years as inferred from the geologic record: Implications for past precipitation in the Sierra Nevada over that time period.

Robert Negrini
Department of Geological Sciences, California State University Bakersfield

Geochemical and geophysical proxy data from the TL05-4 lake-plain cores of Tulare Lake, California, are reported on here representing most of the past 19,000 years. The new record consists of carbon/nitrogen ratios, total organic carbon (TOC), nitrogen (N), total inorganic carbon (TIC), grain size, and magnetic susceptibility analyses from samples taken at 1-cm intervals (~45 yr/sample). Age control is provided by 22 radiocarbon dates. The results are consistent with reconnaissance work done consisting of trench and core descriptions and mapping of surface geomorphic and soil features. The first part of the record (~19.0-14.5 cal ka BP) consists of elevated sand and silt percentages and higher sedimentation rates interpreted as elevated runoff associated with melting of the Tioga-age Sierra Nevada ice cap. The TIC was undetectable and TOC and N were low suggesting low productivity in a relatively sterile, freshwater lake. From 14.5 to 10.3 cal ka BP, the deposits consisted of 50% clay and 50% silt with TIC and TOC extremely low, which is consistent with a stable, low productivity lake. From 10.3 to 7.5 cal ka BP, an initial pulse of fining upward sand gave way to increased clay

deposition that suggests a lake transgression to a stable highstand, coeval with the deep water event found in previously published records of Tulare Lake and other lakes from central and southern California, including Owens Lake and Lake Elsinore. A few-hundred-year duration spikes in TIC centered at 8.0 cal ka BP is suggestive of evaporating lake conditions toward the end of this early Holocene high- stand. Tulare Lake dropped quickly to a relative low at 7.5 cal ka BP, but then lake level increased steadily until 3.0 cal ka BP. High amplitude fluctuation in almost all proxies occurs from 2.5 to 1.8 cal ka BP at the end of the record, suggesting that this time interval was characterized by rapid fluctuations in lake level. Tulare Lake levels during the Holocene vary in conjunction with sea surface temperature (SST) records from the Ocean Drilling Program (ODP) Site 1017 located off the coast of central California, which suggests that variations in SSTs throughout the Holocene drove changes in precipitation in the Sierra Nevada and hence, Tulare Lake level. Since historic lake-level histories have been shown to be directly related to stream discharge from the Sierra Nevada, this observation will be integral in forecasting future decadal-scale changes in southern San Joaquin Valley water supply due to anticipated climate change.

3:15 – 4:00 pm: The Mussel Slough Tragedy: Creating an Historical Context for Soil Study in California's Southern San Joaquin Valley

The Mussel Slough Tragedy: Creating an Historical Context for Soil Study in California's Southern San Joaquin Valley

Robin M. Roberts, Ph.D., USDA-NRCS, Earth Team Volunteer

The Central Valley of California is the largest agricultural economy in the United States and has been called the "Breadbasket of the World." This economy is made possible by three things: soil, water and transportation. Each is a necessary but insufficient requirement for the creation of a large-scale agricultural economy. It is only when all three are present in the same place and interconnected—along with the people to utilize them—that such an economy can exist. The Mussel Slough Tragedy, a local historical event with world-wide ramifications, is the defining event in the development of the agricultural economies of Southern San Joaquin Valley—the site of the 2016 PSSAC Annual Meeting and Field Tour. On May 11, 1880 the long-standing conflict between railroads and settlers erupted into a gunfight which resulted in the second highest number of deaths by such cause in American history. At the heart of that conflict was the monetary value of the land. What is often overlooked is that the value of the land was a function of high quality soil being irrigated by man-made delivery systems and lying in close proximity to long distance transportation services, viz., the Southern Pacific Railroad. The story has oft been told—erroneously in most cases—in some of America's most venerated literature and has assumed almost legendary status among Jeffersonian idealists as a simple case of moral right meeting legal correctness. An examination of this historical instance provides a useful context for studying the soil of the Southern San Joaquin Valley—plus, it's a great story!

4:00 – 4:45 pm: Soils of the Southern San Joaquin Valley: From Buena Vista Lake to Fresno Slough

Soils of the Southern San Joaquin Valley: From Buena Vista Lake to Fresno Slough

Kerry D. Arroues, Retired USDA-NRCS Soil Scientist, Philip D. Smith, USDA-NRCS Soil Scientist, Hanford, CA

Soil, hydrology, geomorphology and stratigraphy of the Buena Vista Lake Basin in Kern County, California provide a foundation to understanding the alluvial and lacustrine (lake) soil deposition in the Southern San Joaquin Valley. Soil scientists began mapping these soils more than 100 years ago, first as reconnaissance soil surveys and then in a more detailed way. They are essentially a "case-study" that repeats itself as the water flows from Buena Vista Lake towards the much larger Tulare Lake fifty miles (80 kilometers) northward and 100 feet (30.5 meters) lower elevation than Buena Vista Lake. Tulare Lake high stand water flows traveled north through the Fresno Slough and San Joaquin River, eventually entering the California Delta and the Pacific Ocean.

7:00 – 9:00 pm: Dinner Banquet in Garden Ballroom. Dinner speakers Kerry Arroues and Robin Roberts present: The Sage of Garza Creek and His Ship of Life: A Case Study at the Intersection of Earth Sciences and History.

The Sage of Garza Creek and His Ship of Life: A Case Study at the Intersection of Earth Sciences and History.

Kerry D. Arroues, Retired USDA-NRCS Soil Scientist, Robin M. Roberts, Educator and Historian, Philip D. Smith, USDA-NRCS Soil Scientist, Hanford, CA

In central Kings County, California a rather unique burial plot exists built by an equally unique individual over the last twenty years of his life. Consisting of a large sandstone

sarcophagus shaped like a ship surrounded by various pieces of sandstone, marine shell fossils, petrified wood and granite sporting carved images and poetry, the gravesite does not include the name of the deceased nor any dates. The gravesite is the visible legacy of a man named Kenzie Whitten “Blackhorse” Jones, also known as “The Sage of Garza Creek.” Garza Creek is an intermittent stream located approximately 6 kilometers west of Avenal, California.

This study details how Soil Science and associated disciplines helped solve mysteries related to Kenzie Whitten Jones’ life and death that had persisted for more than a century. Mysteries surrounding the life of Kenzie Whitten Jones were abundantly evident from information attached to a fence that protects his gravesite. The sign stated that “he died in October, 1909 while leading a horse across a creek.” According to the sign, he raised Black Morgan horses for use by mortuaries and became a recluse as the result of a tragedy that occurred in early adulthood. Events that occurred in 1909, 1978, and subsequent discoveries during the last decade provided answers to many questions.

SOIL SURVEYS OF THE SOUTHERN PART OF THE SAN JOAQUIN VALLEY, CALIFORNIA

United States Department of Agriculture, Natural Resources Conservation Service, 2009. Soil survey of Kern County, California, southwest part. Pages 1168. Accessible online at: http://soils.usda.gov/survey/printed_surveys/

United States Department of Agriculture, Natural Resources Conservation Service, 2007. Soil survey of Kern County, northeastern part, and southeastern part of Tulare County, California. Pages 1432. Accessible online at: http://soils.usda.gov/survey/printed_surveys/

United States Department of Agriculture, Natural Resources Conservation Service, 2006. Soil survey of Fresno County, California, western part. Pages 1144. Accessible online at: http://soils.usda.gov/survey/printed_surveys/

United States Department of Agriculture, Natural Resources Conservation Service, 2003. Soil survey of Tulare County, California, western part. Pages 299. Accessible online at: http://soils.usda.gov/survey/printed_surveys/

Co-author: Hal L. Hill

United States Department of Agriculture, Natural Resources Conservation Service, 1981. Soil survey of Kern County, California, southeastern part. Pages 195. Accessible online at: http://soils.usda.gov/survey/printed_surveys/

1940's

Hal Hill in Uniform during World War II

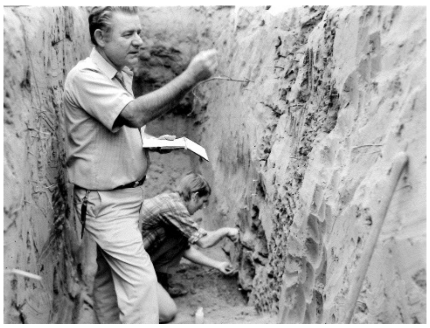
On April 5, 2014, a member of "the greatest generation," Hal L. Hill passed away in Bakersfield, California. Hal Hill was born in Syracuse, Nebraska in 1920. He graduated from the University of Nebraska and also served in World War II. After the war, Hill worked a 28-year career in the United States Department of Agriculture - Soil Conservation Service.

Hill's career with USDA-SCS began in Nebraska where he worked during the mapping season and during the cold snowy winters was detailed to the South to help finish ongoing soil surveys in Louisiana. Hill later moved to California's San Joaquin Valley, where as a USDA-SCS employee working with University of California soil scientists, he helped finish field work for the *Soil Survey of Madera Area, California*. He also worked on the *Soil Survey of Eastern*

Fresno Area, California before completing his career in Bakersfield, where he was the project leader for the *Soil Survey of Kern County, California, Southeastern Part*.
Information courtesy of Kerry Arroues and Kim Chang, soil scientists, USDA-NRCS (retired), and Hill's obituary as printed in the *Bakersfield Californian*.

Co-Author: Carl H. Anderson, Jr.
United States Department of Agriculture, Natural Resources Conservation Service, 1986. Soil survey of Kings County, California. Pages 212. Accessible online at:
http://soils.usda.gov/survey/printed_surveys/

1977



Carl H. Anderson (standing) works on soil description with Dan Vaughn

Carl H. Anderson (1923 – 2003) started work with the Soil Conservation Service in Pomona, CA in 1952 following six years' service in the U.S. Navy. In 1954 he transferred to Hanford, CA as a Soil Scientist with the SCS where he worked until his retirement in 1980. During his career in Hanford, he worked as a Soil Survey Project Leader and was co-author of the Kings County Soil Survey. He also served as an Area Soil Specialist and later as a Soil Consultant with expertise in soil chemistry, drainage, and salinity. (Information and photo courtesy of Kerry Arroues, retired USDA, NRCS)

Author: Kan Kim Chang
United States Department of Agriculture, Natural Resources Conservation Service, 1988. Soil survey of Kern County, California, northwestern part. Pages 304. Accessible online at:
http://soils.usda.gov/survey/printed_surveys/

Kim Chang Describes Soil in California's San Joaquin Valley (1969)

Kan Kim Chang, best known as Kim Chang, is shown describing a Milham soil while working on the Soil Survey of Kern County, California, Northwestern Part. Upon graduating from California Polytechnic State University in San Luis Obispo in 1959, Chang was hired as a fulltime soil scientist by USDA-SCS. After being drafted in 1961, Chang served for two years in the U.S. Army Corps of Engineers, testing soils, asphalt, and concrete. Upon returning to USDA-SCS in 1963, Chang worked on the Soil Survey of Eastern Fresno Area, California, prior to his project leader work on the Soil Survey of Kern County, Northwestern Part, which he authored in 1988.

Chang completed the second half of his illustrious 43-year career as the Area Soil Scientist for the USDA-Natural Resources Conservation Service in Fresno, CA. He was known as an excellent field soil scientist and trainer of soil scientists. In his job as Area Soil Scientist he was responsible for field reviews of soil surveys being conducted by three U.S. Government agencies. As an Area Soil Scientist, Chang worked as a soil liaison with many USDA-NRCS field offices throughout California. He is also known for the valuable assistance he has provided to FFA land judging competitions in the San Joaquin Valley for more than 50 years.

Information courtesy of Kerry Arroues, NRCS, Soil Scientist (retired), Hanford, CA

Author: Gordon L. Huntington
United States Department of Agriculture, Natural Resources Conservation Service, 1971. Soil survey of Eastern Fresno Area, California. Pages 323. Accessible online at:
http://soils.usda.gov/survey/printed_surveys/

1953 **Eastern Fresno Area, California** **1983**

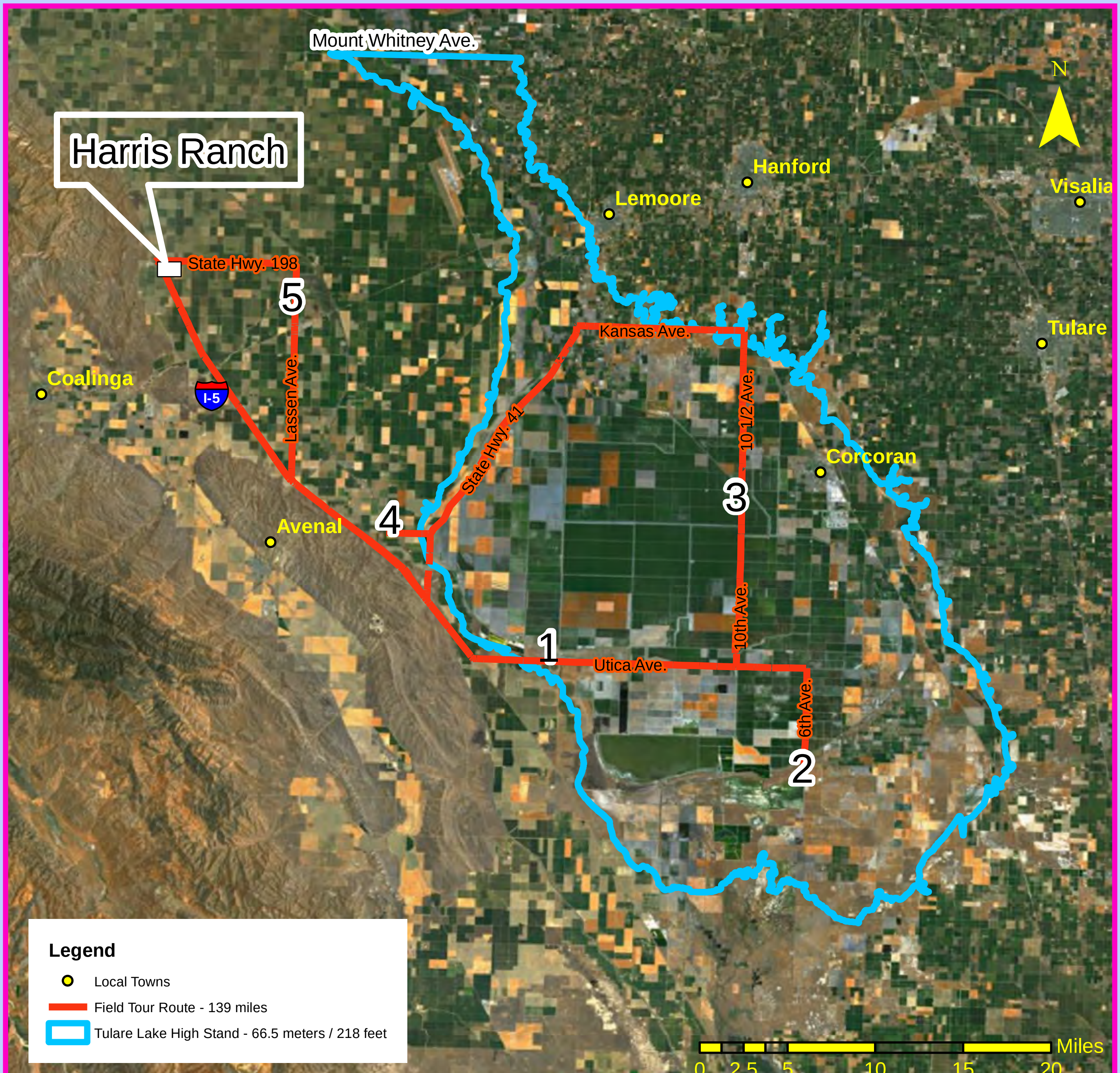
National Park Soil Studies (1983)
Gordon Huntington studies the landscape over a stereoscope in the upper portion of Elk Creek drainage, located in the Kaweah River watershed, while working on a *Soil Resource Inventory of Sequoia National Park, Central Part* in 1983. The study was part of *Pedologic Investigations in Support of Acid Rain Studies, Sequoia National Park, CA.* He is in an area mapped as "Ultic Palexeralfs-Ultic Haploxeralfs complex, 45 to 75 percent slopes." He had a distinguished and long career with the University of California as a student, soil scientist, specialist, and instructor. He held an emeritus position within the Land, Air and Water Resources Department at UC Davis for many years. He was known for his knowledge of a wide range of soils in California and was one of the instructors of a touring field course each summer that helped hundreds of students gain appreciation of soil science. A soil survey of Sequoia and Kings Canyon National Parks, as part of the National Cooperative Soil Survey will begin later this year.
Sources: (Photo: Courtesy of LAWR, UC Davis, CA. Information courtesy of Kerry Arroues NRCS, Hanford, CA).

1920s

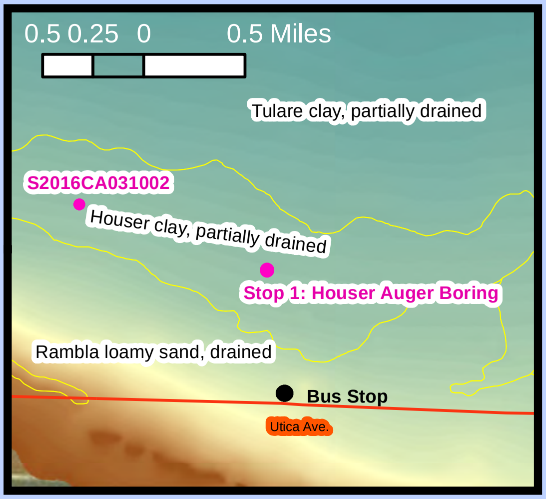
Early Soil Inspectors
Macy Lapham (middle) and UC Berkeley Professor Charles Shaw describe a soil profile along a road cut while working on the Series 1925 Soil Survey of The Salinas Area, California. Macy was a pioneering figure for nearly 45 years as a Senior Soil Scientist Inspector with the USDA-Division of Soil Survey. Macy Lapham's name as Inspector appears in almost all soil surveys published during the first 50 years of soil surveys in the western part of the U.S. His classic book published in 1949 and titled "CRISSCROSS TRAILS—Narrative of a Soil Surveyor" details his professional career which started in 1899, the same year the Soil Survey began. Charles E. Kellogg, Chief, USDA-Division of Soil Survey stated in the Forward of Macy's book: "The West, Macy, and the Soil Survey grew up together. None would have been quite the same without the others." Sources: Photo courtesy of Dr. Stanley W. Cosby Photo Collection. Information courtesy of Kerry Arroues, NRCS, Hanford, CA.

PSSAC 2016 Tulare Lake Field Tour Stops with Aerial Imagery

1: Utica Avenue - Tulare Lake Edge Soils
2: Sand Ridge at 6th Avenue
3: J.G. Boswell Company, El Rico Ranch, Tule River
4: Quail Avenue High Stand Site (66.5 m / 218 ft)
5: Arroyo Pasajero at California Aqueduct



Stop 1: Soil Map



Soils of the southwest corner of Tulare Lake basin near Utica Avenue.

Walk to Houser soil auger site. Discussions of soil salinity catena, drainage, agronomic issues, aeolean influence, archealogical and biological topics.

Legend

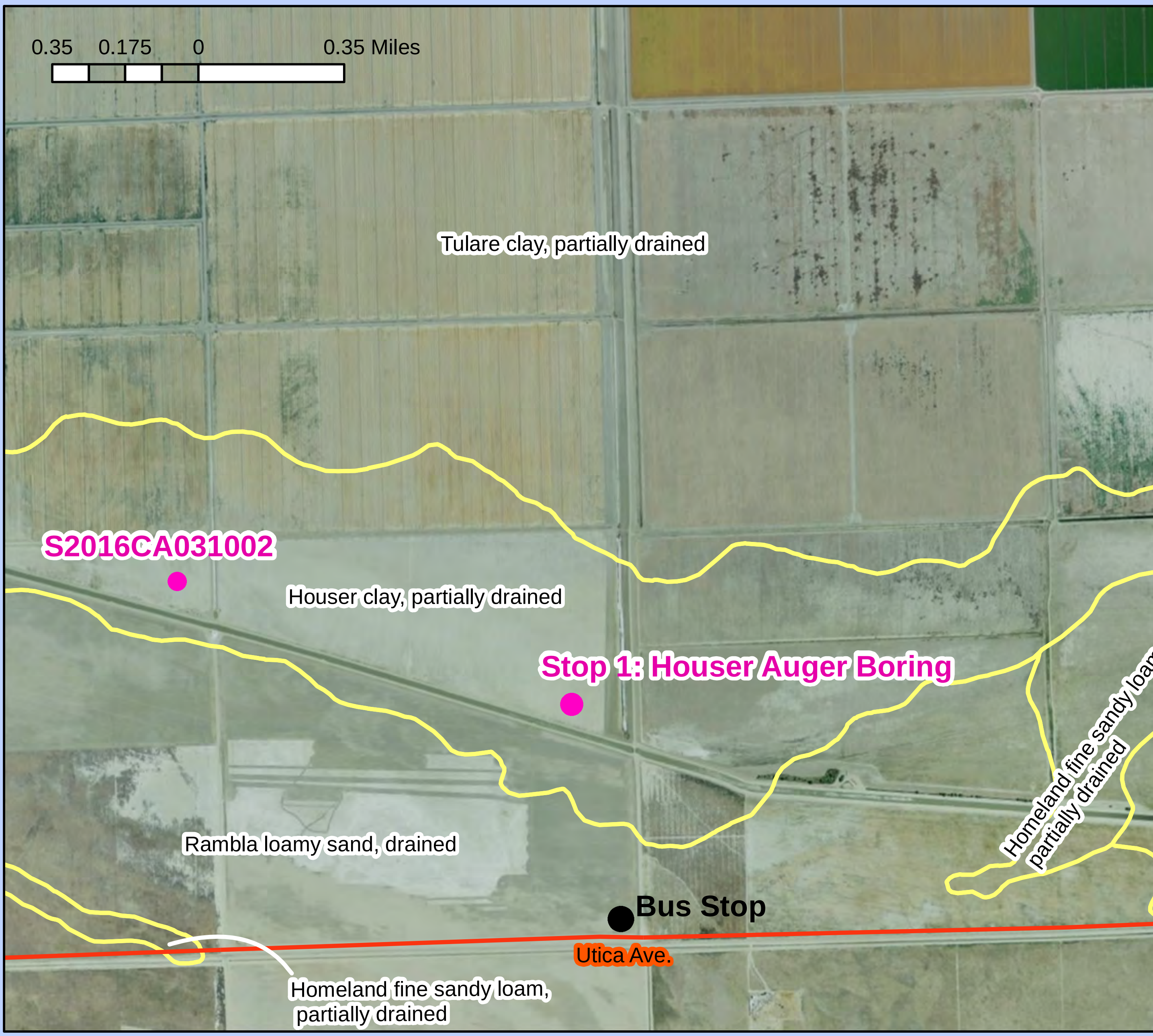
Soil Survey Map Units

Elevation

High : 68.0m

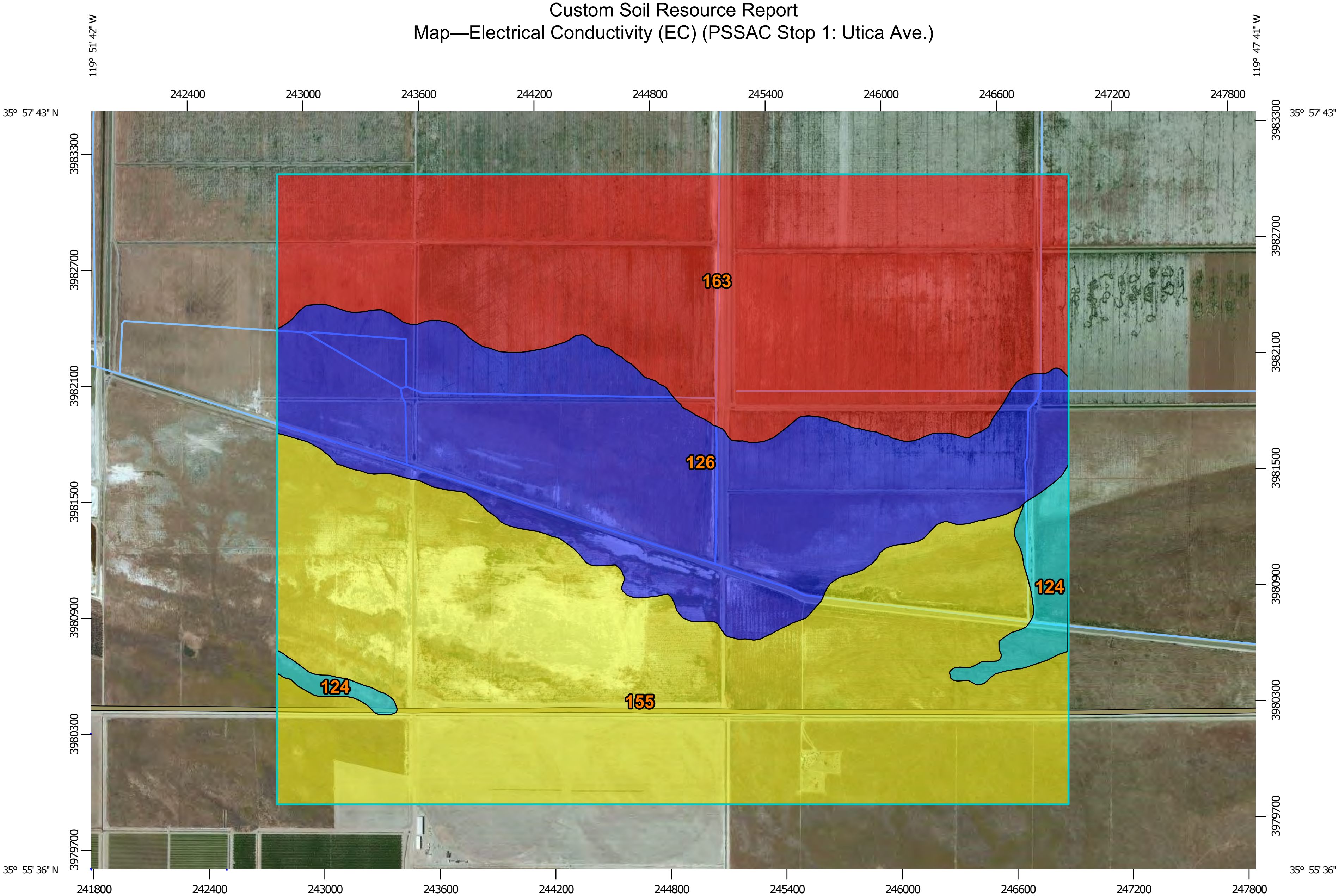
Low : 54.3 m

N



Custom Soil Resource Report

Map—Electrical Conductivity (EC) (PSSAC Stop 1: Utica Ave.)



Map Scale: 1:27,600 if printed on A landscape (11" x 8.5") sheet.

Meters: 0, 400, 800, 1600, 2400

Feet: 0, 1000, 2000, 4000, 6000

N

Map projection: Web Mercator   Corner coordinates: WGS84   Edge tics: UTM Zone 11N WGS84

Table—Electrical Conductivity (EC) (PSSAC Stop 1: Utica Ave.)

Electrical Conductivity (EC)— Summary by Map Unit — Kings County, California (CA031)				
Map unit symbol	**Map unit name**	**Rating (decisiemens per meter)**	**Acres in AOI**	**Percent of AOI**
124	Homeland fine sandy loam, partially drained	10.0	77.8	2.3%
126	Houser clay, partially drained	11.0	849.5	25.6%
155	Rambla loamy sand, drained	9.5	1,320.9	39.8%
163	Tulare clay, partially drained	5.7	1,073.3	32.3%
Totals for Area of Interest			**3,321.5**	**100.0%**

Rating Options—Electrical Conductivity (EC) (PSSAC Stop 1: Utica Ave.)

Units of Measure: decisiemens per meter

Aggregation Method: Dominant Component

Component Percent Cutoff: 15

Tie-break Rule: Higher

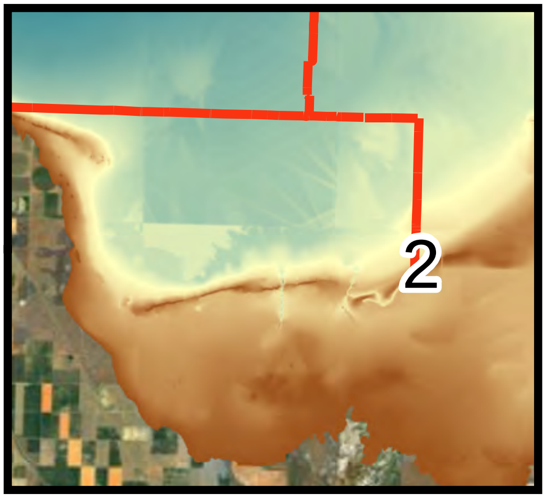
Interpret Nulls as Zero: No

Layer Options (Horizon Aggregation Method): Depth Range (Weighted Average)

Top Depth: 0

Bottom Depth: 152

Units of Measure: Centimeters



Stop 2: Sand Ridge

Legend

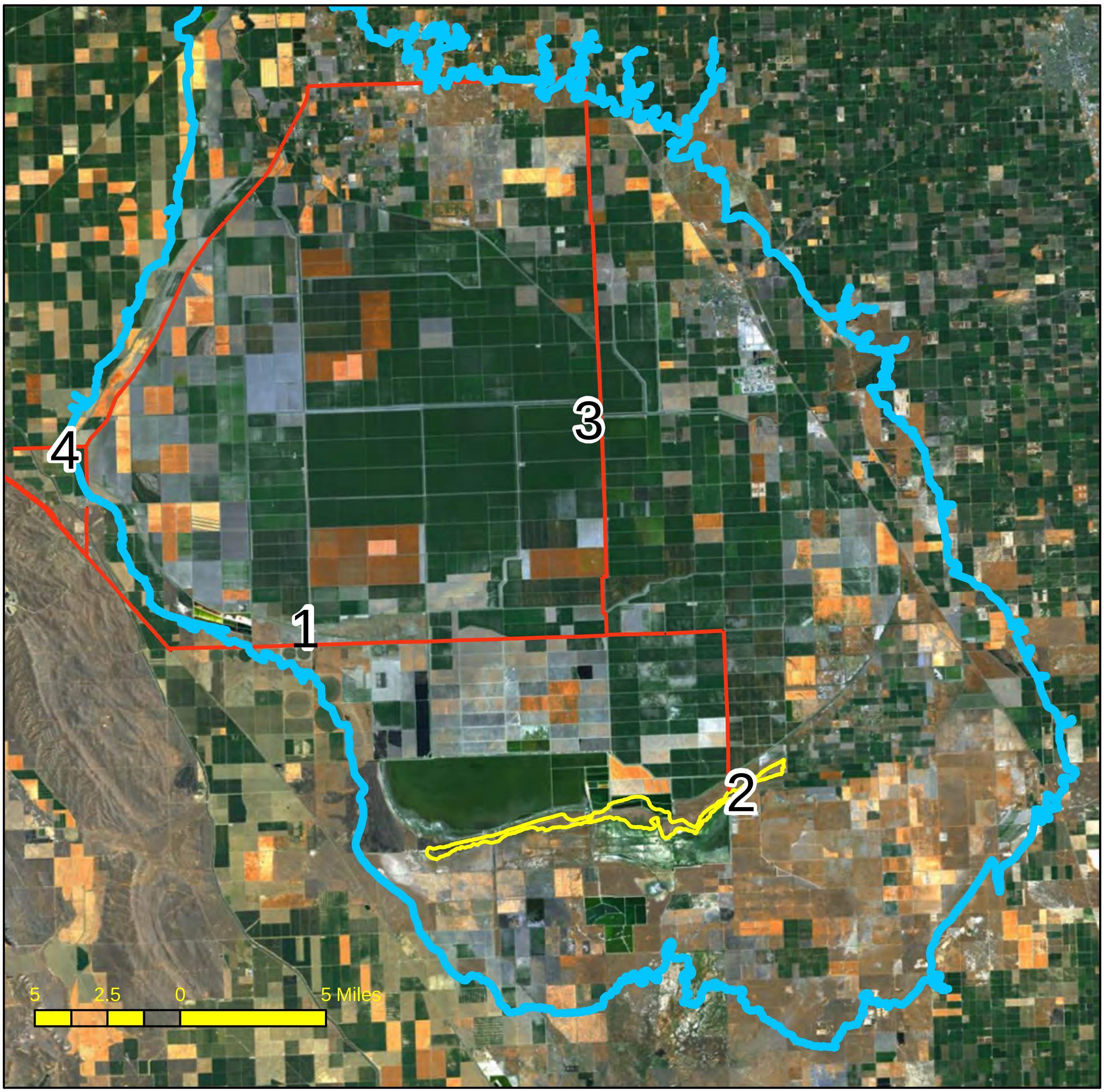
Tour Route

Value

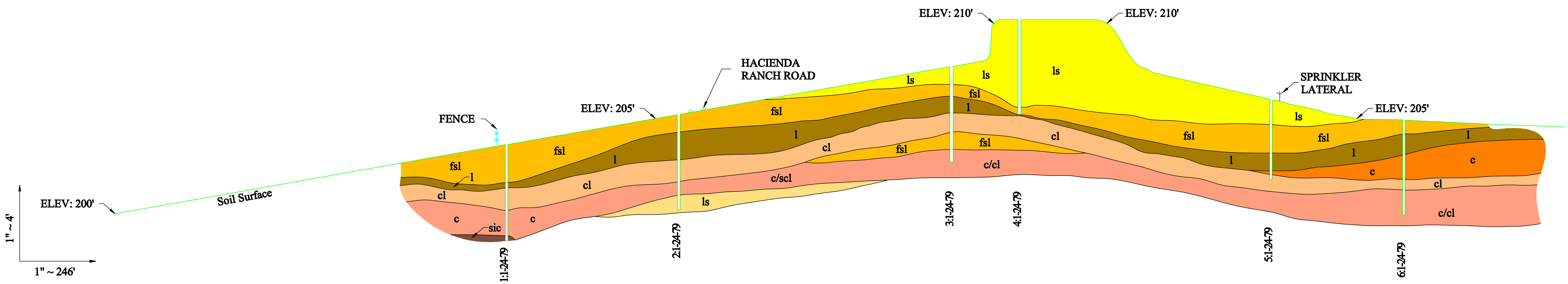
High : 68.009 meters

Low : 54.3353 meters

"Sandridge loamy fine sand, 0 to 3 percent slopes" shown below on Sand Ridge.



SAND RIDGE TRANSECT
All depths in inches
Michael McElhiney and Kerry Arroues
January, 1979



1:1-24-79

	pH	E.C.	S.A.R.
0-8	8.1	.35	3
8-24	8.6	3.2	.8
24-28	8.0	32	74
28-42	8.6	30	158
42-58	8.9	21	161
58-60	9.0	2.6	179

2:1-24-79

	pH	E.C.	S.A.R.
0-10	8.2	.45	4.3
10-30	9.6	1.9	35
30-43	9.6	3.5	68
43-46	9.9	3.5	68
46-52	10.0	3.4	66
52-60	10.0	3.2	63

3:1-24-79

	pH	E.C.	S.A.R.
0-11	7.5	.7	.7
11-18	8.9	.8	5.3
18-42	9.3	3.3	45
42-52	9.8	2.9	56
52-60	9.6	2.5	48

4:1-24-79

	pH	E.C.	S.A.R.
0-12	7.5	.7	1.1
12-35	8.9	.35	3
35-56	9.5	1.7	30
56-59	9.2	3.0	59
59-63	9.7	1.3	23

5:1-24-79

	pH	E.C.	S.A.R.
0-15	8.0	.3	.08
15-33	9.1	.65	5.2
33-49	8.5	1.7	4
49-60	9.0	2.4	18

6:1-24-79

	pH	E.C.	S.A.R.
0-9	8.1	1.9	7.1
9-21	9.0	1.0	11
21-38	9.0	3.0	59
38-43	10.0	3.2	63
43-54	9.2	3.4	66
54-60	9.0	3.2	63

Texture Legend
- ls = loamy sand
- fsl = fine sandy loam
- l = loam
- scl = sandy clay loam
- cl = clay loam
- sic = silty clay
- c = clay

E.C. = Electrical Conductivity (decisiemens per meter)
S.A.R. = Sodium Adsorption Ratio

Loamy Sands and Sands
Fine Sandy Loams
Loams/Clay Loams
Clays

(horizons shown above or between the colored lines have similar chemical and textural properties)

SAND RIDGE TRANSECT
HACIENDA RANCH QUADRANGLE

Approximately ½ mile south of Homeland Canal &
Approximately ¼ mile west of Dairy Ave.

Transect began at the fence line separating the predominately native southern half of Section 10 and proceeded south (parallel to Dairy Ave.) across Sand Ridge into the sprinkler irrigated field.

Field work and lab analysis prepared by Michael McElhiney and Kerry Arroues, Soil Scientists, January 1979

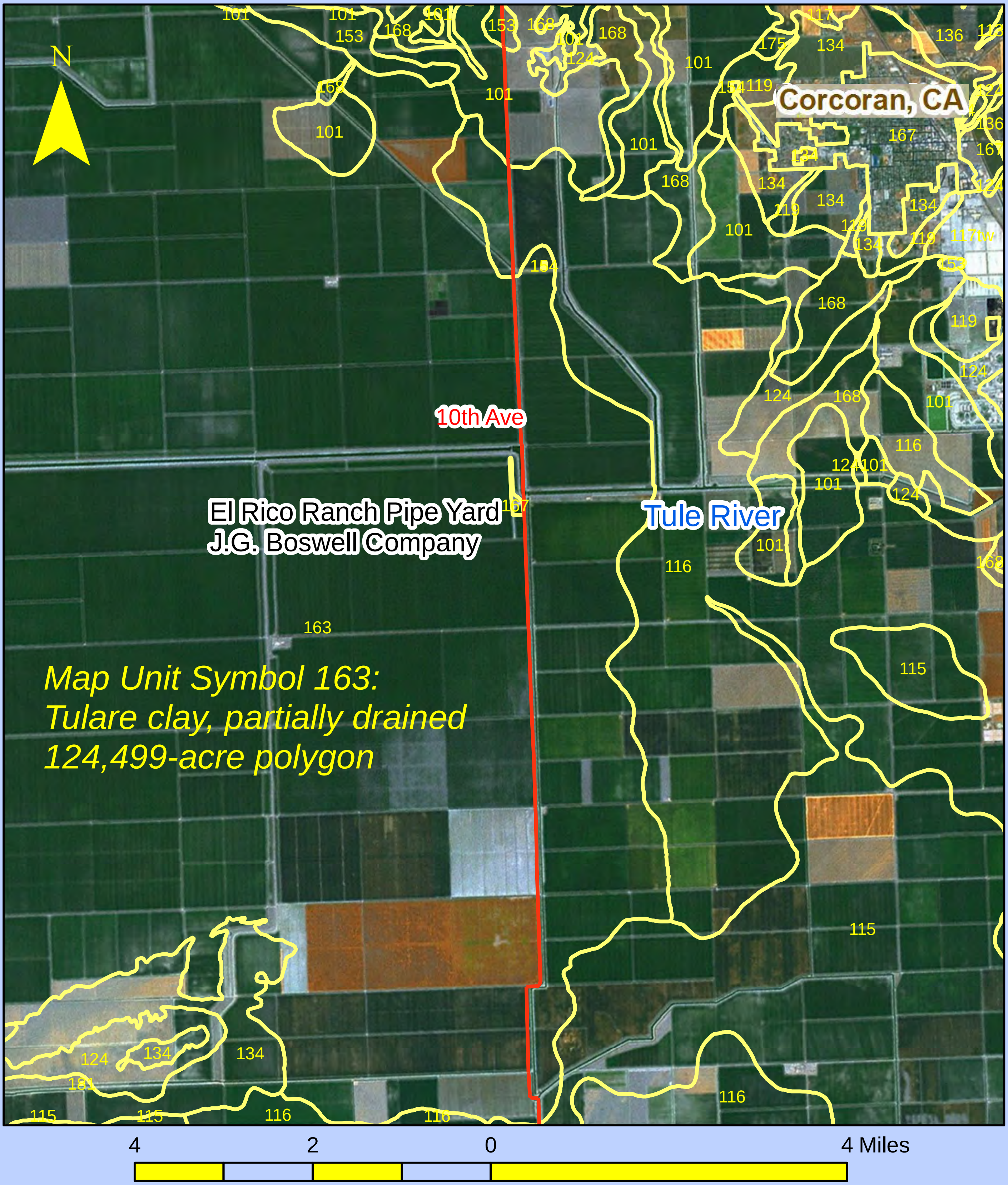
Cross section diagram prepared by Blair Bain, Earth Team Volunteer, March 2012

JOB TITLE
JOB SUB TITLE
Page 1 of ?

NRCS
Design Engineer: David Ramirez, P.E. Civil Engineer Ph. 559-584-9209
File No. Kern's Sand Ridge.dwg
Drawing No. Number
5/10/12 12:03 PM
Sheet 1 of 1

Stop 3: Tule River, J.G. Boswell Company
El Rico Ranch Pipe Yard

Stop includes lunch, view of Tule River, and irrigation canals. Representatives of J.G. Boswell Company will speak about agronomy and farming operations.

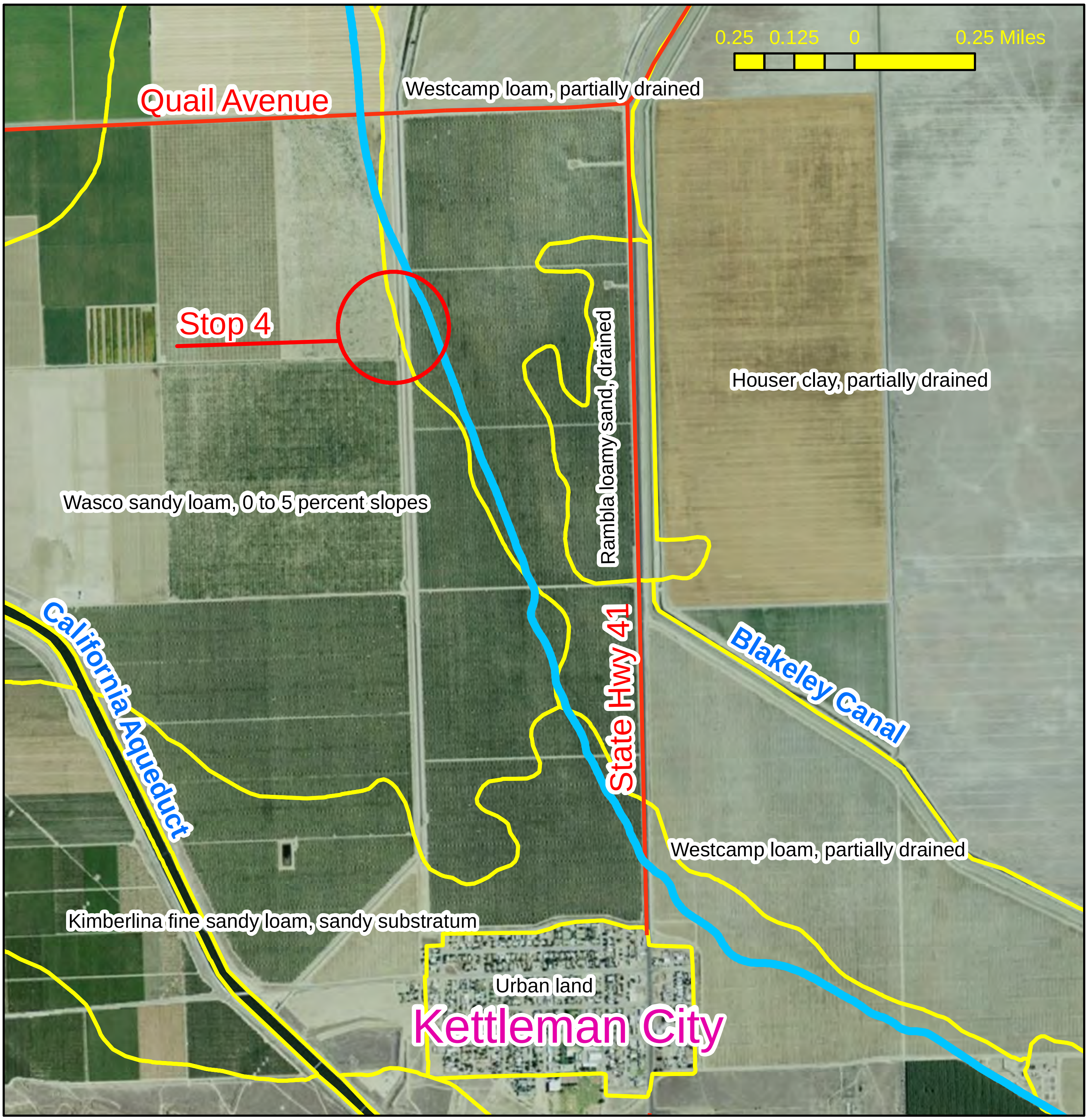


Stop 4: Quail Ave. High Stand Site near Kettleman City

Legend

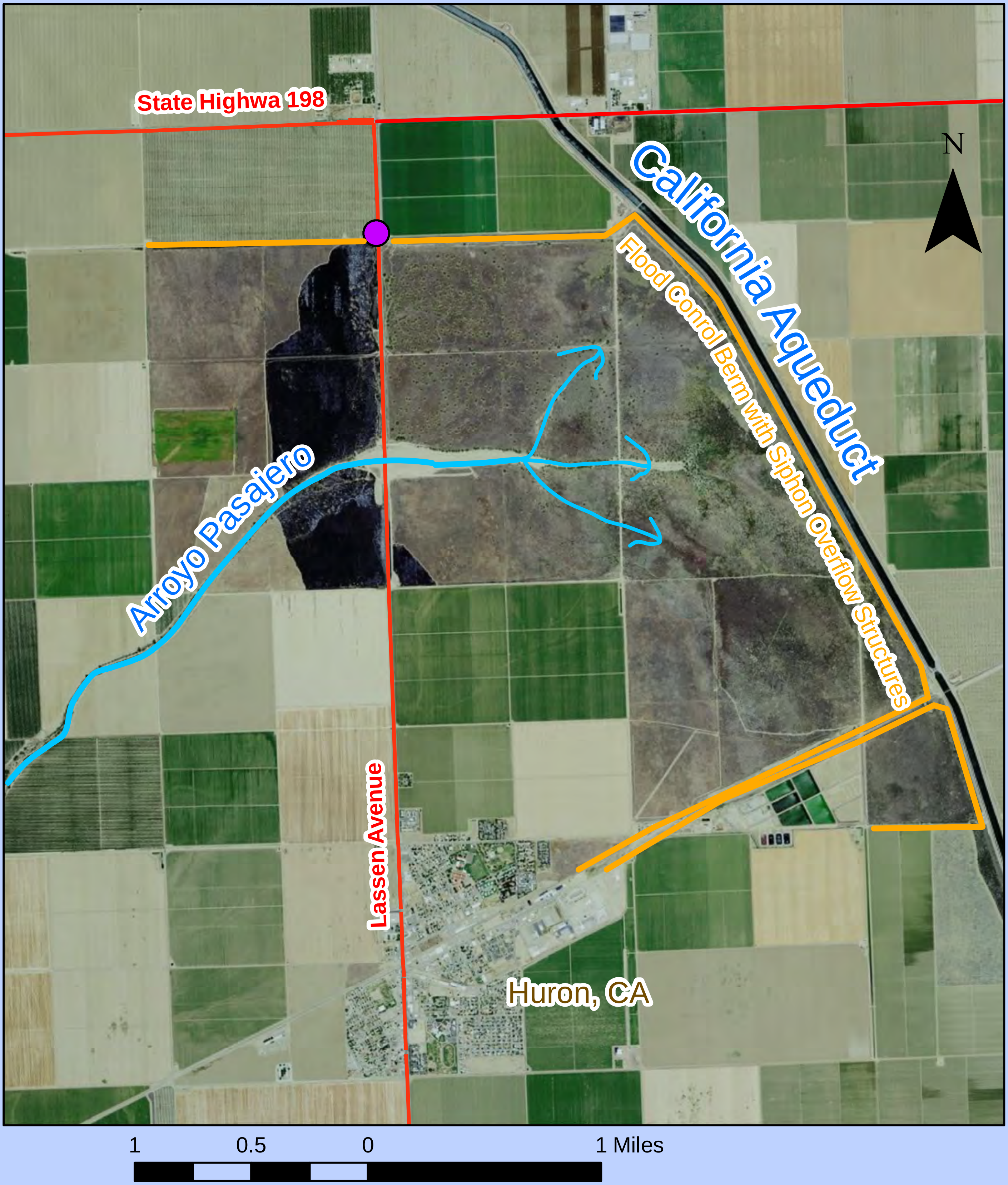
Soil Survey Map Units

Lake High Stand - 218 Feet / 64.5 meters



Stop 5: The Arroyo Pasajero at the California Aqueduct

Views of a flood control berm which protects the California Aqueduct and Highway 198 from flooding of the Arroyo Pasajero. Discussions of the 1995 flood and notation of sediment depths inside the bermed area.



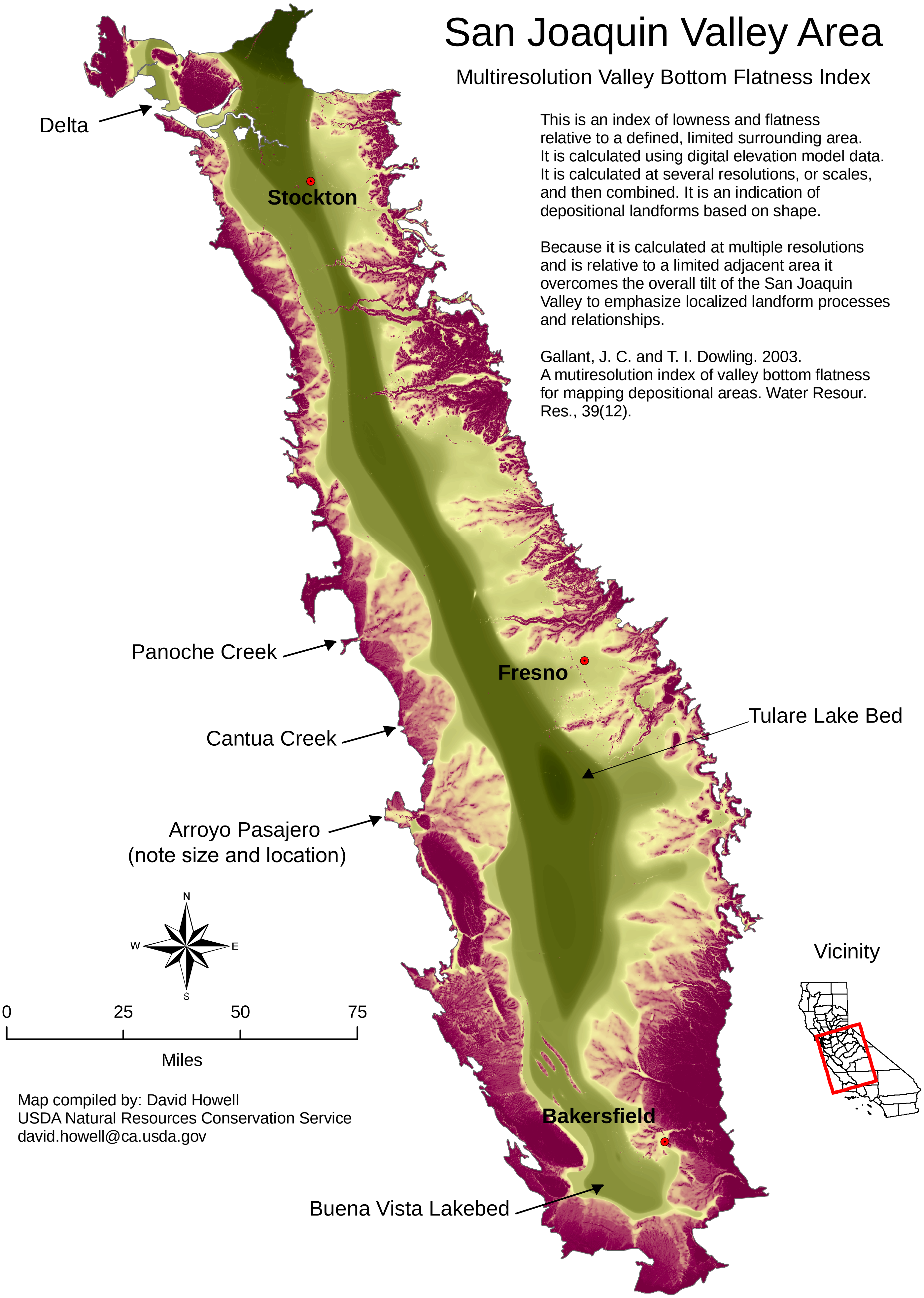
San Joaquin Valley Area

Multiresolution Valley Bottom Flatness Index

This is an index of lowness and flatness relative to a defined, limited surrounding area. It is calculated using digital elevation model data. It is calculated at several resolutions, or scales, and then combined. It is an indication of depositional landforms based on shape.

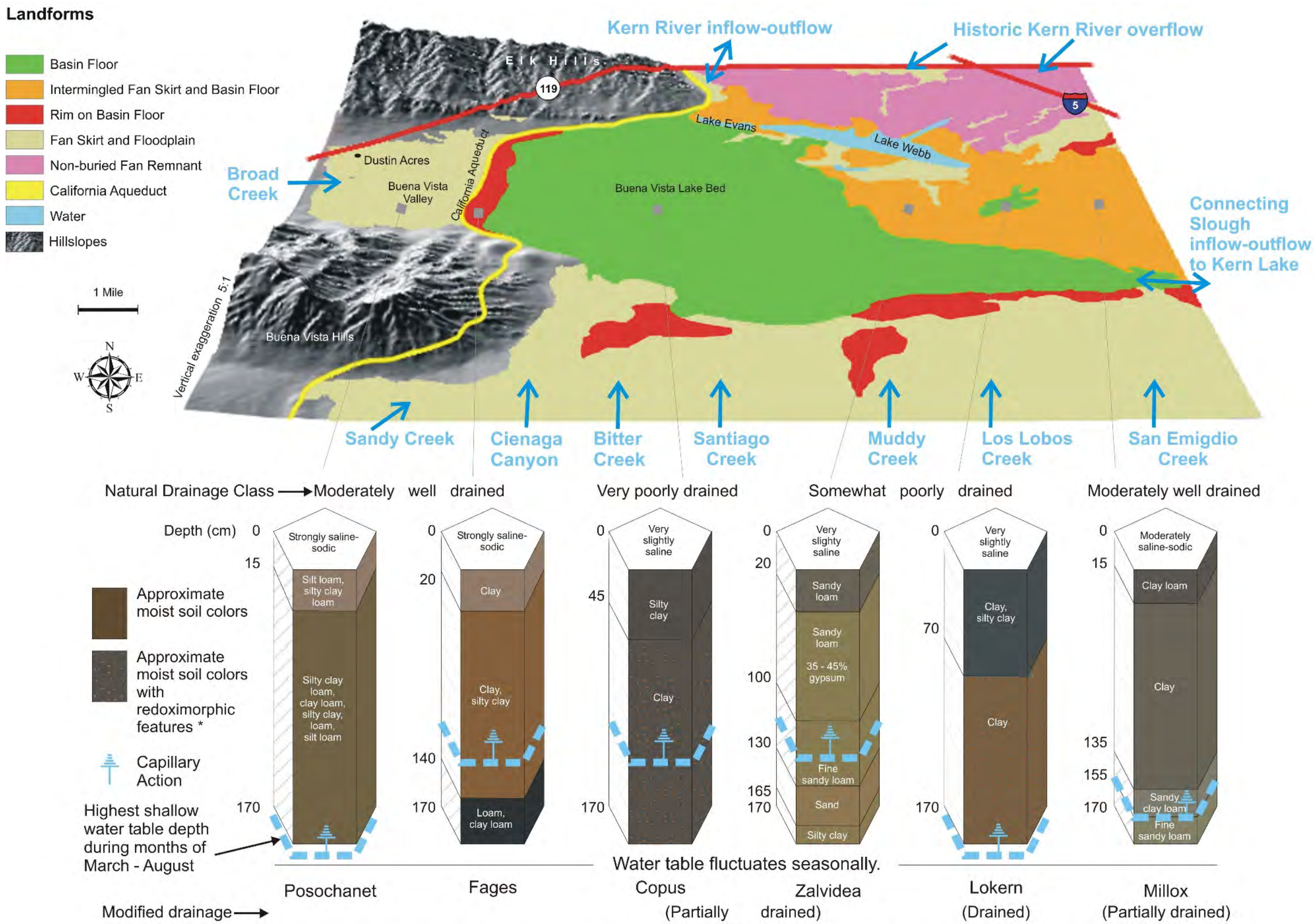
Because it is calculated at multiple resolutions and is relative to a limited adjacent area it overcomes the overall tilt of the San Joaquin Valley to emphasize localized landform processes and relationships.

Gallant, J. C. and T. I. Dowling. 2003. A mutiresolution index of valley bottom flatness for mapping depositional areas. Water Resour. Res., 39(12).



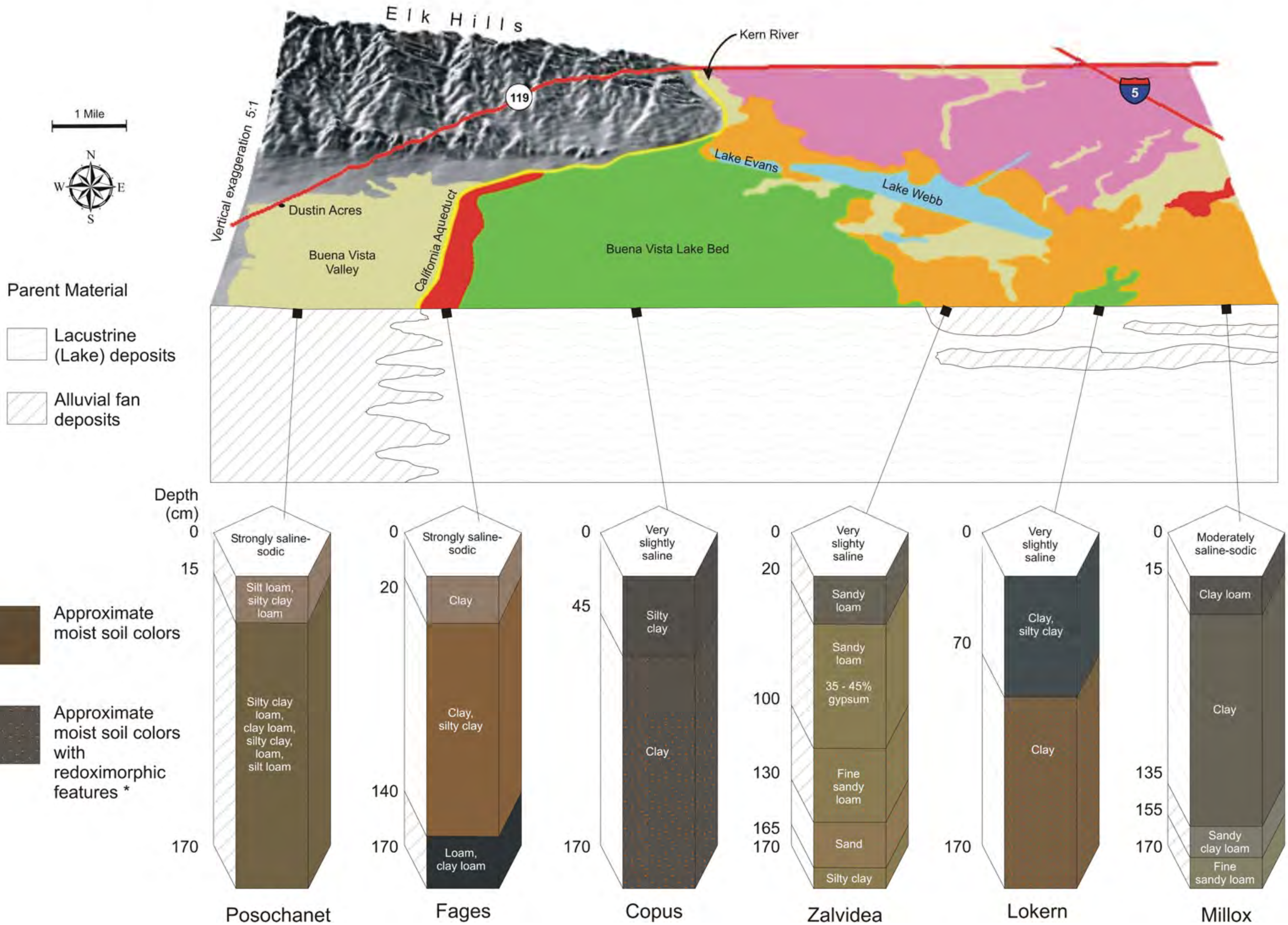
Map compiled by: David Howell
USDA Natural Resources Conservation Service
david.howell@ca.usda.gov

Soils, Hydrology, and Geomorphology Model of Buena Vista Lake Basin, Kern County, CA



* Redoximorphic features that are brighter and/or darker than the soil matrix color, or a soil matrix color that has low chroma, indicate chemical reduction and oxidation of iron and manganese compounds resulting from saturation.

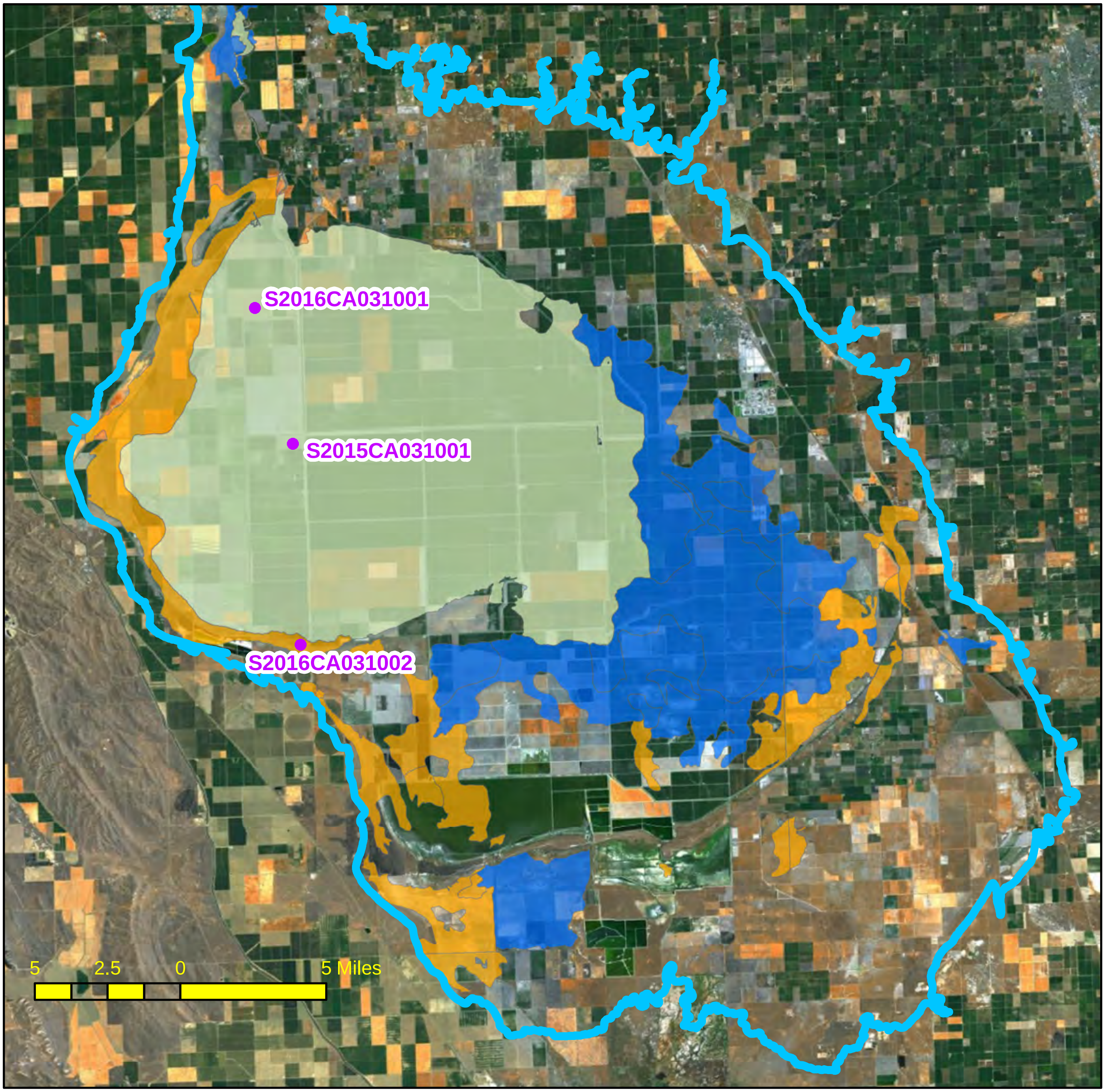
Soil, Landscape and Stratigraphy Model of Buena Vista Lake Basin, Kern County, California

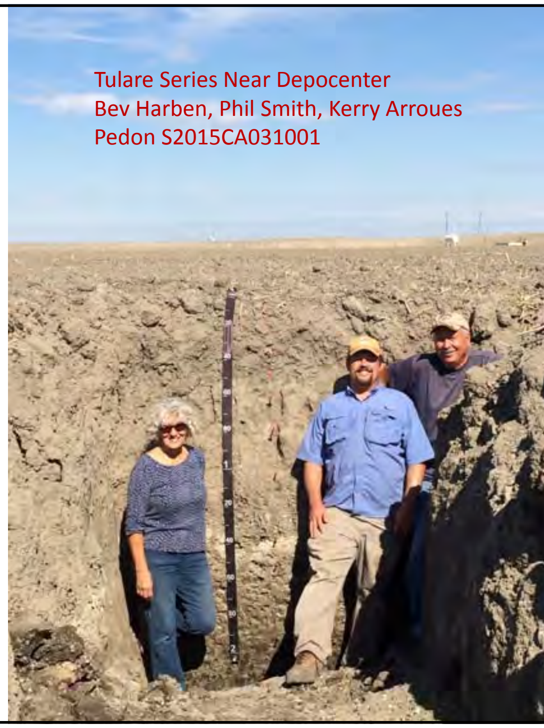


Clayey Soil Map Units of the Tulare Lake Basin and Locations of Three Recent Soil Characterization Sampling Sites for MLRA Soil Survey Updates

Legend

- Gepford soils
- Houser soils
- Tulare soils
- Lake High Stand - 218 Feet / 64.5 meters




Tulare Series Near Depocenter
Bev Harben, Phil Smith, Kerry Arroues
Pedon S2015CA031001


Tulare Soil Pedon
S2016CA031001
Rob Negrini
U-Channel Sampling


Houser Soil
Pedon S2016CA031002
Redoximorphic Features
80
1
20
40
60

PEDON DESCRIPTION – S2015CA031001 – Tulare Series

Print Date: 04/05/2016
Description Date: 10/28/2015
Describer: Phil Smith, Kerry Arroues, Bev Harben

User Site ID: S2015CA031001
User Pedon ID: S2015CA031001

Soil Name as Described/Sampled: Tulare
Taxon Kind as Sampled: Series
Sampled as Classification: Fine, smectitic, calcareous, thermic Fluvaquentic Vertic Endoaquolls

Soil Name as Correlated: Tulare
Taxon Kind as Correlated: Series
Correlated Classification: Fine, smectitic, calcareous, thermic Fluvaquentic Vertic Endoaquolls

Location Information:
State: California
County: Kings
MLRA: 17 -- Sacramento and San Joaquin Valleys
Soil Survey Area: CA031 -- Kings County, California
2-HAN -- Hanford, California
Map Unit: 163 -- Tulare clay, partially drained
Quad Name: Stratford SE, California
Location Description: Near the lowest elevation of the Tulare Lake Bed.
Latitude: 36 degrees 2 minutes 39.50 seconds north
Longitude: 119 degrees 49 minutes 40.70 seconds west
Datum: WGS84
UTM Zone: 11
UTM Easting: 245232 meters
UTM Northing: 3992564 meters

Geomorphic Setting: lakebed
Upslope Shape: linear Cross Slope Shape: linear
Primary Earth Cover: Crop cover
Secondary Earth Cover: Row crop
Parent Material: lacustrine deposits derived from igneous and sedimentary rock
Slope: 0.1%
Elevation: 56 m
Drainage Class: somewhat poorly

Ap1--0 to 9 centimeters; very dark gray (5Y 3/1) broken face clay, gray (5Y 5/1) broken face, dry; strong very coarse cloddy structure, and moderate coarse cloddy structure; friable, hard, very sticky, very plastic; few very fine roots throughout; many coarse irregular pores; violent effervescence; ; clear smooth boundary.

Ap2--9 to 31 centimeters; very dark gray (5Y 3/1) broken face clay, gray (5Y 5/1) broken face, dry; strong very coarse cloddy structure, and moderate medium cloddy structure, and moderate coarse cloddy structure; friable, hard, very sticky, very plastic; few very fine roots throughout; few very fine dendritic tubular pores; violent effervescence; ; clear smooth boundary.

Ap3--31 to 44 centimeters; very dark gray (5Y 3/1) broken face clay, gray (5Y 5/1) broken face, dry; strong very coarse cloddy structure, and moderate medium cloddy structure, and moderate coarse cloddy structure; friable, hard, very sticky, very plastic; few very fine roots throughout; many coarse irregular and few very fine dendritic tubular pores; violent effervescence; ; clear smooth boundary.

Ap4--44 to 56 centimeters; 50 percent dark gray (2.5Y 4/1) broken face and 50 percent dark reddish gray (2.5YR 3/1) broken face and clay, 50 percent gray (5Y 5/1) broken face and 50 percent gray (5Y 6/1) broken face, dry; moderate coarse prismatic structure parts to moderate coarse angular blocky structure; friable, hard, very sticky, very plastic; and few very fine roots throughout; few very fine dendritic tubular pores; 1 percent fine threadlike carbonate masses with sharp boundaries in matrix; 1 percent 5- to 20-millimeter shell fragments; violent effervescence; ; clear smooth boundary.

Bkg1--56 to 74 centimeters; dark gray (5Y 4/1) broken face clay, gray (5Y 5/1) broken face, dry; strong very coarse prismatic structure parts to strong coarse prismatic structure parts to moderate fine subangular blocky structure; friable, hard, very sticky, very plastic; few very fine roots between peds; 3 percent medium prominent irregular yellowish brown (10YR 5/4), dry, and dark yellowish brown (10YR 3/4), moist, masses of oxidized iron with sharp boundaries on faces of peds; 1 percent fine threadlike carbonate masses with sharp boundaries in matrix; 1 percent 5- to 20-millimeter shell fragments; violent effervescence; ; clear smooth boundary.

Bkg2--74 to 100 centimeters; very dark grayish brown (2.5Y 3/2) broken face clay, light brownish gray (2.5Y 6/2) broken face, dry; strong very coarse prismatic structure parts to strong coarse prismatic structure parts to strong fine angular blocky structure; friable, hard, very sticky, very plastic; few very fine roots between peds; 5 percent medium prominent irregular yellowish brown (10YR 5/4), dry, and dark yellowish brown (10YR 3/4), moist, masses of oxidized iron with sharp boundaries on faces of peds; 1 percent fine threadlike carbonate masses with sharp boundaries in matrix; 1 percent 5- to 20-millimeter shell fragments; violent effervescence; ; clear smooth boundary.

Bkg3--100 to 132 centimeters; dark grayish brown (2.5Y 4/2) broken face clay, light brownish gray (2.5Y 6/2) broken face, dry; strong medium angular blocky structure; firm, extremely hard, very sticky, very plastic; few very fine roots between peds; 5 percent medium prominent irregular brown (7.5YR 4/4), moist, masses of oxidized iron with sharp boundaries on faces of peds; 10 percent medium irregular carbonate masses; 1 percent 5- to 20-millimeter shell fragments; violent effervescence; ; clear wavy boundary.

Bkkg--132 to 147 centimeters; grayish brown (2.5Y 5/2) broken face silty clay loam, light gray (2.5Y 7/2) broken face, dry; structureless massive structure parts to strong thick platy structure parts to moderate thin platy structure; firm, extremely hard, very sticky, very plastic; few very fine roots between peds; 3 percent fine prominent irregular masses of oxidized iron with sharp boundaries on faces of peds; carbonate, finely disseminated; 1 percent 5- to 20-millimeter shell fragments; strong effervescence; ; clear wavy boundary.

B'kg1--147 to 187 centimeters; olive gray (5Y 4/2) broken face silty clay; structureless massive; firm, extremely hard, very sticky, very plastic; 8 percent fine prominent irregular masses of oxidized iron with sharp boundaries on faces of peds; 6 percent medium irregular carbonate masses on horizontal faces of peds; strong effervescence; ; gradual smooth boundary.

Bkyg1--187 to 220 centimeters; very dark gray (2.5Y 3/1) broken face and very dark grayish brown (2.5Y 3/2) broken face clay; structureless massive ; firm, extremely hard, very sticky, very plastic; 1 percent fine prominent threadlike yellowish red (5YR 5/8), moist, masses of oxidized iron with sharp boundaries in matrix; 2 percent medium irregular carbonate masses on faces of peds and 10 percent coarse irregular gypsum masses on faces of peds; slight effervescence; ; gradual smooth boundary.

Bkyg2--220 to 275 centimeters; very dark grayish brown (2.5Y 3/2) broken face silty clay; structureless massive; firm, extremely hard, very sticky, very plastic; 1 percent fine prominent irregular red (2.5YR 5/6), moist, masses of oxidized iron with sharp boundaries on faces of peds; and and 2 percent medium irregular gypsum masses on faces of peds and 15 percent coarse irregular gypsum masses on faces of peds; strong effervescence; ; clear boundary.

2Ab1--275 to 290 centimeters; 90 percent dark gray (2.5Y 4/1) broken face and 50 percent dark gray (2.5Y 4/1) broken face and 50 percent black (2.5Y 2.5/1) broken face and 10 percent black (2.5Y 2.5/1) broken face loam, very dark gray (2.5Y 3/1) broken face and very dark gray (2.5Y 3/1) broken face, dry; stuctureless massive; very firm, extremely hard, very sticky, moderately plastic; brittle; noneffervescent.

2Ab2--290 to 312 centimeters; dark greenish gray (10Y 4/1) broken face and gray (10YR 5/1) broken face loam, gray (2.5Y 5/1) broken face and gray (2.5Y 5/1) broken face, dry; structureless massive; friable, hard, very sticky, moderately plastic; very slight effervescence.

2Bg--312 to 320 centimeters; 50 percent olive gray (5Y 4/2) broken face and 10Y 4/ (10Y 4/), and dark grayish olive (10Y 4/2) broken face silty clay loam, light gray (5Y 7/2) broken face and light gray (5Y 7/2) broken face and light gray (5Y 7/2) broken face and light gray (5Y 7/2) broken face, dry; structureless massive; firm, extremely hard, very sticky, very plastic; 10 percent fine prominent threadlike masses of oxidized iron with sharp boundaries in matrix; very slight effervescence .

PEDON DESCRIPTION – S2016CA031001 – Tulare Series

Print Date: 04/05/2016
Description Date: 2/10-11/2016

Describers: Phil Smith, Kerry Arroues, Rafael Ortiz, Genevieve Landucci

User Site ID: S2016CA031001
User Pedon ID: S2016CA031001

Soil Name as Described/Sampled: Tulare
Taxon Kind as Sampled: series
Sampled as Classification: Fine, smectitic, calcareous, thermic Fluvaquentic Vertic Endoaquolls

Soil Name as Correlated: Tulare
Taxon Kind as Correlated: series
Correlated Classification: Fine, smectitic, calcareous, thermic Fluvaquentic Vertic Endoaquolls

Location Information:
Country:
State: California
County: Kings
MLRA: 17 -- Sacramento and San Joaquin Valleys
Soil Survey Area: CA031 -- Kings County, California
2-HAN -- Hanford, California
Map Unit: 163 -- Tulare clay, partially drained

Location Description: Near the lowest elevation of the Tulare Lake Bed.

Latitude: 36 degrees 6 minutes 38.99 seconds north
Longitude: 119 degrees 51 minutes 29.76 seconds west
Datum: WGS84
UTM Zone: 11
UTM Easting: 245232 meters
UTM Northing: 3992564 meters

Geomorphic Setting: lakebed
Upslope Shape: linear Cross Slope Shape: linear

Primary Earth Cover: Crop cover
Secondary Earth Cover: Row crop

Parent Material: lacustrine deposits derived from igneous and sedimentary rock
Slope: 0.1%
Elevation: 57 m
Drainage Class: somewhat poorly

Ap1--0 to 3 centimeters; very dark gray (2.5Y 3/1) clay, gray (2.5Y 5/1), dry; structureless massive; abrupt smooth boundary.

Ap2--3 to 23 centimeters; very dark gray (2.5Y 3/1) clay, gray (5Y 5/1), dry; weak coarse subangular blocky structure, and weak coarse cloddy structure; common fine roots and common very fine roots; common fine tubular and common very fine pores; very slight effervescence, by HCl, 1 normal; ; abrupt smooth boundary.

Ap3--23 to 36 centimeters; very dark grayish brown (2.5Y 3/2) clay, grayish brown (2.5Y 5/2), dry; moderate medium prismatic structure parts to moderate coarse subangular blocky structure; few fine roots and few medium roots and common very fine roots; common very fine dendritic tubular pores; very slight effervescence, by HCl, 1 normal; clear smooth boundary.

Bkg1--36 to 58 centimeters; dark gray (2.5Y 4/1) clay, gray (2.5Y 5/1), dry; moderate medium prismatic structure parts to weak coarse subangular blocky structure; few very fine roots; few very fine dendritic tubular pores; 12 percent fine threadlike white (10YR 8/1) carbonate masses in matrix; very slight effervescence, by HCl, 1 normal; gradual smooth boundary.

Bkg2--58 to 74 centimeters; dark gray (2.5Y 4/1) clay, grayish brown (2.5Y 5/2), dry; moderate medium prismatic structure parts to weak coarse subangular blocky structure; few very fine roots; few very fine dendritic tubular pores; and 8 percent fine threadlike carbonate masses in matrix; very slight effervescence, by HCl, 1 normal; gradual smooth boundary.

Bkg3--74 to 89 centimeters; dark gray (2.5Y 4/1) clay, gray (2.5Y 6/1), dry; moderate fine prismatic structure parts to strong fine subangular blocky structure; few very fine roots; few very fine dendritic tubular pores; 2 percent fine threadlike white (10YR 8/1), moist, carbonate masses; very slight effervescence, by HCl, 1 normal; abrupt wavy boundary.

Bg--89 to 107 centimeters; gray (5Y 5/1) and dark gray (5Y 4/1) clay, light gray (5Y 7/1) and reddish gray (5R 6/1), dry; weak thick platy structure, and weak thick platy structure; common very fine dendritic tubular pores; very slight effervescence, by HCl, 1 normal; abrupt wavy boundary.

2Akyb1--107 to 128 centimeters; very dark grayish brown (2.5Y 3/2) clay, gray (2.5Y 5/1), dry; strong medium subangular blocky structure, and strong fine subangular blocky structure; few very fine dendritic tubular pores; 8 percent medium irregular white (10YR 8/1), moist, gypsum crystals in matrix and 4 percent medium carbonate masses and 8 percent coarse irregular white (10YR 8/1), moist, gypsum crystals in matrix; slight effervescence, by HCl, 1 normal; clear smooth boundary.

2Akyb2--128 to 144 centimeters; black (2.5Y 2.5/1) clay, very dark gray (2.5Y 3/1), dry; strong medium subangular blocky structure, and strong fine subangular blocky structure; few very fine dendritic tubular pores; and 20 percent pressure faces; 1 percent shell fragments and 8 percent medium irregular white (10YR 8/1), moist, gypsum crystals, unspecified in matrix and 8 percent coarse irregular white (10YR 8/1), moist, gypsum crystals, unspecified in matrix and 3 percent coarse irregular moderately cemented white (10YR 8/1), moist, carbonate masses in matrix; very slight effervescence, by HCl, 1 normal; abrupt smooth boundary.

2Bjg--144 to 171 centimeters; 50 percent gray (2.5Y 5/1) and 30 percent light olive brown (2.5Y 5/4) and 15 percent very dark gray (2.5Y 3/1) clay, 50 percent gray (2.5Y 6/1) and 30 percent light brownish gray (2.5Y 6/2) and 15 percent dark gray (2.5Y 4/1), dry; weak medium subangular blocky structure; common very fine dendritic tubular pores; 1 percent fine irregular light gray (2.5Y 7/1), dry, jarosite masses and 5 percent medium irregular dark reddish brown (5YR 3/4), moist, masses of oxidized iron; noneffervescent, by HCl, 1 normal; gradual wavy boundary.

2Bjycg--171 to 200 centimeters; olive gray (5Y 4/2) clay, white (5Y 8/1), dry; strong thin platy structure, and strong medium platy structure; common medium roots throughout; common very fine dendritic tubular pores; 3 percent fine yellowish red (5YR 4/6), moist, masses of oxidized iron on surfaces along root channels and 6 percent fine moderately cemented pale yellow (5Y 7/4), moist, jarosite nodules in matrix; 1 percent very fine gypsum crystals in matrix; clear smooth boundary.

2Bjyg--200 to 218 centimeters; greenish gray (10Y 6/1) clay, white (5Y 8/1), dry; strong thick platy structure; few very fine roots throughout; few very fine dendritic tubular and few very fine tubular pores; 1 percent irregular yellowish red (5YR 4/6), moist, masses of oxidized iron in matrix and 15 percent pale yellow (5Y 7/4), moist, jarosite masses along lamina or strata surfaces; 1 percent very fine gypsum crystals; very abrupt wavy boundary.

Cg1--218 to 245 centimeters; olive gray (5Y 4/2) loamy fine sand, gray (2.5Y 6/1), dry; structureless, massive; 2 percent strong brown (7.5YR 4/6), moist, masses of oxidized iron; gradual smooth boundary.

Cjg1--245 to 257 centimeters; olive (5Y 4/3) loamy fine sand, pale olive (5Y 6/3), dry; stuctureless, massive; 5 percent gray (2.5Y 6/1), moist, iron depletions and 10 percent pink (5YR 8/4), moist, jarosite masses and 40 percent strong brown (7.5YR 5/8), moist, masses of oxidized iron; clear smooth boundary.

Cjg2--257 to 282 centimeters; pale olive (5Y 4/3) loamy fine sand and olive (5Y 6/3), dry; structureless, massive ; 3 percent fine irregular dark yellowish brown (10YR 4/6), moist, masses of oxidized iron in matrix and 3 percent fine platy and yellow (5Y 8/6), moist, jarosite masses in matrix and 5 percent medium platy gray (5Y 6/1), moist, iron depletions in matrix; very abrupt smooth boundary.

Cjyg--282 to 315 centimeters; olive brown (2.5Y 4/3) clay loam, light yellowish brown (2.5Y 6/3), dry; structurelsss, massive ; 3 percent fine yellow (5Y 8/6), moist, jarosite masses and 5 percent medium brown (7.5YR 4/4), moist, masses of oxidized iron and 10 percent medium yellowish brown (10YR 5/8), moist, masses of oxidized iron and 20 percent medium light olive gray (5Y 6/2), moist, iron depletions; 1 percent fine gypsum crystals.

PEDON DESCRIPTION – S2016CA031002 – Houser Series

Print Date: 04/05/2016
Description Date: 2/24/2016
Describer: Phil Smith, Rafael Ortiz, Kerry Arroues

User Site ID: S2016CA031002

User Pedon ID: S2016CA031002

Soil Name as Described/Sampled: Houser
Taxon Kind as Sampled: Series
Sampled as Classification: Fine, smectitic, calcareous, thermic Vertic Fluvaquents

Soil Name as Correlated: Houser
Taxon Kind as Correlated: Series
Correlated Classification: Fine, smectitic, calcareous thermic Vertic Halaquepts

Pedon Type: undefined observation
Pedon Purpose: laboratory sampling site

Location Information:
Country:
State: California
County: Kings
MLRA: 17 -- Sacramento and San Joaquin Valleys
Soil Survey Area: CA031 -- Kings County, California
2-HAN -- Hanford, California

Latitude: 35 degrees 56 minutes 47.21 seconds north
Longitude: 119 degrees 50 minutes 38.61 seconds west
Datum: WGS84

Upslope Shape: linear Cross Slope Shape: linear

Primary Earth Cover: Grass/herbaceous cover
Secondary Earth Cover: Row crop

Parent Material: lacustrine deposits derived from igneous and sedimentary rock
Slope: 0.1%
Elevation: 58.7 m
Drainage Class: somewhat poorly

Ap1--0 to 10 centimeters; olive gray (5Y 4/2) clay, olive gray (5Y 5/2), dry; 40 percent clay; weak fine granular structure; friable, slightly hard, moderately sticky, very plastic; few fine roots throughout and few medium roots throughout; carbonate, finely disseminated; slight effervescence, by HCl, 1 normal; clear smooth boundary.

Ap2--10 to 22 centimeters; dark gray (5Y 4/1) clay, olive gray (5Y 5/2), dry; 42 percent clay; structureless massive structure; firm, hard, very sticky, very plastic; few fine roots throughout and few medium roots throughout; carbonate, finely disseminated and 1 percent medium irregular very strongly cemented carbonate concretions; very slight effervescence, by HCl, 1 normal; clear smooth boundary.

Bknzg1--22 to 42 centimeters; 50 percent N 4/1 (N 4/1) and 40 percent olive (5Y 4/3) clay, 50 percent gray (5Y 5/1) and 40 percent olive (5Y 5/3), dry; 48 percent clay; structureless massive; very firm, extremely hard, very sticky, very plastic; few fine roots throughout and few medium roots throughout; common very fine dendritic tubular pores; 7 percent fine irregular dark brown (7.5YR 3/4), moist,; carbonate, finely disseminated and 3 percent fine threadlike white (2.5Y 8/1) carbonate masses; very slight effervescence, by HCl, 1 normal; very abrupt smooth boundary.

Bknzg2--42 to 54 centimeters; dark gray (5Y 4/1) and olive (5Y 4/3) clay, gray (5Y 6/1) and olive (5Y 5/3), dry; 42 percent clay; structureless massive; very friable, extremely hard, very sticky, very plastic; few medium roots throughout and common very fine roots throughout; many very fine dendritic tubular pores; 3 percent strong brown (7.5YR 4/6), moist, masses of oxidized iron on surfaces along root channels; carbonate, finely disseminated and 1 percent very fine threadlike white (2.5Y 8/1), moist, carbonate masses in matrix; very slight effervescence, by HCl, 1 normal; very abrupt smooth boundary.

Bnzg--54 to 67 centimeters; olive brown (2.5Y 4/3) silt loam, light olive brown (2.5Y 5/3), dry; 20 percent sand; 26 percent clay; structureless massive structure; very friable, slightly hard, moderately sticky, moderately plastic; few medium roots throughout and few very fine roots throughout; many very fine dendritic tubular pores; 10 percent fine irregular yellowish red (5YR 4/6), moist, masses of oxidized iron in matrix and 30 percent medium irregular dark grayish brown (2.5Y 4/2), moist, iron depletions in matrix; noneffervescent, by HCl, 1 normal; abrupt smooth boundary.

Bnyzg1--67 to 87 centimeters; olive gray (5Y 4/2) clay, light olive gray (5Y 6/2), dry; 50 percent clay; weak coarse subangular blocky structure; very firm, extremely hard, very sticky, very plastic; few very fine roots throughout; common very fine dendritic tubular pores; 3 percent coarse dark reddish brown (5YR 3/4), moist, masses of oxidized iron in matrix and 15 percent medium dark reddish brown (5YR 3/4), moist, masses of oxidized iron in matrix and 30 percent irregular gray (5Y 5/1), moist, in matrix; 10 percent medium irregular gypsum crystals; noneffervescent, by HCl, 1 normal; gradual smooth boundary.

Bnyzg2--87 to 120 centimeters; olive gray (5Y 4/2) clay, olive gray (5Y 5/2), dry; 50 percent clay; weak very coarse angular blocky structure; very firm, extremely hard, very sticky, very plastic; few very fine roots throughout; few very fine dendritic tubular pores; 1 percent coarse irregular yellowish red (5YR 4/6), moist, masses of oxidized iron in matrix; 10 percent medium irregular gypsum crystals in matrix and 5 percent coarse gypsum crystals, unspecified; noneffervescent, by HCl, 1 normal; abrupt smooth boundary.

Bnyzg3--120 to 196 centimeters; 70 percent dark yellowish brown (10YR 4/6) and 30 percent olive gray (5Y 4/2) silt loam, 70 percent yellowish brown (10YR 5/6) and 30 percent light olive gray (5Y 6/2), dry; 25 percent sand; 20 percent clay; structureless massive; friable, slightly hard, slightly sticky, slightly plastic; 30 percent very coarse strong brown (7.5YR 4/6), moist, masses of oxidized iron; carbonate, finely disseminated and 1 percent medium gypsum crystals in matrix; slight effervescence, by HCl, 1 normal; very abrupt smooth boundary.

Bknyzcg--196 to 215 centimeters; dark gray (5Y 4/1) clay, light gray (5Y 7/1), dry; 55 percent clay; structureless structure; firm, extremely hard, very sticky, very plastic; and 1 percent dark yellowish brown (10YR 3/4), moist, masses of oxidized iron along lamina or strata surfaces and 1 percent very dark gray (7.5YR 3/1), moist, iron-manganese masses and 5 percent coarse irregular dark yellowish brown (10YR 4/6), moist, masses of oxidized iron; and 1 percent fine gypsum crystals, along lamina or strata surfaces and 1 percent medium irregular moderately cemented carbonate concretions in matrix and 1 percent very fine gypsum crystals in matrix; noneffervescent, by HCl, 1 normal.

LOCATION ARMONA CA
Established Series
Rev. TDC/KDA/ARW
12/2002

ARMONA SERIES

The Armona series consists of very deep, poorly drained soils on flood plains on basin floors and basin rims. These soils formed in alluvium from igneous and/or sedimentary rock. Slope is 0 to 1 percent. Mean annual precipitation is about 7 inches and mean annual temperature is about 64 degrees F.

TAXONOMIC CLASS: Fine-loamy, mixed, superactive, calcareous, thermic Fluvaquentic Endoaquolls

TYPICAL PEDON: Armona loam, on a slope of less than 1 percent under irrigated cultivation at 200 feet elevation. (Colors are for dry soil unless otherwise stated. When described on 2/14/77 the soil was moist throughout and had a water table at a depth of 51 inches.)

Ap--0 to 9 inches; dark gray (5Y 4/1) loam, black (5Y 2/1) moist; weak medium subangular blocky structure; hard, very friable, slightly sticky and slightly plastic; many very fine roots; many very fine interstitial and common very fine tubular pores; electrical conductivity is 3.0 decisiemens per meter; sodium adsorption ratio is 2; slightly alkaline (pH 7.5); abrupt smooth boundary. (8 to 11 inches thick)

Bknz--9 to 14 inches; gray (5Y 5/1) loam, very dark gray (5Y 3/1) moist; weak medium subangular blocky structure; very hard, friable, slightly sticky and moderately plastic; many very fine roots; many very fine interstitial and common very fine tubular pores; common fine prominent yellowish brown (10YR 5/4) redoximorphic masses of iron accumulation, dark reddish brown (5YR 3/4) moist; common fine gypsum crystals; slightly effervescent, carbonates disseminated; electrical conductivity is 13.5 decisiemens per meter; sodium adsorption ratio is 18; moderately alkaline (pH 7.9); abrupt wavy boundary. (2 to 6 inches thick)

Bkgnyz--14 to 19 inches; gray (5Y 5/1) loam, dark gray (5Y 4/1) moist; massive; very hard, friable, slightly sticky and slightly plastic; common very fine roots; many very fine interstitial and common very fine tubular pores; common fine prominent strong brown (7.5YR 5/6) redoximorphic masses of iron accumulations, dark reddish brown (5YR 3/2) moist; common fine gypsum crystals; slightly effervescent, carbonates disseminated; electrical conductivity is 18 decisiemens per meter; sodium adsorption ratio is 25; moderately alkaline (pH 7.9); abrupt wavy boundary. (5 to 8 inches thick)

2Bkgnz1--19 to 22 inches; gray (5Y 5/1) sandy loam, dark gray (5Y 4/1) moist; massive; very hard, very friable, nonsticky and nonplastic; few very fine roots; many very fine interstitial and common very fine tubular pores; common fine prominent strong brown (7.5YR 5/6) redoximorphic masses of iron accumulation, dark reddish brown (5YR 2/2) and reddish brown

(5YR 4/4) moist; slightly effervescent, carbonates disseminated; electrical conductivity 16 decisiemens per meter; sodium adsorption ratio 32; moderately alkaline (pH 8.2); abrupt wavy boundary. (2 to 6 inches thick)

2Bkgnz2--22 to 25 inches; light gray (5Y 7/2) sandy loam, olive gray (5Y 5/2) moist; massive; very hard, very friable, nonsticky and nonplastic; many very fine interstitial and common very fine tubular pores; common fine prominent yellowish brown (10YR 5/4) redoximorphic masses of iron accumulation, brown (7.5YR 4/4) moist; slightly effervescent, carbonates disseminated; electrical conductivity is 19 decisiemens per meter; sodium adsorption ratio is 30; slightly alkaline (pH 7.8); abrupt wavy boundary. (2 to 6 inches thick)

3Bkgnyz--25 to 30 inches; gray (5Y 5/1) clay loam, dark gray (5Y 4/1) moist; massive; very hard, friable, moderately sticky and very plastic; many very fine and fine interstitial and common very fine tubular pores; common fine prominent reddish yellow (7.5YR 6/6) and common fine faint dark gray (5Y 4/1) redoximorphic masses of iron accumulation, brown (7.5YR 4/4) and black (5Y 2.5/1) moist; common fine gypsum crystals; slightly effervescent, carbonates disseminated; electrical conductivity is 20 decisiemens per meter; sodium adsorption ratio is 30; slightly alkaline (pH 7.8); clear smooth boundary. (2 to 6 inches thick)

4Bkgnzb1--30 to 36 inches; olive gray (5Y 5/2) loam, dark olive gray (5Y 3/2) moist; massive; very hard, friable, moderately sticky and very plastic; many very fine and fine interstitial and common very fine tubular pores; common fine prominent dark yellowish brown (10YR 4/4) and common fine faint dark gray (5Y 4/1) redoximorphic masses of iron depletion, dark reddish brown (5YR 3/2) and black (5Y 2.5/1) moist; common fine gypsum crystals; slightly effervescent, carbonates disseminated; electrical conductivity is 18 decisiemens per meter; sodium adsorption ratio is 18; slightly alkaline (pH 7.7); abrupt smooth boundary. (0 to 8 inches thick)

4Bkgnzb2--36 to 41 inches; olive gray (5Y 5/2) silt loam, olive gray (5Y 4/2) moist; massive; very hard, friable, moderately sticky and moderately plastic; many very fine interstitial and common very fine tubular pores; common fine distinct very dark gray (5Y 3/1) moist redoximorphic masses of iron depletion; slightly effervescent, carbonates disseminated; electrical conductivity is 17 decisiemens per meter; sodium adsorption ratio is 26; slightly alkaline (pH 7.5); abrupt smooth boundary (2 to 6 inches thick)

5Bgnzb--41 to 60 inches; light gray (5Y 7/1) sand, gray (5Y 6/1) moist; massive; hard, loose; many very fine interstitial and few very fine tubular pores; common fine prominent brown (7.5YR 4/4) redoximorphic masses of iron accumulation, dark reddish brown (5YR 3/2) moist; electrical conductivity is 21 decisiemens per meter; sodium adsorption ratio is 19; slightly alkaline (pH 7.5).

TYPE LOCATION: Kings County, California; about 0.75 mile south of the city Stratford, about 200 feet north of the Tulare Lake Canal and 300 feet west of 20 1/2 Avenue; 900 feet south and 2,300 feet east of the northwest corner of section 20 T. 20 S., R. 20 E., MDB&M; Latitude 36 degrees, 10 minutes, 46 seconds north Longitude 119 degrees, 49 minutes, 32 seconds west; USGS Stratford Topographic Quadrangle, NAD 27.

RANGE IN CHARACTERISTICS: The soil is 60 inches or more deep. The soil is saturated in some part during the year, unless artificially drained. The mean annual soil temperature is 60 degrees to 62 degrees F. Depth to stratified alluvium is 11 to 14 inches. Organic matter is 1 to 2 percent in the surface horizon and decreases irregularly with increasing depth. The soil is saline-sodic in some part during the year.

The A horizon has color of 10YR 4/1, 5/1, 5/2; 2.5Y 5/2; 5Y 4/1, 5/1 or 5/2. Moist color is 10YR 3/1, 3/2; 2.5Y 3/2; 5Y 2/1, 2/2, 3/1 or 3/2. Faint to prominent moist redoximorphic concentrations are present in some pedons. Texture is sandy loam or loam. Calcium carbonate equivalent is 1 to 5 percent. Gypsum content is 0 to 3 percent. Electrical conductivity is 0 to 16 decisiemens per meter. Sodium adsorption ratio is 2 to 30. Electrical conductivity, sodium adsorption ratio and gypsum content are affected by agricultural practices and the depth to a high water table. Reaction is slightly alkaline to strongly alkaline.

The B horizon has color of 10YR 5/1; 2.5Y 5/2, 6/2, 7/2; 5Y 5/1, 5/2, 6/2, 6/3, 7/1 or 7/2. Moist color is 10YR 3/1, 3/2; 2.5Y 3/2, 4/2; 5Y 2/1, 3/1, 4/1, 4/2, 5/1, 5/2, 5/3, 6/1 or 6/2. Moist redoximorphic accumulations and depletions of iron and manganese are faint to prominent. Texture is stratified sandy loam, loam or clay loam and clay content averages 20 to 35 percent, but the particle-size control section has thin horizons that range from sand to clay. Clay content is 18 to 35 percent in the upper part and 0 to 45 percent in the lower part. Calcium carbonate equivalent is 1 to 10 percent. Gypsum content is 0 to 4 percent. Electrical conductivity is 0 to 30 decisiemens per meter. Sodium adsorption ratio is 2 to 80. Electrical conductivity, sodium adsorption ratio and gypsum content are affected by agricultural practices and the depth to a high water table. Some pedons contain up to 15 percent durinodes and/or carbonate concretions at a depth below 40 inches. Reaction is slightly alkaline to very strongly alkaline.

COMPETING SERIES: There are no competing series at this time.

GEOGRAPHIC SETTING: Armona soils are on flood plains on basin floors and basin rims. Slope is 0 to 1 percent. These soils formed in alluvium from igneous and/or sedimentary rock. Elevations are 115 to 250 feet. The climate is semiarid with hot dry summers and cool moist winters. The mean annual precipitation is 7 to 8 inches. Mean January temperature is about 45 degrees F.; mean July temperature is about 82 degrees F.; mean annual temperature is 62 to 66 degrees F. Frost-free season is 220 to 275 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Gepford, Grangeville, Tachi and Tulare soils. Gepford soils, on flood plains and basin floors, have a fine particle-size control section. Grangeville soils, on alluvial fans and flood plains, have a coarse-loamy particle-size control section. Tachi soils, on flood plains and basin floors, have a very fine particle-size control section. Tulare soils, on basins, have a fine particle-size control section.

DRAINAGE AND PERMEABILITY: Poorly drained; This soil has altered drainage because of dams and reservoirs in the Sierra Nevada, pumping from the water table, the use of tile and interceptor drains, and filling and leveling of the sloughs in the vicinity. This soil is protected from flooding by dams, canals and levees. Negligible or low runoff; moderately slow or slow permeability due to sodicity and stratification. A perched water table occurs at a depth of 24 to

72 inches from January through December. The soil is wet throughout from December through March, unless drained. The soil remains moist below a depth of 6 inches from April through November, unless drained.

USE AND VEGETATION: Used mainly for irrigated crops such as wheat, barley and cotton. The natural vegetation is iodine bush (Allenrolfea occidentalis) and alkali blite.

DISTRIBUTION AND EXTENT: San Joaquin Valley. Series is moderately extensive. MLRA 17.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

REMARKS: Diagnostic horizons and features recognized in this pedon:

1.0 Mollic Epipedon--The zone from the soil surface to a depth of about 14 inches (Ap and Bknz horizons).

2.0 Particle Size Family--Fine-loamy, the 10 to 40 inch particle size control section averages 20 to 35 percent clay.

3.0 Aquic Moisture Regime--The soil is saturated in some or all parts most of the year, or is drained. Redoximorphic features are present.

4.0 Stratification--The soil is highly stratified from a depth of about 11 inches to 60 inches. Organic matter decreases irregularly with increasing depth.

5.0 Calcium Carbonate--The 10 to 20 inch zone in the soil always has 1 to 5 percent calcium carbonate, and is always effervescent throughout.

ADDITIONAL DATA: NSSL Pedon S84CA-031-006 (CP85CA052) sampled near the series type location, and S88CA-107-010 (RP88CA259).

LOCATION GEPFORD CA
Established Series
Rev. CHA/ARW/CAF/KDA
10/2002

GEPFORD SERIES

The Gepford series consists of very deep, poorly drained soils that formed in mixed alluvium derived dominantly from granitic rocks, and influenced by lacustrine sediments. Gepford soils are on flood plains, basin floors and basin rims. Slope is 0 to 1 percent. The mean annual precipitation is 7 inches and the mean annual temperature is 64 degrees F.

TAXONOMIC CLASS: Fine, smectitic, thermic Typic Natraquerts (Note: Will be reclassified utilizing newest Soil Taxonomy as: (Fine, smectitic, thermic Sodic Endoaquerts).

TYPICAL PEDON: Gepford clay on a slope of less than 1 percent under a cotton crop at 210 feet elevation. (Colors are for dry soil unless otherwise noted. When described on 11/2/78 cotton was mature and the soil was moist to 40 inches and wet below this point, water table was at 44 inches.)

Ap1--0 to 12 inches; gray (5Y 5/1) clay, very dark gray (5Y 3/1) moist; strong very coarse prismatic structure parting to strong medium and coarse angular blocky; hard, very firm, moderately sticky and moderately plastic; many very fine and few fine roots; common very fine tubular and many very fine interstitial pores; strongly effervescent, carbonates disseminated and segregated as few fine irregularly shaped soft masses; few fine distinct pale olive (5Y 6/3) and dark yellowish brown (10YR 4/4) masses of redoximorphic iron accumulation, olive (5Y 5/3) and dark yellowish brown (10YR 4/4) moist; slightly alkaline (pH 7.8); abrupt smooth boundary. (6 to 13 inches thick)

Ap2--12 to 25 inches; variegated gray (5Y 5/1), dark gray (5Y 4/1) and gray (N 5/0) clay, dark olive gray (5Y 3/2), dark gray (5Y 4/1) and black (5Y 2.5/1) moist; moderate very coarse prismatic structure; cracks 1.5 inches wide to a depth of 19 inches; hard, firm, moderately sticky and very plastic; many very fine and common fine roots; common very fine tubular and many very fine interstitial pores; strongly effervescent, carbonates disseminated and segregated as few fine irregularly shaped soft masses; common medium distinct greenish gray (5G 6/1) redoximorphic iron depletions, greenish gray (5G 5/1) moist and few fine distinct light olive brown (2.5Y 5/4) moist masses of iron accumulation; moderately alkaline (pH 8.0); abrupt smooth boundary. (10 to 16 inches thick)

Bkg1--25 to 30 inches; olive (5Y 5/3) clay, olive (5Y 4/3) moist; massive; hard, firm, very sticky and very plastic; many very fine tubular pores; slightly effervescent, carbonates disseminated and segregated as few fine irregularly shaped soft masses; common pressure faces and wedge-shaped aggregates which are tilted at a 30 degree angle; many fine distinct very dark gray (5Y 3/1) manganese concretions, black (5Y 2.5/1) moist and many fine faint olive (5Y 5/4) masses of iron accumulation, dark yellowish brown (10YR 3/4) moist; moderately alkaline (pH 8.2); abrupt smooth boundary. (4 to 12 inches thick)

Bkg2--30 to 38 inches; gray (5Y 6/1) clay, dark gray (5Y 4/1) moist; massive; very hard, firm, moderately sticky and very plastic; many very fine tubular pores; slightly effervescent, carbonates disseminated and segregated as few fine irregularly shaped soft masses and common medium very hard nodules; common pressure faces and wedge-shaped aggregates which are tilted at a 30 degree angle; many fine distinct pale olive (5Y 6/3) masses of redoximorphic iron accumulation, olive (5Y 4/3) moist; moderately alkaline (pH 8.3); abrupt smooth boundary. (5 to 20 inches thick)

2Bkg3--38 to 54 inches; light olive gray (5Y 6/2) clay loam, gray (5Y 5/1) moist; massive; very hard, firm, moderately sticky and moderately plastic; many very fine interstitial pores; slightly effervescent, carbonates disseminated and segregated as common medium very hard nodules; common pressure faces; many fine distinct and prominent light yellowish brown (2.5Y 6/4) and few fine distinct brown (7.5YR 5/4) and grayish brown (10YR 5/2) masses of redoximorphic iron accumulation, light olive brown (2.5Y 5/4), brown (7.5YR 4/4) and very dark grayish brown (10YR 3/2) moist; moderately alkaline (pH 8.3); abrupt smooth boundary. (4 to 20 inches thick)

2Bkg4--54 to 60 inches; pale yellow (5Y 7/3) clay loam, olive (5Y 5/3) moist; massive; very hard, friable, moderately sticky and moderately plastic; many very fine interstitial pores; slightly effervescent, carbonates disseminated and segregated as common medium very hard nodules; few fine distinct gray (5Y 6/1) iron depletions, gray (5Y 5/1) moist, and pale yellow (2.5Y 7/4) masses of redoximorphic iron accumulation that are light olive brown (2.5Y 5/4) moist; moderately alkaline (pH 8.2).

TYPE LOCATION: Kings County, California; about 800 feet west of the North Fork Kings River and 60 feet north of Grangeville Blvd.; 2300 feet east and 60 feet north of the southwest corner of section 22, T. 18 S., R. 19 E., MDB&M; Latitude 36 degrees, 20 minutes, 38 seconds north and Longitude 119 degrees, 53 minutes, 47 seconds west; USGS Vanguard Topographic Quadrangle, NAD 27.

RANGE IN CHARACTERISTICS: The mean annual soil temperature ranges from 63 to 68 degrees F. The moisture control section is moist in some part all of the time and is saturated for up to 4 months, unless drained. Average clay in the 10 to 40 inch control section is 50 to 60 percent. Organic matter is 1 to 3 percent in the surface horizons and decreases irregularly with increasing depth. Calcium carbonate equivalent is 1 to 5 percent in the surface horizon and 2 to 15 percent in the lower horizons. Carbonate is disseminated and/or segregated as concretions, threads, nodules and soft masses. Conductivity of the saturation extract ranges from 2 to 16 decisiemens per meter. Sodium adsorption ratio is 2 to 30 in the surface layer and 8 to 50 in the subsoil, and some part of the subsoil always is greater than 13. Reaction of the soil profile is slightly alkaline to strongly alkaline, typically increasing in alkalinity with increasing depth.

The A horizon has color of 5Y 4/1, 4/2, 5/1, 5/2 or 6/2. Moist color is 5Y 2/1, 2.5/1, 3/1, 3/2, 4/2, 4/1, or N 5/0. Texture is clay or silty clay. Cracks, when dry, range from 1/4 to 1 inch wide and extend up to 29 inches deep in the soil. Redoximorphic features may be present in some A horizons.

The B horizon has color of 2.5Y 6/2, 6/4; 5Y 4/1, 5/1, 5/2, 5/3, 6/1, 6/2, 7/1, 7/2, 7/3 or 8/1. Moist color is 2.5Y 4/4, 5/4; 5GY 4/1, 5/1; 5Y 3/1, 3/2, 4/1, 4/2, 4/3, 5/1, 5/2 or 5/3. Moist colors of redoximorphic features are 7.5YR 4/4; 10YR 3/2, 3/4, 3/6, 4/4, 4/6; 2.5Y 4/4, 5/4; 5Y 2/1, 2.5/1, 4/1, 4/3, 4/4, 5/1, 5/2 5/3, 6/2, 6/3, 6/4; 5GY 4/1, 4/2, 5/1; 5G 5/1; N 2/0, 5/0; 5YR 3/2 or 3/3. Texture is clay loam, clay or silty clay in the upper part and may have thin strata of sand to clay in the lower part. Hard carbonate nodules are few or common. Few to common pressure faces are in the B horizons. Wedge-shaped aggregates that are tilted at least 10 degrees occur in all pedons. Some pedons have Bkyg horizons. Gypsum content is variable due to additions of gypsum as a soil amendment.

COMPETING SERIES: There are no competing series at this time.

GEOGRAPHIC SETTING: Gepford soils are on flood plains, basin floors and basin rims. The soils formed in mixed alluvium derived dominantly from granitic rocks, and influenced by lacustrine sediments. Slope is0 to 1 percent. Elevations are 120 to 250 feet. Climate is arid to semiarid and has hot dry summers and cool moist winters. Mean annual precipitation varies from 6 to 8 inches. Mean January temperature is 45 degrees F.; mean July temperature is 82 degrees F.; mean annual temperature is 62 to 66 degrees F. Frost-free season varies from 220 to 275 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Lethent, Pitco, Tachi and Vanguard series. Lethent soils on fan remnants have a natric horizon and an ochric epipedon. Pitco soils on basin rims and flood plains lack carbonates in any part of the profile. Tachi soils on basin floors and flood plains have a very-fine particle-size control section. Vanguard soils on flood plains have a coarse-loamy particle-size control section.

DRAINAGE AND PERMEABILITY: Poorly drained; ponded in some areas; runoff is medium or high; very slow permeability. Sandy substratum phases occur with moderately rapid or rapid permeability in the substratum. The perched water table has been lowered to 30 to 72 inches because runoff water has been intercepted. Unless protected, the soil is flooded for 30 to 90 days from January through March once every 3 years. Many areas that are protected by upstream diversions of water (such as dams, levees and canals) are rarely flooded.

USE AND VEGETATION: Used primarily for irrigated cropland to produce barley, cotton, safflower, grain, sorghum, and sugar beets. It is also used for dairy and cattle production and building site development.

DISTRIBUTION AND EXTENT: San Joaquin Valley, California. The series is of moderate extent. MLRA 17.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

REMARKS: Reaction is highly variable as a result of addition of gypsum and sulfur by farmers. Where farmers have added significant amounts of gypsum or sulfur the soil reaction will be lowered. These horizons with segregated gypsum are designated with the "y" horizon suffix.
The Gepford series was initially classified as Vertic Haplaquolls. This was changed to Typic Natraquerts when wedge-shaped aggregates weredescribed in the Gepford profiles.
The original competing series before taxonomy change were the Dospalos, Portageville (T), and Tulare series. Dospalos soils have 35 to 50 percent clay in the particle-size control section and have a conductivity of less than 2 decisiemens per meter. Portageville soils lack salinity. Tulare soils have a horizon with more than 15 percent calcium carbonate and lack carbonate nodules in the B horizon. They also lack redoximorphic features in the A horizons.

Diagnostic Features and Characteristics:
1.0 Mollic Epipedon--The zone from the soil surface to a depth of about 25 inches (Ap horizons). These layers are not designated with a "g" horizon subscript because it has been ripped and tilled.
2.0 Fine Particle Size Family--The zone from a depth of 10 inches to a depth of about 40 inches has an average of 50 to 60 percent clay.

LOCATION HOMELAND CA
Established Series
Rev. CHA/KKC/TDC
2/80

HOMELAND SERIES

The Homeland series consists of deep, poorly drained soils that formed in alluvium from igneous and sedimentary rocks. Homeland soils occur on basin rims and have slopes of 0 to 1 percent. The mean annual temperature is about 64 degrees F., and the average annual precipitation is about 6 inches.

TAXONOMIC CLASS: Sandy, mixed, thermic Aeric Fluvaquents

TYPICAL PEDON: Homeland fine sandy loam, on a slope less than 1 percent under irrigated barley at 188 feet elevation. (Colors are for dry soil unless otherwise stated. When described on 5/11/76 the soil was moist and the water table was at a depth of 41 inches.)

Ap--0 to 8 inches; light olive gray (5Y 6/2) fine sandy loam, olive gray (5Y 4/2) moist; massive; slightly hard, very friable, nonsticky and slightly plastic; common very fine roots; common fine vesicular and many very fine interstitial pores; strongly effervescent, disseminated lime; EC 29 mmhos; SAR 96; moderately alkaline (pH 8.4); abrupt smooth boundary. (6 to 10 inches thick)

C1--8 to 12 inches; light gray (5Y 7/2) very fine sandy loam, olive gray (5Y 5/2) moist; many fine distinct white (5Y 8/2) and common fine prominent yellowish brown (10YR 5/8) mottles, pale olive (5Y 6/4) and dark yellowish brown (10YR 4/6) moist; massive; slightly hard, very friable, nonsticky and slightly plastic; few very fine roots; many very fine interstitial pores; strongly effervescent, disseminated lime; EC 18 mmhos; SAR 107; moderately alkaline (pH 8.2); abrupt wavy boundary. (3 to 5 inches thick)

C2--12 to 15 inches; variegated light gray (5Y 7/2) and pale yellow (5Y 8/4) sandy loam, olive (5Y 5/3) and pale olive (5Y 6/3) moist; few fine prominent yellowish brown (10YR 5/8) mottles, dark yellowish brown (10YR 4/6) moist; massive; soft, very friable, nonsticky and nonplastic; few very fine roots; many very fine interstitial pores; slightly effervescent, disseminated lime; EC 5.0 mmhos; SAR 37; moderately alkaline (pH 8.0); abrupt wavy boundary. (2 to 5 inches thick)

C3--15 to 19 inches; variegated pale yellow (5Y 8/3) and light gray (5Y 7/2) loamy sand, pale olive (5Y 6/3) and olive gray (5Y 5/2) moist; single grained; loose; many very fine interstitial pores; EC 5.5 mmhos; SAR 31; moderately alkaline (pH 8.0); abrupt boundary. (4 to 21 inches thick)

C4--19 to 24 inches; variegated pale yellow (5Y 8/3) and light gray (5Y 7/2) loamy fine sand, pale yellow (5Y 7/3) and olive (5Y 5/3) moist; massive; loose; many very fine interstitial pores; EC 6.5 mmhos; SAR 33; moderately alkaline (pH 8.0); abrupt wavy boundary. (4 to 6 inches

thick)
C5--24 to 32 inches; variegated white (5Y 8/2) and light gray (5Y 7/2) loamy fine sand, olive gray (5Y 5/2) and pale yellow (5Y 7/3) moist; massive; loose; many very fine interstitial pores; thin (3 to 10 mm) strata of very fine sandy loam to sandy loam; EC 12 mmhos; SAR 53; moderately alkaline (pH 8.3); abrupt smooth boundary. (7 to 10 inches thick)

C6--32 to 60 inches; variegated pale yellow (5Y 8/3) and pale yellow (5Y 7/3) loamy fine sand, olive gray (5Y 5/2) and pale olive (5Y 6/3) moist; massive; loose; many very fine interstitial pores; thin (3 to 10 mm) strata of very fine sandy loam loam; EC 18 mmhos; SAR 49; moderately alkaline (pH 8.2).

TYPE LOCATION: Kings County, California; approximately 1 mile north of Utica Avenue; 400 feet west and 75 feet south of the NE corner sec. 11, T. 23 S., R. 20 E., MDB&M.

RANGE IN CHARACTERISTICS: The soil is more than 60 inches deep and is weakly stratified. The solum typically is about 8 inches thick but ranges from 6 to 10 inches thick. The depth to a perched water table ranges from 2 to 4 feet. The soil is typically strongly saline-alkali and ranges from slightly saline-alkali. Mean annual soil temperature is 64 degrees to 67 degrees F.

The A horizon has dry color of 5Y 6/2, 7/2; 2.5Y 7/2 or 6/2 and moist color of 5Y 4/2, 5/2; 2.5Y 4/2 or 5/2. It is strongly effervescent or violently effervescent with disseminated lime.

The C horizon has dry color of 5Y 7/2, 7/3, 8/2, 8/3, 8/4; 2.5Y 5/2 or 6/2 and moist color of 5Y 5/2, 5/3, 6/3, 7/3; 2.5Y 3/2 or 4/2. Mottles are few to many, fine or medium, distinct or prominent and have color of 5GY 4/1; 5BG 4/1; 5Y 6/4 or 10YR 4/6 moist. More than 40 percent of the moist matrix colors, at depths of 10 to 30 inches, have a chroma of 3 or more when mottles are present in the substratum. Chroma is 2 or 3 when no mottles are present. This horizon is dominantly loamy sand and loamy fine sand with thin horizons of very fine sandy loam, fine sandy loam, or sandy loam. It is slightly effervescent to strongly effervescent with disseminated lime to a depth of 15 inches. It is typically noneffervescent below 15 inches but lime is present in some pedons below this depth.

COMPETING SERIES: These are the Dello, Duckston, Lang, and Laugenour series in other families. Dello, Duckston, and Lang soils have a sandy particle-size control section. Laugenour soils have a coarse-loamy particle-size control section.

GEOGRAPHIC SETTING: Homeland soils occur on basin rims. Slopes are 0 to 1 percent. The soils formed in alluvium from igneous and sedimentary rocks. Elevations are 185 to 220 feet. The average annual precipitation is 6 to 7 inches. The climate is arid with cool moist winters and hot dry summers. Mean January temperature is about 64 degrees F. Frost-free season is 255 to 270 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Armona, Lakeside, Rambla and Tulare soils. Armona, Lakeside, and Tulare soils have a mollic epipedon. Rambla soils have clay textures in some horizon below a depth of 9 inches.

DRAINAGE AND PERMEABILITY: Poorly drained; slow runoff; moderate permeability. Depth to the surface of a perched water table is 2 to 4 feet. The frequency of flooding is rare and the duration of flooding is more than one month.

USE AND VEGETATION: This soil is used for irrigated barley and cotton.

DISTRIBUTION AND EXTENT: San Joaquin Valley, California. The series is of small extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

National Cooperative Soil Survey
U. S. A.

LOCATION HOUSER CA
Established Series
Rev. KDA-ARW-JJJ
09/1999

HOUSER SERIES

The Houser series consists of very deep, somewhat poorly drained soils that formed in mixed alluvium dominantly from granitic and sedimentary rocks. Houser soils occur on basin rims and have slopes of 0 to 1 percent. The mean annual temperature is about 65 degrees F. and the mean annual precipitation is about 6 inches.

TAXONOMIC CLASS: Fine, smectitic, calcareous, thermic Vertic Fluvaquents (Note: Being considered for reclassification: (Fine, smectitic, calcareous, thermic Vertic Halaquepts).

TYPICAL PEDON: Houser clay, on a nearly level slope of less than 1 percent under irrigated barley at 189 feet elevation. (Colors are for dry soil unless otherwise stated. When described on 5/13/76 the soil was moist below 9 inches.)

Ap--0 to 9 inches; light olive gray (5Y 6/2) light clay, olive gray (5Y 4/2) moist; moderately coarse subangular blocky structure; extremely hard, firm, sticky and plastic; common very fine roots; few very fine interstitial and tubular pores; slightly effervescent, disseminated carbonates; electrical conductivity 3.5 decisiemens per meter; sodium adsorption ratio 8; moderately alkaline (pH 8.2); abrupt smooth boundary. (7 to 10 inches thick)

Bgnyz1--9 to 20 inches; gray (5Y 6/1) clay, variegated very dark olive gray (5Y 3/2) and olive (5Y 4/3) moist; moderate coarse subangular blocky structure; extremely hard, firm, sticky and plastic; common very fine roots; few very fine interstitial and tubular pores; common fine prominent yellowish brown (10YR 5/4) redoximorphic masses of iron accumulation, yellowish brown (10YR 5/6) moist; few fine black (N 2/0) redoximorphic manganese concretions; slightly effervescent, disseminated carbonates; common scattered gypsum crystals; electrical conductivity 14 decisiemens per meter; sodium adsorption ratio 31; moderately alkaline (pH 8.0); abrupt wavy boundary. (9 to 14 inches thick)

Bgnyz2--20 to 23 inches; light olive gray (5Y 6/2) silt loam, olive (5Y 5/3) moist; massive; very hard, firm, slightly sticky and slightly plastic; few very fine roots; few very fine tubular pores; common fine prominent yellowish brown (10YR 5/6) redoximorphic masses of iron accumulation, dark brown (7.5YR 4/4) moist; common scattered gypsum crystals; electrical conductivity 19 decisiemens per meter; sodium adsorption ratio 50; moderately alkaline (pH 8.0); abrupt wavy boundary. (3 to 5 inches thick)

Bgnyz3--23 to 31 inches; gray (5Y 6/1) clay, olive gray (5Y 4/2) moist; massive; extremely hard, firm, sticky and plastic; few very fine roots; few very fine tubular pores; many medium prominent yellowish brown (10YR 5/4) redoximorphic masses of iron accumulation, yellowish brown (10YR 5/6) moist; common scattered gypsum crystals; electrical conductivity 28 decisiemens per meter; sodium adsorption ratio 52; moderately alkaline (pH 8.0); abrupt smooth boundary. (7 to 10 inches thick)

Bgnyz4--31 to 60 inches; olive gray (5Y 5/2) clay, olive gray (5Y 4/2) moist; massive; extremely hard, firm, sticky and very plastic; few very fine roots; few very fine tubular pores; common scattered gypsum crystals; electrical conductivity 30 decisiemens per meter; sodium adsorption ratio 51; many medium prominent dark brown (7.5YR 4/4) iron concentrations, yellowish red (5YR 4/6) moist; moderately alkaline (pH 8.2).

TYPE LOCATION: Kings County, California; 150 feet north of Blakeley Canal; 150 feet west and 825 feet south of the northeast corner of section 7, T. 23 S., R. 20 E., MDB&M; Latitude 35 degrees, 56 minutes, 47 seconds north and Longitude 119 degrees, 50 minutes, 35 seconds west; USGS Dudley Ridge Quadrangle.

RANGE IN CHARACTERISTICS: The soil is more than 60 inches deep and is stratified. Vertical cracks extend from the surface and range from 1/2 to 1 inches wide at a depth of 20 inches at some time in most years. A few slickensides are present in most pedons but they do not intersect, or wedge-shaped aggregates are present. The organic matter is 1 percent or less at the surface and decreased irregularly with increasing depth. It is typically saline-sodic below the A horizon. Salinity ranges from 1 to 16 decisiemens per meter in the surface and 4 to 30 decisiemens per meter in the lower part of the profile. The soil ranges from slightly effervescent to violently effervescent with carbonates throughout to a depth of 20 inches. The substratum below a depth of 20 inches ranges from noneffervescent to violently effervescent. Gypsum crystals may absent in some pedons and are a result of additions of gypsum to the soil by farmers. The mean annual soil temperature is 64 to 67 degrees F. Distinct or prominent redoximorphic iron and manganese accumulations or depletions occur in the lower part of the A horizon and in the B horizon.

The A horizon has dry color of 5Y 7/1, 6/1 or 6/2, and 2.5Y 6/2, and moist color of 5Y 3/2, 4/2, 5/2 or 4/3, and 2.5Y 4/2. It commonly is clay or silty clay but may have thin (3 to 6 inches) surface layers of fine sandy loam. This horizon is moderately alkaline to strongly alkaline.

The B horizon has dry color of 5Y 5/1, 6/1, 7/1, 5/2, 6/2; 10YR 7/3; or 2.5Y 6/2 and 7/2, and moist color of 5Y 4/1, 4/2, 5/2, 5/3, 4/3; 2.5Y 4/2 and 5/2; or 10YR 5/4. It is clay or silty clay and has thin strata of silt loam or silty clay loam. This horizon is moderately alkaline to very strongly alkaline.

COMPETING SERIES: There are no other soils in this family.

GEOGRAPHIC SETTING: Houser soils occur on basin rims. Slopes are 0 to 1 percent. The soils formed in mixed alluvium dominantly from granitic and sedimentary rocks. Elevations are 180 to 220 feet. The mean annual precipitation is 6 to 7 inches. The climate is arid with cool moist winters and warm dry summers. The mean January temperature is about 47 degrees F.; mean July temperature is about 85 degrees F.; mean annual temperature is 62 to 65 degrees F. Frost-free season is 260 to 275 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Lethent and Rambla soils. Lethent soils have a natric horizon. Rambla soils have a contrasting particle-size control section of sandy over clayey and lack cracks in the surface.

DRAINAGE AND PERMEABILITY: Somewhat poorly drained; medium runoff; very slow permeability. Most areas of this soil are now partially drained or drained due to dams and drainage ditches in the area. The previous water table was at 1 to 2 feet. A water table now varies with depth depending on the amount and kind of reclamation. The frequency of flooding is none to rare and the duration of flooding is more than one month.

USE AND VEGETATION: Irrigated cropland, mainly cotton and barley. Some areas are used for building site development.

DISTRIBUTION AND EXTENT: San Joaquin Valley. The series is of small extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

LOCATION RAMBLA CA
Established Series
Rev. KDA/CHA/TDC/ET
03/2003

RAMBLA SERIES

The Rambla series consists of deep, moderately well drained soils that formed in alluvium from igneous and sedimentary rocks. Rambla soils occur on basin rims and have slopes of 0 to 2 percent. The mean annual temperature is about 65 degrees F., and the average annual precipitation is about 6 inches.

TAXONOMIC CLASS: Sandy over clayey, mixed, superactive, calcareous, thermic Typic Fluvaquents

TYPICAL PEDON: Rambla loamy sand, on a slope of less than 1 percent under irrigated barley at 197 feet elevation. (Colors are for dry soil unless otherwise stated. When described on 5/24/76 the soil was moist below 15 inches.)

Ap1--0 to 5 inches; gray (5Y 6/1) loamy sand, dark gray (5Y 4/1) moist; single grained; loose; few fine and many very fine roots; many very fine interstitial pores; strongly effervescent, disseminated lime; moderately alkaline (pH 8.0); abrupt smooth boundary. (5 to 7 inches thick)

Ap2--5 to 15 inches; gray (5Y 6/1) loamy sand, dark gray (5Y 4/1) moist; single grained; loose; common very fine roots; many very fine interstitial pores; strongly effervescent, disseminated lime; moderately alkaline (pH 8.0); abrupt wavy boundary. (5 to 10 inches thick)

C1--15 to 19 inches; gray (5Y 6/1) loamy fine sand, dark gray (5Y 4/1) moist; massive; slightly hard, very friable; common very fine roots; common very fine interstitial pores; strongly effervescent, disseminated lime; moderately alkaline (pH 8.4); abrupt wavy boundary. (3 to 20 inches thick)

IIC2gca--19 to 27 inches; gray (5Y 6/1) clay, gray (5Y 5/1) moist; few fine prominent strong brown (7.5YR 4/6) mottles, dark brown (7.5YR 3/4) moist; massive; very hard, firm, very sticky and very plastic; common very fine roots; few fine and common very fine tubular pores; strongly effervescent, common medium segregated lime in irregularly shaped soft masses; moderately alkaline (pH 8.3); clear wavy boundary. (7 to 10 inches thick)

IIC3gca--27 to 35 inches; gray (5Y 6/1) clay, olive gray (5Y 5/2) moist, many fine prominent yellowish brown (10YR 5/4) mottles, dark yellowish brown (10YR 4/4) moist; massive; very hard, firm, very sticky and very plastic; common very fine roots; few very fine tubular pores; strongly effervescent, common medium segregated lime irregularly shaped soft masses; moderately alkaline (pH 8.2); a abrupt smooth boundary. (8 to 18 inches thick)

IIC4g--35 to 45 inches; variegated gray (5Y 6/1) and very pale brown (10YR 8/3) clay, olive gray (5Y 5/2) and very pale brown (10YR 7/3) moist; many fine prominent yellowish brown (10YR 5/6) mottles, dark yellowish brown (10YR 4/4) moist; massive; very hard, very firm, very sticky and very plastic; very fine tubular pores; strongly effervescent, disseminated lime; moderately alkaline (pH 8.2); abrupt smooth boundary. (8 to 10 inches thick)

IIIC5g--45 to 60 inches; light gray (5Y 7/1) loamy sand, olive gray (5Y 5/2) moist; massive; loose, many very fine interstitial pores; slightly effervescent, disseminated lime; moderately alkaline (pH 8.2).

TYPE LOCATION: Kings County, California; 100 feet south of Utica Avenue; 1,370 feet west and 100 feet south of the NE corner of sec. 17, T.23S. R.20E., MDB&M.

RANGE IN CHARACTERISTICS: The soil is more than 60 inches deep and is strongly stratified. The organic matter is less than 1 percent at the surface and decreases irregularly with increasing depth. The soil is typically nonsaline-nonalkali at the surface and saline-alkali below a depth of 19 inches. The soil is slightly effervescent to strongly effervescent. The lime is disseminated in soft masses. Mean annual soil temperature is 64 degrees to 67 degrees F. This soil would have an aquic moisture regime but is now artificially drained. Depth to the IIC horizon is 19 to 36 inches.

The A horizon has dry color of 10YR 4/3, 5/3, 5/2; or 2.5Y 6/4 and moist color of 10YR 3/3, 4/3, 4/2; or 2.5Y 4/4. In some pedons the surface horizon has value of 3 moist, but it is less than 2 inches thick. The A horizon has strong fine or medium granular, strong coarse or very coarse prismatic, or moderate or strong medium or coarse subangular blocky structure. It is neutral to moderately alkaline.

The C horizon has dry color of 5Y 6/1 or 7/1; 10YR 7/2 or 8/3 and moist color of 5Y 4/1, 5/1, 5/2; 10YR 6/2 or 7/3. There are few to many fine or medium, distinct or prominent mottles that have color of 7.5YR 3/4, 4/4; or 10YR 4/4. This horizon is moderately alkaline or strongly alkaline.

The C1 horizon is loamy sand or sandy loam and averages 2 to 10 percent clay. In the upper part of the C horizon moist chroma is 1 or less and if there are mottles the moist chroma is 1 or 2.

COMPETING SERIES: These are the Camarillo, Columbia, Hueneme, and Laugenour series in other families. All of these soils lack a contrasting particle-size control section. Camarillo soils have less than 40 percent clay throughout the profile. Columbia, Hueneme, and Laugenour soils have a coarse-loamy particle-size control.

GEOGRAPHIC SETTING: Rambla soils occur on basin rims. Slopes are 0 to 2 percent. The soils formed in alluvium from igneous and sedimentary rocks. Elevations are 190 to 235 feet. The climate is arid with hot dry summers and cool moist winters. The average annual precipitation is 6 to 7 inches. The mean January temperature is about 47 degrees F. and the mean July temperature is about 85 degrees F. The mean annual temperature is about 65 degrees F. The frost-free season is 260 to 275 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Homeland, Houser Milham, Panoche, Tulare, Twisselman, and Wasco soils. Homeland soils lack a contrasting particle-size control section. Milham soils have an argillic horizon. Panoche soils have a fine-loamy particle-size control section. Tulare soils have a mollic epipedon. Houser and Twisselman soils have a fine particle-size control section. Wasco soils have a coarse-loamy particle-size control section.

DRAINAGE AND PERMEABILITY: Moderately well drained; slow runoff; moderately rapid permeability in the upper 19 inches and very slow in the underlying material. The soil is artificially drained and the water table is at a depth of more than 6 feet.

USE AND VEGETATION: This soil is used for irrigated barley and cotton.

DISTRIBUTION AND EXTENT: San Joaquin Valley. The series is of small extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

REMARKS: The activity class was added to the classification in February of 2003. Competing series were not checked at that time. - ET

LOCATION SANDRIDGE CA
Established Series
Rev. BLH/CHA/KKC/TDC
2/80

SANDRIDGE SERIES

The Sandridge series consists of deep, somewhat excessively drained soils that formed in wind-blown deposits derived dominantly from lake beach sediments composed of acid igneous and sedimentary rock. Sandridge soils are on basin rims and have slopes of 0 to 3 percent. The average annual precipitation is 6 inches, and the mean annual temperature is 65 degrees F.

TAXONOMIC CLASS: Siliceous, thermic Typic Torripsamments

TYPICAL PEDON: Sandridge loamy fine sand, on a smooth slope of 1 percent under red brome and saltgrass at 212 feet elevation. (Colors are for dry soil unless otherwise stated. When described on 5/25/79 the soil was slightly moist below 2 feet but the moisture was estimated to be held at a tension of greater than 15 bars.)

A11--0 to 1 inch; grayish brown (2.5Y 5/2) loamy fine sand, very dark grayish brown (2.5Y 3/2) moist; weak medium platy structure; soft, very friable; many very fine roots; many very fine interstitial pores; slightly effervescent (1 percent calcium carbonate) broken shell fragments less than 0.5mm; EC 0.6mmhos; SAR 1; slightly acid (pH 6.4); abrupt smooth boundary. (1 to 2 inches thick)

A12--1 to 24 inches; light gray (2.5Y 7/2) loamy fine sand, dark grayish brown (2.5 4/2) moist; single grained; loose; many very fine roots; many very fine interstitial pores; strongly effervescent (2 percent calcium carbonate) broken shell fragments less than 0.5mm; disseminated lime; EC 0.25mmhos; SAR 4; mildly alkaline (pH 7.4); abrupt smooth boundary. (12 to 30 inches thick)

C--24 to 60 inches; light gray (5Y 7/1) loamy fine sand, olive gray (5Y 5/2) moist; massive; soft, very friable, few very fine roots; many very fine interstitial pores; strongly effervescent (3 percent calcium carbonate) broken shell fragments less than 0.5mm; disseminated lime; EC 0.6mmhos; SAR 29; very strongly alkaline (pH 9.5).

TYPE LOCATION: Kings County, California; about 7.2 miles south of Utica Avenue and 3.5 miles east of Interstate 5; about 100 feet south of a dirt road; 1,520 feet east and 1,720 feet south of the northwest corner of sec. 19, T.24S., R.21E, MDB&M.

RANGE IN CHARACTERISTICS: The mean annual soil temperature ranges from 66 degrees to 67 degrees F. and the soil temperature is always above 47 degrees F. The soil is typically loamy fine sand but may be loamy sand or sand. The soil between depths of 12 and 35 inches is dry in all parts from March through December 1 and is not moist in some or all parts for as long as 75 consecutive days. The soil is more than 60 inches deep. Organic matter is less than 0.5

percent. The soil is effervescent throughout, with calcium carbonate ranging from 1 to 5 percent. The soil is effervescent throughout, with calcium carbonate ranging from 1 to 5 percent. There are a few shell fragments throughout the soil profile. The A horizon has dry color of 2.5Y 5/2, 7/2 or 7/1 and moist color of 2.5Y 3/2, 4/2 or 5/2. It is slightly acid to strongly alkaline.

The C horizon has dry color of 5Y 7/1 or 2.5YR 7/1 and moist color of 5Y 5/2 or 2.5Y 5/2. SAR ranges from 13 to 60. This horizon is moderately alkaline to very strongly alkaline.

COMPETING SERIES: These are the Kermit series in the same family and the Cajon series. Kermit soils are noneffervescent throughout and are moist in the control section during the summer. Cajon soils have mixed mineralogy.

GEOGRAPHIC SETTING: Sandridge soils occur on basin rims. Slopes are 0 to 3 percent. The slopes formed in wind-blown deposits derived dominantly from lake beach sediments composed of acid igneous and sedimentary rock. Elevations are 195 to 220 feet. The climate is arid and has hot, dry summers and mild, somewhat moist winters. The average annual precipitation is 6 inches. Mean January temperature is 47 degrees F.; mean July temperature is 85 degrees F.; mean annual temperature is 65 degrees F. Frost-free season is 255 to 270 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Boggs, Rambla and Westcamp soils. Boggs soils have a salic horizon and coarse-loamy particle-size control section. Rambla soils have a sandy over clayey particle-size control section and an aquic soil moisture. Westcamp soils have an aquic soil moisture regime and a fine-silty particle-size control section.

DRAINAGE AND PERMEABILITY: Somewhat excessively drained; very slow runoff; moderately rapid permeability.

USE AND VEGETATION: This soil is used for irrigated cropland such as cotton, barley, alfalfa or grapes, and used as wildlife land. Natural vegetation is grasses and forbs.

DISTRIBUTION AND EXTENT: San Joaquin Valley, California. The series is of small extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

REMARKS: The mineralogy family was determined by microscope and enlarged close-up photography.

National Cooperative Soil Survey
U. S. A.

LOCATION TULARE CA
Established Series
Rev. MAM/CHA/TDC
05/2001

TULARE SERIES

The Tulare series consists of deep, somewhat poorly drained soil that formed in alluvium from igneous and sedimentary rock. Tulare soils are in basins and have slopes of 0 to 1 percent. The average annual precipitation is about 7 inches and the mean annual temperature is about 64 degrees F.

TAXONOMIC CLASS: Fine, smectitic, calcareous, thermic Fluvaquentic Vertic Endoaquolls

TYPICAL PEDON: Tulare clay, on slopes of less than 1 percent under barley at 180 feet elevation. (Colors are for dry soil unless otherwise stated. When described on 7/2/58 the soil was moist below 6 inches and had a water table at 72 inches.)

Ap1--0 to 0.25 inch; gray (10YR 5/1) clay, very dark gray (10YR 3/1) moist; strong fine granular structure; very hard, friable, sticky and plastic; many very fine tubular pores; violently effervescent (16 percent calcium carbonate, disseminated); moderately alkaline (pH 8.3); abrupt smooth boundary. (0.25 to 0.5 inch thick)

Ap2--0.25 to 16 inch; gray (10YR 5/1) clay, very dark gray (10YR 3/1) moist; common fine faint light brownish gray (10YR 6/2) mottles, grayish brown (10YR 5/2) moist; strong very coarse prismatic structure parting to strong, coarse subangular blocky; very hard, friable, sticky and plastic; many very fine and common fine roots; many very fine tubular pores; violently effervescent (18 percent calcium carbonate, disseminated); moderately alkaline (pH 8.3); abrupt smooth boundary. (14 to 25 inches thick)

C1--16 to 31 inches; light gray (5Y 7/2) clay, dark gray (N 4/0) moist; common fine distinct olive brown (2.5Y 4/4) dry and moist mottles; strong very coarse prismatic structure; hard, friable, sticky and plastic; common pressure faces; common very fine roots; common very fine tubular pores; violently effervescent (19 percent calcium carbonate, disseminated); moderately alkaline (pH 8.3); abrupt smooth boundary. (10 to 15 inches thick)

C2ca--31 to 48 inches; light olive gray (5Y 6/2) clay, olive gray (5Y 5/2) moist; common fine distinct olive brown (2.5Y 4/4) dry and moist mottles; massive; hard, friable, sticky and plastic; common pressure faces; common very fine and few fine roots; common very fine tubular pores; violently effervescent (21 percent calcium carbonate, disseminated and as shell fragments); moderately alkaline (pH 8.0); abrupt smooth boundary. (15 to 18 inches thick)

C3--48 to 60 inches; grayish brown (2.5Y 5/2) clay, very dark grayish brown (2.5Y 3/2) moist; massive; hard, friable, sticky and plastic; pressure faces; few very fine tubular pores; violently effervescent (15 percent calcium carbonate, disseminated and as shell fragments); moderately alkaline (pH 8.0).

TYPE LOCATION: Kings County, California; about five miles southwest of Corcoran; approximately 1/2 mile west of 10th Avenue and 100 feet north of Redding Avenue in sec. 12, T.22S., R. 21E., MDB&M.

RANGE IN CHARACTERISTICS: The soil is 60 inches or more deep. The mean annual soil temperature is 60 degrees to 63 degrees F. The soil is saturated in a reduced state at some time of the year. The A horizon or mollic epipedon is 14 to 25 inches thick. Organic matter is 2 to 3 percent in the surface horizon and decreases irregularly with increasing depth. Calcium carbonate is 15 to 25 percent throughout the profile and is dominantly disseminated although thin layers of decomposed shell fragments occur at random depths. When the soil is dry in late summer, vertical cracks extend from the surface to a depth of 25 to 50 inches and are 2 to 5 inches wide. Pressure faces occur at a depth of 25 to 40 inches. There are no intersecting slickensides.

The A horizon has dry color of 10YR 4/1, 5/1; 5Y 4/1 or 5/1 and moist color of 10YR 3/1, 3/2; or 5Y 3/1. It has mottles in the lower part that have color of 10YR 3/1, 5/2; 5YR 4/2 or 4/3. This horizon is dominantly clay and less commonly silty clay.

The C horizon has dry color of 2.5Y 5/2; 5Y 5/1, 5/3, 6/1, 6/2, 7/1 or 7/2 and moist color of 2.5Y 3/2, 4/2; 5Y 4/1, 4/2, 4/3, 5/2, 5/3 or N 4/0. It has mottles that have color of 2.5Y 4/4; 5Y 2.5/2, 4/2 or 4/3. This horizon is dominantly clay or silty clay and averages 40 to 60 percent clay.

COMPETING SERIES: These are the Dospalos, Gepford and Tinn series in the same family and the Iberia, Omni, and Zaca series. Dospalos and Gepford soils have less than 15 percent calcium carbonate. Tinn soils have mean annual soil temperatures of 66 degrees to 71 degrees F. and have and A horizon 25 to 70 inches thick. Iberia soils have mean soil temperature warmer than 66 degrees F., are not calcareous, and have a B2g horizon. Omni soils have a B2g horizon and do not have cracks that are 1 cm. or more wide at a depth of 50 cm., that are at least 30 cm. long, and that extend upward to the surface. Zaca soils are well drained and have a xeric moisture regime.

GEOGRAPHIC SETTING: Tulare soils are in concave basins. Slopes are 0 to 1 percent. The soils formed in alluvium from igneous and sedimentary rocks. Elevations are 175 to 195 feet. The climate is semiarid and has hot dry summers and cool moist winters. Average annual precipitation is 6 to 7 inches. Mean January temperature is about 45 degrees F.; mean July temperature is about 82 degrees F.; mean annual temperature is 64 degrees F. Frost-free season is 250 to 275 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Grangeville, Houser, Lethent, and Pitco soils. Grangeville soils have a coarse-loamy particle-size control section. Houser soils lack a mollic epipedon. Lethent soils have a natric horizon and have an ochric epipedon. Pitco soils are noneffervescent.

DRAINAGE AND PERMEABILITY: Somewhat poorly drained; very slow runoff or ponded; very slow permeability. The soils are occasionally flooded for very long periods between January and March. A perched water table occurs at a depth of 48 to 72 inches from January through March. The soil is wet from the first part of December to the end of March. The soil remains moist below 6 inches from April through November.

USE AND VEGETATION: Used primarily for irrigated crops such as alfalfa, barley, cotton, safflower, sorghum, sugar beets, and wheat.

DISTRIBUTION AND EXTENT: San Joaquin Valley. The series is extensive.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Reconniassance Soil Survey of the Upper San Joaquin Valley, California, 1917.

REMARKS: Portions of the Reconnaissance Soil Survey of the Upper San Joaquin Valley (1917) where Tulare clay was previously mapped and established are in Kings County and those areas are now mapped as Tulare. This is a classification change from Typic Haplaquents to Vertic Haplaquolls.

LOCATION WESTCAMP CA
Established Series
Rev. KDA/ARW/CAF
10/1999

WESTCAMP SERIES

The Westcamp series consists of very deep, somewhat poorly drained soils that formed in mixed alluvium weathered from sedimentary and/or igneous rocks. Westcamp soils are on basin rims and flood plains and have slopes of 0 to 2 percent. The mean annual precipitation is 6 inches and the mean annual temperature is 64 degrees F.

TAXONOMIC CLASS: Fine-silty, mixed, superactive, calcareous, thermic Fluvaquentic Endoaquepts

TYPICAL PEDON: Westcamp loam, on an east facing slope of 1 percent under irrigated safflower at 197 feet elevation. (Colors are for dry soil unless otherwise stated. When described 3/22/73 the soil was moist from 0 to 26 inches and was saturated below.)

Ap--0 to 7 inches; light brownish gray (2.5Y 6/2) loam, dark grayish brown (2.5Y 4/2) moist; massive; slightly hard, very friable, slightly sticky and slightly plastic; common very fine and fine roots. Many very fine interstitial pores; strongly effervescent (2 percent calcium carbonate equivalent) carbonates disseminated; electrical conductivity 3.0 decisiemens per meter; sodium adsorption ratio 4; slightly alkaline (pH 7.4); abrupt smooth boundary. (4 to 10 inches thick)

A--7 to 10 inches; light brownish gray (2.5Y 6/2) silt loam, dark grayish brown (2.5Y 4/2) moist; massive; slightly hard, friable, sticky and slightly plastic; many very fine and common fine roots; few very fine tubular and many very fine interstitial pores; strongly effervescent (3 percent calcium carbonate equivalent) carbonates disseminated; electrical conductivity 2.7 decisiemens per meter; sodium adsorption ratio 8; moderately alkaline (pH 7.9); abrupt smooth boundary. (0 to 8 inches thick)

Bg--10 to 14 inches; light brownish gray (2.5Y 6/2) silt loam, dark grayish brown (2.5Y 4/2) moist; massive; slightly hard, very friable; sticky and slightly plastic; many very fine and few fine roots; few very fine tubular and many very fine interstitial pores; strongly effervescent (2 percent calcium carbonate equivalent), carbonates disseminated; electrical conductivity 3.8 decisiemens per meter; sodium adsorption ratio 11; common fine distinct light gray (5Y 7/1) and few fine distinct yellow (10YR 7/6) iron depletions, gray (5Y 5/1) and yellowish brown (10YR 5/6) moist; moderately alkaline (pH 8.2); abrupt smooth boundary. (0 to 5 inches thick)

Bng--14 to 20 inches; pale yellow (2.5Y 7/4) silt loam, olive brown (2.5Y 4/4) moist; massive; slightly hard, very friable, slightly sticky and nonplastic; few very fine and fine roots; common very fine tubular and many very fine interstitial pores; slightly effervescent (2 percent calcium carbonate equivalent), carbonates disseminated; electrical conductivity 3.1 decisiemens per meter; sodium adsorption ratio 32; many medium distinct light gray (5Y 7/1) iron depletions, dark gray (5Y 4/1) moist; strongly alkaline (pH 8.8); abrupt smooth boundary. (0 to 7 inches thick)

Bkng--20 to 26 inches; variegated light gray (2.5Y 7/2) and light gray (5Y 7/1) silty clay loam, with many thin strata of silt loam, dark grayish brown (2.5Y 4/2) and olive gray (5Y 5/2) moist; massive; hard, firm, very sticky and very plastic; few very fine roots; many very fine tubular and common very fine interstitial pores; violently effervescent (14 percent calcium carbonate equivalent), carbonates disseminated and segregated as common fine soft masses; electrical conductivity 4.7 decisiemens per meter; sodium adsorption ratio 52; many medium distinct yellow (10YR 7/6) iron depletions, yellowish brown (10YR 5/4) moist; strongly alkaline (pH 8.8); abrupt smooth boundary. (4 to 30 inches thick)

Bzng--26 to 37 inches; very pale brown (10YR 7/3) silt loam, brown (10YR 4/3) moist; massive; slightly hard, very friable, slightly sticky and nonplastic; few very fine roots; many very fine tubular and interstitial pores; slightly effervescent (2 percent calcium carbonate equivalent), carbonates disseminated; electrical conductivity 27 decisiemens per meter; sodium adsorption ratio 99; many fine distinct light gray (5Y 7/1) iron depletions, dark gray (5Y 4/1) moist; moderately alkaline (pH 8.2); abrupt smooth boundary. (0 to 15 inches thick)

2Bkzng--37 to 58 inches; variegated light gray (2.5Y 7/2), white (5Y 8/1), and pale yellow (2.5Y 7/4) silty clay; grayish brown (2.5Y 5/2), gray (5Y 5/1), and light yellowish brown (2.5Y 6/4) moist; massive; extremely hard, firm, very sticky and very plastic; violently effervescent (4 percent calcium carbonate equivalent), carbonates disseminated and segregated in common medium soft masses; electrical conductivity 19 decisiemens per meter; sodium adsorption ratio 77, strongly alkaline (pH 8.5); abrupt smooth boundary. (0 to 21 inches thick)

3Bznyg--58 to 72 inches; light gray (5Y 7/1) clay, bluish gray (5B 5/1) moist which quickly oxidizes to gray (N 6/) moist when exposed to air, dark yellowish brown (10YR 4/4) moist; massive, extremely hard, very firm, very sticky and very plastic; slightly effervescent (2 percent calcium carbonate equivalent), carbonates segregated as few fine soft masses; common fine crystalline gypsum; electrical conductivity 22 decisiemens per meter; sodium adsorption ratio 91; few fine prominent brownish yellow (10YR 6/6) iron depletions; moderately alkaline (pH 7.9).

TYPE LOCATION: Kings County, California; about 100 feet north of Quail Avenue and 0.2 mile west of Hwy 41; about 1,650 feet east and 100 feet north of the southwest corner of section 6, T. 22 S., R. 19 E, MDB&M; Latitude 36 degrees, 02 minutes, 12 seconds north and Longitude 119 degrees, 57 minutes, 42 seconds west; USGS Kettleman City Quadrangle.

RANGE IN CHARACTERISTICS: The soil is more than 60 inches deep and is very stratified. Organic matter is less than 1 percent at the surface and decreases irregularly with increasing depth. Electrical conductivity is 2 to 16 decisiemens per meter throughout the profile. Sodium adsorption ratio is 2 to 100 usually increasing with depth. The electrical conductivity, sodium adsorption ratio and profile reaction are highly variable due to the soil amendments added to the soil by farmers, such as gypsum, which effect these values, as well as the addition of large amounts of irrigation water. The mean annual soil temperature ranges from 64 degrees to 67 degrees F.

The A horizon has dry color of 2.5Y 5/2, 6/2, 7/2; or 5Y 6/2 and moist color of 2.5Y 3/2, 4/2, 5/2; 5Y 4/1, or 4/2. It is clay loam, loam or silt loam. It is slightly alkaline to very strongly alkaline. It is slightly effervescent to violently effervescent. Calcium carbonate equivalent ranges from 1 to 3 percent.

The B horizon has dry color of 10YR 6/2 or 7/3; 2.5Y 4/2, 5/2, 5/4, 6/2, 7/2, 7/4, N 4/0, 8/0, 8/2; 5Y 4/1, 6/2, 8/1, 8/2, 7/1 or 8/1, and moist color of 10YR 4/3; 2.5Y 3/2, 4/2, 4/4, 5/2, 6/2, 6/4, 7/2; 5Y 3/1, 3/2, 4/1, 4/2, 4/3, 5/1, 5/2; 5GY 5/1; N 3/0, 6/0; or 5B 5/1. Iron depletions and accumulations have moist color of 5YR 3/4, 4/4; 7.5YR 4/4, 5/8; 10YR 3/3, 4/4, 5/4, 5/8, 2.5Y 6/4, 7/2, 7/6; 5Y 3/1, 4/1, 5/1; or N 3/0, 5/0; 5GY 5/1. More than 40 percent of moist matrix colors at depths of 10 to 30 inches have chroma of 3 or more when iron depletions occur in the substratum. When there are no iron depletions the matrix chroma is 2 or 3. It ranges from fine sandy loam to silty clay and the particle-size control section is 18 to 35 percent clay and less than 15 percent fine sand or coarser. This horizon is moderately alkaline to very strongly alkaline. Calcium carbonate equivalent ranges from 1 to 14 percent. Carbonates are disseminated and segregated in soft masses, nodules, and filaments. Gypsum is present in some pedons.

COMPETING SERIES: These are no other series in this family.

GEOGRAPHIC SETTING: Westcamp soils are on basin rims and flood plains at elevations of 190 to 220 feet. Slopes are 0 to 2 percent. The soils formed in mixed alluvium weathered from sedimentary and/or igneous rocks. The climate is arid and has hot, dry summers and mild, somewhat moist winters. The mean annual precipitation is 6 to 7 inches. The mean January temperature is 47 degrees F., and the mean July temperature is 85 degrees F.; the mean annual temperature is 62 to 65 degrees F. The frost-free season is 260 to 275 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Armona, Boggs, Houser, Kimberlina, Tulare, Wasco, and Westhaven series. Armona and Tulare soils have a mollic epipedon. Boggs soils have a salic horizon. Houser soils have a fine particle-size control section. Kimberlina and Wasco soils have a coarse-loamy particle-size control section. Westhaven soils have a torric moisture regime and are not artificially drained.

DRAINAGE AND PERMEABILITY: Somewhat poorly drained; medium or high runoff; very slow permeability. Most areas of this soil are now artificially drained because of dams and drainage ditches in the area. The previous water table was at a depth of 1 to 2 feet. A water table now occurs at a depth of 4 to 6 feet. The frequency of flooding is none to rare and the duration of flooding is more than one month.

USE AND VEGETATION: This soil is used for irrigated cropland to produce barley, cotton and safflower. It is also used for livestock grazing and building site development.

DISTRIBUTION AND EXTENT: San Joaquin Valley. The series is moderately extensive. MLRA 17.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Davis, California

SERIES ESTABLISHED: Kings County, California, 1980.

REMARKS: Diagnostic Horizons and Features Recognized in this Pedon are:

1.0 Ochric epipedon: The zone from the soil surface to a depth of 10 inches (Ap and A horizons).

2.0 Calcic horizon: The zone from a depth of 20 to 26 inches (Bkng horizon).

References: Five papers on Tulare Lake sediments:

1. The 1986 Atwater paper was the first modern look at the Tulare Lake sediments (15 pages)
Atwater, B.F., Adam, D.P., Bradbury, J.P., Forester, R.M., Mark, R.K., Lettis, W.R., Fischer, G.R., Gobalet, K.W., Robinson, S.W., 1986. A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada. Geol. Soc. Am. Bull. 97, 97–109.

2. In 1999, Owen Kent Davis at the University of Arizona provided a record of late Quaternary climate for the Tulare Lake region based on the palynology (pollen study) of a depocenter core. Davis's study found that the vegetation of the southern San Joaquin Valley used to resemble that of the contemporary Great Basin, including abundant greasewood. He also found that giant sequoia was widespread along the Sierra Nevada streams draining into Tulare Lake prior to 9,000 year B.P. The end of Great Basin plant assemblages 7,000 B.P. coincided with increased charcoal (i.e., fire frequency in the woodland and grasslands). Davis's study also included conclusions regarding relative lake levels throughout the Holocene (9 pages)
Davis, O.K., 1999. Pollen analysis of Tulare Lake, California: great basinlike vegetation in central California during the full-glacial and early Holocene. Review of Palaeobotany and Playnology 107, 249–257.

3. In 2006, Rob Negrini and his associates at CSU Bakersfield built on Davis's results with improved constraints on elevations and ages of past lake levels from trench sites at higher elevations in the Tulare Lakebed (20 pages)
Negrini, R.M., Wigand, P.E., Draucker, S., Gobalet, K., Gardner, J.K., Sutton, M.Q., Yohe, R.M., 2006. The Rambla highstand shoreline and the Holocene lake-level history of Tulare Lake, California, USA. Quaternary Science Reviews 25, 1599-1618.

4. The 2012 Kirby paper shows that the Tulare Lake record also reflects long-term precipitation in Southern California (9 pages)
Kirby, M.E., Zimmerman, S.R.H.,Patterson, W.P., Rivera, J.J., 2012. A 9170-year record of decadal-to-multi-centennial scale pluvial episodes from the coastal Southwest United States: a role for atmospheric rivers? Quaternary Science Reviews 46, 57-65.

5. 2015 Blunt and Negrini Paper titled: Lake Levels for the past 19,000 years from the TL05-4 cores, Tulare Lake, California, USA: Geophysical and geochemical proxies. Ashleigh B. Blunt, Robert M. Negrini (9 pages)
Blunt, A.B., Negrini, R.M., Lake levels for the past 19,000 years from the TL05-4 cores, Tulare Lake, California, USA: Geophysical and geochemical proxies, Quaternary International (2015), http://dx.doi.org/10.1016/j.quaint.2015.07.001.

6. **Preston, W.L. 1981.Vanishing Landscapes: Land and Life in the Tulare Lake Basin. University of California Press, Berkeley, CA.**

A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada

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ABSTRACT

Historic fluctuations and late Quaternary deposits of Tulare Lake, in the southern San Joaquin Valley, indicate that maximum lake size has depended chiefly on the height of a frequently overtopped spillway. This dependence gives Tulare Lake a double record of paleoclimate. Climate in the Tulare Lake region has influenced the degree to which the lake fills its basin during dry seasons and dry years: during the past 100,000–130,000 yr, incidence of desiccation of Tulare Lake (inferred from stiffness, mud cracks, and other hand-specimen properties) has been broadly consistent with the lake's salinity and depth (inferred from diatoms and ostracodes) and with regional vegetation (inferred from pollen). Climate, however, also appears to control basin capacity itself: Tulare Lake becomes large as a consequence of glacial-outwash aggradation of its alluvial-fan dam.

Late Wisconsin enlargement of Tulare Lake probably resulted from the last major glaciation of the Sierra Nevada. The lake's spillway coincides with the axis of the glacial-outwash fan of a major Sierra Nevada stream; moreover, sediment deposited in the transgressive lake resembles glacial rock flour from the Sierra Nevada. Differential tectonic subsidence and deposition by a Coast Range creek facilitated the building of Tulare Lake's fan dam during the late Wisconsin but were less important than deposition of Sierra Nevada outwash. Four stratigraphically consistent ^{14}C dates on peat and wood give an age of 26,000 yr B.P. for the start of Tulare Lake's late Wisconsin transgression. The last major Sierra Nevada glaciation (Tioga glaciation) thus may have begun about 26,000 yr B.P., provided that vigorous glacial-outwash deposition began early in the glaciation. Onset of the Tioga glaciation about 26,000 yr B.P. is consistent with new stratigraphic and radiocarbon data from the northeastern San Joaquin Valley. These data suggest that the principal episode of glacial-outwash deposition of Wisconsin age began in the San Joaquin Valley after 32,000 yr B.P., rather than at least 40,000 yr B.P., as previously believed.

An earlier enlargement of Tulare Lake probably resulted from a fan dam produced by the penultimate major (Tahoe) glaciation of the Sierra Nevada. Average sedimentation rates inferred from depths to a 600,000-yr-old clay and from radiocarbon dates indicate that this earlier lake originated no later than 100,000 yr B.P. The Tahoe glaciation therefore is probably pre-Wisconsin.

INTRODUCTION

Little is known about the number and timing of Wisconsin glaciations of the Sierra Nevada. Exposed moraines probably record a small fraction of late Pleistocene glacial events (Bateman and Wahrhaftig, 1966, p. 162; Gibbons and others, 1984). Radiometric dates pertaining to these moraines indicate nothing more specific than a Wisconsin age (about 10,000–75,000 yr B.P.) for the last major glaciation and an early Wisconsin or pre-Wisconsin age for the penultimate major glaciation (Burke and Birkeland, 1979; Gillespie, 1982). Lakes near the Sierra Nevada offer climatic records with better continuity and age control than in the mountains themselves, but few of these records have direct ties to Sierran glacial events.

Tulare Lake, west of the Sierra Nevada in the southern San Joaquin Valley (Fig. 1), offers a moderately continuous and datable climatic record that appears to have a relatively direct linkage to Sierra Nevada glaciation. This linkage follows from 4 aspects of the history that we infer for Tulare Lake of the past 100,000–130,000 yr. (1) Tulare Lake has routinely overflowed a valley-floor divide that forms the lake's spillway. (2) Owning to this ease of overflow, spillway height has routinely limited the maximum size of Tulare Lake, so that major change in maximum lake size typically reflects major change in spillway height. (3) The main cause of spillway heightening has been glacial-outwash deposition on the alluvial fan of a Sierra Nevada stream. (4) This outwash-fan deposition was heavy during glacial advance, as well as during glacial retreat. Thus our central hypothesis, that a spillway-controlled increase in Tulare Lake's maximum size accompanied each major Wisconsin glaciation of the Sierra Nevada.

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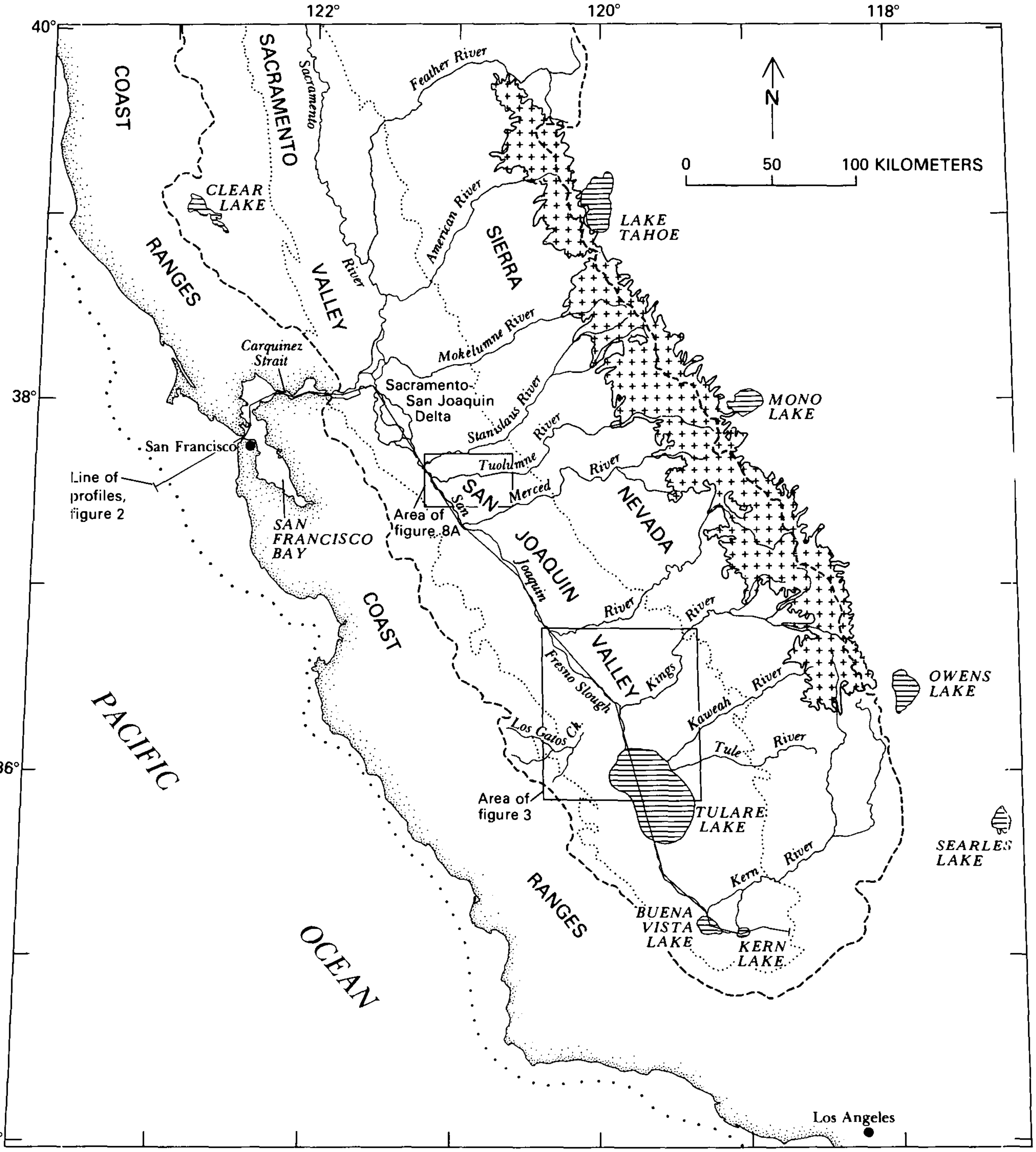
A folded insert accompanies this article. Figures 3, 4, 6, and 8 and Tables 3, 4, and 5 appear on it.

Geological Society of America Bulletin, v. 97, p. 97–109, 9 figs., 5 tables, January 1986.



EXPLANATION

- Maximum extent of glaciers during the Tahoe glaciation
- Boundary of area tributary to San Joaquin and Sacramento Valleys
- Edge of San Joaquin and Sacramento Valleys
- Outer margin of continental shelf
- Lake

Figure 1. San Joaquin Valley, Sierra Nevada, and vicinity. Ice limits for the Tahoe glaciation (the Tahoe stage of Blackwelder, 1931) generalized slightly from Wahrhaftig and Birman (1965, p. 305).

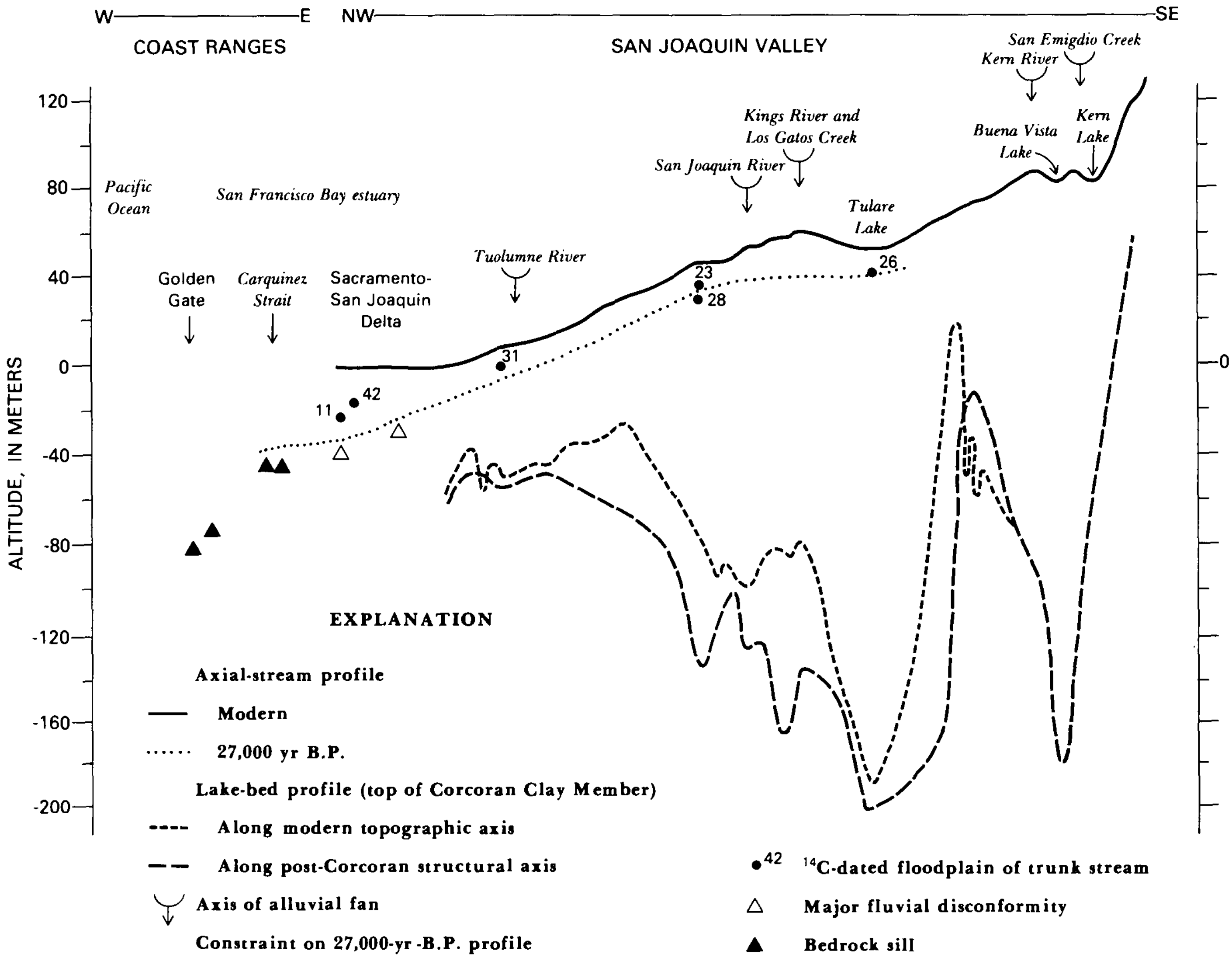


Figure 2. Present configuration of the profile of the axial stream of the San Joaquin Valley of historic times and of 27,000 yr B.P. and of the bed of a valley-floor lake of about 600,000 yr B.P. Historic profile (solid line) follows present topographic axis of valley; where this axis coincides with a trunk stream, profile represents the low-water surface of the stream as shown on U.S. Geological Survey topographic maps surveyed with 5-ft contour intervals 1910–1935. 27,000-yr-B.P. profile (dotted line) is fitted to bedrock sills, former thalwegs, and dated flood plains along present topographic axis; we presume that the trunk stream of 27,000 yr ago was graded to a sea level no higher than the present altitude of the sills at Carquinez Strait (Fig. 1). 600,000-yr-B.P. profiles (dashed lines) are defined by the top of the Corcoran Clay Member of the Turlock Lake and Tulare Formations (configuration from Davis and others, 1959, and Croft, 1972; age from Janda and Croft, 1967, p. 164; and Dalrymple, 1980); short dashes show profile beneath present topographic axis; long dashes show profile along synclinal axis projected to present topographic axis. Sources of data for 27,000-yr-B.P. profile: bedrock sills from Carlson and McCulloch (1970) and highway-bridge borings; thalwegs positioned at major fluvial disconformities at base of late Wisconsin(?) alluvial fill as inferred from highway-bridge and aqueduct borings; dated flood plains positioned mainly at tops of fining-upward fluvial sequences and dated with woody-plant fragments (Tables 3, 4; Atwater, 1982) from lower in the sequences.

THE HISTORIC LAKE

Historic Tulare Lake (now farmland) occupied a broad, shallow basin behind a valley-floor divide that coincides with the toes of the Kings River and Los Gatos Creek alluvial fans (Figs. 2, 3; Fig. 3 on folded insert). The basin coincides with a tectonic depression in which depths to a 600,000-yr-old clay suggest average subsidence rates as great as 0.4 m/1,000 yr (Figs. 2, 4; Fig. 4 on folded insert). Principal tributaries are Sierra Nevada streams (Kings, Kaweah, Tule, and Kern Rivers) that together account for ~95% of the runoff at the edge of the southern San Joaquin Valley (Table 1). At the historic overflow altitude of 64 m, the basin has an area of 1,600 km^2, a maximum depth of 10 m, and a capacity of 7 km^3. The climate is warm and dry

TABLE 1. ELEMENTS OF THE WATER BUDGET OF HISTORIC TULARE LAKE

Parameter	Minimum	Mean	Maximum	Period of record (water years)*	Typical seasonality	Reference
Runoff as measured at edge of San Joaquin Valley (km³/yr)						
Kings River (drainage basin 3,955 km²)	0.47	2.04	5.17	1896–1981	75% Apr.–July, peak May–June	U.S. Geological Survey (1951); Calif. Dept. of Water Resources Flood Forecasting Branch, unpub. compilation, 1982
Kern River (drainage basin 5,070 km²)	0.23	0.82	2.74	1894–1981	-do-	-do-
Kaweah River (drainage basin 1,451 km²)	0.11	0.52	1.56	1904–1981	70% Jan.–June	-do-
Tule River (drainage basin 922 km²)	0.02	0.17	0.62	1902–1981	-do-	-do-
All other principal tributaries to Tulare, Buena Vista, and Kern Lakes†	..	0.15	..	1940–1980	mostly Nov.–April	Harding (1927a, p. 29); U.S. Geological Survey (1951, 1981)
Estimated unimpaired inflow to Tulare Lake from Sierra Nevada (km³/yr)§	0	1.8–2.3	8	1904–1981	Like runoff from Kings River	This report
	0.30	1.84	7.7	1850–1872	-do-	Harding (1949)
Hypothetical outflow from Tulare Lake (km³/yr)	0	..	0.2	-do-	-do-	-do-
Rainfall at Hanford (Fig. 3) (m/yr)	0.08	0.21	0.46	1899–1969	mostly Nov.-April	Hydrology Branch (1970) National Oceanic and Atmospheric Administration (1971–1981)
Gross evaporation (m/yr)						
Pan at El Rico Ranch (Fig. 3)	1.88	2.13**	2.31	1958–1969	60% May–Sept., peak June–Aug.	-do-
Tulare Lake at levels below 60 m	..	1.40	..	1906–1916	70% May–Sept., peak June–July	Harding (1927b, 1935)

*Water year begins October 1 of the preceding calendar year. For example, water year 1930 began October 1, 1929, and ended September 30, 1930.
†Total includes Los Gatos Creek.
§Difference between inflow and runoff reflects seepage into alluvial fans, evapotranspiration by riparian plants, and pre-emption of Kern River water by other valley-floor lakes (Harding, 1949, p. 36).
**Implies gross lake evaporation of 1.6 m/yr, assuming lake-to-pan coefficient at 0.75 (Hydrology Branch, 1970, Table 39)

(historic lake-surface evaporation generally exceeded precipitation by at least 1.0 m/yr), and the range of natural inflow is large (0–8 km³/yr; Table 1).

TABLE 2. COMPARISON OF SOME WATER-BUDGET PARAMETERS FOR TULARE LAKE AND GREAT SALT LAKE

Lake	Inflow (km³/yr) (I)	Precipitation (km³/yr) (P)	Evaporation (km³/yr) (E)	Maximum depth (m)	Range of maximum depth (m)	Range of volume (km³)	Basinal volume (km³) (V)
Tulare Lake	0–8	0.2–0.9	1–3	12	12	11	7
Great Salt Lake	2–6	0.6–1.8	2–7	13	6	20	4700 at Provo level

Estimates of evaporation, inflow, and precipitation are adjusted to minimize effects of man. Sources: Whitaker (1971), Eardley and others (1957, p. 1145), and Arnow (1980) for Great Salt Lake; Harding (1949) and Table 1 and Figure 5 of this report for Tulare Lake.

The combination of a shallow basin, an arid climate, and a great range in annual inflow evidently allowed historic Tulare Lake to range from occasionally dry to frequently overflowing. Occasional desiccation is suggested by three lines of evidence (top part of Fig. 5). (1) Although never totally dry, the lake of 1850–1872 (the only period of archival record for natural Tulare Lake; Harding, 1949, p. 4) stood below overflow level about three-fourths of the time and occasionally shrank to as little as one-half its overflow-level volume. (2) Stumps and erect branching trunks of pre–Gold Rush willows at altitude 60 m suggest that for many consecutive decades before the mid-1800s—perhaps during the great California drought of 1760–1820 (Fritts and Gordon, 1982)—Tulare Lake generally stood no more than one-half full by depth and no more than two-fifths full by volume (Grunsky, 1930; Harding, 1949, p. 10). (3) Modeled lake levels for 1873–1981 (curve B in Fig. 5) imply that Tulare Lake would have nearly dried out during drought in the 1930s had man not already eliminated the lake. Tulare Lake nonetheless also overflowed and historically did so far more often than it approached dryness. Between 1850 and 1872, the lake overflowed during parts of at least 3 yr, and without human intervention it probably would have overflowed during parts of at least 10 yr since then (Fig. 5). The overflowing lake had a maximum surface altitude of ~66 m, 2 m above the threshold altitude, and a volume of ~11 km³.

The ease with which Tulare Lake evidently ranged from dry to overflowing during the latest Holocene contrasts with the behavior of Great Salt Lake, remnant of late Wisconsin Lake Bonneville. As shown in Table 2, Great Salt Lake resembles Tulare Lake in historic inflow, precipitation, evaporation, maximum depth, and range in depth and volume. Great Salt Lake,

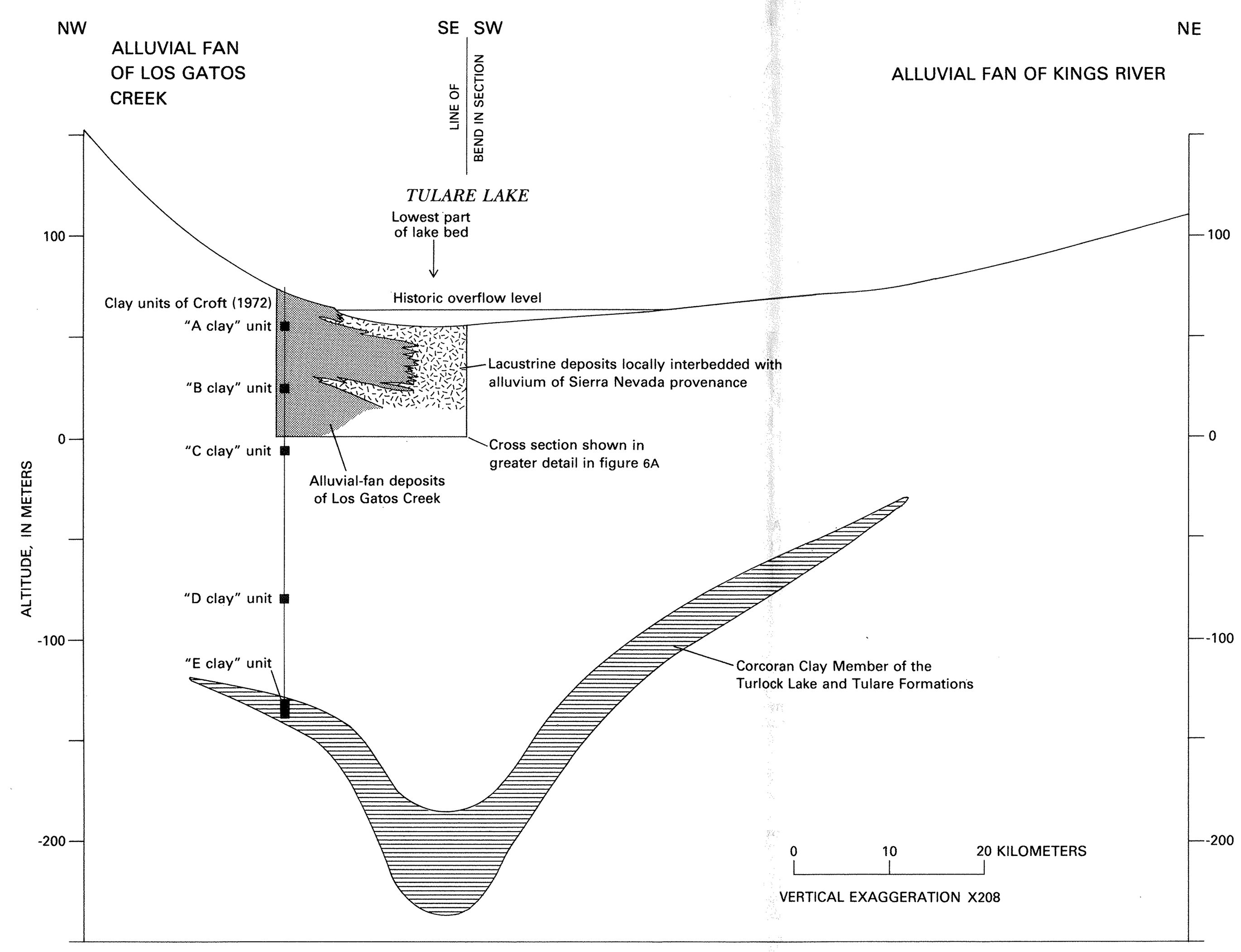
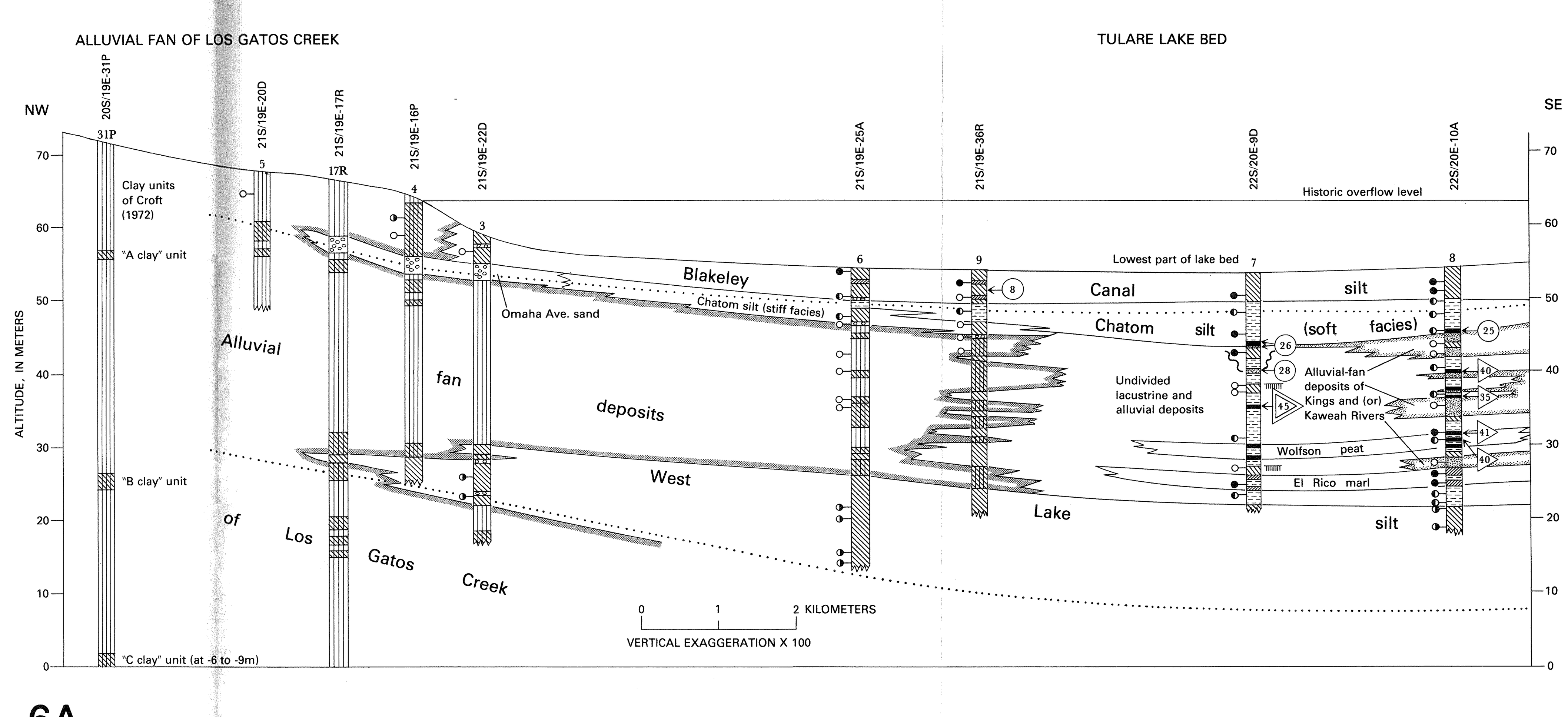


Figure 4. Partial cross section of Quaternary deposits between apices of the Los Gatos Creek and Kings River fans. Line of cross section shown in Figure 3. Configuration of Corcoran Clay Member of the Turlock Lake and Tulare Formations is from Croft (1972).



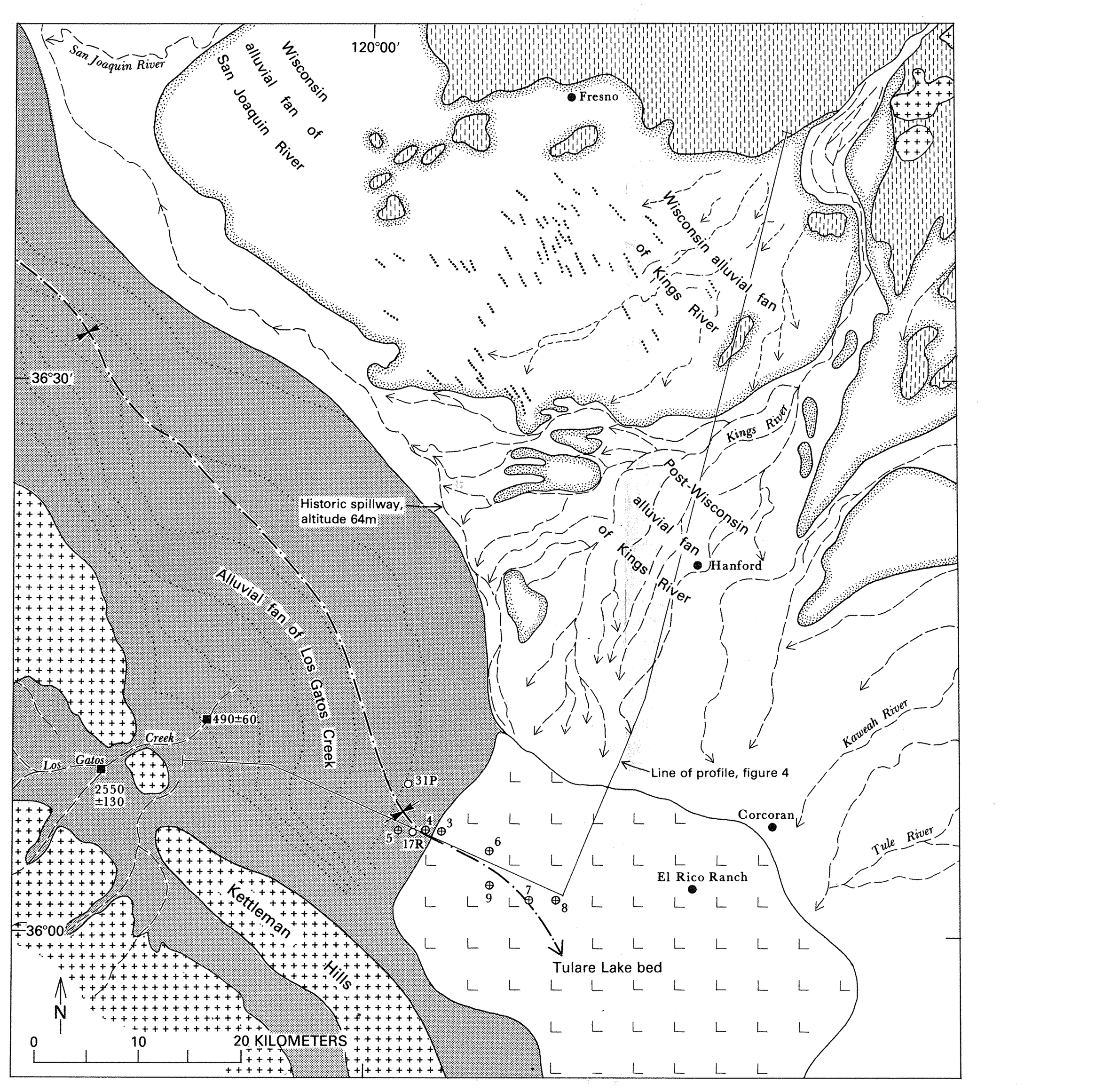
6A

MISCELLANEOUS SYMBOLS IN FIGURE 6A

LINEAR AND PLANAR FEATURES
- PROBABLE BURIED SOIL
- BOUNDARY BETWEEN PRINCIPAL LITHOLOGIC UNITS
- PROBABLE EROSIONAL SURFACE--Drawn schematically
- APPROXIMATE TIME LINE--Connects deposits presumed to be approximately coeval

SAMPLE STUDIED FOR DIATOMS AND OSTRACODES
- Contains diatoms and ostracodes
- Contains only Diatoms
- Contains only ostracodes
- Contains neither diatoms nor ostracodes

RADIOCARBON DATE--Rounded to nearest 1000 ^{14}C years
- 28 Presumed accurate
- 41 Probably limiting minimum despite laboratory's report of finite age (see Table 4, footnote §)
- 45 Limiting minimum reported by laboratory



EXPLANATION

ALLUVIUM DERIVED CHIEFLY OR WHOLLY FROM THE SIERRA NEVADA

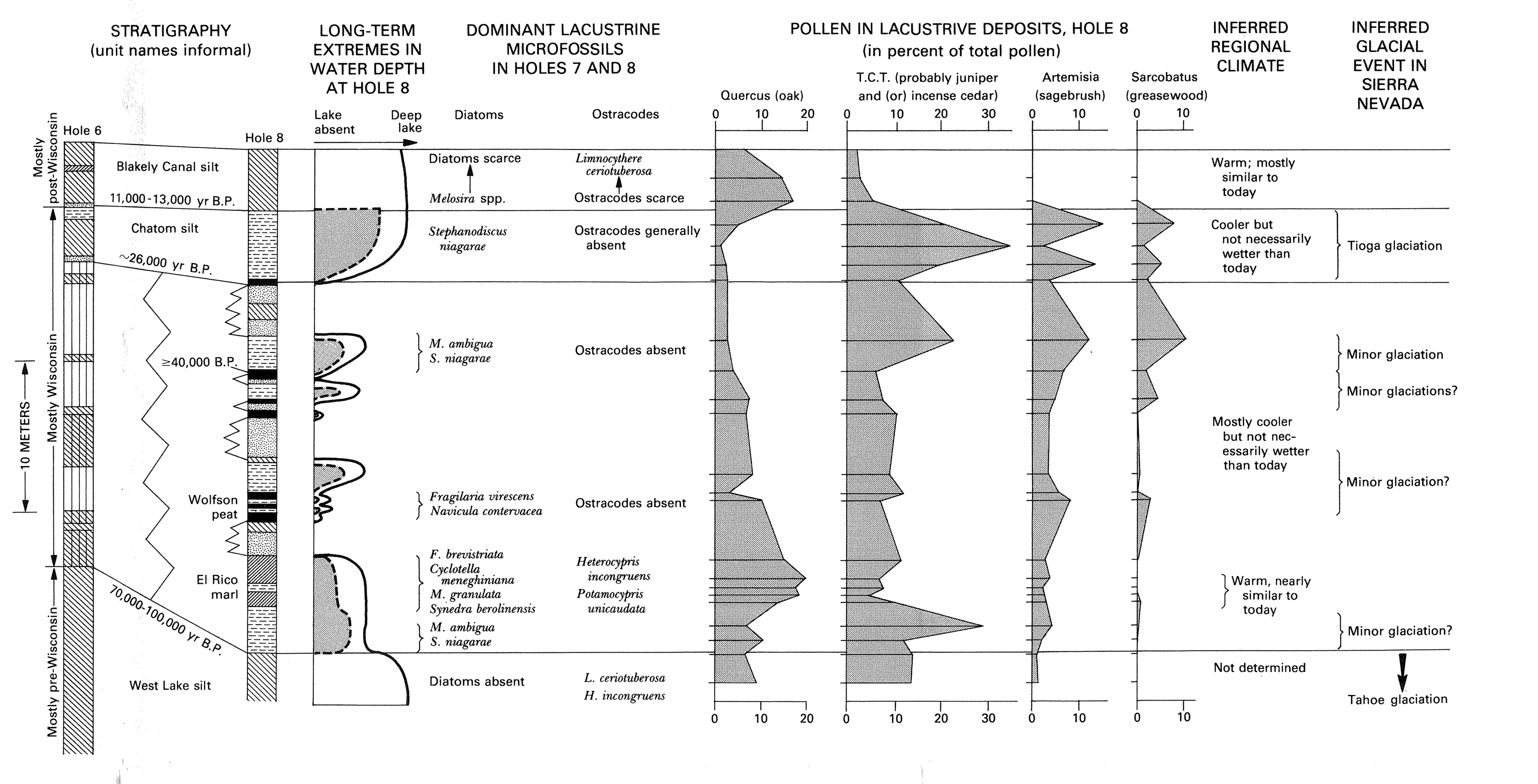
- ALLUVIAL-FAN, FLOODPLAIN, AND DELTAIC DEPOSITS (Holocene)
- MODESTO FORMATION (Pleistocene)--Alluvial-fan and eolian deposits bearing brown soils mostly lacking argillic B horizons
- RIVERBANK FORMATION (Pleistocene)--Chiefly alluvial-fan deposits bearing reddish soils with argillic B horizons

ALLUVIUM DERIVED FROM COAST RANGES (Holocene and Pleistocene)--Dotted lines show topographic contours at 15-m intervals on major fans

SEDIMENTARY AND IGNEOUS ROCKS (early Pleistocene and older)

- Boundary between map units
- Channels
  - Post Wisconsin; largely active in historic time
  - Wisconsin; largely filled with eolian sand
- Long axes of longitudinal eolian dunes; dominant winds probably blew from northwest
- Axis of plunging syncline in upper part of the Corcoran Clay Member of the Turlock Lake and Tulare Formations (from Davis and others, 1959, pl. 14)
- 490±60 Radiocarbon date from alluvial-fan deposits of Los Gatos Creek (Table 4)
- Line of cross section in Fig. 4
- 9 o31P Boreholes shown in Fig. 6A

Figure 3. Generalized geology of part of the southern San Joaquin Valley near the historic outlet of Tulare Lake. Map units delineated by methods of Marchand and Allwardt (1981) with particular reference to soil surveys (Storie and others, 1940; Retzer and others, 1946; Huntington, 1971) and archival topographic maps.



6B

LITHOLOGIC FACIES IN FIGURES 6A AND 6B

SOFT GRAY SILT (lacustrine, not desiccated). Fine silt, softer than 0.5 kg/cm², uniformly gray in greenish-yellow hue (5GY 5/1). Commonly contains pyrite. Deposited on floor of lake where not subject to subaerial exposure.

PEAT AND MUCK (paludal, not desiccated). Silty, softer than 0.5 kg/cm², typically dark grayish brown (10Y 3/2), although peat blackens upon exposure to air. Micaceous, particularly above the Wolfson peat. Commonly contains pyrite. Deposited in marshes.

MARL (lacustrine or paludal, perhaps slightly saline). Silty, firm (1-2 kg/cm²), light gray (5Y 6/1) to weak red (2.5YR 4/2), but unmottled. Fish remains abundant. The El Rico marl contains pyrite; marl beds in Blakeley Canal silt do not. Deposited in shallow lakes or marshes.

NON-MICACEOUS SAND (littoral). Very fine and fine sand, gray (5G-5GY 5/1), locally mottled light olive brown (2.5Y 5/4). Contains sparse hypersthene, augite, blue amphibole, and green hornblende. Probaby supplied by Los Gatos Creek but deposited on beaches.

STIFF GRAY SILT (mostly lacustrine, desiccated). Very fine to medium silt, typically clayey, locally coarsening to silty very fine sand. Typically stiffer than 3 kg/cm²; locally as soft as 1 kg/cm², particularly in lowermost part of the Blakeley Canal silt in hole 6. Sparsely aggregated into hard, subangular, slickensided granule-sized masses. Gray in bluish-green to yellowish hues (5BG-5Y 5/1), commonly mottled in yellowish hues (5Y-2.5Y). Commonly contains root pores, locally contains unidentified bivalve shells, rarely contains fish remains. Commonly contains nodules or seams of calcite and sugary masses of gypsum. Extensive, tabular bodies of this facies record occasional subaerial exposure of lake bottom. Small bodies of stiff gray silt between the El Rico marl and Chatom silt in holes 7 and 8 probably accumulated on an alluvial flood plain because they commonly grade into alluvial sand and (or) lack lacustrine microfossils.

STIFF MOTTLED SILT (alluvial, Coast Range source; transitional to lacustrine). Intermediate in properties between the "stiff gray silt" and "olive-brown silt" units. Principally light olive brown (2.5Y 5/4) but highly mottled in olive gray and gray (hues 2.5Y and 5Y). Deposited on Los Gatos Creek fan where occasionally inundated by lake and (or) subject to high water table.

OLIVE-BROWN SILT (alluvial, Coast Range source). Very fine to medium silt, typically clayey, locally coarsening to fine sand. Typically stiffer than 3 kg/cm². Dominant colors olive brown (2.5Y 4/4) and light olive brown (2.5Y 5/4). Commonly contains root pores, sugary masses or rhombs of gypsum, seams or nodules of calcite, and specks or shot of a black Mn or Fe oxide. Deposited on Los Gatos Creek fan, generally above level of lacustrine inundation.

MICACEOUS SAND (alluvial, Sierra Nevada source). Very fine to fine with interbeds of silt too thin to show in Figure 6A and thicker alluvial interbeds shown separately as the "stiff gray silt" unit. Predominantly gray in a greenish hue (5G 5/1). Abounds in green hornblende; source probably granitic rocks. Deposited on toe of alluvial fan of Kings or Kaweah River (hole 8) and, perhaps, in channel of valley-axis trunk stream (hole 7, immediately above inferred erosional surface).

Note: Samples from boreholes 3-7 were recovered between the spiral blades of solid-stem augers. The augers, 5 cm in stem diameter and 13 cm in total diameter, were slowly rotated into the ground like a screw in increments (drives) of 6 m or less. After each drive, the augers were pulled out with little or no rotation. This method, illustrated by Kraft (1971, p. 214-217), allowed us to drill and log seven holes in three days. Solid-stem augering, however, has inherent disadvantages. One cannot fully recover loose wet sand, much of which falls off the auger. Contrasting beds thinner than ~5 cm are generally swirled and distorted; sedimentary structures are destroyed. Long drives tend to displace and spread sediment up the augers; stratigraphic order is preserved, but some of our sample depths have uncertainties as great as 1.5 m. We partly overcame problems of depth assignment by carefully noting changes in drilling rates and then relating these changes to contacts observed in deposits brought to the surface.

Figure 6. Late Quaternary deposits beneath northwestern Tulare Lake bed. In lithologic descriptions, degree of consolidation is reported as unconfined shear strength (measured with pocket penetrometer on least-disturbed augered material), and color names follow the Munsell system. All lithostratigraphic names are informal. A. Cross section. Alphanumeric labels (for example, 20S/19E-31P) locate boreholes within 0.16-km² tracts (Croft, 1972, p. 7). Holes 31P and 17R were cored by the U.S. Bureau of Reclamation. All others were drilled with solid-stem augers (Kraft, 1971) by the U.S. Geological Survey. B. Selected paleoecologic data and interpretations. Bathymetry shown schematically as long-term minimum (dashed line) and maximum (solid line) for deepest part of lake. The long-term maximum can be viewed as approximating the relative height of an alluvial dam for Tulare Lake; a deep lake needs a high dam, and absence of a lake at hole 8 suggests that the dam was low or absent. TCT pollen includes the families Taxodiaceae, Cupressaceae, and Taxaceae and probably represents chiefly *Juniperus* and (or) *Calocedrus*. Climate is interpreted solely from pollen. Timing of the Tioga and Tahoe glaciations (Tioga and Tahoe stages of Blackwelder, 1931) is read solely from inferred bathymetric changes. Minor glaciations are interpreted both from inferred bathymetric changes and from pollen and diatom data as calibrated against the Tioga glaciation. See text for assumptions and qualifications.

TABLE 4. RADIOCARBON DATES FROM MARSH AND STREAM DEPOSITS BENEATH NORTHWESTERN TULARE LAKE BED, FROM TRUNK-STREAM ALLUVIUM OF THE CENTRAL SAN JOAQUIN VALLEY, AND FROM ALLUVIUM OF THE LOS GATOS CREEK FAN

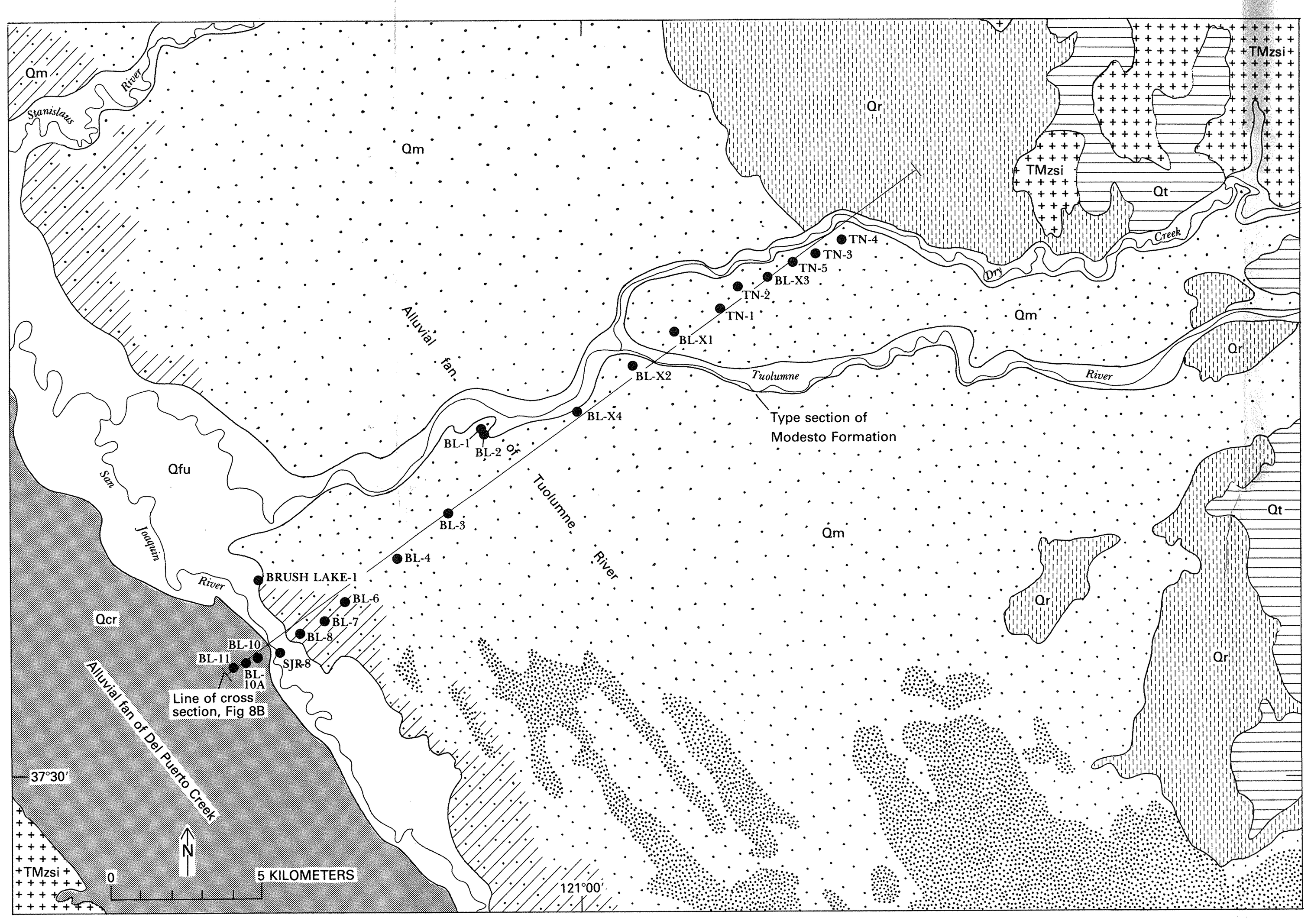
Lab no.	Age in ^{14}C yr B.P.	Material dated*	Location	Depositional environment
BETA-4238	490 ± 60	Charcoal, angular	36°10′52″/120°09′50″, 1.5 m below surface of fan (Fig. 3)	Alluvial fan of Los Gatos Creek
BETA-4239	2550 ± 130	Charcoal, rounded	36°08′46″/120°16′31″, 4.5 m below surface of fan (Fig. 3)	-do-
USGS-1494	8180 ± 45	Muck, desiccated	Hole 9, 3.0 ± 0.5 m below surface of lake bed (Fig. 6A)	Marsh or strand-line of an ancestral Tulare Lake
USGS-1201	22,670 ± 200	Woody plant fragments	36°45′22″/120°18′56″ altitude 38.6 m	Trunk stream near San Joaquin River fan (Fig. 2)
USGS-1497	24,930 ± 90	Peat	Hole 8, 8.1 ± 0.3 m below surface of lake bed (Fig. 6A)	Marsh fringing a nascent ancestral Tulare Lake
BETA-4355 USGS-1500	22,210 ± 350† 25,650 ± 140	Peat	Hole 7, 8.9 ± 0.3 m below surface of lake bed (Fig. 6A)	-do-
USGS-1495	25,900 ± 380	Woody plant fragments	Hole 7, 9.2 ± 0.3 m below surface of lake bed (Fig. 6A)	Trunk stream at site of Tulare Lake
USGS-1501	27,700 ± 1000	-do-	Hole 7, 12.7 ± 0.3 m below surface of lake bed (Fig. 6A)	-do-
USGS-1197	28,200 ± 330	-do-	36°44′50″/121°19′39″, altitude 34.3 m	Trunk stream near San Joaquin River fan (Fig. 2)
USGS-1498	39,700 + 1900–1600§	Muck; 6.5 g-C	Hole 8, 14.1 ± 0.5 m below surface of lake bed (Fig. 6A)	Marsh fringing an ancestral Tulare Lake
USGS-1503	35,210 ± 620§	Organic silt; 3.8 g-C	Hole 8, 16.6 ± 0.5 m below surface of lake bed (Fig. 6A)	-do-
USGS-1496	45,000	Muck; 5.4 g-C	Hole 7, 18.2 ± 0.5 m below surface of lake bed (Fig. 6A)	-do-
USGS-1499	41,120 ± 810§	Peat; 3.2 g-C	Hole 8, 21.9 ± 0.3 m below surface of lake bed (Fig. 6A)	Marsh fringing a small, shallow, ancestral Tulare Lake
USGS—1504	39,500 ± 580§	Peat; 7.4 g-C	Hole 8, 22.5 ± 0.3 m below surface of lake (Fig. 6A)	-do-

*g-C, grams of carbon counted.
†The 3,400-yr discrepancy between USGS-1500 and BETA-4355 should not have arisen from differences in age between bottom and top of the 0.5-m-thick peat bed in hole 7 because, although about 1 m higher in altitude than this bed, the peat in hole 8 is only about 700 yr younger according to USGS ages. Possible explanations for the discrepancy include (a) contamination of BETA-4355 with 1.8% modern carbon and (b) a systematic difference between laboratories like that suggested by McLaughlin and others (1983, p. 37).
§Probably limiting-minimum age because close to maximum age-limit for laboratory and (or) inconsistent with date on overlying sample. Lab's report of a finite age may reflect the kind of bacterial contamination described by Geyh and others (1974); our samples were left at room temperature at least two weeks before pre-treatment and combustion.

TABLE 3. PALEOLIMNOLOGY OF TULARE LAKE AS INFERRED FROM OSTRACODES AND DIATOMS

Unit	Dominant lacustrine microfossils		Paleolimnologic interpretations				
(Fig. 6A)	Ostracodes and charophytes (c)	Diatoms [b, benthic; p, planktonic; b-p, benthic and (or) planktonic]	Relative depth	Salinity (ppt)	pH	Solutes	Other
Blakeley Canal silt upper part, holes 6 and 9	*Limnocythere ceriotuberosa*	Rare benthic species	Very shallow				Substrate probably well-oxygenated, at least in vicinity of holes 6 and 9
marl beds, holes 6 and 9	*L. ceriotuberosa* also, in upper marl in hole 6: *Cypridopsis vidua* *Heterocypris incongruens* *Chara* spp. (c)	*Melosira ambigua* (p) *Fragilaria brevistriata* (b) Many benthic and epiphytic species	Shallow but stable	0.5–4.0	7.5–9.0	Na, Ca, Mg, HCO_3, CO_3, and variable amounts of Cl and SO_4	Water not much warmer than in historic Tulare Lake because modern *L. ceriotuberosa* lives mostly north and east of Tulare Lake
lowermost part, holes 7 and 8	None	*M. ambigua* (p) *M. granulata* (p)	.... Transitional to lake of Chatom-silt time				
Chatom silt, soft facies	*L. ceriotuberosa* juveniles (very few)	*Stephanodiscus niagarae* (p)	Deep*	Mainly below 2	7–10	Ca, Na, HCO_3, and some SO_4	Scarcity of ostracodes suggests that lake bottom was soft and anoxic Abundance of *S. niagarae,* found today in a cool-temperature lake, suggests water temperature cooler than in preceding or succeeding lakes
Unnamed silt at depth 14 m in hole 8	None	*M. ambigua* (p) *S. niagarae* (p)	Deep*	Mainly below 2	7–10	Ca, Mg, HCO_3, SO_4	. .
Wolfson peat	None	*F. virascens* (b-p) *Navicula confervacea* (b) *Epithemia turgida* (b) *Rhopalodia gibba* (b) *Amphora veneta* (b) *Cocconeis placentula* (b)	Very shallow	Mainly below 3	Below 8 but often above 7	Abundant N	Cladoceran *ephippia* and diatoms demonstrate presence of standing water for much of the year
El Rico marl	*H. incongruens* *Potamocypris unicaudata*	*F. brevistriata* (b) *F. construens* v. *trigona* (b) *Cyclotella meneghiana* (p) *M. granulata* (p) *Synedra berolinensis* (b-p)	Shallow	Mainly below 5	7.5–9.0	Na, Ca, Cl, SO_4	Many of the diatoms, particularly *C. meneghiana* and *M. granulata,* suggest water temperature warmer than in lake of Chatom-silt time
Unnamed silt between El Rico marl and West Lake silt	None	*M. ambigua* (p) *S. niagarae* (p)	Deep*	Mainly below 2	7–10	Ca, Mg., HCO_3, SO_4	. .
West Lake silt most of unit	*L. ceriotuberosa* *H. incongruens*	None	Shallow	1–10	Variable, mostly 8–10	Na, HCO_3, and CO_3 and lesser amounts of Mg, SO_4, and Cl	Lack of diatoms suggest destruction of frustules in turbulent, alkaline lake
hole 6, bottom (depth 39 m)	*H. incongruens* *L. bradburyi*						Modern *L. bradburyi* has not been found north of central Mexico

*Suggested, though not required, by great abundance of planktonic diatoms and scarcity of benthic diatoms. The abundance of planktonic diatoms suggests that water was deep enough to stratify seasonally and/or that seasonal influx of nutrients combined with turbulence to maintain a planktonic-diatom community. The scarcity of benthic diatoms suggests that shallow-water environments were distant, or perhaps that high turbidity prevented development of shallow-water benthic floras by shading the bottom.

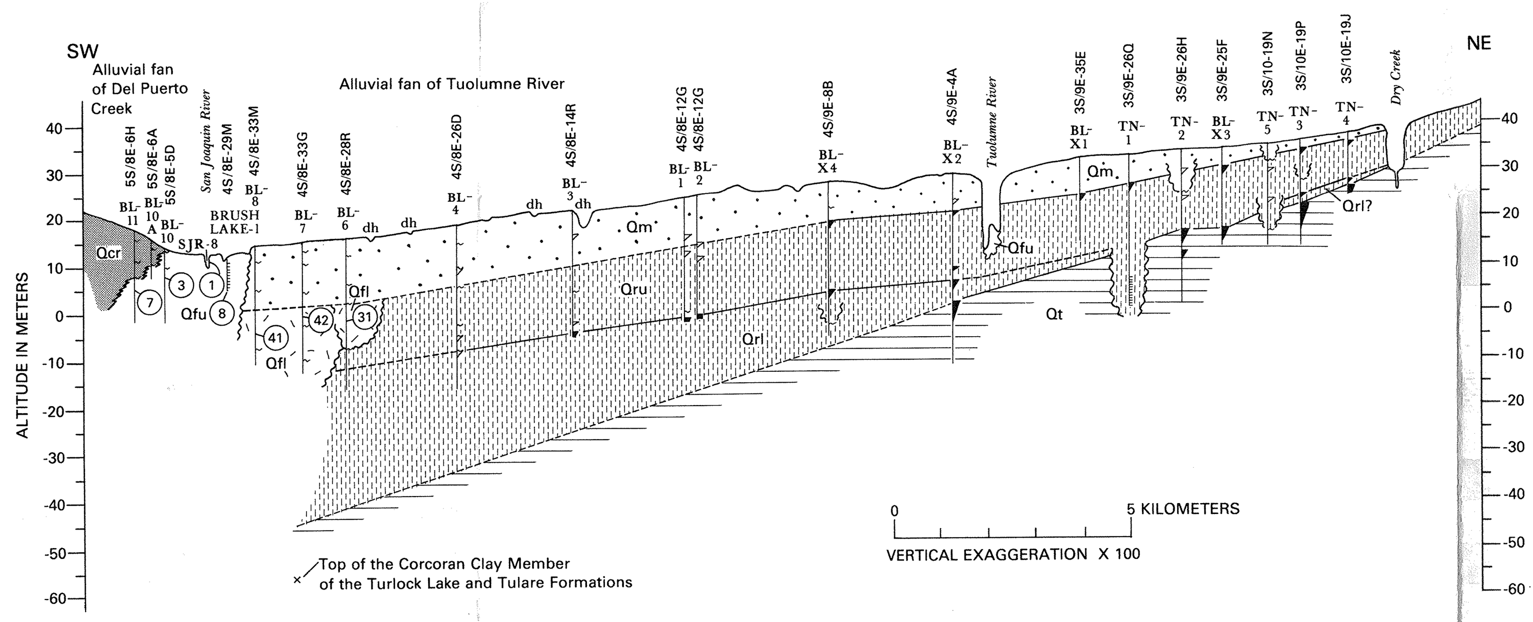


8A

MISCELLANEOUS SYMBOLS ON FIGURE 8A

—— CONTACT

● BL-5 BOREHOLE OR OUTCROP



8B

MISCELLANEOUS SYMBOLS ON FIGURE 8B

CONTACT--Dashed where location approximate, wavy where marking an inferred erosional unconformity

BOREHOLE--Location specified by well-numbering system of Croft (1972, p. 7) (see Fig. 6)

(7) RADIOCARBON DATE--Rounded to nearest 1000 ^{14}C yr (Table 5)

BURIED SOIL

WELL-DEVELOPED--Length of symbol shows approximate thickness of B horizon. Contains argillic horizon with conspicuous clay coatings on sand grains. Hue 10YR or redder. Developed in poorly sorted silty sand or sandy silt, probably recessional outwash. Typically overlain by unweathered, well-sorted silt or very fine sand, probably glacial rock flour

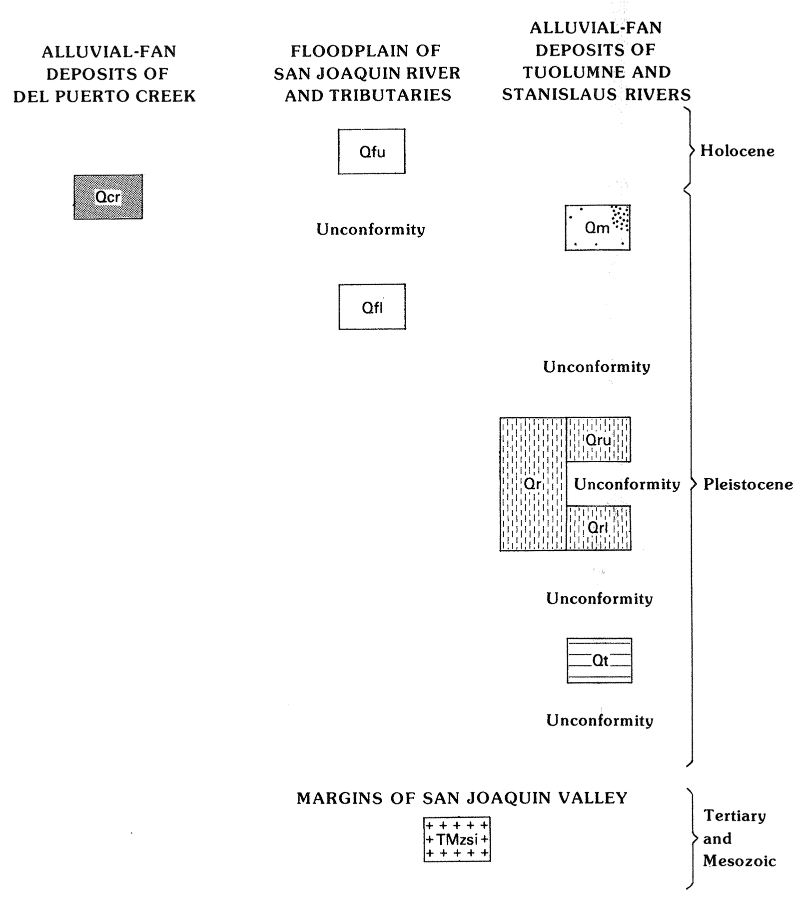
INCIPIENT--Length of symbol shows approximate thickness of poorly sorted silt. Lacks argillic horizon and reddish color but inferred to mark hiatus because poor sorting suggests homogenization by roots. Top of symbol wavy where horizon overlain by fine or coarser sand, straight where overlain by very fine sand or silt

BASE OR SIDE OF ANCIENT CHANNEL--Abrupt contact of sand, typically medium or coarse and in places gravelly, over finer-grained deposits. Sand typically fines upward

LACUSTRINE DEPOSIT--Silt, clay, and minor very fine sand, mostly gray

Figure 8. Quaternary deposits of the Tuolumne River fan and vicinity. A. Generalized surficial geology, mainly from Arkley (1964, p. 120). B. Subsurface stratigraphy, inferred mainly from material recovered on solid-stem augers in 1981.

CORRELATION OF UNITS



DESCRIPTION OF UNITS

Qcr ALLUVIAL-FAN DEPOSITS OF COAST RANGE PROVENANCE (Holocene and upper Pleistocene). Silt, sand and gravel, mostly brown in 10YR hue. All of unit shown in cross section appears to be Holocene, but older deposits may crop out farther upfan within map area.

FLUVIAL DEPOSITS (Holocene and upper Pleistocene). Light gray arkosic sand, locally with gravel, locally with plant fragments, commonly fining upward into micaceous silt, locally capped with dark gray, silty clay. Individual fining-upward sequences typically thicker than 5 m. Deposited mostly in or beside deep channels. Divided into:

Qfu Upper unit (Holocene). Inset into Modesto Formation. Yields Holocene ^{14}C ages along San Joaquin River.

Qfl Lower unit (upper Pleistocene). Inset into Riverbank Formation and overlain by Modesto Formation. ^{14}C ages suggest that unit comprises two non-coeval fills separated by erosional unconformity.

ALLUVIAL-FAN DEPOSITS OF SIERRA NEVADA PROVENANCE (Pleistocene). Light gray and light brown, arkosic, micaceous silt and sand. Commonly thin bedded, with a few channel-fill deposits thicker than 5 m. For the most part, probably deposited in and between distributaries carrying glacial outwash. Includes minor eolian and lacustrine deposits. Divided into three formations that differ most conspicuously in geomorphic position, degree of dissection, and degree of soil development, but that also crop out in superposition.

Qm MODESTO FORMATION: forms youngest fan of Tuolumne and Stanislaus Rivers. Undissected except for channels cut by Tuolumne and Stanislaus Rivers and by Dry Creek. Bears brown soils in which argillic B horizon is either lacking or minimal; fan-toe facies bearing alkaline soils with argillic horizons (mostly soils of the Fresno series) are diagonally ruled on map and cross section. Upper part of formation includes eolian sand (dense stipple on map) and is locally pocked with deflation hollows (dh in cross section).

Qr RIVERBANK FORMATION. Crops out mostly near and above apex of Modesto Formation fan as slightly to moderately dissected, probably uplifted remnant of earlier fan or fans. Bears reddish-brown soils with argillic horizons, commonly also with SiO_2-cemented hardpans. In cross section, divided into two informal units:

Qru Upper unit. Top marked by buried soil as far downfan as hole BL-X4; farther southwest, we position the unit's top by extrapolation. Unit probably correlates with the upper unit of the Riverbank of Marchand and Allwardt (1981, p. 49).

Qrl Lower unit. Contact with upper unit (Qru) marked by a buried soil that can be traced most confidently between holes BL-4 and BL-X2. Correlation with the Riverbank units of Marchand and Allwardt (1981) is unknown.

Qt TURLOCK LAKE FORMATION. Preserved at surface as deeply eroded remnants cropping out mostly above and east of the exposed Riverbank Formation. Bears soils that are noticeably thicker, redder, and more clay rich than soils developed on the Riverbank Formation (Marchand and Allwardt, 1981, p. 6). In subsurface, top marked by buried soil that similarly is more strongly developed than buried soils on or within the Riverbank Formation. Top of the Turlock Lake approximately positioned beneath toe of Tuolumne River fan by presumptive projection over top of Corcoran Clay Member (compare Marchand and Allwardt, 1981, p. 34); top of Corcoran beneath site of hole BL-7 determined from cuttings of "Observation Well A," Stanislaus Test Wells Project of Pacific Gas and Electric Co., logged 1975 by G. C. Hill of Bookman-Edmonston Engineering, Inc., Bakersfield, California.

TMzsi SEDIMENTARY AND IGNEOUS ROCKS (Tertiary and Mesozoic). Unit is Miocene and Pliocene in age in northeast corner of map area, Mesozoic and Tertiary in southwest corner.

TABLE 5. RADIOCARBON DATES FROM THE TUOLUMNE RIVER FAN AND VICINITY

Lab no.	Age in ^{14}C yrs B.P.	Material dated*	Location (Fig. 8)	Depositional environment
BETA-2786	1110 ± 50	Charcoal rounded and surely detrital	Cut bank of San Joaquin River; 37°32′11″/121°06′35″; locality SJR-8	San Joaquin River, probably point bar
BETA–2788	3330 ± 60	Woody plant fragments, probably detrital	Beneath fan of Del Puerto Creek; 37°32′06″/121°-07′05″; hole BL-10	–do–
USGS-1241	6890 ± 60	–do–	Beneath fan of Del Puerto Creek; 37°31′50″/121°-07′32″; hole BL-11	–do–
BETA-2787	8230 ± 30	–do–	Beneath bed of Brush Lake, a mostly filled oxbow in the floodplain of the San Joaquin River; 37°33′30″/121°07′02″; hole Brush Lake 1	Oxbow Lake immediately after inception; dated material from contact between channel gravel and 5 m of overlying lacustrine clay, silt, and sand
USGS-1239	31,250 ± 325	Reddish wood and black bark, probably a log fragmented by auger; 3.14 g-C	Beneath toe of Tuolumne River fan; 37°33′07″/121°05′05″; hole BL-6	River, probably channel or point bar of San Joaquin River
USGS-1240	41,300 ± 1200	Chunks of wood as in USGS-1239; 4.32 g-C	Beneath toe of Tuolumne River fan; 37°32′30″/121°06′06″; hole BL-8	–do–
USGS-429	42,400 ± 1600	Chunks of wood; 3.75 g-C	Beneath toe of Tuolumne River fan; 37°32′51″/121°05′32″† 30 m WSW of hole BL-7	–do–

*g-C, grams of carbon counted.
†NW corner of SW/4 of NE/4 sec. 33, T. 4 S., R. 8 E. (site erroneously assigned to NW/4 of sec. 34 by Marchand and Allwardt, 1981, p. 57).

however, comes nowhere near filling its basin, because the present (Provo-level) volume of Lake Bonneville basin is 670 times larger than the present volume of Tulare Lake basin (Table 2). Whereas Great Salt Lake has ample room to grow before overflowing, Tulare Lake might respond to a pluvial climate by desiccating less and overflowing more without greatly increasing in maximum size.

LATE QUATERNARY PALEOLIMNOLOGY

Large lakes have often occupied the San Joaquin Valley during the Quaternary. The largest Pleistocene lake, recorded by the Corcoran Clay Member of the Turlock Lake and Tulare Formations (Frink and Kues, 1954; Marchand and Allwardt, 1981, p. 34), extended nearly the whole length of the valley and probably resulted from temporary tectonic blockage of the valley's outlet through the Coast Ranges (Davis and others, 1959, p. 71). A volcanic ash bed in the upper part of the Corcoran dates the demise of this lake at approximately 600,000 yr B.P. (Janda and Croft, 1967, p. 164; Dalrymple, 1980). Subsequent large lakes in the San Joaquin Valley were confined to the vicinity of Tulare, Buena Vista, and Kern Lakes (Croft, 1972; Lettis, 1982, p. 142), where well logs suggest four major lacustrine episodes of post-Corcoran age (Croft, 1972; clays A through D in Fig. 4).

During only 2 periods in the past 100,000–130,000 yr was Tulare Lake commonly as large as the overflowing Tulare Lake of the 19th century. The more recent of these periods produced the Chatom silt and immediately overlying Blakeley Canal silt, and the earlier period produced the West Lake silt (names informal, as are all other lithostratigraphic terms introduced in this report[1]). Deposits between the West Lake and Chatom silts record a time when Tulare Lake was generally small and on a few occasions was probably replaced by a trunk-stream flood plain (Fig. 6, on folded insert).

Chatom and Blakeley Canal Silts

The more recent large-lake episode had two parts. First, a small marsh evolved into a perennial lake; second, the lake changed little in maximum size but fluctuated greatly in area and depth and occasionally dried out altogether. The Chatom silt records the marsh and the growing perennial lake: it contains basal peat, overlaps alluvium, and consists largely of soft gray silt that shows no sign of desiccation of the central part of Tulare Lake. The overlying Blakeley Canal silt, by contrast, consists primarily of stiff gray silt the lateral extent of which requires a large lake, although its consolidation, root pores, soil-like mottling and precipitates, and mud-cracked aggregates indicate occasional subaerial exposure and desiccation of the entire lake bed.

Deposition of the Chatom silt began with the spread of a marsh-fringed lake onto an alluvial plain at holes 7 and 8 (Fig. 6, upward sequence of sand to peat to soft gray silt). Differences in the altitude and age of the Chatom silt's basal peat between holes 7 and 8 imply that the lake had a net rise of ~1 m within its first 500–1,000 yr. As the lake rose higher, the persistent fringe of peat-producing marshland around it evidently was replaced by the frequently shifting shorelines implied by the stiff gray silt that we designate, without paleontologic proof, as a stiff facies of the Chatom silt. The area of persistent inundation also expanded, as suggested by the soft gray silt overlying stiff gray silt in the vicinity of holes 6 and 9. A dominance of the planktonic diatom *Stephanodiscus niagarae* in the soft facies of Chatom silt accords with persistence of a deep lake and further shows that salinity rarely (if ever) exceeded 2 parts per thousand (ppt) (Table 3, on folded insert). The Omaha Avenue sand implies frequent high water and hence may be coeval with a deep-water part of the Chatom silt (time line in Fig. 6A).

The Blakeley Canal silt probably represents fluctuations in lake depth, like those we have described for historic Tulare Lake (Fig. 5), with the bed of which the Blakeley Canal silt is continuous (Fig. 6A). In particular, the occasional desiccation that we infer from hand-specimen properties of the Blakeley Canal silt is probably analogous to the desiccation postulated above for droughts of 1760–1820 and the early 1930s. With sedimentation rates estimated below at 0.3–0.4 m/1,000 yr, desiccation once per century would probably suffice to modify lake-bottom silt by dewatering, injection of roots, precipitation of nodular calcite and gypsum, and penetration of mud cracks.

Relative abundances of diatoms and ostracodes imply over-all shallowing of Tulare Lake during deposition of the Blakeley Canal silt. The basal few metres of the Blakeley Canal silt, at the central part of the lake basin, resemble the Chatom silt, in that diatoms are common and ostracodes scarce; the opposite is true higher in the Blakeley Canal silt (Table 3). This inverse distribution of diatoms and ostracodes is probably related to depth through wave-induced turbulence. The greater lake-bottom turbulence of a shallow lake may decrease diatom productivity by increasing turbidity; simultaneously, it may promote dissolution of diatom frustules; also, it may increase the productivity of benthic animals like ostracodes by supplying oxygen to the lake bottom.

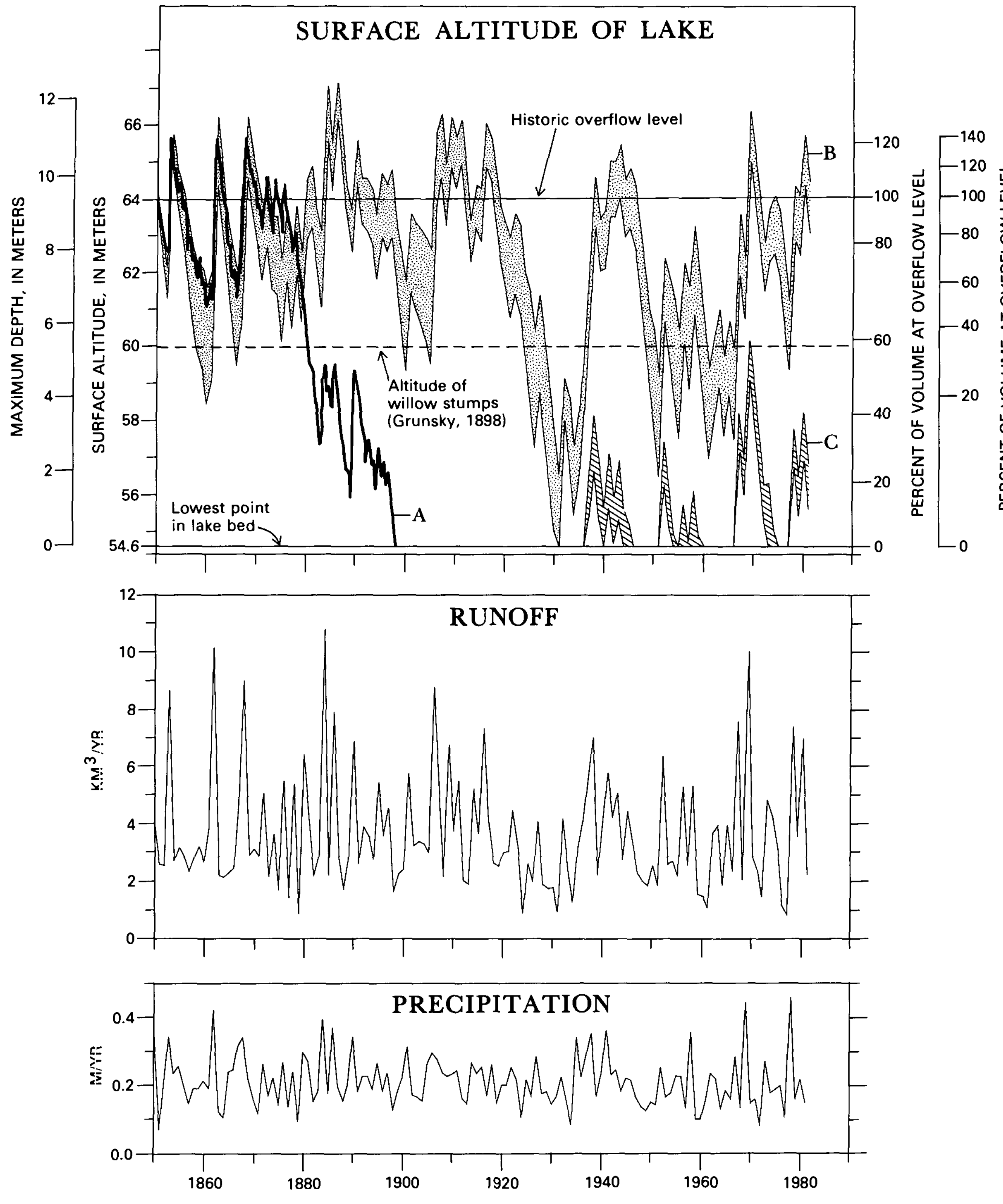
The Chatom silt began to form about 26,000 yr B.P. and the Blakeley Canal silt about 11,000–13,000 yr B.P. (Figs. 6 and 7); thus, the Chatom is of late Wisconsin age and the Blakeley Canal chiefly post-Wisconsin. Stratigraphic consistency among two ^{14}C ages on the basal peat layer of the Chatom silt (USGS-1497 and -1500; Table 4, on folded insert) and two ^{14}C ages on woody-plant fragments from underlying sand (USGS-1495 and -1501) probably invalidates a discrepant ^{14}C age of ~22,000 yr (BETA-4355) on the basal peat layer of the Chatom silt (Table 4, footnote †). In estimating the age of the lowermost part of the Blakeley Canal silt, we assume average sedimentation rates of 0.3–0.4 m/1,000 yr for the 1.2 m of silt and marl between the base of the Blakeley Canal silt and a desiccated muck with a ^{14}C age of 8,200 yr (USGS-1494). These sedimentation rates are consistent with the depth of the dated muck, as well as with the long-term averages graphed in Figure 7.

Deposits between the West Lake and Chatom Silts

During the interval between deposition of the West Lake and Chatom silts, Tulare Lake was never as large as it became historically, yet it generally avoided desiccation. We interpret lake size from the small lateral extent of lacustrine deposits from this interval. The only evidence suggesting that the lake was large is the sporadic appearance in holes 7 and 8 of a diatom flora dominated by planktonic species (chiefly *Melosira ambigua* and *Stephanodiscus niagarae;* Fig. 6B). This flora suggests that lake margins lay a considerable distance from holes 7 and 8, but it may also befit a small, shallow lake turbid enough to shade the bottom or other substrates normally within the photic zone (Table 3, footnote *). The lake probably was perennial, because the principal lacustrine facies is soft gray silt that, like the soft part of the Chatom silt, shows no sign of subaerial exposure and drying. Even when reduced to marshes, the lake retained standing water most of the year: the Wolfson peat lacks megascopic evidence of desiccation, abounds in epiphytic diatoms, and contains cladoceran ephippia (water-flea egg cases).

The lake between West Lake and Chatom time fluctuated in maximum depth on a time scale of 10^3 to 10^4 yr, several times even being replaced by a trunk stream. Deposits between

[1]The new, informal terms, from oldest to youngest: West Lake silt, El Rico marl, Wolfson peat, Chatom silt, Omaha Avenue sand, and Blakely Canal silt.



altitudes 35 m and 45 m in hole 8 contain 2 cycles in which sand passes upward through peat or muck into soft gray silt, then back into sand (Fig. 6). Each cycle implies spread of a rising, marsh-fringed lake across the toe of an alluvial fan, followed either by drainage of the lake or by progradation of a delta. Replacement of Tulare Lake by a trunk stream is suggested in hole 7 by two probable buried soils and an inferred channel: bracketed laterally by alluvial-fan deposits, these features leave little room for a lake along the line of our cross section. The probable buried soils consist of gray silt that stiffens markedly upward to an abrupt contact with overlying soft silt. They differ from typical desiccated-lake deposits in containing neither diatoms nor ostracodes (Fig. 6A). The two sand lenses are inferred to be channel deposits, be-

Figure 5. Surface altitudes of Tulare Lake, combined runoff from major tributaries, and rainfall in the vicinity of the lake, water years 1850–1981. Measured altitude (A) declines after the 1870s in response to diversion of tributaries (Harding, 1949). Hypothetical altitude with B and without C inflow from the Kings River is computed from a model (see below) and shown as ranges (stippled) to allow for uncertainties in estimating loss of stream flow between edge of San Joaquin Valley and Tulare Lake. Runoff, giving total for Kings, Kern, Kaweah, and Tule Rivers at edge of San Joaquin Valley, is from estimates for 1850–1903 (Harding, 1949, Tables 17, 18) and from measurements for 1904–1981 (Table 1); precipitation is from estimates for 1850–1898 (Harding, 1949, Tables 17, 18) and from measurements at Hanford (Fig. 3) 1899–1981 (Table 1); and overflow level is from Lee (1907).

The model uses: relations of altitude to area and capacity as tabulated by Harding (1949, p. 27); precipitation (P) as shown in the figure; hypothetical unimpaired inflow (I) to the lake as estimated by correcting total runoff at the edge of the San Joaquin Valley (shown in the figure) for intransit losses within the valley of 1.2–1.7 km^3/yr (Harding, 1949, p. 36) and by correcting runoff without the Kings River for losses of 0.7–1.2 km^3/yr; annual outflows (0) for lake levels exceeding 64 m as estimated by Harding (1949, p. 32); and a constant gross evaporation rate (E) of 1.4 m/yr (Table 1). Starting points are the reported lake level for the beginning of water year 1850 and, for modeling runoff without the Kings River, a dry lake for the end of water year 1931. Subsequent changes in level are calculated iteratively from changes in volume (delta V) as determined from the equations:

$$\Delta V_i = [I(T) + O(V) + (P(T)-E) x A(V)]\ \Delta T,$$

and

$$V_{i+1} = V_i + \Delta V,$$

where A and O are functions of V, and I and P are time series. Values of I and P are annually averaged and the iteration interval (ΔT) is 0.01 yr.

cause (1) they are the only known sands in the center of the lake basin, and (2) the depths and ^{14}C ages of the sand lenses suggest a sedimentation rate much higher than the long-term rates (Fig. 7). Alluvial cut-and-fill explains this anomalous sedimentation rate better than does tectonic subsidence, because underlying strata in hole 7 reveal no exceptional downwarping (Fig. 6A).

Fossils indicating salinities below 3 ppt predominate in most lacustrine deposits between the West Lake and Chatom silts except the El Rico marl. This calcareous silt contains diatoms and ostracodes that allow salinities as great as 5 ppt. Brackish-water deposition of the El Rico is also consistent with the abundant ctenoid scales of *Archoplites interruptus* (Sacramento perch) and pharyngeal teeth of *Orthodon microlepidotus* (a minnow) in the El Rico. These species, although native to fresh-water lakes and slow-moving rivers of the San Joaquin Valley, thrive in modern waters too saline for other fresh-water fish (Moyle, 1976).

Deposits between the West Lake and Chatom silts probably range in age from ~25,000 yr to ~70,000–100,000 yr, thus representing most of Wisconsin time and perhaps some of pre-Wisconsin time as well. We do not accept the reported ages for the three deepest ^{14}C-dated samples in hole 8, because these ages are stratigraphically inconsistent (Table 4, footnote §).

West Lake Silt

Like the Blakeley Canal silt, the West Lake silt suggests the existence of a lake that was commonly large (lateral extent of unit; Figs. 4, 6A), yet also occasionally dry (physical properties of the "stiff gray silt" facies; Fig. 6). Substantial fluctuation in water depth is further suggested in both units by the presence of *Limnocythere ceriotuberosa*, an ostracode generally associated with seasonal bathymetric changes and with salinities in the range of 1–10 ppt. In some other respects, the West Lake and Blakeley Canal silts differ: the shallow-lake ostracode *Heterocypris incongruens* is found primarily in the West Lake silt; only the Blakeley Canal silt contains diatoms; and the uppermost part of the West Lake silt contains proportions of pollen types different from those of the Blakeley Canal silt (Fig. 6B). But none of these differences negates the general similarity in depositional environment suggested by properties held in common.

The West Lake silt also resembles the Blakeley Canal silt in probable provenance. Both units contain much more quartz then feldspar, as judged from X-ray patterns of smeared bulk-sediment samples. The soft facies of the Chatom silt, by contrast, is highly feldspathic in X-ray pattern and also contains far more green hornblende than do the Blakeley Canal and the West Lake silts, as judged from X-ray pattern and petrography. Probably granitic rock was less abundant, more slowly eroded, and (or) more deeply weathered in source areas for the West Lake and Blakeley Canal silts than in main source areas for the Chatom silt.

All of the West Lake silt probably accumulated in pre-Wisconsin time. Average sedimentation rates of 0.33–0.40 m/1,000 yr (Fig. 7) suggest an age of 70,000–100,000 yr for the uppermost part of the West Lake silt. We know too little about the configuration of the base

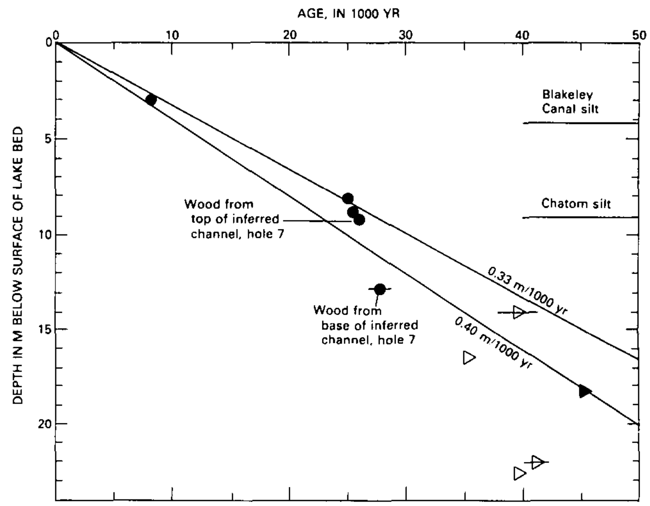


Figure 7. Ages and depths of radiocarbon-dated samples from deposits beneath northwestern Tulare Lake (Table 3). Envelope shows range of average sedimentation rates as inferred from depths to top of Corcoran Clay Member of the Turlock Lake and Tulare Formations near holes 3–8 (see Fig. 4). Ages: (●), probably finite and accurate; (▷), probably limiting minimum; (►), limiting minimum. Error bars shown only where exceeding size of symbol. Lithostratigraphic names informal.

of West Lake silt to specify when the unit began to accumulate. The 12-m minimum thickness in hole 6, however, implies that the West Lake silt spans at least 30,000 yr and hence probably originated no later than 100,000–130,000 yr B.P.

Depiction of Inferred Paleobathymetry

Many of the foregoing paleoecologic interpretations can be summarized in terms of minimum and maximum relative depth at a deep part of Tulare Lake (Fig. 6B). In estimating relative depth, we assume approximate proportionality between depth and lateral extent, except where we know or suspect that shoaling occurred (see "Volume of Tulare Lake Basin" below). We make minimum depth a large fraction of maximum depth for lakes whose central parts were continuously present, whereas we assign minimum depths of zero to lakes that were occasionally dry. A substantial minimum depth and an even greater maximum depth thus represent the upper part of the Chatom silt (large, fluctuating but continuously present lake), whereas maximum depth remains great and minimum depth is zero for the Blakeley Canal silt (lake often large but occasionally dry).

We argue below that relative amounts of inflow, precipitation, and evaporation at Tulare Lake have largely governed the difference between long-term minimum and maximum depth but not maximum depth itself, which we relate instead to the height of Tulare Lake's spillway. The crux of this argument is that Tulare Lake not only overflowed frequently in historic time (Fig. 5) but also overflowed frequently during nearly all of the prehistoric period represented by the deposits shown in Figure 6A.

LATE QUATERNARY OVERFLOW

A lake's susceptibility to overflow depends chiefly on the lake basin's overflow-level volume (V) relative to the volume difference between the basin's evaporation (E) and the sum of its inflow and precipitation (I + P). Historic Tulare Lake overflowed frequently because V was often approached or exceeded by (I + P) – E (Table 2).

For long periods (thousands of years, say) during the past 100,000–130,000 yr, three conditions possibly prevented Tulare Lake from overflowing. First, as allowed by diatom and ostracode assemblages (Table 3), Tulare Lake basin may have been much deeper in parts of Pleistocene time than it was during the Holocene, so that V was correspondingly larger. Second, as suggested by the courses of its northern distributaries, the Kings River may have largely or totally bypassed Tulare Lake, thereby reducing I by at least one-half (Table 1). Third, it is possible that past climates were substantially warmer or drier than those of historic time; I and P could have been lower and (or) E could have been higher in direct response to climatic change.

It is unlikely, however, that any of these three conditions prevailed for large fractions of the past 100,000–130,000 yr. And even if one or more of them did, Tulare Lake's paleolimnology suggests that, with a few possible exceptions, the lake still overflowed frequently.

Volume of Tulare Lake Basin

The Corcoran Clay Member is the only known evidence of a Quaternary lake basin in the Tulare Lake area with a volume vastly greater than that of historic Tulare Lake basin. Lacustrine deposits of the past 100,000–130,000 yr neither approach the Corcoran in lateral extent, nor are known to exceed greatly the extent of historic Tulare Lake at overflow level (Figs. 4, 6). Tulare Lake basin probably was somewhat deeper than it is today during deposition of the upper part of the Chatom silt and during deposition of the lower part of the Blakeley Canal silt (Table 3). It is unlikely, however, that the late Wisconsin basin was too large to allow overflow under a climate like that of the 19th century. If post-Chatom sedimentation in Tulare Lake has almost offset tectonic subsidence at the 0.33–0.40 m/1,000 yr rates implied by depth to the Corcoran Clay Member (Figs. 4, 7), and if the lake's spillway has undergone little post-Chatom incision or aggradation, then the post-Chatom volume of Tulare Lake basin has been decreased chiefly by subsidence of the spillway. If the spillway has subsided in post-Chatom time at the rate of 0.2 m/1,000 yr implied by depth to the Corcoran (Fig. 2), then 11,000–13,000 yr of spillway subsidence affecting a 2,000-km^2 lake would have reduced lake-basin volume by 5–6 km^3. Tulare Lake basin therefore may have held ~12–13 km^3 at the Chatom–Blakeley Canal transition, nearly twice as much as the historic basin but only 1–2 km^3 more than the volume attained by Tulare Lake when overflowing at altitude 66 m in A.D. 1853, 1862, and 1868. From these considerations, we generalize that there is no plausible value of V that could have kept Tulare Lake from overflowing frequently during the past 100,000–130,000 yr without a substantial decrease in (I + P) – E.

Course of the Kings River

Although little is known about prehistoric variations in I at Tulare Lake, two properties of the Kings River's exposed distributary systems suggest that the Kings, Tulare Lake's chief tributary, rarely made a prolonged, total bypass of the lake during the past 100,000–130,000 yr. First, both of the distributary systems having modern geomorphic expression include channels that are directed toward Tulare Lake (Fig. 3). Such channels probably made up about one-half of the channels of the older system, the axis of which points at Tulare Lake's spillway, and they make up nearly all of those of the younger system, the axis of which points south of the spillway. Second, the southerly axis of the younger distributary system may reflect a tendency for southward flow of the Kings River between major periods of alluvial-fan deposition. The older, spillway-centered distributary system dates from the last of these periods and probably has a late Wisconsin age (Huntington, 1980, p. 14–15). The breadth and symmetry of the older system reflects widespread aggradation by Kings River at that time. The younger, post-Wisconsin distributary system is restricted to a southerly course by incision into the upper part of the late Wisconsin fan (Huntington, 1980, p. 34). The southward trend of the post-Wisconsin system may reflect blockage of late Wisconsin channels by eolian sand, blown from the northwest off the late Wisconsin fan of the San Joaquin River (Fig. 3, longitudinal dunes). Such blockage may have also occurred during incision predating the late Wisconsin alluviation. If so, eolian blockage provides a means of keeping the axis of the Kings River distributary system no farther north than Tulare Lake's spillway.

Even if the Kings River were diverted out of Tulare Lake basin, wet-year inflow from other tributaries would probably fill one-third of today's basin under today's climate (Fig. 5, curve C). A pollen record from hole 8, moreover, suggests wisconsin-age climates in the Tulare Lake region that may have been cool enough to ensure overflow of such a basin, with or without Kings River inflow.

Regional Climate

Probable source areas for pollen deposited in Tulare Lake include the Coast Ranges, the San Joaquin Valley, and the Sierra Nevada. The relative importance of these source areas could have changed significantly if the Kings River—and its supply of water-borne pollen—bypassed Tulare Lake. But because prolonged, total bypass is unlikely, we assume that the pollen record described below reflects regional climatic change more than it reflects (hypothetical) diversion of the Kings River. We support this assumption by showing that the climatic history implied by Tulare Lake's pollen record generally agrees with climatic records from other parts of

California and with the climatic history implied by much of Tulare Lake's paleolimnology.

The four pollen types in Figure 6B imply an over-all cooling that began with the top of the El Rico marl, culminated in the Chatom silt, and reversed to an abrupt warming at the base of the Blakeley Canal silt. The pollen types do not require long periods of precipitation enormously different from today's. The ratio of precipitation to evaporation in the Tulare Lake region thus was probably greater during most or all of Wisconsin time than in post-Wisconsin time. These interpretations rest on the following premises concerning deposits of Tulare Lake. (1) Abundant *Quercus* (oak) pollen indicates warm, dry climates like today's (compare Adam and West, 1983). (2) Abundant pollen of the families Taxodiaceae, Cupressaceae, and Taxaceae (TCT), probably from juniper or incense cedar, implies cooler but probably not much wetter climates if due to dominance of juniper in nearby parts of the Sierra Nevada (Cole, 1983) but allows wetter climates if due to descent of incense cedar into the foothills of the Sierra Nevada and into the Coast Ranges. (3) Abundant pollen of *Artemisia* (probably sagebrush) and *Sarcobatus* (greasewood) suggest a climate cooler but not much if any wetter than today's, because these two genera today coexist in alkaline parts of Great Basin deserts, primarily north of latitude 37° (Spaulding and others, 1983, p. 259) and, in California, exclusively east of the Sierra Nevada above altitude 1,000 m (Munz and Keck, 1959, p. 383; McMinn, 1964, p. 106). The relatively scarce oak pollen and abundant TCT, sagebrush, and greasewood pollen in much of the section between the West Lake and Blakeley Canal silts may thus indicate cooler conditions with precipitation no higher than today's. Conversely for the El Rico marl and Blakeley Canal silt, the combination of abundant oak pollen and sparse TCT, sagebrush, and greasewood pollen suggests climates approximately like the modern one at Tulare Lake.

These inferences are compatible with climatic histories read from plant fossils elsewhere in California. Over-all Wisconsin-age cooling and abrupt post-Wisconsin warming have been inferred from pollen assemblages at Clear Lake, 400 km northwest of Tulare Lake in the Coast Ranges (Adam and West, 1983). Pollen data from Clear Lake also allow precipitation much greater than today's during the Wisconsin (Adam and West, 1983), but 120 km northeast of Tulare Lake, at Kings Canyon in the Sierra Nevada, late Wisconsin megafossils and pollen imply a higher ratio of precipitation to evaporation (greater effective soil moisture) but do not require significant increase in precipitation (Cole, 1983). Such a cool, dry climate is consistent with the observed increase in greasewood and sagebrush pollen at Tulare Lake during late Wisconsin time.

Our interpretation of the pollen data from hole 8 also accords well with much of the paleolimnology of Tulare Lake. The lake generally avoided desiccation and maintained low salinity during times of inferred cool climate (represented by the Chatom silt and many underlying deposits). Conversely, it occasionally dried up and (or) supported salt-tolerant organisms during times of inferred warm climate (represented by the Blakeley Canal silt and El Rico marl) (Fig. 6B). Little about Tulare Lake's paleolimnology, however, suggests prolonged lack of overflow under either cool or warm climate.

Paleolimnologic Evidence of Overflow

Overflow is suggested by two inferred properties of cool-climate Tulare Lake. First, inferred low salinity (<2 ppt) indicates that dissolved solids flowed out of the lake. Second, lack of desiccation implies susceptibility to overflow, because the relatively small Tulare Lake basin cannot exist in a nondesiccated *and* nonoverflowing state, except within a narrow range of (I + P) – E (see Table 2). This range would have to be particularly narrow if fresh-water marshes in the center of the basin, such as those indicated by the Wolfson peat, are to be explained without allowing overflow to limit the range of seasonal water-level fluctuations.

Even the warm-climate Tulare Lake represented by the Blakeley Canal silt should have overflowed frequently if, as argued above, that lake fluctuated approximately like historic Tulare Lake. The same analogy applies to the West Lake silt because the West Lake resembles the Blakeley Canal. Marl is the only Tulare Lake deposit consistent with prolonged lack of overflow; the abundant carbonate may reflect entrapment of solutes. But marl is a relatively minor lacustrine facies at Tulare Lake, known only as a few beds within the El Rico marl and Blakeley Canal silt, with an aggregate thickness of ~3 m (Fig. 6A) and a total time value (at 0.3 m/1,000 yr) of 10,000 yr. Periods when Tulare Lake failed to flush its solutes for thousands of consecutive years thus make up no more than about one-tenth of the past 100,000–130,000 yr. Tulare Lake's paleolimnology, therefore, considered together with estimates of regional climate, Kings River diversion, and lake-basin volume, indicates frequent overflow during the past 100,000–130,000 yr.

PALEOCLIMATIC SIGNIFICANCE OF LAKE SIZE

The history of long-term maximum water depth (Fig. 6B) thus translates into a history of the height of the spillway relative to the floor of Tulare Lake basin. The vertical difference between spillway and floor (Δ H) was large during deposition of the West Lake silt. Next, it decreased suddenly, then fluctuated at small values, and occasionally reached zero until deposition of the Chatom silt. During deposition of the Chatom silt, Δ H increased as fast as 1–2 m/ka until reaching a value similar to that implied by the West Lake silt. Finally, during deposition of the Blakeley Canal silt, Δ H remained large but decreased slightly.

This inferred history of a frequently overtopped spillway resolves seeming paradoxes in the relation between the regional paleoclimate implied by our pollen record and the paleobathymetry suggested by lateral extent of lacustrine deposits. If post-Wisconsin climates produced less effective moisture than did Wisconsin climates, then why was Tulare Lake often about as deep (extensive) in post-Wisconsin time as it was during late Wisconsin time? Similarly, why was Tulare Lake often deeper (more extensive) in post-Wisconsin time than it ever was in the early and middle Wisconsin? Our answer is that long-term maximum depth (maximum extent) depends on Δ H rather than on (I + P) – E.

Dependence of maximum depth on spillway height does not, however, uncouple Tulare Lake's paleobathymetry from paleoclimate. Climate probably dictates much of the short-term difference between minima and maxima in the depth of Tulare Lake; above, we have shown that this difference, expressed by such properties as water salinity and degree of lake-bottom desiccation, is consistent with the paleoclimate that we infer from pollen. But as we show below, deposits beneath Tulare Lake may also provide fairly direct evidence of the age and extent of mountain ice caps far upstream.

SPILLWAY AS FAN DAM

Building of Dam

Hypothetically, Δ H might increase from aggradation by the Kings River, aggradation by Los Gatos Creek, differential tectonic subsidence, or some combination of these processes. It is suggested by three lines of evidence, however, that aggradation by the Kings River is the dominant cause of the late Wisconsin increase in Δ H.

1. *During the late Wisconsin, aggradation on the Kings River fan was probably much more rapid than either aggradation on the Los Gatos Creek fan or differential tectonic subsidence between spillway and basin.* We acknowledge that Tulare Lake's spillway coincides with the toe of the Los Gatos Creek fan, as well as with the toe

of the Kings River fan (Figs. 2, 3; Mendenhall and others, 1916, p. 21) and that Coast Range streams aggrade episodically (Bull, 1964; Lettis, 1982). The Kings River, however, not only aggraded primarily in pulses that may make up less than one-third of the past 600,000 yr (Janda and Croft, 1967, p. 182), but its most recent aggradational pulse (represented by the Modesto Formation; Fig. 3) probably began in Wisconsin time and ended about 10,000 yr B.P. (Marchand and Allwardt, 1981, p. 60–61). At least the latest part of an episode of vigorous aggradation on the Kings River fan thus coincides with the time of spillway rise represented by the Chatom silt. By contrast, the Los Gatos Creek fan lacks prominent buried soils (U.S. Geological Survey and U.S. Bureau of Reclamation, unpub. borehole data 1960–1982) and has widespread late Holocene deposits at its apex (Fig. 3), evidence that the Los Gatos Creek fan has been aggraded more continuously than has the Kings River fan (the apex of which has strong buried soils) and not necessarily in phase with the late Wisconsin rise of Tulare Lake's spillway.

As for differential tectonic subsidence, we acknowledge that Tulare Lake's basin has subsided faster than its spillway in Quaternary time (Fig. 2; Davis and Green, 1962). This differential would, however, have to exceed the long-term average (~0.2 m/1,000 yr) at least five-fold in order to cause the spillway rise of 1–2 m/ka implied by the altitudes and U.S. Geological Survey ^{14}C ages of transgressive peat at the base of the Chatom silt. Although tectonism near Tulare Lake has been episodic during the late Cenozoic (Harding, 1976; Stein and King, 1984), no independent evidence suggests five-fold increase in differential-subsidence rate during late Wisconsin time. Moreover, it seems more than fortuitous that the greatest spillway rise of the past 70,000–100,000 yr should coincide with the greatest departure from modern vegetation within that time period (Fig. 6B). The late Wisconsin increase in Δ H is better explained as a by-product of extreme climate than as a consequence of extraordinary tectonism.

2. *The Kings River carried the same kind of detritus that accumulated in Tulare Lake while the spillway rose in late Wisconsin time.* Modesto Formation silt on the Kings River fan closely resembles the Chatom silt petrographically and in X-ray pattern: both are arkosic and micaceous, and both contain unweathered plagioclase and much unweathered green hornblende. Deposits of the Los Gatos Creek fan have none of these properties. If Los Gatos Creek caused most of the spillway rise in Chatom-silt time, then it must have scarcely aggraded that half of its fan bordering Tulare Lake basin, despite an evident tendency toward symmetry (Fig. 3, dotted-line contours). More probably, the Kings River vigorously aggraded Tulare Lake's spillway by means of central distributaries, simultaneously delivering detritus to the lake itself via more southerly channels.

3. *Los Gatos Creek deposition and differential tectonic subsidence have merely facilitated damming of Tulare Lake by the Kings River fan.* Deposition by Los Gatos Creek appears to have pushed the San Joaquin Valley's axial drainage well east of the valley's structural axis during the past 600,000 yr (Fig. 3). This apparent deflection may have facilitated rapid deposition by the Kings River at Tulare Lake's spillway by displacing the spillway up the Kings River fan, to a location where the Kings River might supply more and coarser sediment. Differential tectonic subsidence has probably promoted Kings River deposition at the spillway by flattening the gradient of trunk drainage across the site of the spillway. Such flattening probably accounts for the slope change in the trunk-stream profile of 27,000 yr B.P. near the San Joaquin River fan (Fig. 2).

Alluvial damming by Kings River sediment may also explain some of the lacustrine transgressions that predate the Chatom silt. Soft silt resembling Kings River detritus makes up the soft silt in the sand–peat–soft gray silt sequences between the Wolfson peat and the Chatom silt. By the reasoning in 2 above, it is unlikely that these transgressive sequences result from damming by Los Gatos Creek alluvium. They result from damming by Kings River alluvium or, perhaps, from rapid differential subsidence.

Lowering of Dam

Δ H might decrease by sedimentary filling of the basin, tectonic subsidence of the spillway, incision of the spillway, or some combination of these processes. We speculate that filling, subsidence, and incision all contributed to the great shrinkage of Tulare Lake basin that is implied by the top contact of the West Lake silt.

The West Lake silt probably could not have filled Tulare Lake basin without concurrent subsidence of the basin's spillway. If sedimentation in the basin approximately offsets tectonic subsidence, the time required to fill the basin depends primarily on the absolute rate of spillway subsidence, provided the spillway neither aggrades nor gets incised. With the spillway subsiding at 0.2 m/1,000 yr, the lowest part of the present lake basin (10 m below threshold) would approach spillway level after ~50,000 yr of basin sedimentation. Drastic reduction in the volume of Tulare Lake basin would probably occur sooner, within 20,000 yr, because the average depth of the present basin is 4 m (depth at 50% of overflow-level area; Fig. 5). Estimating 10,000 yr since completion of today's dam, we thus argue by analogy that the Tulare Lake basin represented by the West Lake silt greatly decreased in volume within 30,000 yr of its dam's completion and may have disappeared altogether within another 30,000 yr thereafter.

After subsiding for tens of thousands of years, Tulare Lake's spillway may have been lowered further, and more suddenly, by incision. The top of the West Lake silt so nearly parallels inferred time lines that it suggests abrupt lowering of maximum water level (incision of the fan dam) rather than gradual lakeward progradation of Los Gatos Creek fan. This incision may have been caused by climatic change: the silt immediately overlying the West Lake in holes 7 and 8 suggests more frequent overflow and consequently suggests greater likelihood of incision than does the West Lake itself, because this overlying silt lacks sign of lake-wide desiccation (Fig. 6B). Less probably, the incision was caused by lowering of sea level; far downstream at Carquinez Strait (Fig. 1), bedrock sills at modern altitudes near −40 m limit allowable low-stand incision along San Joaquin Valley drainages (Fig. 2).

Inferred History of Dam

Tulare Lake's spillway is a fan dam, the history of which can be summarized as follows.

West Lake Silt. The relatively high dam that held the lake in which the West Lake silt accumulated originated at some time before 100,000–130,000 yr B.P. We have no direct evidence that Kings River alluvium built the dam, but similarities between the West Lake and Blakeley Canal silts suggest that this is so. The dam impounded an extensive, occasionally dry lacustrine basin for at least 30,000 yr. During much of this time, the dam was gradually lowered relative to part or all of the basin by the combined effects of differential subsidence and basin sedimentation. Eventually, as the basin began to hold a perennial lake, the overflow-level area of Tulare Lake basin shrank drastically, perhaps by incision of the fan dam.

Deposits between the West Lake and Chatom silts. The basin stayed small during the next 45,000–75,000 yr; the fan dam was low. On at least three occasions (represented by the probable buried soils and inferred channel in hole 7), the dam was so low with respect to the basin floor that the site of Tulare Lake was an alluvial plain traversed by a trunk stream. But most of the time a low dam held an overflowing lake. A few times the dam grew so rapidly that it caused small lacustrine transgressions. These transgressions may have been due to dam building by Kings River alluvium.

Chatom and Blakeley Canal silts. The dam for Tulare Lake basin was low or nonexistent at 26,000–27,000 yr B.P. Immediately thereafter, the Kings River began to build a dam that eventually reached the size of the large dam represented by the West Lake silt. The dam of the past 26,000 yr was frequently overtopped, more so before about 11,000–13,000 yr B.P. (during deposition of the Chatom silt) than since that time (during deposition of the Blakeley Canal silt). Substantial growth of the dam probably ended when deposition of the Modesto Formation ceased about 10,000 yr B.P. Height of the dam above the basin has probably been reduced since then by combined effects of basin sedimentation and spillway subsidence. Today's spillway is chiefly a relict dam.

SYNCHRONEITY OF GLACIATION AND DAM-BUILDING

Last Major Glaciation

If Kings River alluviation produced the high dam that impounded Tulare Lake in Chatom-silt time, then that dam was probably a result of glaciation in the Sierra Nevada because, as shown by Arkley (1962), Janda and Croft (1967), and Marchand (1977), glaciers induced the major episodes of late Pleistocene aggradation by major streams of the eastern San Joaquin Valley. Glacial rock flour is among the best evidence of this proglacial deposition. As first reported by Arkley (1962), arkosic silt in the major aggradational units of the eastern San Joaquin Valley (Modesto, Riverbank, and Tulock Lake Formations; Figs. 3, 8; Figure 8 is on folded insert) abounds in hornblende and plagioclase characterized by angularity and lack of weathering that indicate glacial abrasion. Such rock flour makes up much of the Modesto Formation on the Kings River fan (Huntington, 1980, p. 120–121) and also predominates in the Chatom silt, which is probably coeval with most of the Modesto Formation (see below). The accumulation of glacial rock flour on the Kings River fan and in the lake behind the growing fan dam thus suggests that outwash built much of the dam itself (Fig. 9).

Three further lines of evidence imply that the Kings River fan began to dam Tulare Lake during and probably early in the last major Sierra Nevada glaciation. First, the Chatom silt originated at least 10,000 yr *before* the last major *de*glaciation, which is recorded at Tulare Lake by the onset of intermittent desiccation and by shift to warm-dry vegetation and weathered and (or) granite-poor source areas (contact between the Chatom and Blakeley Canal silts). Second, there was probably little delay between establishment of widespread glaciers in the Sierra Nevada and onset of widespread outwash-fan deposition in the San Joaquin Valley. Many al-

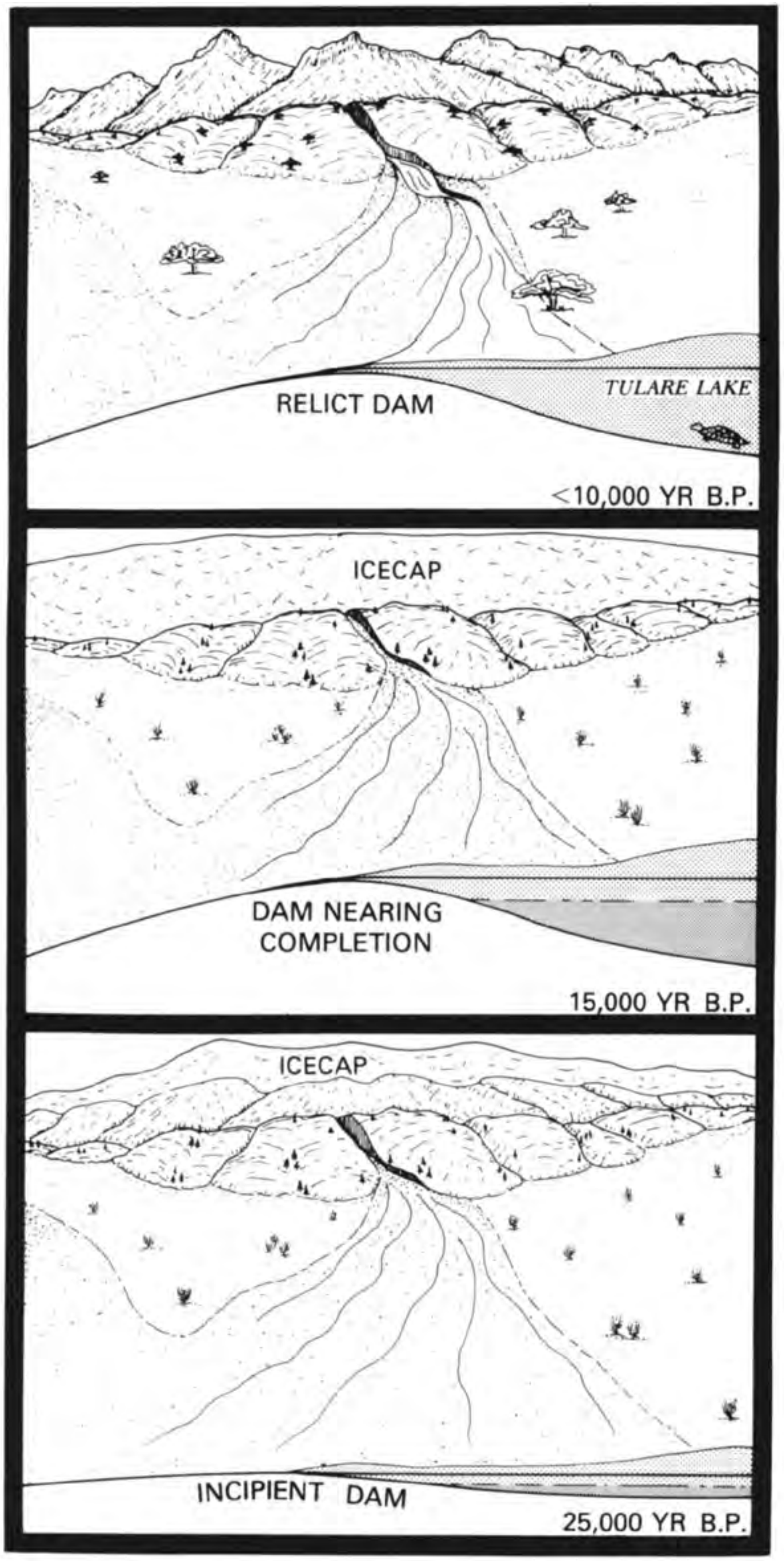


Figure 9. Model for history of Tulare Lake during past 25,000 yr. On schematic cross sections, lake is shaded where perennial, unshaded where intermittent. Bottom: incipient dam at toe of vigorously aggrading Kings River fan, shortly after onset of last major glaciation of Sierra Nevada. Level of shallow lake behind dam ranges between horizontal dashed and solid lines; probably the lake overflows the dam most of the time. Sagebrush dots floor of valley; juniper and (or) incense cedar grow in foothills. San Joaquin River fan at left. Middle: late-glacial dam, relatively deep lake kept mainly full by melt water and low rate of evaporation; vegetation same as in bottom view. Top: relict dam 10–13 m above lowest part of basin. Occasionally dry lake, oak savanna, and absence of mountain ice cap reflect change to relatively warm climate with less effective moisture. Incision of Kings River fan reflects low sediment yield from formerly glaciated parts of Sierra Nevada.

pine glaciers of late Wisconsin age in western North America generated large quantities of outwash during advances (Hamilton, 1982; Clague, 1976). The rock flour of San Joaquin Valley fans probably represents such outwash because it commonly bears a cap of sand that suggests erosion of freshly bared till during glacial recession (Arkley, 1962; Marchand, 1977). Third, although a case can be made for a long lag, available evidence favors a short lag between the onset of outwash-fan deposition and initiation of prodigious dam-building in Wisconsin time.

The case for a long lag entails early-glacial aggradation of narrow, wedge-shaped sectors on the sides, but not on the axial part, of the Kings River fan. The apparent structural high at Tulare Lake's present spillway (Fig. 2, short-dashed line) could have prevented building of the dam prior to deposition of fan segments on either side. Such sectored aggradation also could account for the small maximum depths (low dams) inferred for Tulare Lake of the early and middle Wisconsin (Fig. 6B), times for which Marchand and Allwardt (1981, p. 57) presumed episodically heavy glacial-outwash deposition in the San Joaquin Valley. These arguments, however, can be turned around to support dam-building by outwash early in the last glaciation.

The apparent structural high at the present spillway is an artifact of deflection of the San Joaquin Valley's topographic axis away from the post-Corcoran synclinal axis; the Corcoran Clay Member beneath the Kings River fan strikes parallel to the over-all trend of the San Joaquin Valley and normal to the axis of the Wisconsin-age Kings River fan (Davis and others, 1959, Pl. 14; Croft, 1972, Pl. 4). The deformation expressed by the Corcoran therefore probably provided no barrier to widespread deposition on the Kings River fan, including that part coinciding with Tulare Lake's spillway.

Although Marchand and Allwardt (1981, p. 57) inferred occasional heavy deposition of early or middle Wisconsin outwash in the San Joaquin Valley, subsequent work shows that this outwash was probably deposited during late Wisconsin time. On solid-stem augers we have recovered wood with a ^{14}C age of 31,250 ± 325 yr (USGS-1239) ~5 m below the base of the Modesto Formation at the northwestern toe of the Tuolumne River fan (Fig. 8 and Table 5; both on folded insert). We approximate the base of the Modesto Formation by downfan projection of a buried soil that immediately underlies the Modesto (top of the Riverbank Formation), parallel to both the top of the Modesto Formation and the top of a unit within the Riverbank Formation (Fig. 8B). The date suggests that the Modesto Formation, which probably embraces all of the widespread Wisconsin-age outwash in the San Joaquin Valley, is younger than 32,000 yr.

The early or middle Wisconsin age inferred by Marchand and Allwardt (1981) for the oldest part of the Modesto Formation was based upon two arguments that now seem doubtful. One argument is that the soils on some fan-toe facies of the Modesto Formation suggest a parent-material age greater than late Wisconsin. The Fresno series, the most widespread and strongly developed of these soils, was regarded as diagnostic of relatively great age because it contains an argillic B horizon and a SiO_2- and $CaCO_3$-cemented hardpan (Marchand and Allwardt, 1981, p. 6, 55–56, 61). But Arkley (1964) has mapped a Fresno-series soil at the ground surface 20 m above the wood of USGS-1239. Perhaps that date is erroneously young, like some of our dates from Tulare Lake. More probably, Fresno-series soils at the toe of the Tuolumne River fan began to form long after 32,000 yr B.P and developed quickly because, as reported by Arkley (1964), these soils contain finer sediment and more pore-water sodium than do soils farther up the Modesto-age fan.

The other argument of Marchand and Allwardt (1981) involves a ^{14}C date of 42,400 ± 1,000 yr B.P. (USGS-429) on wood from a sketchily logged water well. Marchand and Allwardt (1981, p. 57) inferred that the wood came from fan deposits of the Modesto Formation. A new drill hole beside that water well establishes, however, that the wood came from a fining-upward channel-fill sequence much thicker than the channel fills typically found in fan deposits of the Tuolumne River (Fig. 8B). The wood was probably deposited in a channel fill of the trunk San Joaquin River, and the aggradation that it dates was probably restricted to the vicinity of that trunk stream, rather than involving much of the Tuolumne River fan. If so, the wood need not date any part of the Modesto Formation. No other middle or early Wisconsin ^{14}C ages have been assigned to the Modesto Formation. An experimental uranium-trend age (Rosholt, 1980) of 95,000 ± 45,000 yr from a soil on a high (old) Modesto Formation terrace near the Merced River (Marchand and Allwardt, 1981, p. 57) was recently revised to 42,000 ± 16,000 yr (J. N. Rosholt, 1982, personal commun.). Our 31,250-yr ^{14}C age (USGS-1239) thus stands uncontradicted as a limiting maximum for the Modesto Formation; probably fewer than 6,000 yr elapsed between the onset of the last major episode of outwash-fan aggradation in the northern San Joaquin Valley (oldest part of the Modesto Formation at the toe of the Tuolumac River fan) and the birth of the last major fan dam for Tulare Lake (basal peat layer of the Chatom silt).

Penultimate Major Glaciation

If the fan dam that allowed deposition of the Chatom silt was, indeed, a result of the last major glaciation of the Sierra Nevada, then similar dams should have been built by earlier major glaciations. None of the lacustrine deposits between the West Lake and Chatom silts, however, have sufficient lateral extent to suggest a high dam from the penultimate major Sierra Nevada glaciation. Rather, we predict that a penultimate-glacial analog of the Chatom silt lies immediately beneath the central part of the West Lake silt, no shallower than the lower time line in Figure 6A, the approximate age of which by the average sedimentation rates in Figure 7 falls between 100,000 and 130,000 yr.

TIMING OF SIERRA NEVADA GLACIATIONS

We thus interpret the depositional history of Tulare Lake as indicating that the last major glaciation of the Sierra Nevada, the Tioga stage of Blackwelder (1931), began about 26,000 yr B.P. and that the preceding major glaciation, probably Blackwelder's Tahoe stage (Burke and Birkeland, 1979), began before 100,000 yr B.P. (Fig. 6B). This suggested chronology places the onset of the Tioga glaciation near the first late Wisconsin advance of the Huron Lobe of the Laurentide Ice Sheet (about 23,000 yr B.P.; Dreimanis and Goldthwait, 1973, p. 89), near the beginning of late Wisconsin glaciation of Alaska's Brooks Range (between 30,000 and 24,000 yr B.P.; Hamilton, 1982), and near the beginning of marine oxygen-isotope stage 2 (29,000 yr B.P.; Hays and others, 1976). Our estimate for the Tahoe glaciation conflicts with the Tahoe's traditional assignment to the early Wisconsin (Blackwelder, 1931; Wahrhaftig and Birman, 1965, p. 307) but allows contemporaneity with the penultimate major glaciation recorded in the Rocky Mountains (about 140,000 yr B.P.; Pierce and others, 1976).

A particularly interesting aspect of our proposed glacial history is that it disallows major glaciation of early or middle Wisconsin age in the Sierra Nevada. Major early or middle Wisconsin glaciation has been inferred not only for the Sierra Nevada (Wahrhaftig and Birman, 1965, p. 307; Gillespie, 1982), but also as part of the last major glaciation in the Rocky Mountains (the Pinedale stage of Blackwelder, 1915). Pinedale glaciers originated at least 45,000 yr ago and were near their maximum extent in some drainages at least once before 25,000 yr B.P., according to Pierce and others (1976), who cited obsidian-hydration ages for glacial abrasion near West Yellowstone, Montana, and according to Porter and others (1983, p. 97–100), who reviewed additional evidence from weathering rinds and radiocarbon dates. Perhaps some of these earlier Pinedale events correspond to minor glacial events in the Sierra Nevada. The uppermost soft gray silt beneath the Chatom silt in hole 8 could mark such a minor Sierra Nevada glaciation because, although small, this body of silt closely resembles the soft facies of Chatom silt in overlapping peat and sand and in containing abundant *S. niagarae* and TCT pollen. Deeper small bodies of soft gray silt may likewise represent minor glaciations, most of early Wisconsin age (Fig. 6B).

Regarding pre-Wisconsin glaciations, it is intriguing that Croft's (1972) "A clay" unit occupies the same approximate depth range as does our Blakeley Canal and Chatom silts and that his "B clay" unit likewise coincides approximately with our West Lake silt. [These correlations are stronger beneath Tulare Lake bed (see Croft, 1972, Pls. 1, 3) than high on the fan of Los Gatos Creek, where brown-and-gray-mottled alluvial silt that Croft (1972, p. 9) correlated with his "A clay" and "B clay" unit matches poorly with our major lucustrine units (Figs. 4, 7A)]. If the bulk of the "A clay" indeed accumulated behind a dam of glacial outwash, then all of Croft's other lacustrine units above the Corcoran Clay Member ("B clay," "C clay," and "D clay" units; Fig. 4) may have the same origin. Deposits beneath Tulare Lake bed may thereby provide a record of at least 4 major Sierra Nevada glaciations younger than 600,000 yr.

Tulare Lake's history could be too complex to serve as a proxy for the glacial history of the Sierra Nevada. Perhaps the glacial signal at Tulare Lake has been obscured by change in course of the Kings River, by aggradation on the Los Gatos Creek fan, by differential tectonic subsidence, by fluctuation of sea level, by sectored aggradation on the Kings River fan, or by other complicating processes. The evidence available at present, however, grants Tulare Lake unusual potential as a recorder of the timing, magnitude, and climatic context of Sierra Nevada glaciations.

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Lake levels for the past 19,000 years from the TL05-4 cores, Tulare Lake, California, USA: Geophysical and geochemical proxies

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Geochemical and geophysical proxy data from the TL05-4 lake-plain cores of Tulare Lake, California, are reported on here representing most of the past 19,000 years. The new record consists of carbon/nitrogen ratios, total organic carbon (TOC), nitrogen (N), total inorganic carbon (TIC), grain size, and magnetic susceptibility analyses from samples taken at 1-cm intervals (~45 yr/sample). Age control is provided by 22 radiocarbon dates. The first part of the record (~19.0–14.5 cal ka BP) consists of elevated sand and silt percentages and higher sedimentation rates interpreted as elevated runoff associated with melting of the Tioga-age Sierra Nevada ice cap. The TIC was undetectable and TOC and N were low suggesting low productivity in a relatively sterile, freshwater lake. From 14.5 to 10.3 cal ka BP, the deposits consisted of 50% clay and 50% silt with TIC and TOC extremely low, which is consistent with a stable, low productivity lake. From 10.3 to 7.5 cal ka BP, an initial pulse of fining upward sand gave way to increased clay deposition that suggests a lake transgression to a stable highstand, coeval with the deep water event found in previously published records of Tulare Lake and other lakes from central and southern California, including Owens Lake and Lake Elsinore. A few-hundred-year duration spikes in TIC centered at 8.0 cal ka BP is suggestive of evaporating lake conditions toward the end of this early Holocene highstand. Tulare Lake dropped quickly to a relative low at 7.5 cal ka BP, but then lake level increased steadily until 3.0 cal ka BP. High amplitude fluctuation in almost all proxies occurs from 2.5 to 1.8 cal ka BP at the end of the record, suggesting that this time interval was characterized by rapid fluctuations in lake level. Tulare Lake levels during the Holocene vary in conjunction with sea surface temperature (SST) records from the Ocean Drilling Program (ODP) Site 1017 located off the coast of central California, which suggests that variations in SSTs throughout the Holocene drove changes in precipitation in the Sierra Nevada and hence, Tulare Lake level. Since historic lake-level histories have been shown to be directly related to stream discharge from the Sierra Nevada, this observation will be integral in forecasting future decadal-scale changes in southern San Joaquin Valley water supply due to anticipated climate change.

1. Introduction

Tulare Lake is located in the San Joaquin Valley of central California, one of the world's foremost agricultural regions, between the Coast Ranges and the Sierra Nevada (Fig. 1). Over the past 19,000 years Tulare Lake has fluctuated by several tens of meters in response to regional climate change and changes in elevation of the sill formed at the northern end of the lake by alluvial fans from the Sierra Nevada and Coast Ranges (Fig. 1) (Atwater et al., 1986; Davis, 1999; Negrini et al., 2006). The relative lake level history of Tulare Lake is an important source of data toward understanding paleoclimate change in western North America following the last glacial maximum.

Davis (1999) produced a record of late Quaternary climate change for the Tulare Lake region based on the palynology of a depocenter core and provided conclusions on relative lake level during the late Pleistocene and Holocene. Negrini et al. (2006) refined this study using shoreline and lake-plain trenches to constrain absolute elevations and dates of lake levels throughout the Holocene. The study reported here builds on the previous two by providing an improved chronology (22 radiocarbon dates) and much higher resolution sampling (one sample per cm = one sample per <50 y) for the latest Pleistocene and late Holocene using geochemical and geophysical proxies for relative lake level.

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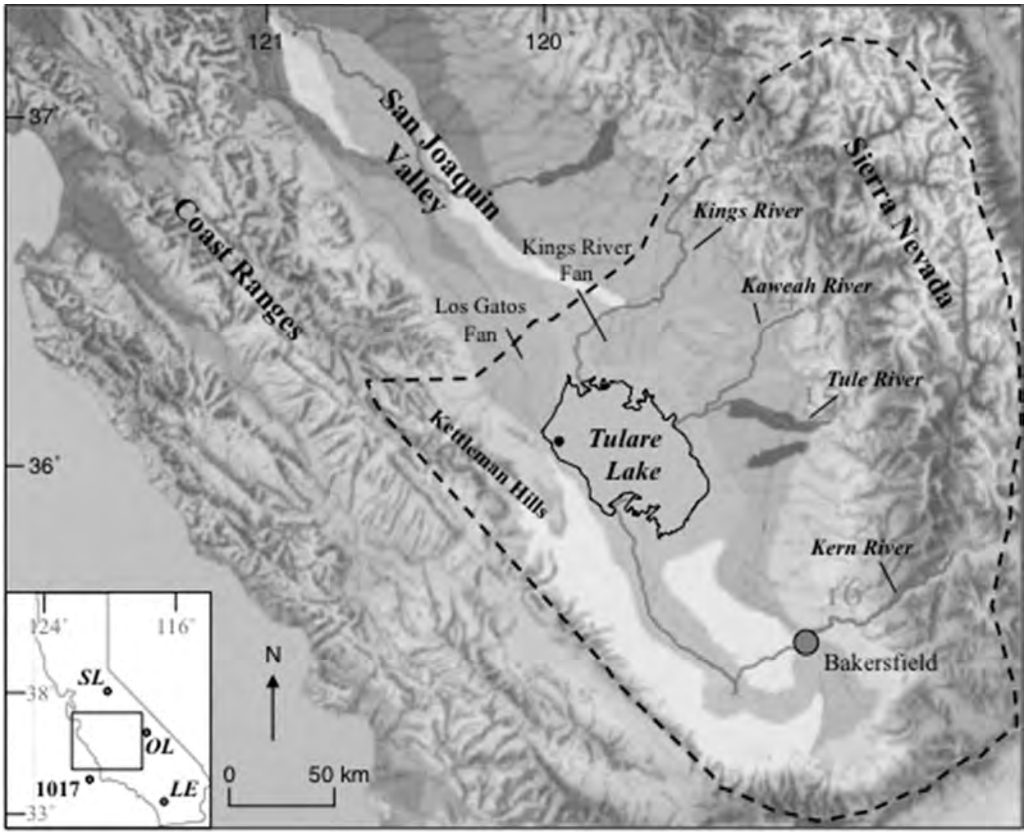

Fig. 1. Map of Tulare Lake and surrounding area. Tulare Lake drainage basin is outlined by bold dashed line. Filled circle near the northwestern margin of Tulare Lake shows the location of the TL05-4 cores taken adjacent to trenches upon which the previous study of Tulare Lake is based (see also Fig. 5 of Negrini et al., 2006). Inset shows location of Swamp Lake (SL), Owens Lake (OL), Lake Elsinore (LE), and ODP Site 1017 which are all referred to in the text.

This refined lake level history has the potential to constrain decadal-to centennial-scale forecasts of water resource variations in the San Joaquin Valley, forecasts at time scales relevant to water management policy decisions. Of further relevance is the fact that Tulare Lake level has been linked closely with the composite discharge of southern Sierra Nevada streams as established by water balance modeling (Harding, 1949; Atwater et al., 1986) wherein the 30 years of historical lake-level records (1850–1880) prior to drainage diversion were modeled accurately based on stream discharge data for the same time period. Furthermore, understanding the lake-level history of Tulare Lake over the past 15,000 years is important toward understanding early Paleo-Indian occupation of North America. High concentrations of Clovis-age and younger artifacts are found in an areally restricted, elongate region that is parallel to the southern margin of the lake basin and at an elevation of 56–58.5 masl (Riddell and Olsen, 1969; Wallace and Riddell, 1988; West et al., 1991; Fenenga, 1993). The locations of associated occupation sites were proposed to have been the result of a stable and low surface elevation of Tulare Lake during the "Clovis Drought" of Haynes (1991) at 12.9 cal ka BP and into the Holocene. The testing of this hypothesis has proved difficult largely due to agricultural disturbances that have disrupted or destroyed stratigraphic relationships.

2. Regional setting

2.1. Modern climate

As defined by the Köppen Climate Classification System, Tulare Lake is currently a semi-arid steppe characterized by low relative humidity, sporadic rainfall, and potential evapotranspiration that exceeds average rainfall (Köppen, 1936; Peel et al., 2004). Mean annual temperatures are 16.5–17.5 °C (62–63.5 °F). Summers have mean high temperatures of 33–37 °C (91–98 °F) and mean low temperatures of 15–17 °C (59–63 °F). Mean high temperatures in the winter are within 12–17 °C (54–63 °F) and winter mean low temperatures are within 1–5 °C (34–41 °F). Mean annual precipitation is 19.3–21.8 cm (7.6–8.6 in). The wettest months are October to March when 85–92% of rainfall occurs. Northwest and west-northwest winds with speeds of 5–25 kmph (3–15 mph) are common (Preston, 1981). Low precipitation and high temperatures produce evaporation rates of standing water of at least 1 m (3.3 ft)/yr, which exceeds annual precipitation rates by almost an order of magnitude (Atwater et al., 1986), thus runoff from the Sierra Nevada is required to produce a perennial lake. The western Sierra Nevada is characterized by warm, dry summers and cool, wet winters. Summer temperatures average 20.4 °C (68.7 °F) and winter temperatures average 4.1 °C (39.4 °F). Annual precipitation averages between 81 and 163 cm (32–64 in) with 90% occurring between November and May. Snowfall comprises between 25 and 40% of precipitation and averages from 184 to 402 cm (72–158 in) annually.

2.2. Geological setting

Tulare Lake is located in the San Joaquin Valley of California between the Kettleman Hills of the Coast Ranges and the Sierra Nevada (Fig. 1). Although currently dry due to agriculture diversion, historical data shows that Tulare Lake was the largest freshwater lake in the US by surface area (1600 km^2) west of the Great Lakes with a maximum depth of 12 m. Tulare Lake is fed by the Kings, Kaweah, Tule, and Kern Rivers the headwaters of which are in the Sierra Nevada (Fig. 1). The ephemeral streams emanating from the

Kettleman Hills to the west did not significantly affect lake level historically (Atwater et al., 1986). Nonetheless, at the north end of Tulare Lake, the alluvial fans of Los Gatos Creek and the Kings River meet in the valley and formed a sill during the last glacial maximum (MIS2) and effectively transformed the area into a closed basin lake system (Atwater et al., 1986).

The sediments of Tulare Lake are primarily silt and clay. West of the Tulare Lake beds, between the lake bed and the Kettleman Hills, the lake deposits are overlain and/or intercalated with alluvial fan deposits formed by ephemeral streams (Negrini et al., 2006).

3. Methods

Two adjacent, multidrive cores, TL05-4A (36.0066094, −119.936270) and TL05-4B (36.0065750, −119.9362444), were obtained from within 100 m of Lake Plain Trench A, the location of which is shown in Fig. 5 of Negrini et al. (2006) (Fig. 1). TL05-4A consisted of ten drives and reached a depth of 15.1 m below ground surface level (mbgs). TL05-4B consisted of nine drives and extended to 11.7 mbgs.

The top three drives of TL05-4A (0.33–4.40 mbgs) and the second drive of TL05-4B (1.08–2.45 mbgs) were split, described, digitally photographed, and sampled at a 1-cm interval (N = 440) for all analyses described below unless otherwise stated. Drive 2 of TL05-4B provided coverage for an unrecovered 64-cm long section of TL05-4A. Magnetic susceptibility was used to correlate individual cores and construct a composite core.

Twenty-two bulk organic carbon samples were collected for AMS ^{14}C dating. Samples for radiocarbon dating were collected every 20–40 cm from core TL05-4A and every 15–20 cm from core TL05-4B. Samples were processed and analyzed at the University of California, Irvine Keck Carbon Cycle AMS Laboratory or the University of Arizona AMS Laboratory. All dates were calibrated using CALIB 6.0 and the INTCAL09.14c data set (Stuiver and Reimer, 1993; Reimer et al., 2009).

Grain size was determined using a Malvern Mastersizer 2000 laser diffraction, grain-size analyzer. Sediment samples were soaked in deionized water at least 24 h and sieved to <1 mm. Grains larger than 1 mm were rarely found and never accounted for more than a few milligrams. Two methods of analysis were employed: 1) a splitter aliquot was utilized to reach ideal laser obscuration, as discussed in Sperazza et al. (2004), and 2) settled grains were extracted via pipette from samples vigorously stirred and allowed to settle for 1.5 min. The latter method was designed to better identify the grain size of the coarse fraction whose corresponding peaks would otherwise be convolved with the rest of the grain-size distribution.

Magnetic susceptibility was measured at 1 cm intervals with a Bartington MS2/MS2B magnetic susceptibility meter/sensor combination. Meter readings were multiplied by 1E-06 to yield dimensionless cgs units of volume-normalized susceptibility.

Total inorganic carbon (TIC) for core TL05-4A was determined at CSU Bakersfield using a UIC model 5020 Carbon Coulometer CM150 after the TIC was liberated from the sample in the form of CO_2 gas in a UIC CM5230 Acidification Module. One hundred milligram samples were ground and dried at 105 °C for at least 24 h, placed into silicone cups and acidified. The TIC for core TL05-4B was analyzed at the University of Minnesota Limnological Research Center Core Facility (LacCore) using the same methodology and equipment as with the samples run at CSU Bakersfield. In both cases, instrument sensitivity was 1 μg C or, given typical sample sizes of 100 mg, ~10 ppm. Sample reproducibility was better than 1%, both within and between laboratories.

Total carbon (TC) and nitrogen were determined using a Costech 4010 Elemental Analyzer. Ten mg samples were ground, dried at 105 °C at least 24 h, placed into tin cups, and combusted within the elemental analyzer to determine mass percent TC and N with sensitivities down to 10 ppm. Total organic carbon (TOC) was determined by subtracting TIC results from TC results. TOC and N were then used to determine C/N ratios, which were converted to molar ratios after McFadden et al. (2005).

4. Results

4.1. Age control

Two radiocarbon dates (TL04A-2-50-52 and 04B-2-100-102) were rejected due to stratigraphic inversions (e.g. older over younger) (Table 1). A two-part age model was constructed minimizing the sum of the squared residuals for exponential ($r^2 = 0.872$; n = 14; p = 0.0001) and 2nd order polynomial ($r^2 = 0.952$; n = 6; p = 0.0002) curves from the remaining twenty AMS ^{14}C dates (Fig. 2). Based on the model, the sediments in the cores range in age from approximately 19.0–1.8 cal ka BP. The sedimentation rates vary from 11.7 to 122.6 yr/cm with a mean of 42.9 yr/cm. Expressed in cm/yr, sedimentation rates vary from 0.012 to 0.086 cm per year with a mean of 0.032 cm/yr.

Table 1
Bulk organic radiocarbon dates for TL05-4A and TL05-4B cores.

Sample name	Lab#	Depth interval (cm)	Depth (cm)	^{14}C age BP	±	Cal yr BP mean	Cal yr 2σ
TL05-4A-1-82-85	UCI36682	76–79	77.5	3110	30	3342	3256–3392
TL05-4B-2-11-14	AA100123	110–113	111.5	2655	40	2771	2736–2849
TL05-4B-2-21-24	AA100124	120–123	121.5	2695	52	2807	2741–2888
TL05-4B-2-40-42	AA100125	139–141	140.0	3038	42	3257	3141–3361
TL05-4B-2-55-57	AA100126	154–156	155.0	3509	42	3779	3687–3893
TL05-4A-2-26-32	UCI36684	163–169	166.0	4585	20	5310	5287–5322
TL05-4A-2-37-39	AA100117	174–176	175.0	5708	57	6502	6397–6656
TL05-4B-2-81-84	AA100127	180–183	181.5	5232	45	5988	5912–6032
TL05-4A-2-50-52	UCI36692	187–189	188.0	7665	30	8447	8403–8522
TL05-4B-2-100-102	AA100128	199–201	200.0	4275	43	4847	4811–4922
TL05-4B-2-118-120	AA100129	217–219	218.0	7366	51	8186	8040–8322
TL05-4B-2-132-134	AA100130	230–232	231.0	6357	51	7295	7235–7418
TL05-4A-2-95-97	UCI36685	232–234	233.0	8020	25	8896	8857–9008
TL05-4A-2-101-103	AA100118	238–240	239.0	7408	51	8250	8157–8364
TL05-4B-2-144-146	AA100131	243–245	244.0	7521	54	8341	8277–8411
TL05-4A-2-113-117	AA100119	250–254	252.0	7682	70	8479	8380–8592
TL05-4A-2-131-134	AA100120	268–271	269.5	9750	72	11,171	11,066–11,306
TL05-4A-2-144-147	AA100121	281–284	282.5	9995	82	11,497	11,237–11,817
TL05-4A-3-12-17	AA100122	303–308	305.5	10,907	73	12,782	12,605–12,971
TL05-4A-3-20-24	UCI36686	313–317	315.0	12,665	25	15,011	14,642–15,228
TL05-4A-3-54-60	UCI36687	345–349	347.0	13,040	30	15,719	15,181–16,346
TL05-4A-3-100-104	UCI36691	390–394	392.0	14,525	40	17,687	17,370–17,940

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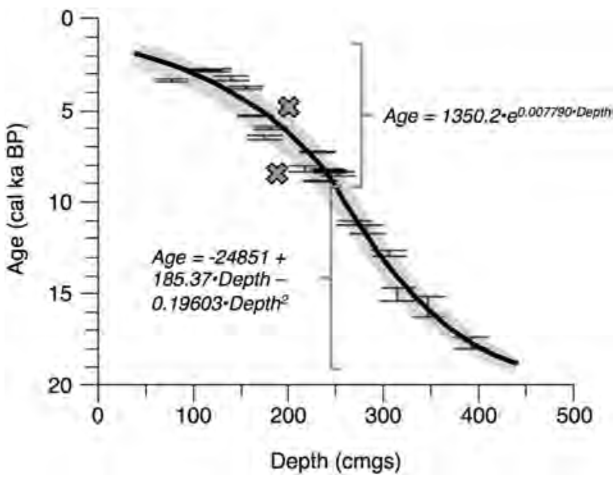

Fig. 2. Calibrated radiocarbon dates from the TL05-4A and -4B cores. Error bars correspond to 2-sigma range of output from CALIB 6.1/INTCAL09 ^{14}C calibration (Reimer et al., 2009). Cross symbols point to samples not used in chronology model due to age inversion.

The bulk radiocarbon ages (Fig. 2; Table 1) may overestimate the actual age by as much as a few hundred years due to possible incorporation of reworked organic matter. Previously published dates on organic matter (2.75 ± 0.113 ^{14}C ka BP) were essentially the same as that (2.74 ± 0.040 ^{14}C ka BP) from an *Anodonta* shell obtained from the same horizon sampled in a set of trenches adjacent to the coring site (Unit 4a of the lake plain trench of Negrini et al., 2006). This observation suggests that the bulk organic matter age offsets are similar to that of the lake reservoir effect associated with dates on the freshwater mussel shells. Because *Anodonta* live in relatively freshwater lakes and streams, dates on their shells likely require relatively small lake reservoir corrections (Ingram, 1948), a presumption consistent with 0.340 ± 0.020 ka offset between shell and charcoal dates from the nearby Buena Vista Lake bed reported by Culleton (2006). Furthermore, sediments in the studied interval of the TL05-4 cores contain an average of <1% total inorganic carbon, an observation that is consistent with a small lake reservoir effect.

Six of the twenty AMS ^{14}C dates used in the age model for the TL05-4 cores in the present study fall within the 18–10 ka time interval interpreted by Davis (1999) to be missing from the Tulare Lake record due to an unconformity. Because no obvious lithologic features commonly associated with unconformities are present in the TL05-4 cores in the corresponding depth range, and because the unconformity hypothesis is based on only one anomalously old radiocarbon date (Fig. 2 of Davis, 1999), we reject this hypothesis in favor of the continuous sedimentation throughout this interval as indicated by the chronology in Fig. 2 of this article. We note that the youngest portion of the age model (5.0–1.8 cal ka BP) may be several hundred years younger than suggested by the model because the first sample TL05-4A-1-82-85 (see Table 1) is considerably older than the next three stratigraphically lower samples.

4.2. Core descriptions

The composite stratigraphy of Drives 1–3 of TL05-4A and Drive 2 of TL05-4B is described from the bottom of Drive 3 to the top of Drive 1 below and summarized in Fig. 3. Overall, grain size was silt to clay reflecting the prevalence of a lacustrine setting. The bottom 27 cm of the core (429–407 cm) is composed of fining upward olive to olive-gray silts to medium grained sands. Thick olive to olive-gray clay-rich silts with frequent iron staining comprise the majority of the latest Pleistocene sediments in Units 1–6 (407–272 cm). The bottom of the Holocene section consists of Units 7–13 (272–103 cm) which are comprised of dark grayish-brown to light olive-brown clay-rich silt to silty-clay units with abundant gypsum stringers and occasional iron staining (Unit 10; 187–183 cm). Unit 14 (79–64 cm) extends to 2.5 cal ka BP and consists of laminated, light olive-brown (2.5Y 5/4) silty clay to fine grained sand. Unit 15 (64–51 cm), which extends through 2.3 cal ka BP, consists of dark grayish-brown (2.5Y 4/2) mottled clays and silts with gypsum stringers and nodules. Fluctuating dark grayish-brown (2.5Y 4/2) clays, silts, and sands comprise the sediments of Unit 16 which extend upward in age to ~1.8 cal ka BP. The top unit (Unit 17), spanning a depth range from 33 to 0 cm, is separated from the younger units by a sharp contact. It consists of coarser-grained sediments up into the medium-sand range.

4.3. Geochemical and geophysical measurements

4.3.1. Laser granulometry and the designation of Zones 1–6

Mean bulk grain size (Fig. 4a) is near the silt/clay boundary for most of the record. The grain size of the coarse fraction (Fig. 4b) is initially ~240 μm at 18.8–18.0 cal ka BP and drops to 10–20 m throughout the remainder of the Pleistocene. Within the Holocene there are several grain-size excursions in the coarse fraction that approach or even exceed 100 μm.

The sand, silt, and, clay percentages were used to identify six zones (Fig. 4c). Zone 1 (19.0–18.0 cal ka BP) is highly sand dominated (Fig. 4c). Within Zone 2 (18.0–14.4 cal ka BP), silt decreases and clay increases steadily until they each comprise 50% each of the sediment. The relative amount of silt and clay remains the same through Zone 3 until its termination at 10.3 cal ka BP. Clay content reaches a maximum of 60% throughout a plateau that defines most of Zone 4 from 10.3 to 7.5 cal ka BP. An asymmetric, fining-upward peak in sand percentage to 20% occurs at the beginning of Zone 4. An increase/decrease in silt/clay of ~20% each occurs at 7.5 cal ka BP after which overall grain size gradually decreases through Zone 5 until silt and clay percentages again become equal at 3.0 cal ka BP. This is followed by a period of rapid, high amplitude fluctuations in sand, silt, and clay percentages until the top of the record at 1.8 cal ka BP (Zone 1).

4.3.2. Magnetic susceptibility

Magnetic susceptibility (κ) is generally highest during the latest Pleistocene with peak Pleistocene values of ~1E-5 cgs units within Zone 3 (Fig. 4d). After the onset of the Holocene, κ steadily decreases to a minimum of less than 1E-6 cgs units. Thereafter it quickly rises to a plateau centered around 5E-06 cgs with relative maxima of 8E-06 cgs at 4.0 and 3.2 cal ka BP. Finally, κ reaches its highest values of >2E-05 cgs units twice at 2.5 and 2.1 cal ka BP. These two, high frequency peaks are separated by a distinct minimum down to 2E-06 cgs units at 2.3 cal ka BP.

4.3.3. Carbon and nitrogen geochemistry

The TIC, TOC, N, and C/N levels were low throughout the latest Pleistocene with TIC essentially undetectable; TOC is typically <1%, N is typically <0.2%; and C/N is <10 (Fig. 4e–h). These values remained similar until approximately 8.0 cal ka BP where frequent high amplitude variations in TIC, TOC, and C/N up to 3%, 3%, and 50, respectively, occurred throughout the remainder of the Holocene. The TIC remained very low until the early middle Holocene except for a few-hundred-year-long spike centered at 8.0 cal ka BP. Thereafter, TIC is relatively high at >2%. In Zone 6, high amplitude, high frequency oscillations in TIC are exactly out of phase with similarly high-frequency variations in C/N and grain-size (Fig. 4a–c,e,h). The data from the overlapping part of the TL05-

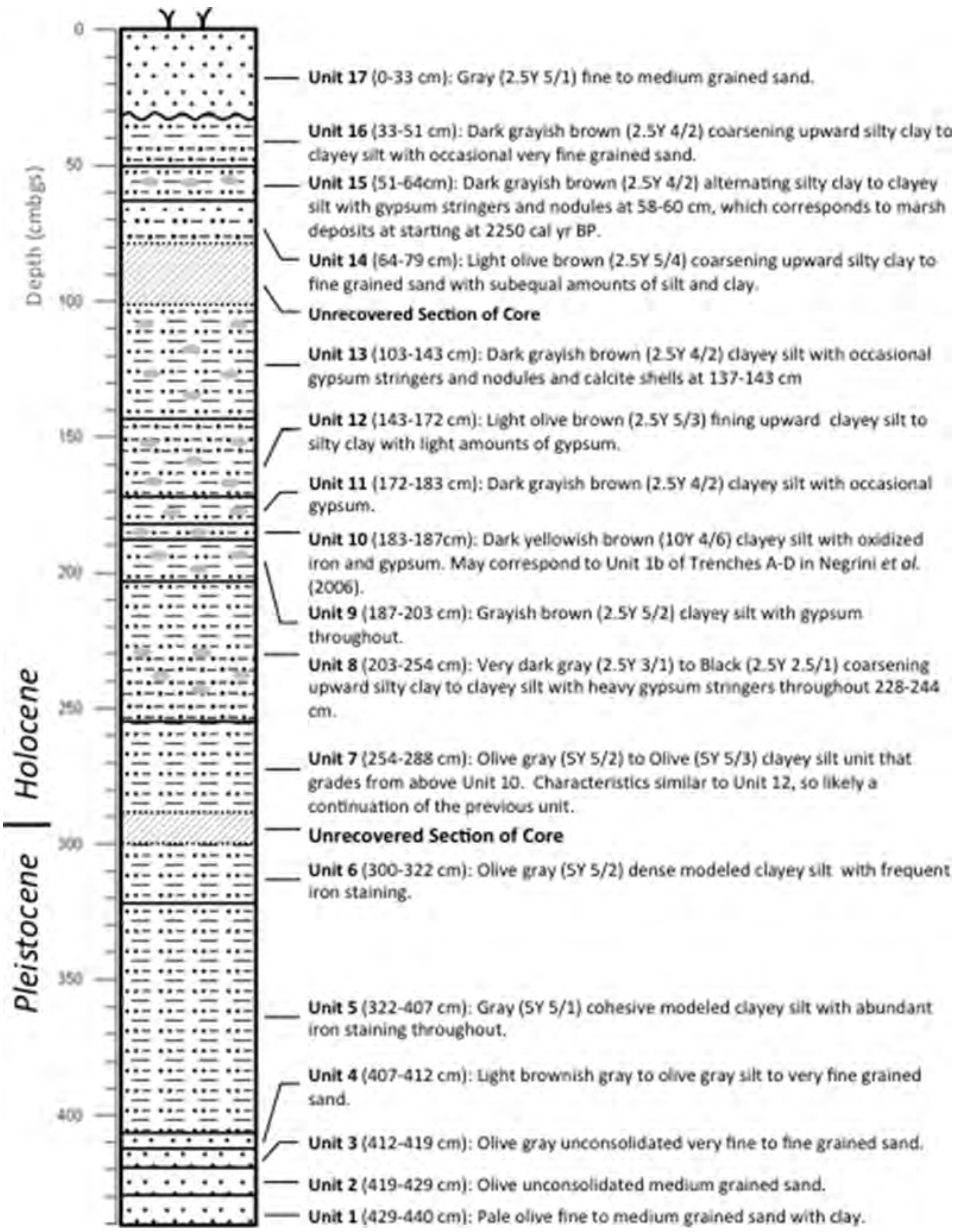

Fig. 3. Composite stratigraphic section of TL05-4 cores. Depth is measured in centimeters relative to ground surface level (58 masl).

4A-2 and TL05-4B-2 drives shown in Fig. 4 generally agree very well. An exception is the TOC% data (Fig. 4f), which are lower for the B drive by ~0.5–1% between 6.5 and 5.0 cal ka BP. The associated C/N data are also lower (Fig. 4f). As a result, only changes in TOC% of more than 1% will be considered to be significant.

5. Interpretations and discussion

The results presented above suggest varying lacustrine environments throughout the past 19,000 years represented by the TL05-4 cores. The lone exception is that of the alluvial fan deposits in the top 33 cm (Unit 17), which are separated from the rest of the section by an angular unconformity mapped in adjacent trenches (Figs. 8–9 of Negrini et al., 2006). The five lacustrine environments of deposition are as follows:

5.1. Latest Pleistocene discharge from glacial outwash: 19.0–14.5 cal ka BP; Zone 1,2

At the beginning of the record (Zone 1), from 19.0 to 18.0 ka, the sediments of the TL05-4 core contain 65–90% sand, decreasing significantly over a thousand years or so to a silt-dominated sediment with little or no sand (Fig. 4). Magnetic susceptibility was near peak values at this time suggesting a dominance of detrital sources for the lake sediments (Gale and Hoare, 1991; Evans and Heller, 2003; Rosenbaum and Heil, 2009). The TIC% was negligible as

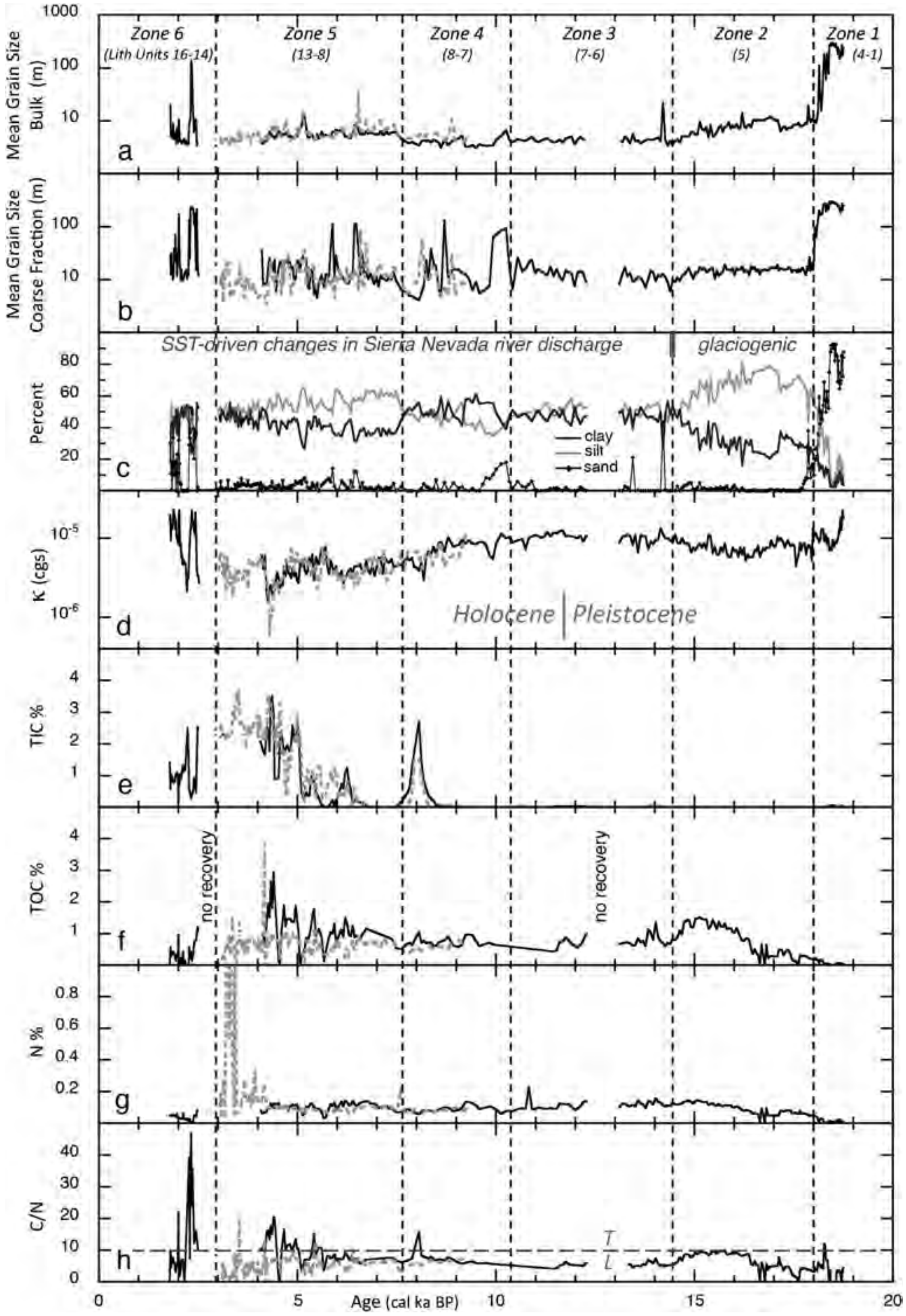

Fig. 4. Geophysical and geochemical proxies from TL05-4 cores. The TL05-4A core data are shown by solid black line, TL05-4B data by dashed grey line except for Fig. 4c which is a composite of data from both cores. Zones 1–6 are defined principally by sand/silt/clay percentage in Fig. 4c. Vertical, bold grey line segments at both end of Zone 3 in Fig. 4c separate lake regimes as defined in text. EOD = environment of deposition. κ = volume normalized magnetic susceptibility, TIC = total inorganic carbon, TOC = total organic carbon, N = nitrogen, C/N = carbon nitrogen ratio and is expressed as a molar ratio.

were TOC%, N%, and C/N. Collectively, these data suggest a freshwater (low TIC%), shallow, and unproductive (low TOC% and N%) lake, dominated by coarse-grained, terrigenous detritus (high κ) with relatively little detrital organic matter (low C/N) (Cohen, 2003). From 18,0 to 14.5 cal ka BP (Zone 2), silt was the dominant grain size reaching a maximum of 80%. Clay increased steadily at the expense of silt until the sediment consisted of equal parts silt and clay at 14.5 cal ka BP. During this transition out of a silt-dominated lake phase, TIC% remained undetectable. As silt steadily decreased starting at the middle of Zone 2, concurrent slight rises in TOC% and N% up to 1.5% and 0.15%, respectively, suggest increasing productivity in the lake, or perhaps, less dilution of lacustrine organic matter by silt. A slightly elevated C/N to >10 during this time interval is consistent with increased transport of terrestrial vegetation into the total mix of organic matter possibly due to an increasingly less barren post-glacial (i.e., warmer) landscape, but this C/N value is still well within the threshold for lacustrine vegetation (Meyers and Lallier-Vergès, 1999). Increased productivity could be due to increased visibility in the water column as the percentage of glacial flour decreased and/or higher temperatures in the lake and surrounding landscape.

This above interpretation for the 19.0–14.5 cal ka BP sediment interval (Zones 1 and 2) is consistent with outwash, first sand and then silt-sized glacial flour, transported via the four major Sierra Nevada rivers flowing into Tulare Lake. The headwaters of all of these rivers originate in regions formerly occupied by the Sierra Nevada ice cap at its ~23 ka MIS2 maximum extent (Martinson et al., 1987). The cessation of the outwash by the end of Zone 2 suggests that bulk of the melting was completed by 14–15 cal ka BP. This timing is consistent with that cited in Gillespie and Zehfuss (2004). The timing of a decrease in sedimentation rates at ~15.0 cal ka BP (Fig. 2) also supports this hypothesis.

5.2. Stable, freshwater lake conditions throughout the Pleistocene–Holocene transition: 14.5–10.3 cal ka BP; Zone 3

Zone 3 is characterized by uniformity in all proxies. Sediment size is dominated by equal parts silt and clay with essentially no sand component. TIC% is negligible, TOC% and N% are low (1%) suggesting an unproductive lake. Magnetic susceptibility is at a relative high suggesting that terrigenous input dilutes whatever organics might be present. Because C/N is low, the terrigenous input appears to be devoid of organic matter.

The uniformity shown throughout the Pleistocene–Holocene transition in the Tulare Lake record contrasts the variability shown by records of Younger Dryas glaciation in southern California (e.g., Owen et al., 2003) and by other records of lakes from the region (Fig. 1), including Swamp Lake (Street et al., 2012), Owens Lake (Bacon et al., 2006; Orme and Orme, 2008; Reheis et al., 2014), and Lake Elsinore (Kirby et al., 2013). In the latter two cases, lake-level change is apparently timed in tune with archetypical millennial-scale change observed throughout the northern hemisphere at that time (i.e., the Older Dryas, Bølling-Allerød, and Younger Dryas events). The lack of consistency between these four records at this time is either due to the failure of the proxies at one or more of the lakes to reliably represent changes in catchment basin environment or geography-related variability in the response of separate regions to latest Pleistocene millennial-scale climate drivers (e.g., Kirby et al., 2013). Notably, the Tulare Lake drainage basin, principally the west side of the Sierra Nevada south of 37.1° N, is distinct geographically from the others. Swamp Lake and Owens Lake receive their water from farther north in the Sierra Nevada; Lake Elsinore, in the Peninsular Range in southern California, is more southerly and proximal to the Pacific Ocean.

5.3. Lake-level maximum in the early Holocene: 10.3–7.5 cal ka BP; Zone 4

The early Holocene at Tulare Lake is characterized by a plateau in clay percentage that persists for more than 2000 years. At the onset of Zone 4 an asymmetric peak in sand percent marks a fining upward sand that is interpreted to be a transgressive sand at the beginning of this highstand. The end of the highstand is marked by a 3% peak in TIC that may signal the onset of evaporation as the lake rapidly drops in elevation. The timing of this long-lived highstand during the early Holocene is consistent with that shown in the record of Negrini et al. (2006) based on sediments exposed in "shoreline trench" excavations on the west side of the Tulare Lake basin, WNW of the TL05-4 cores (Fig. 5a). We note that the TL05-4 core record improves our knowledge of the timing of this highstand because that of the previous work was based upon only one radiocarbon-dated horizon on a charcoal fragment found at the top of a 0.5 m-thick clay layer coupled with the presumption of a 0.038 cm/yr sedimentation rate for that clay layer, a rate suggested by that of deep water clays in Tulare Lake found by Davis (1999). Unlike the late Pleistocene, the mean grain size of the coarse fraction throughout the entire Holocene part of the record frequently contains high-amplitude (~100 μm), high-frequency peaks suggesting a contribution to the discharge into this lake in the form of significant storm events (e.g., Kirby et al., 2012).

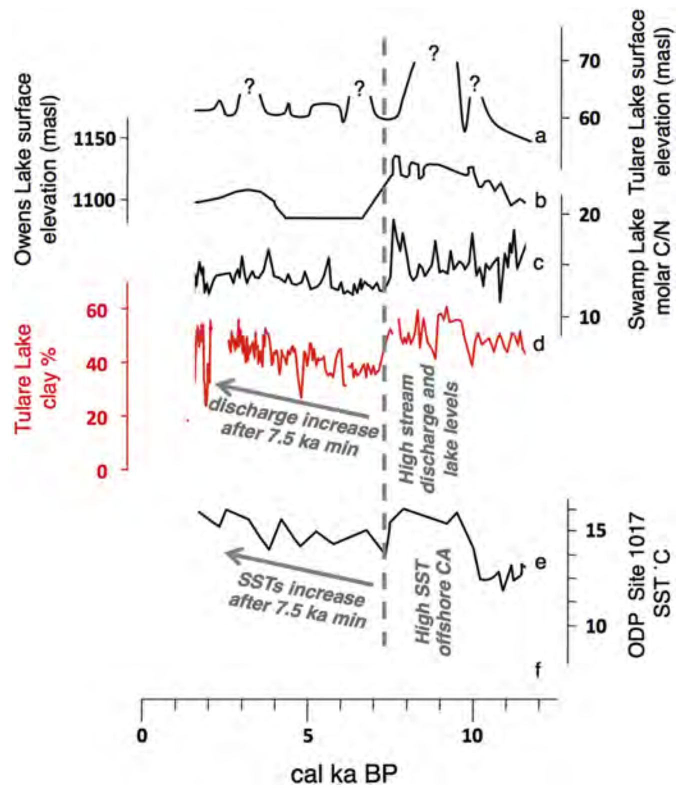

Fig. 5. Lake-level/stream discharge records for three lakes filled with water draining from the central and southern Sierra Nevada. a) Tulare Lake level-stream discharge history based primarily on trench exposures (Davis, 1999; Negrini et al., 2006). b) Outcrop-based record for Owens Lake (Bacon et al., 2006; Orme and Orme, 2008; Reheis et al., 2014). c) Swamp Lake carbon/nitrogen record (Street et al., 2012). d) Tulare Lake level-stream discharge history from this study based on clay percent. e) Alkenone-based sea-surface temperature estimates from ODP Site 1017 core (Seki et al., 2002).

5.4. Middle Holocene regression followed by recovery to deep lake conditions: 7.5–3.0 cal ka BP; Zone 5

The middle Holocene begins with a significant, rapid drop in lake level indicated by the sharp decrease in clay% observed at 7.5 cal ka BP. Subsequently, a steadily increasing clay percentage at the expense of silt throughout the remainder of this 4500 year interval indicates a return to deep lake conditions by 3.0 cal ka BP. Increasing volatility in most other proxies suggests an increased level of storm activity contributing to the discharge into the lake. Combined with the long highstand earlier in the Holocene (Zone 4), this lake-level history bears a strong resemblance to a Swamp Lake discharge proxy record and the lake-level record from Owens Lake (Fig. 5b–d) and to two other lakes in southern California (Kirby et al., 2012). This is in contrast to the disparate behavior of these lakes during the Pleistocene–Holocene transition, suggesting a common climate driver for the southwestern United States throughout the Holocene.

5.5. High variability in lake conditions during the late Holocene: 2.5–1.8 cal ka BP; Zone 6

The top of the record consists of an ~700 year interval from 2.5 to 1.8 cal ka BP characterized by rapid, high amplitude changes in all lake-level proxies. High stream discharge occurred toward the beginning of this interval as suggested by coarse grain size, and high magnetic susceptibility. The TIC% was low at this time and the lake was not very productive (low TOC% and N%). High C/N values (>40) indicate that whatever organic matter was present was brought in by high discharge events. A few hundred years later (2.2 cal ka BP), the environment switched to one where fine grains were deposited, terrigenous input was low (low coarse fraction grain-size, low κ, and low C/N), and TIC was nearly always >1%. We interpret this sequence to represent an early, storm-driven, high lake episode followed by a shallow water marsh environment. The final interval at the top of the record reverted to the deposition of coarser grains, high □, and higher TIC%, though C/N remained low (<10).

6. Conclusions

6.1. Influence of the melting Sierra Nevada ice cap during the late Pleistocene

Conditions in Tulare Lake during the late Pleistocene appear to be driven by dynamic clastic input from the melting of the Sierra Nevada ice cap, the evidence for which is sandy outwash followed by silt-sized glacial flour and elemental geochemistry suggesting freshwater and sterile conditions (undetectable TIC, low TOC, and N). Post-glacial conditions during the latest Pleistocene, in contrast, resulted in static rather than dynamic clastic input into a still sterile, freshwater lake, the evidence for which is homogenous granulometry and no change in the elemental geochemistry from earlier.

6.2. Pacific sea surface temperatures drive post-glacial precipitation in the Sierra Nevada

Variations in the depth of Tulare Lake through time are implied primarily by changes in the clay% because finer grains are usually deposited in deeper lake environments. A deeper Tulare Lake, in turn, is linked to increased discharge from the Sierra Nevada through the hydrologic balance models of Harding (1949) and Atwater et al. (1986). During the Holocene, in the absence of a significant ice cap, stream discharge is likely linked to precipitation in the Sierra Nevada. Thus we make the connection from Tulare Lake sediment clay% to precipitation.

The Holocene Tulare Lake level-Sierra Nevada precipitation record shown here, is consistent with the previous work in the basin (Fig. 5a,d) based on trench exposures and the pollen record of a depocenter core (Davis, 1999; Negrini et al., 2006). The clay% proxy for lake level-precipitation also bears resemblance to records from Owens (Bacon et al., 2006) and Swamp (Street et al., 2012) Lakes, two lakes also fed by precipitation that falls in the nearby Sierra Nevada, though from farther north in the central rather than southern Sierra Nevada (Fig. 5b–d). The Owens Lake record is primarily based on shoreline evidence from outcrops, thus it directly reflects lake level. The Swamp Lake record consists of a myriad of geochemical, geophysical, and geobiological proxies. Of these, C/N is plotted here as an indicator of the relative input of terrestrial vs. lacustrine organic matter, thus discharge into the lake and, hence, lake level. This assertion is supported by a demonstrated correlation of paleo-C/N values with those from modern plant matter (Fig. 3 of Street et al., 2012) and the fact that the Swamp Lake watershed is relatively small and uncomplicated much like that of Lower Bear Lake in the California Transverse Ranges (Kirby et al., 2012), which has a C/N record that accurately reflects lake level and regional climate change.

The Tulare Lake record most notably bears remarkable resemblance to variations in sea surface temperatures (SSTs) from offshore California during the Holocene (Fig. 5). Because the levels of these lakes are ultimately dependent on the discharge of streams coming from the Sierra Nevada (e.g., Atwater et al., 1986), this result strongly suggests that Pacific SSTs exerted the dominant control on Holocene precipitation in the Sierra Nevada and therefore, stream discharge.

6.3. Implications for central California water resources due to anthropogenic climate change

The SST record shown in Fig. 5e represent the temperatures associated with the California Current which, though affected on an annual to decadal time scale by high frequency climate variations, such as ENSO and the PDO, responds more or less linearly to the long-term anthropogenic global warming signal (Field et al., 2006) of 0.8C° over the past century. The major drop in Tulare Lake of ~10 m in elevation (Fig. 5a) at ~7.5 cal ka BP corresponds to a change in SST of at least 2C°. In turn, the change in total discharge from the Sierra feeding Tulare Lake that corresponds to a drop in lake level from ~70 to ~60 masl would be ~6 km^3/y (~five million acre•ft/y) (Atwater et al., 1986). Presuming a linear relationship as a point of departure, and thus scaling down to the 0.8C° change in SST over the past century, the Tulare Lake basin should have seen an increase in discharge over this time of ~2.4 km^3/y (two million acre•ft/y). This is a difficult number to reconcile given the current state of drought in the American Southwest, including the southern and central Sierra Nevada. One explanation for this is that the average time represented by each sample in the Tulare Lake record is ~50 years, too long a time to capture an analogous Holocene drought lasting less than a decade. Second, this discrepancy supports the modeling results of Sewall and Sloan (2004) and Sewall (2005), who used a fully coupled Earth system model wherein SSTs were raised in the absence of Arctic sea ice. Their results demonstrated that a large region of the western US including California will experience a decrease in precipitation in response to rising SSTs rather than the increase in precipitation suggested, at least for the central and southern Sierra Nevada, by the Tulare Lake record. This discrepant result suggests, in turn, that the sign of the response of precipitation in the western US to changes in SST varies dependent on boundary conditions, specifically, the volume of Arctic sea ice. It remains to be seen whether the effect of increasing SSTs will eventually overtake the effect due to the shrinking Arctic sea ice a century or more from now after the sea ice is completely gone (Knies et al., 2014).

6.4. Implications for Clovis-age sites around Tulare Lake

In theory, the alluvial fans extending from the Kettleman Hills would have made an ideal location for Clovis-age settlements. The sandy fan deposits would have provided a well-drained location in close proximity to food and other resources. The sediment depth in the TL05-4 cores corresponding with the oft-cited age of Clovis occupations (13.5–13.0 cal ka BP) is ~3 mbgs, which places Clovis-age shorelines at approximately 55 masl, slightly lower than the 56–58.5 masl elevation previously suggested for this time (Wallace and Riddell, 1988; West et al., 1991; Fenenga, 1993). As discussed above, Tulare Lake was characterized by deep, colder waters from 14.0 to 12.0 cal ka BP, throughout the entire Clovis period. Thus, the 56.0–58.5 masl elevation was likely well under water at this time and could not have served as settlement sites for Clovis peoples. However, there is a section of 12 cm of unrecovered core from the bottom of one of the core drives that, were it recovered, would have represented 13.1–12.2 ka cal, a time interval which includes the "Clovis Drought" discussed by Haynes (1991). Because sands are often lost at the base of core drives due to their unconsolidated nature, this break in the record could conceivably have contained coarse-grained, nearshore sediments indicating lower lake-level conditions during this time. Additionally, differential subsidence due to modern groundwater withdrawal may have resulted in the lower than expected relative depth of the Clovis-age sediments on the western Tulare Lake margin.

Acknowledgments

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Pollen analysis of Tulare Lake, California: Great Basin-like vegetation in Central California during the full-glacial and early Holocene

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Abstract

Pollen analysis and nine radiocarbon dates of an 853-cm core from historically drained Tulare Lake, south-central California are reported prior to 7000 yr B.P., the vegetation of the southern San Joaquin Valley (central California) resembled that of the contemporary Great Basin, including abundant greasewood (*Sarcobatus*), which currently does not occur west of the Sierra Nevada. The early-Holocene pollen assemblage is dominated by Cupressaceae (>40%), *Pinus* (>20%), *Quercus* (5–20%), *Artemisia* (>15%), and *Sarcobatus* (>5%), suggesting pinyon–juniper–oak woodland in the uplands, with greasewood on the saltflats near the lake. Giant sequoia was widespread along the Sierra Nevada streams draining into Tulare Lake, prior to 9000 yr B.P. as *Sequoiadendron* pollen is greater than 4%. The pollen assemblages before 18,500 yr B.P. are similar to those of the early Holocene (Cupressaceae, *Artemisia*, and *Sarcobatus*), but a gap in sedimentation from ca. 18,500–10,500 yr B.P. prohibits characterization of full-glacial vegetation. The end of Great Basin-like pollen assemblages 7000 yr B.P. (demise of *Sarcobatus*) coincides with increased frequency of charcoal; i.e., greater fire frequency in the Holocene woodland and grassland. From 7000–4000 yr B.P. the pollen assemblage is dominated by Other Compositae and Chenopodiaceae–*Amaranthus* pollen, suggesting expansion of xerophytic steppe at the expense of oak woodland. Higher percentages of littoral pollen (Cyperaceae, *Typha–Sparganium*) and lower percentages of pelagic algae (*Botryococcus* + *Pediastrum*) during the middle Holocene indicate lake levels generally lower than during the early Holocene. The late Holocene begins with a cold-wet period 3500–2500 yr B.P. followed by progressive drying of the lake. Climate estimates based on modern pollen analogs confirm the climate implications of the vegetation and lake history. Early Holocene climate was cold and wet, and maximum Holocene temperature and drought occurred between 7000 and 4000 yr B.P. Cool-moist climate from 4000 to 2000 yr B.P. is followed by a return to aridity and high temperature ca. 1000 yr B.P.

Keywords: Quaternary; vegetation; California; palynology; climate change; biogeography

1. Introduction

In 1985, David Adam concluded a overview of the Quaternary palynology of California without a regional synopses, because too few pollen diagrams had been published in the state. Since then, Adam's pioneering research (Adam, 1967; Adam et al., 1981) has been augmented by well-dated pollen diagrams for coastal southern California (Heusser, 1978; Davis, 1992, 1996; Cole and Liu, 1994) and the Sierra Nevada (Davis et al., 1985; Davis and

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Moratto, 1988; Anderson, 1990; Smith and Anderson, 1992; Anderson and Smith, 1994). It is now clear that the vegetation and climatic chronology of coastal central California differs from that of the Sierra Nevada. The early Holocene of coastal California (Adam et al., 1981; Heusser, 1978) is characterized by pollen percentages of arboreal species: *Pinus*, *Quercus*, and *Alnus*; greater than present suggesting climate cooler and wetter than the middle Holocene. In contrast, the early Holocene of the Sierra Nevada exhibits comparatively low percentages of arboreal pollen, and elevated percentages of shrub and herb pollen (particularly *Artemisia*) (Davis et al., 1985; Davis and Moratto, 1988; Anderson, 1990; Smith and Anderson, 1992; Anderson and Smith, 1994), indicating that effective moister was less than the middle Holocene. The geographical position of the boundary between early-Holocene aridity in the Sierra Nevada vs. early-Holocene coastal moistness is unclear, because paleoenvironmental studies of the low-elevation Central Valley have not been published.

Adam (1985) also called for a detailed refinement of his preliminary study of the sediments of Tulare Lake (Atwater et al., 1986). Only 23 samples from a 24-m auger-core were analyzed — just 3 for the Holocene. The Holocene samples contain 5–20% *Quercus* pollen, and older samples contain 10–30% Cupressaceae and 5–10% *Sarcobatus*. The presence of *Sarcobatus*, a desert plant currently restricted to east of the Sierra Crest, is an important biogeographic discovery. Research by Atwater et al. (1986) demonstrated good pollen preservation in Tulare Lake sediment, recorded a radiocarbon-dated sedimentation rate of over 0.33 mm/yr, and suggested that lake depth is controlled by climate and by aggradation of the alluvial and fluvial fans that dam the lake at its northern margin. Its location and elevation (36ºN, 112ºW, elev. 54 m) make it ideal for testing the nature of the early-Holocene climate of the California interior: was it drier like the Sierra Nevada, or wetter like the coast?

The studies of aquatic sediment have been supplemented by packrat midden research (Cole, 1983), which has provided interesting biogeographic insights. Seven middens from 920–1270 m in Kings Canyon (Fig. 1), contain needles of single-leaf pinyon (*Pinus monophylla*), currently much more common east of the Sierra Nevada, and pollen of giant sequoia (*Sequoiadendron*), which Cole (1983) suggests was more common during the Pleistocene at lower elevation, along waterways. The late-Pleistocene expansion of giant sequoia also is indicated by the presence of *Sequoiadendron* pollen in a diagram from Exchequer Meadow, 5 km from the nearest extant grove (elev. 2219 m, 64 km northwest of the Kings Canyon midden site; Davis and Moratto, 1988). Additional evidence for the late-glacial–early-Holocene spread of giant sequoia comes from the persistence of *Sequoiadendron* pollen at Mono Lake 11,000–7800 yr B.P., east of the Sierra Nevada crest (Davis, 1998).

2. Site description and setting

At its historic maximum (A.D. 1770–1850), Tulare Lake was the largest body of fresh water (2200–1900 km^2; Atwater et al., 1986) in the U.S.A. west of the Mississippi River. Its size declined rapidly after 1850 due to progressive diversion of inflowing streams for irrigation (Haslam, 1989). The Tulare Basin is dammed by the alluvial fans of the Kings River, draining the Sierra Nevada to the east, and Los Gatos Creek, which drains the Coast Range to the west (Fig. 1). At spill-over, the lake was ca. 10 m deep, with a water volume of 7 km^3. The other major tributaries to Tulare Lake basin are the Kaweah, Tule and Kern rivers, which drain the western slope of the southern Sierra Nevada.

The late-Quaternary sediments of the Tulare Basin (Atwater et al., 1986) are comprised of the Chatom silt (ca. 26,000–13,000 yr B.P.), and older units, overlain by the less extensive Blakeley Canal silt (younger than 13,000 yr B.P.). Diatom and ostracode analyses indicate a deep, relatively cool lake during deposition of the Chatom silt, and a well-oxygenated, shallow lake of variability salinity and pH during deposition of the Blakeley Canal silt (Atwater et al., 1986).

Pre-settlement (ca. A.D. 1770) upland vegetation near Tulare Lake was a mosaic of grassland and oak savanna. Tule (*Scirpus*) marsh lined the southern margin of the lake and saltbursh (*Atriplex*) scrub covered much of the eastern and western margins (Preston, 1981). The lake depth was constantly fluc-

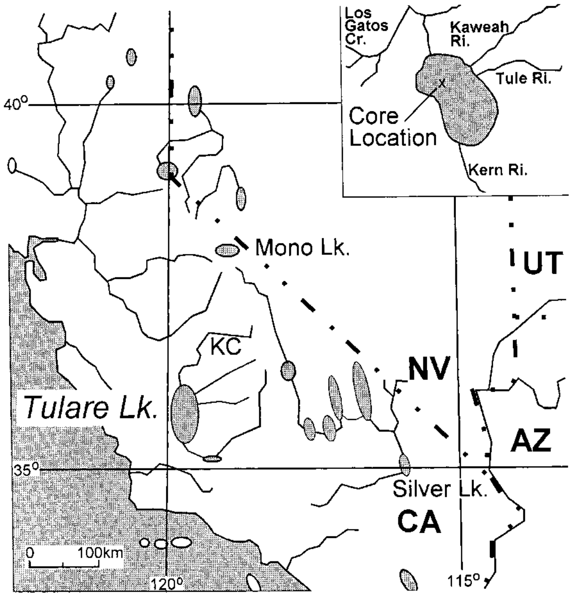

Fig. 1. Location of Tulare Lake and other sites mentioned in text, including the Kings River Canyon (*KC*) packrat midden site in California.

tuating (Atwater et al., 1986) so near-shore vegetation was impermanent.

Before it dried, Tulare Lake hosted a diverse fauna of mollusks, fish, and waterfowl, making it a locus for Indian activity. The earliest evidence for human presence is what appears to be Clovis points, followed in age by Lake Mojave points, Pinto Basin points, Elko series projectile points and late prehistoric artifacts (Wallace, 1991). Although the older artifacts are not securely dated, human occupation of the shores of Tulare Lake probably spans ca. 11,000 years.

3. Methods

The goal in sampling the sediments of Tulare Lake was to obtain continuous cores to provide a detailed chronology of vegetation, climate, and lake-level change for a low-elevation, interior site west of the Sierra Nevada. Three overlapping cores were taken on Sept. 31, 1988 in sect. 10, T 22 S, R 20 E, about 9 miles east of Kettleman City. This site is the approximate depo-center for the basin. Sediment at ca. 790 cm depth at this site had been dated 24,930 ± 90 yr B.P. (core 7 of Atwater et al., 1986). The cores were taken with a 9 cm diameter split-stem core mounted in a rotary auger drill. Presently, the site is at the edge of an agricultural field, cotton was being grown at the time of coring.

The cores are uniform gray (10YR 6/1) to brown (10YR 4/2) silt and clay, except for dark layers at 225 and 340 cm and a black organic layer at 770 cm. Fragmented snail shells were present at 89–91 cm. Core 2, 853 cm in length, was sampled at 20 cm intervals for pollen, and ten bulk sediment samples were selected for radiocarbon dating.

Routine pollen extraction included the addition of *Lycopodium* spores as tracers, HF and HCl treatment, acetolysis, 10% KOH treatment, staining, and mounting in glycerine. Three hundred pollen grains of upland plants were counted per sample. The pollen sum (divisor for percentages) includes pollen of upland plants and deteriorated grains. Pollen clumps were counted as four grains.

The identification of *Sequoiadendron* pollen is based on the presence of a papilla. Although this morphological character also appears on *Sequoia* and *Taxodium* pollen, the presence of these taxa in the Sierra Nevada during the late Pleistocene is very unlikely. Cupressaceae pollen probably is mostly *Juniperus* pollen, but *Calocedrus* pollen might also be present, because both taxa are present in late-glacial and early-Holocene macrofossil assemblages from packrat middens (Cole, 1983; Davis and Moratto, 1988). *Taxus* pollen is excluded from the 'Cupressaceae' category by its dense sculpturing. The *Cercocarpus–Purshia* pollen type is distinguished from *Quercus* by the grain's oval (vs. quadrangular) outline and stronger (vs. bent or protruding) mid-furrow. *Sarcobatus* pollen is distinguished from all other Chenopodiaceae by its protruding, annulate pores and its irregular shape (not spherical).

Vegetation change is computed as the squared chord distance between adjacent samples, expressed as change per 100 years (Jacobson and Grimm, 1986). The calculations are based on 17 upland pollen types that reach peak abundances of greater than 2% in the Tulare Lake core. Climate reconstructions use the squared chord distance metric calculated using the same 17 abundant upland pollen types. Annual precipitation and temperature are calculated as the average of the precipitation and temperature values of all modern analogs for each fossil sample. The upper limit of dissimilarity for the analogs is 0.15. Climate parameters are not calculated for fossil samples without at least two modern analogs. The database of modern analogs includes 1400 contemporary surface samples (Davis, 1995).

4. Results and interpretation

Fig. 2 shows the age model for the Tulare lake core. The three lower dates, from USGS cores, are from nearby cores. Apparently, the gently-sloping subsurface topography produces similar age–depth relationships among the dated cores. The radiocarbon dates show a gap in sedimentation of 8000 yr between the Blakeley Canal silt (proposed as ca. 26,000–13,000 yr B.P. by Atwater et al., 1986) and the Chatom silt (13,000–0 yr B.P., Atwater et al., 1986). Sedimentation was 0.03 cm yr^{-1} from 27,700 to 23,850 yr B.P., and slowed to 0.02 cm yr^{-1} from 23,850–18,370 yr B.P. Above the hiatus, sedimentation was very rapid (0.26 cm yr^{-1}) from 10,110 yr B.P. to 9100 yr B.P., then slowed to 0.04 cm yr^{-1} from 9100 to the surface. One-third of the core was deposited during the 1000-year period 10,100–9100 yr B.P. (Fig. 1). This rapid sedimentation indicates intense erosion of soil-surface material into the

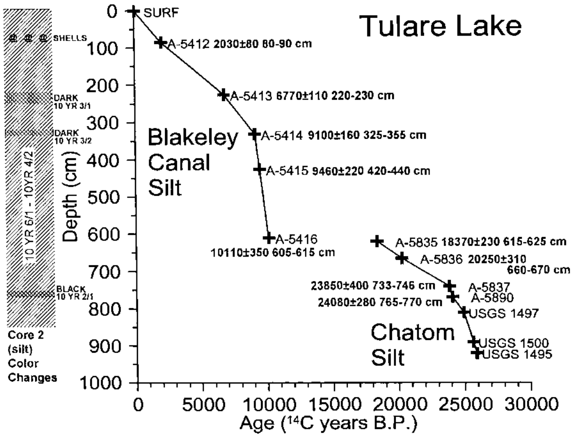

Fig. 2. Depth–age model for Tulare Lake core 2. Radiocarbon laboratory numbers and depths shown right of each symbol. Sediment composition noted at right. Core 2 is texturally uniform with modest variations in color shown as Munsell values in the column at right.

lake, and rapid construction of the Kings–Los Gatos alluvial fans that dam Tulare Lake.

I interpret the sedimentation chronology (Fig. 2) as two lake-filling cycles separated by an erosional event. The Chatom silt was deposited after the closure of the Tulare Lake basin by deposition of the Kings River–Los Gatos Creek alluvial fans ca. 28,000 yr B.P. From 28,000–24,000 yr B.P. the sedimentation rate in the lake was more rapid due to high sediment delivery by the tributary streams (Fig. 1). This rapid sedimentation also built the alluvial fan dams. From 24,000–18,400 yr B.P. the sedimentation was slower due to lower sediment load, lower stream discharge, or both. The sediment hiatus 18,400–10,100 yr B.P. is not interpreted as a lowstand because the sediments are not oxidized nor is the pollen at the contact deteriorated. Rather, I interpret the gap as the erosional product of downcutting of the Kings–Los Gatos alluvial fans by the Kern River, followed by deposition of the Holocene Blakeley Canal Silt. The lack of sedimentary evidence for the event may indicate a rapid transition between erosion and deposition. Evidence for lake drying 18,400–10,100 yr B.P. may have been removed by subsequent erosion.

The second sedimentation cycle lasted from 10,110 yr B.P. until historic drying. Prior to 10,100 yr B.P., Kings River and Los Gatos Creek once again deposited alluvial fan dams on the Kern River. From 10,220–9100 yr B.P., infilling of the lake was rapid (0.26 cm yr^{-1}), but slowed after 9100 yr B.P., depositing the Blakeley Canal silt in a lake-filling cycle similar to that which produced the Chatom silt.

The pollen diagram (Fig. 3) permits refinement of the lake-level record derived from the sedimentation chronology. The relative proportions of littoral indicators (*Typha*, *Sparganium*, Cyperaceae) are used as a measures of the proximity of the shore to the basin-center core site; i.e., high percentages indicate low lake depth. Relative to the littoral indicators, the colonial green algae *Pediastrum* and *Botryococcus* are used as indicators of open (deep, pelagic; Rawson, 1956; Castenholz, 1957; Whiteside, 1965) water at the coring site. The relatively low percentages of littoral indicators (50–100% of the upland pollen sum) during deposition of the Chatom silt are consistent with diatom and ostracod indications of a deep lake (Atwater et al., 1986). Greater abundance

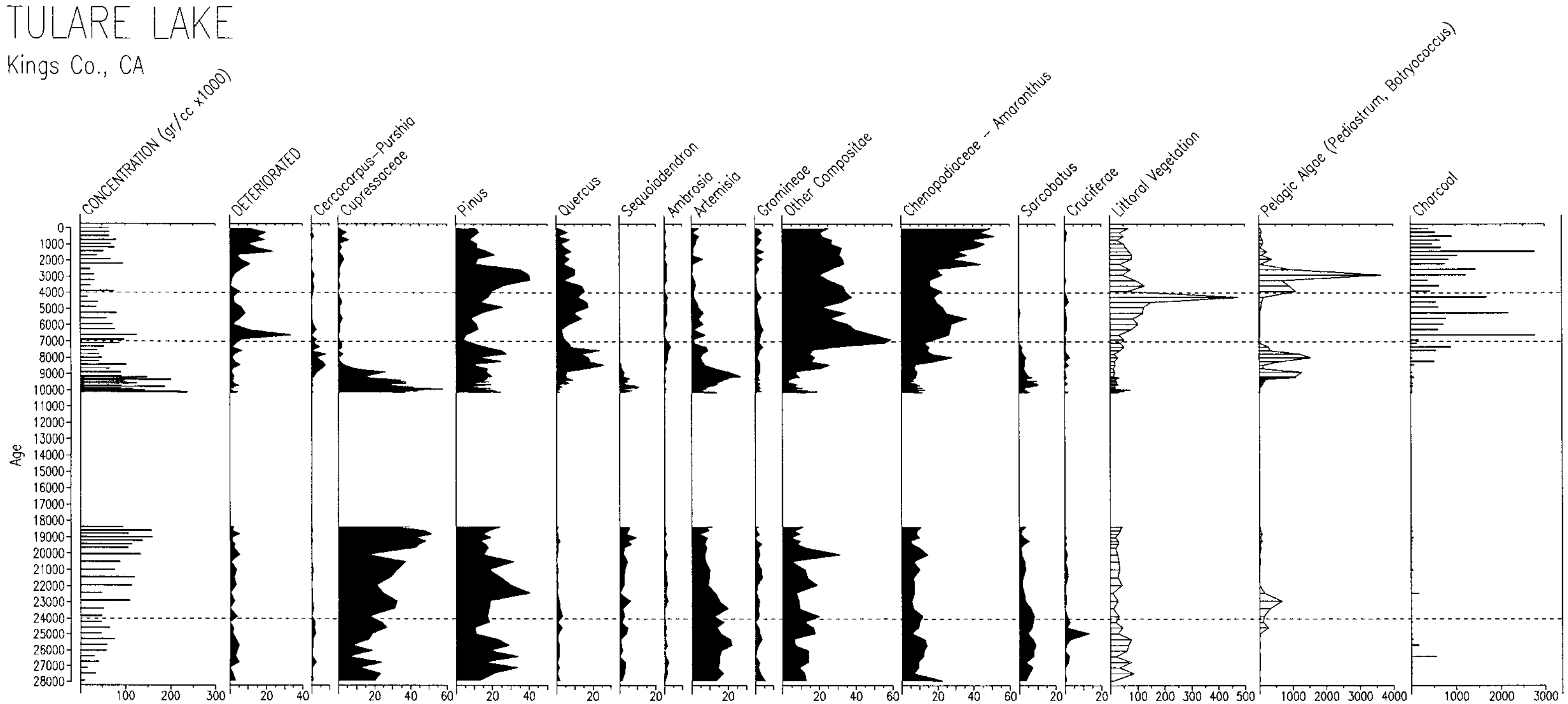

Fig. 3. Percentage pollen diagram for selected (abundant) palynomorphs from Tulare Lake core 2. Types right of Cruciferae are not included in the pollen sum (divisor for pollen percentages). Horizontal lines denote important events in the record (not zone boundaries) the lowest line at 24,000 yr B.P. marks a decreased sedimentation rate and a decrease in lake level. The 7000 yr B.P. line marks the last occurrence of the pollen of *Sarcobatus* a Great Basin species. The 4000 yr B.P. line marks the beginning of higher lake levels during the late Holocene.

(150–250%) of these palynomorphs suggest generally lower lake levels during the deposition of the Blakeley Canal silt (Fig. 3).

Pulses of high percentages (>500% of the pollen sum) of the *Pediastrum* and *Botryococcus* pelagic indicators are interpreted as brief, high-lake events. These occurred 24,000–23,000, 9200–7000, and 4000–2500 yr B.P.(Fig. 3). Low values 8500 yr B.P. interrupt the 9200–7000 high-lake interval.

High pollen concentration (>100,000 grains cm^{-3}, Fig. 3) at the top of the Chatom silt and at the base of the Blakeley Canal silt are given different interpretations. The upward-increasing concentration in the Chatom silt (50,000–150,000 grains cm^{-3}, Fig. 3) is matched by the declining sedimentation rate (Fig. 2), so the upper Chatom silt sediments have greater pollen concentration because each sample represents a longer interval of pollen accumulation. In contrast, the high pollen concentration in the basal Blakeley Canal silt occurs in sediments with a very high sedimentation rate (2.8 cm yr^{-1}). This may result from erosion of pollen-rich sediments from the tributary watersheds, and rapid deposition of these sediments in Tulare Lake; however, the percentages of deteriorated pollen are not high in this interval nor are there other indications of pollen redeposition.

The pollen stratigraphy of the Tulare Lake core (Fig. 3) is consistent with Adam's preliminary work (Atwater et al., 1986), and indicates a dramatic transformation of the vegetation surrounding Tulare Lake. However, Fig. 3 demonstrates that the palynological transition from dominance by Cupressaceae (TCT in Atwater et al., 1986) and *Artemisia* to *Quercus* takes place *within* the Blakeley Canal silt rather than at the transition between the Blakeley Canal and the Chatom silts.

The pollen assemblage of the Chatom silt resembles contemporary samples collected east of the Sierra Nevada in its high percentages of Cupressaceae (20–40%, probably *Juniperus*), *Artemisia* (10–20%), and *Sarcobatus* (5–10%). The low percentages of *Quercus* (<4%) in these samples can be duplicated in surface samples from the eastern Sierra Nevada (Anderson and Davis, 1988), but the consistent low values (2–5%) of *Sequoiadendron* are not currently found east of the Sierra Crest. *Sarcobatus* percentages are highest before 24,000 yr B.P. when percentages of littoral shrubs and herbs are also high (Fig. 3) indicating relatively lower lake level and extensive salt flats. Tulare Lake was low during this interval of rapid sedimentation, as the alluvial fan-dams grew.

The high Cupressaceae *Artemisia*, *Sarcobatus* and *Sequoiadendron* pollen values support Cole (1983) packrat midden-based suggestions that giant sequoia was widespread during the full and late glacial, and that Great Basin-like vegetation was present west of the Sierra Nevada. Upland vegetation near the site is interpreted as pine (probably including pinyon pine)–juniper woodland, with an understory of sagebrush; with salt flats near the lake containing *Sarcobatus*. Pinyon pine pollen is present in samples older than 13,000 yr B.P., but few pine grains of any type were identified. The demise of Great Basin-like vegetation is contemporaneous with the transition from open, sagebrush-dominated vegetation to Sierra Montane forest at higher elevation in the western Sierra Nevada (Davis et al., 1985; Davis and Moratto, 1988).

From 10,100–8500 yr B.P., the pollen assemblage of the Blakeley Canal silt is similar to that of the Chatom silt (Fig. 3). However, after 8500 yr B.P., *Sequoiadendron* pollen disappears and Cupressaceae pollen drops to <5%. *Sarcobatus* pollen persists at low values until 7000 yr B.P., and from 8500–7000 yr B.P. *Quercus* and *Cercocarpus–Purshia* reach maximum values for the diagram. The upland vegetation sequence is interpreted as oak woodland and chaparral replacing pine–juniper woodland. Prior to the Cupressaceae/*Quercus* transition, *Artemisia* percentages peak at 27% (9135 yr B.P.), and pelagic algae reach low values (113%) 8656 yr B.P., suggesting that a drying trend is associated with the transition. Percentages of charcoal increase after 8500 yr B.P. indicating increased importance of fire in the vegetation of Tulare Lake watershed, or perhaps more intense utilization of Tulare Lake by Indians.

The middle Holocene (7000–4000 yr B.P.) begins with a brief (6900–6600 yr B.P.) lake low-stand marked by a decline in pelagic algae, drops in the percentage of the pollen of *Quercus*, *Cercocarpus–Purshia*, and *Sarcobatus*, and peaks of deteriorated and Other Compositae pollen (Fig. 3). Steadily increasing percentages of littoral palynomorphs and declining pollen concentration during this interval (with apparently constant sedimentation, Fig. 2) may indicate gradually declining stream inflow. Lake levels were low 7000–4000 yr B.P., based on the low percentages of pelagic algae. The middle Holocene ends with a lake-drying event, indicated by peak percentages (500%) of littoral species. Charcoal percentages are high throughout the middle Holocene.

The late Holocene (4000 yr B.P.–historic) begins with a dramatic highstand (3500–2500 yr B.P.) indicated by peak percentages of pelagic algae. This peak coincides with very abundant (40%) *Pinus* pollen, and generally low pollen concentration ($<$40,000 grains cm^{-3}, Fig. 3). This climatic event is recorded by expansion of conifers at low elevation throughout western North America (Davis et al., 1986); and is particularly well-represented (*Pinus* $>$ 80%; 3600–2800 yr B.P.) in a core from Mono Lake (Fig. 1; Davis, 1998), where it immediately follows a lake low-stand. It may correspond to a lake-full event a Silver Lake (Fig. 1; Enzel, 1992) dated 3620 $\pm$ 70 yr B.P.

Following the lake-full event, percentages of *Pinus* and *Quercus* gradually decline as percentages of Chenopodiaceae–*Amaranthus* increase, indicating expansion of basin-margin saltbrush vegetation, and the decline of oak woodland near the lake. The steady increase of deteriorated pollen probably results from increasing frequency of lake-desiccations, as recorded in the historic period.

Vegetation change(Fig. 4) is greatest at 10,100, 8200, 3900, and 2200 yr B.P. The 10,100 yr B.P. event corresponds to the Cupressaceae peak at the base of the Blakeley Canal silt; the 8200 yr B.P. event to the transition from Great Basin woodland to oak woodland, and the 3900 and 2200 yr B.P. events coincide with the high *Pinus* percentages during the late Holocene.

Low temperatures and high precipitation are computed for the early Holocene (Fig. 4), and the modern analogs for this interval are from Great Basin vegetation from southern Idaho to southern Nevada. Although *Sequoiadendron* pollen is present (generally 2–5%) before 8500 yr B.P. the modern analogs are from the Great Basin, the average number of analogs per sample is 13.7 before 8500 yr B.P. vs. 11.6 for the entire core. Climate reconstruction for the pre full-glacial Chatom silt (not shown) are for cold (average 8ºC), wet (average 363 mm/year) climate.

Although modern analogs west of the Sierra Nevada are more frequent after 8500 yr B.P. there are no obvious latitudinal shifts in the distribution of Great Basin analogs prior to that time. The increase in precipitation and decrease of temperature at the right terminus of the smooth line (historic values) are the result of the smoothing function used (a fifth degree polynomial).

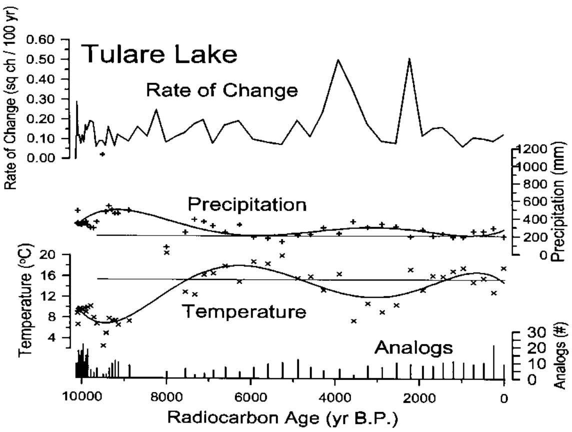

Fig. 4. Rates of vegetation change, annual precipitation, and annual temperature computed for the Tulare Lake core 2 pollen diagram. Vegetation change is computed as the squared chord distance between adjacent pollen samples. Climate variables are the averages of best analogs for each fossil sample from a database of 1400 modern surface samples (Davis, 1995). The bar graph at the bottom shows the number of modern analogs per fossil sample upon which the climate values are based.

5. Conclusions

The present study confirms the general conclusions of Atwater et al. (1986), but the greater numbers of radiocarbon dates in this study (Fig. 2) and the pollen analysis permits two revisions. First, the gap between the Chatom and Blakeley Canal silts is of 8000 years duration, during which the alluvial dam impounding the lake was breached by a through-flowing Kern River. Although low stands may have occurred during this interval (ca. 18,400–10,100 yr B.P.), no sedimentary evidence for drying is preserved, possibly due to subsequent erosion. The timing of the event brackets the age of high-stands of Great Basin pluvial lakes east of the Sierra Nevada (Benson et al., 1990), suggesting that a positive hydrologic balance produced sufficient discharge for the Kern River to cut through the alluvial fans deposited by the Kings River and Los Gatos Creek.

The second revision of Atwater et al. (1986) chronology is that the transition between Great Basin-like vegetation to oak woodland and grassland occurs within the Blakeley Canal silt rather than between it and the underlying Chatom silt. Thus, the major transformation of the upland vegetation is not synchronous with the boundary between the two silts. Rather, the two silts are interpreted as products of lake-filling cycles, associated with deposition of the alluvial fans of the Kings River and Los Gatos Creek. At the core site, sedimentation is rapid in the first part of both cycles, as the fan-dams aggrade. As concluded by Atwater et al. (1986), both alluvial dam height and climatic change have influenced the water balance of Tulare Lake during the late-Quaternary, but the fan-building events are of much lower frequency than lake-level fluctuations.

The vegetation and climatic chronology of Tulare Lake is more similar to that of coastal California than to that of the Sierra Nevada, in that arboreal pollen percentages are greater in the early Holocene (Fig. 3); i.e. the early Holocene was wetter than the mid-Holocene (Fig. 4). However, the early-Holocene aridity of the Sierra Nevada appears to contrast with early-Holocene wetness at low elevation on both sides of these mountains (e.g., Quade et al., 1998; Davis, 1998). Paradoxically, the primary source of water for Tulare Lake is Sierra Nevada streams (Fig. 1), and the lake level seems to have been high (but variable) during the early Holocene. Early Holocene persistence of *Sequoiadendron* also is best explained by greater available moisture (Cole, 1983). Perhaps greater seasonality of the early Holocene (Davis, 1984) can explain the elevational contrast. Greater summer insolation may have produced drought on well-drained shallow soils of the Sierra Nevada, but greater winter snow depth due to lower winter insolation may have increased spring runoff from the Sierra Nevada. The increased spring discharge would have favored *Sequoiadendron* growing in the valley bottoms, and would have filled Tulare Lake.

The climate reconstructions (Fig. 4) generally match the lake-levels shown by the littoral pollen and pelagic algae (Fig. 3); i.e. high but fluctuating lake levels during the cool wet early-Holocene, low lake levels during the warm dry mid-Holocene, and peak lake level during the cool-moist climate at the beginning of the late-Holocene.

The Tulare Lake pollen diagram (Fig. 3) records two significant biogeographic phenomena. The abundance of giant sequoia (*Sequoiadendron*) pollen 8500–24,000 yr B.P. attests to the expansion of this California endemic along valley bottoms of the Sierra Nevada. Also, greasewood (*Sarcobatus*), now found only east of the Sierra crest, was common in the area (Fig. 3), probably on saltflats surrounding Tulare Lake. The demise of *Sarcobatus* ca. 7000 yr B.P. also is recorded in a pollen diagram (1–2%) from Shellmaker Island in Newport Bay, coastal California (Davis, 1996). The collapse of Great Basin-like vegetation in central California, and the contraction of the range of giant sequoia precedes the establishment modern vegetation, and the beginning frequent fires in southern California.

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A 9170-year record of decadal-to-multi-centennial scale pluvial episodes from the coastal Southwest United States: a role for atmospheric rivers?

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ABSTRACT

A well-dated, 9170 calendar year before present (cal yr BP) paleohydrologic reconstruction is presented from Lower Bear Lake in the San Bernardino Mountains of the coastal southwest United States. This new multi-proxy record is characterized by alternating organic-rich/carbonate-rich sediment units, interpreted to reflect hydrologically-forced changes in the lake's depositional environment. Our interpretation of the proxy data indicates nine decadal-to-multi-centennial pluvial episodes (PE) over the past 9170 cal yr BP. Of these nine inferred pluvials, five are interpreted as more pronounced based on their combined proxy interpretations: (PE-V) 9170?–8250, (PE-IV) 7000–6400, (PE-III) 3350–3000, (PE-II) 850–700, and (PE-I) 500–476 (top of core) cal yr BP. The Lower Bear Lake record indicates that the San Bernardino Mountains, source region for the Mojave River and its terminal playa, was wet during the same periods (within dating errors), to several of the major pluvials proposed from the lakes in the sink of the Mojave River. Our comparison extends north also to Tulare Lake, which drains the southcentral-western Sierra Nevada Mountains. This temporally and spatially coherent signal indicates that a similar climate forcing acted to increase regional wetness at various times during the past 9170 cal yr BP. As originally proposed by Enzel, Ely, and colleagues (e.g., Enzel et al., 1989; Enzel, 1992; Ely et al., 1994; Enzel and Wells, 1997), we too contend that Holocene pluvial episodes are associated with changing the frequency of large winter storms that track across a broad region at decadal-to-multi-centennial timescales. We build upon their hypothesis through the addition of new and better-dated site comparisons, recent advances in the understanding of atmospheric rivers, and improved knowledge of the ocean–atmosphere dynamics that caused the early 20th century western United States pluvial.

1. Introduction

Southern California (or the coastal southwest United States) is subject to a variety of natural hazards. Besides the earthquakes, fires, and perennial water shortages, the coastal southwest United States (US) is also impacted occasionally by extreme storms, which promote large floods, coastal erosion, and landslides (Enzel, 1992; Ely et al., 1993; Enzel and Well, 1997; Westerling et al., 2003; Skinner et al., 2008; Dettinger, 2011). So significant is this risk that the USGS has created the ARkStorm Project (Porter et al., 2011). This project aims to prepare California for a future storm(s) on the scale of the disastrous winter of 1861–1862 A.D. Unfortunately, our knowledge of pre-measurement wetter-than-average climate episodes at decadal-to-multi-centennial timescales (i.e., pluvials), including their frequency, timing, and duration, is not well understood for the coastal southwest US, especially into the mid-to-early Holocene (Fye et al., 2004; Hidalgo, 2004; Woodhouse et al., 2005; Cook et al., 2007, 2011; Herweijer et al., 2007). It is now well-documented that the largest flood-producing precipitation events in the coastal southwest are associated with atmospheric river (AR) storms (Ralph et al., 2006; Neiman et al., 2008; Leung and Qian, 2009; Ralph and Dettinger, 2011). The abrupt topography of the coastal southwest enhances the hydrologic impact of AR storms via rapid orographic uplift and consequent moisture release (Neiman et al., 2008). This rapid de-watering generates copious single storm precipitation amounts that are rivaled only by the hurricanes of the American southeast (Dettinger et al., 2011).

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Inland from the coastal southwest US is the arid Mojave Desert. Today, the Mojave region is dotted with ephemeral lakes, many of which are fed by the Mojave River – a river sourced in the mountains of the coastal southwest US (i.e., San Bernardino Mountains). A wealth of research using stranded beaches, playa lake cores, and exposed lacustrine sediments from the Mojave Desert has generated important insight to episodes of wetter-than-average Holocene climate interpreted to reflect more frequent Pacific storms and their resultant extreme floods (e.g., Enzel et al., 1989; Enzel and Wells, 1997; Wells et al., 2003; Miller et al., 2010). The length of the transmitting ephemeral channel from its source (the mountains of the coastal southwest US) to its sink (modern playa-lakes fed by the Mojave River) produces a natural filter that excludes records of events below the minimum discharge required to produce and sustain Mojave lakes for more than a few months (Enzel, 1992; Enzel and Wells, 1997). The ocean–atmosphere conditions required to form and sustain lakes in the sink of the Mojave River are associated with more frequent and larger magnitude winter storms as well as their interannual seasonal persistence (Enzel et al., 1989; Enzel, 1992; Ely et al., 1994; Enzel and Wells, 1997; Redmond et al., 2002).

Here, we present a 9170 calendar years before present (hereafter cal yr BP), paleohydrologic reconstruction from Lower Bear Lake in the San Bernardino Mountains of the coastal southwest US. Because Lower Bear Lake is located at the source region for the Mojave River and its terminal playa, Lower Bear Lake presents a unique opportunity to compare and contrast pluvial episode timing, duration, and frequency between source and sink. To evaluate our new record, we compare also the Lower Bear Lake pluvials to comparably dated sites across the coastal southwest US (e.g., Lake Elsinore, Dry Lake, and Tulare Lake).

2. Setting and background

Lower Bear Lake is located in the east–west trending San Bernardino Mountains within the Big Bear Valley water shed, approximately 160 km northeast of Los Angeles (Fig. 1). For clarity, the term Lower Bear Lake is used in a public land survey in 1857 A.D. for the small lake within Big Bear Valley before the construction of the dam in 1884 A.D. (Leidy, 2003). Modern bathymetry reveals a distinct depression in the near-center of modern Big Bear Reservoir, representing the original Lower Bear Lake (Fig. 2). Early survey reports show that Lower Bear Lake was full in 1857 A.D. and 1878 A.D., prior to dam construction (Leidy, 2003). It also retained water during the 1950's A.D. drought, which temporarily dried the bathymetrically higher portions of the reservoir (Fig. 2). Based on the public land survey from 1857 A.D., Lower Bear Lake measured approximately 2.9 km $\times$ 0.8 km. Its pre-dam depth ca. 1884 A.D. is unknown but was likely less than 3 m based on the modern bathymetry of Big Bear Lake (Reservoir). The early Holocene Lower Bear Lake depth, however, was potentially >8 m allowing for the accumulated sediment. Extrapolating from the reservoir's modern drainage basin, Lower Bear Lake's drainage basin would comprise approximately 82 km^2 (Leidy, 2003). Included in Lower Bear Lake's paleo-drainage basin are two main tributaries: Grout Creek and Rathbun Creek. Rathbun Creek drains a large portion of the north-facing Bear Mountains, which obtain an elevation in excess of 2590 m. A number of smaller ephemeral creeks directly flow into Lower Bear Lake. In addition to these creeks, groundwater, direct run-off from precipitation events, and spring snowmelt run-off contribute to the lake's overall hydrologic budget. Lower Bear Lake would have drained along the same path to the west as the modern reservoir assuming the lake spilled over its western outlet (Fig. 2).

Southern California climate is categorized as a coastal Mediterranean climate with hot, dry summers and cool, wet winters (Bailey, 1966). Annual mean wet precipitation is 56 cm for Big Bear Lake (www.wrcc.dri.edu). Most of the annual precipitation is recorded during the months of November through March. Maximum snowfall occurs in the months of January thru March with an annual average of 158 cm at Big Bear Lake. Kirby et al. (2006, 2010) have shown that regional lake levels rise and fall in

Fig. 1. Regional map with relevant lake sites and their major rivers. Tulare lake mid-to-late 19th century reconstruction is modified from Page (1986). LBL = Lower Bear Lake; SG Mtns = San Gabriel Mountains; SB Mtns = San Bernardino Mountains; SJ Mtns = San Jacinto Mountains.

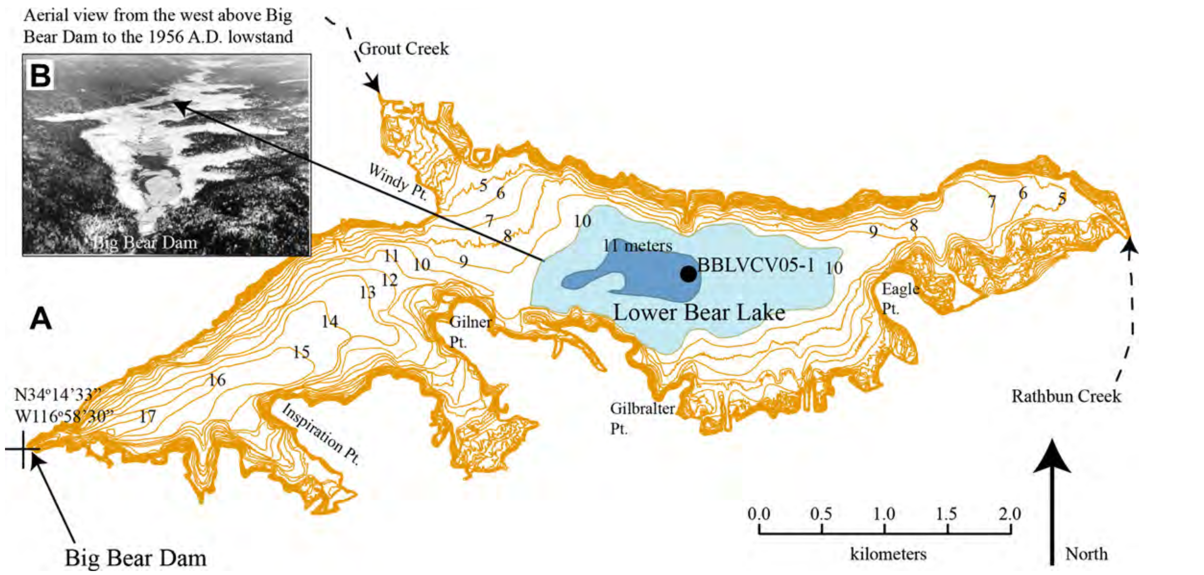

Fig. 2. A) Bathymetric map for modern Big Bear Reservoir with Lower Bear Lake shown based on bathymetric data. B) Aerial view of 1956 A.D. lowstand revealing Lower Bear Lake when the reservoir is dry.

near unison with changes in total winter season precipitation, including Baldwin Lake, which is located 7.5 km east, down-valley from Lower Bear Lake. There is a small summer/early fall contribution to annual total precipitation (<14%) at Big Bear Lake caused by localized orographic convection and/or occasional monsoonal moisture from the Gulf of California (Tubbs, 1972; Adams and Comrie, 1997). Recent studies show that dissipating eastern tropical north Pacific cyclones may also be important to summer/fall precipitation in the coastal southwest (Ritchie et al., 2010). However, it is unlikely, now, or at any time in the Holocene, that summer precipitation played the predominant role in the total annual hydrologic budget of the coastal southwest US (Bird and Kirby, 2006; Kirby et al., 2007).

The principal mechanism that forces weather patterns in the coastal southwest US is the interaction between Pacific Ocean sea surface temperatures and atmospheric circulation (Pyke, 1972; Trenberth and Hurrell, 1994; Namias et al., 1998). In summer, sea surface temperatures shift the north Pacific High pressure system to the north diverting storms tracks to higher latitudes. As a result, the coastal southwest receives little or no summer precipitation associated with jet stream entrained cyclones (Barlow et al., 2001). The north Pacific High shifts southward in the northern hemisphere winter, steering winter storms across western North America and occasionally across the coastal southwest (Cayan and Peterson, 1989). Namias et al. (1988) observed that persistent sea surface temperature (SST) patterns modulate the position of the polar front jet stream, and can sustain winter climate states from year-to-year, affecting the amount of winter precipitation reaching the coastal southwest US. The most persistent SST patterns favor colder than average SST in the northeast Pacific, which favors a southerly depression of the polar front jet stream (Namias et al., 1988). In turn, the latter scenario promotes more frequent storms across the coastal southwest US, including Pineapple Express-type, AR storms that tap into sub-tropical moisture (Fye et al., 2004; Cook et al., 2011).

Other important features of the coastal southwest US climate include the El Nino-Southern Oscillation (ENSO) that plays a major role in controlling year-to-year winter precipitation in the coastal southwest (Redmond and Koch, 1991; Cayan et al., 1999) and the Pacific Decadal Oscillation (PDO) that forces decadal-to-multi-decadal winter precipitation across the study region (Mantua and Hare, 2002; Hanson et al., 2006). In general, both El Nino and a positive PDO favor greater winter season precipitation across the study region. The relationship, however, between ENSO, PDO, and AR storm activity is less well understood (Dettinger, 2004; Cook et al., 2011; Dettinger et al., 2011).

3. Methods

A single drive, 4.5 m-long sediment core (BBLVC05-1) was extracted from Lower Bear Lake in 2005. The core was split, described, digitally photographed, and sub-sampled in the CSUF Paleoclimatology and Paleotsunami Laboratory. Mass magnetic susceptibility, LOI 550 °C (% total organic matter), and LOI 950 °C (% total carbonate) were determined at 1 cm contiguous intervals (e.g., 0–1 cm = 0.5 cm, 1–2 cm = 1.5 cm etc.) following the same protocol as Kirby et al. (2007). Counts per 1 g dry sediment weight were determined on the >125 μ size fraction at 10 cm intervals (e.g., 0–1 cm = 0.5 cm, 10–11 cm = 10.5 cm etc.) for ostracods and gastropods. Prior to wet-sieving, each microfossil sample was pre-treated with ≥30 mL of 30% H_2O_2 at 100 °C to remove organic material to facilitate counting. Grain size measurements were determined at 2 cm intervals (e.g., 0–1 cm = 0.5 cm, 2–3 cm = 2.5 cm, etc) using a Malvern laser diffraction grain size analyzer. All grain samples were pre-treated with ≥30 mL of 30% H_2O_2 to remove organics, ≥10 mL of 1 N HCl to remove carbonates, and ≥10 mL of 1 N NaOH to remove biogenic silica. CN ratios were determined at 2 cm intervals (same as grain size) on bulk sediment at the University of Saskatchewan Isotope Laboratory. Samples were acidified to remove carbonate material. The residue was then homogenized and loaded into tin capsules and analyzed using a Thermo Finnigan Flash 1112 EA. CN data were converted to molar values using the equation from McFadden et al. (2005). Thirty-three AMS ^{14}C dates (31 on discrete organic materials [e.g., charcoal, seeds] and 2 on bulk organic carbon) were obtained from the upper 405 cm of the sediment core. Samples were picked at California State University, Fullerton and processed at either the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry (CAMS) or at the University of California, Irvine Keck Carbon Cycle AMS Laboratory (UCI).

4. Results and proxy interpretations

Of the 33 AMS ^{14}C dates obtained from BBLVC05-1, 23 were used to construct an age model (Table 1). All dates were corrected to calibrated years before present using the online CALIB Program version 6.0.0 and the intcal09.14c calibration data set (Stuiver and Reimer, 1993; Reimer et al., 2009). Ten dates were dismissed for several reasons including coupled bulk-discrete samples with different ages ($n = 2$), coupled discrete ages on different materials with different ages ($n = 4$), stratigraphic inversion (old over young) ($n = 3$), and obvious reworking or contamination ($n = 1$) (Table 1). Dismissed dates are shown on Fig. 3 and labeled for comparison to Table 1 with their respective dismissal reasons. A four-part age model was developed using the remaining 23 AMS ^{14}C dates (Fig. 3). Based on the model, age resolution per centimeter ranges from 5 to 62 years with an average resolution of 22 years.

From the core bottom at 4.5 m (no age estimate) to approximately 3.8 m (9170 cal yr BP), the core is characterized as a gray sandy silt with occasional gravel (Fig. 4). From 4.04 m (~9350 cal yr BP) to 3.8 m, the sand contribution declines to levels (~10%) similar to the remainder of the core. From 0 to 3.8 m, the sediment alternates between dark brown to black organic-rich clayey silts and variegated browns to beige carbonate and gastropod-rich clayey silts (Fig. 3). Faint layering occurs between 330 and 317 cm, 287–257 cm, and 172–165 cm. Because the bottom 0.70 m of the core represents a distinctly different depositional environment than the upper 3.8 m, we did not extend the age model below 3.8 m. Tentatively, the bottom 0.70 m of sandy silts with occasional gravel is interpreted to represent the latter part of the late-glacial to Holocene transition characterized by vigorous run-off and rapid, high energy sedimentation. The core site was likely located at the distal end of a fan delta complex associated perhaps with a high discharge Rathbun Creek, which drains the snowy, north-facing Bear Mountains. By 3.8 m (9170 cal yr BP), Lower Bear Lake transitioned to its Holocene depositional

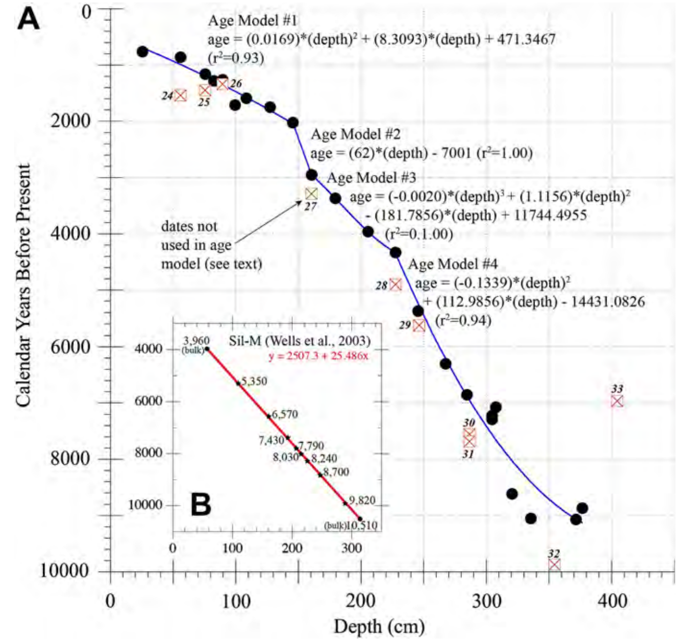

Fig. 3. A) Age models for core BBLVC05-1 with r^2-values. Boxes with an enclosed X are numbered and correspond by number to Table 1. B) Silver lake age model using two bulk ^{14}C dates from Wells et al. (2003). See Section 5.1 above for details on Silver lake age model.

Table 1
Age data for core BBLVC05-1.

Number	Lab ID	Sample name	Depth interval	Avg. depth (cm)	Material dated	^{14}C age (BP)	±	cy BP	2-sigma	Probability	Reason for rejection
1	UCI 33358	BBLVC05-1	25–26 cm	25.50	Bark?	855	15	760	731–788	1.000	N/A
2	LLNL 147173	BBL 1 55–57 cm	55–57 cm	56.00	Seeds	940	30	860	791–925	1.000	N/A
3	LLNL 148757	BBL 75	75–76 cm	75.50	Seed	1210	40	1160	1055–1263	0.985	N/A
4	LLNL 147174	BBL 2	82–83 cm	82.50	Charcoal	1350	40	1280	1227–1336	0.861	N/A
5	LLNL 148759	BBL 89	89–90 cm	89.50	Seed	1305	25	1260	1224–1291	0.685	N/A
6	LLNL 149024	BBL 99	99–100 cm	99.50	Wood	1775	35	1711	1604–1817	0.997	N/A
7	UCI 45333	BBLVC05-1	108–109 cm	108.50	Seed	1705	20	1590	1548–1633	0.725	N/A
8	LLNL 149025	BBL 127	127–128 cm	127.50	Mixed macros	1830	70	1747	1593–1900	0.978	N/A
9	LLNL 147175	BBL 3	145–146 cm	145.50	Charcoal	2050	35	2020	1926–2118	1.000	N/A
10	LLNL 147176	BBL 4	160–161 cm	160.50	Charcoal	2830	35	2950	2853–3039	0.977	N/A
11	UCI 33359	BBLVC05-1	179–180 cm	179.50	Wood	3135	20	3370	3330–3401	0.976	N/A
12	LLNL 148761	BBL 205	205–206 cm	205.50	Mixed macros	3625	50	3960	3828–4089	0.996	N/A
13	LLNL 147178	BBL 6	227–228 cm	227.50	Wood	3905	45	4330	4226–4440	0.948	N/A
14	LLNL 149026	BBL 245	245–246 cm	245.50	Mixed macros	4705	50	5373	5319–5427	0.495	N/A
15	LLNL 148762	BBL 267	267–268 cm	267.50	Mixed macros	5490	60	6300	6182–6914	0.999	N/A
16	UCI 33360	BBLVC05-1	284–285 cm	284.50	Wood	6005	25	6850	6780–6914	0.966	N/A
17	LLNL 148763	BBL 304	304–305 cm	304.50	Seeds	6275	45	7220	7154–7294	0.889	N/A
18	LLNL 148764	BBL 304-rep	304–305 cm	304.50	Seeds	6370	25	7290	7254–7333	0.846	N/A
19	LLNL 147125	BBL 9	307–308 cm	307.50	Seeds	6160	25	7071	6981–7161	1.000	N/A
20	LLNL 149030	BBL 320	320–321 cm	320.50	Mixed macros	7820	100	8616	8420–8811	0.834	N/A
21	UCI 45334	BBLVC05-1	335–336 cm	335.50	Bark	8110	25	9050	8999–9092	0.957	N/A
22	LLNL 149031	BBL 371	371–372 cm	371.50	Bark	8130	45	9070	8995–9144	0.877	N/A
23	UCI 33361	BBLVC05-1	376–377 cm	376.50	Seeds	7980	25	8870	8751–8994	0.980	N/A
Rejected samples											
24	LLNL 147172	BBL 1 55–57 cm	55–57 cm	56.00	Charcoal	1580	140	1540	1262–1822	0.999	Coupled – too old
25	LLNL 148758	BBL 75	75–76 cm	75.50	Wood	1555	30	1450	1380–1525	1.000	Coupled – too old
26	LLNL 148760	BBL 89	89–90 cm	89.50	Wood	1440	30	1340	1296–1382	1.000	Coupled – too old
27	LLNL 147177	BBL 5	160–161 cm	160.50	Bulk	3080	35	3290	3215–3373	1.000	Bulk
28	LLNL 147123	BBL 6	227–228 cm	227.50	Leaf?	4315	45	4902	4827–4977	0.996	Coupled – too old
29	LLNL 147124	BBL 8	246–247 cm	246.50	Bulk	4905	25	5626	5590–5661	0.995	Bulk
30	LLNL 149027	BBL 286	286–287 cm	286.50	Bark	6690	30	7558	7505–7611	1.000	Old above young
31	LLNL 149028	BBL 286-rep	286–287 cm	286.50	Bark	6845	35	7682	7607–7757	1.000	Old above young
32	LLNL 147126	BBL 10	354–355 cm	354.50	Wood	8850	25	9870	9777–9962	0.438	Old above young
33	LLNL 147127	BBL 11	404–405 cm	404.50	Roots or stems?	6115	30	6964	6897–7031	0.724	Contaminated?

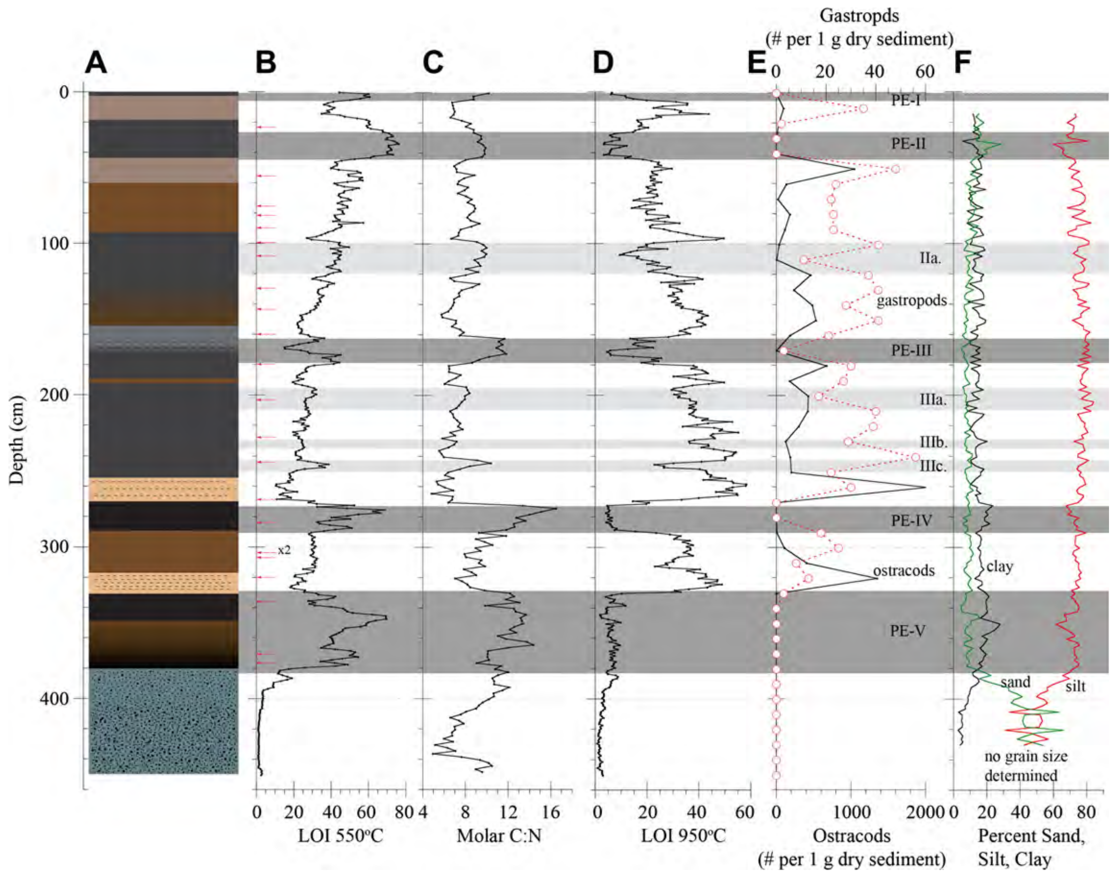

Fig. 4. BBLVC05-1 data versus depth. A) Core lithology (color represents true sediment color from split core). B) LOI 550 °C. C) Molar CN ratios. D) LOI 950 °C. E) Micro-fossil counts. F) Grain size. Small arrows on (B) show location of radiocarbon dates used in the age model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

environment – an isolated lake with a distal stream influence – as characterized by alternating organic and carbonate-rich units. The remainder of the paper will focus on the upper 3.8 m of sediment.

Magnetic susceptibility is relatively low and invariant throughout the core and is therefore not shown. Low magnetic susceptibility values are expected in organic and carbonate-rich sediment that are generally diamagnetic (Gale and Hoare, 1991). Similarly, grain size, with the exception of the bottom 0.70 m of the core, is without distinction and is shown only by depth for general sediment characterization (Fig. 4). LOI 550 °C (% total organic matter), LOI 950 °C (% total carbonate), CN ratios, and microfossil counts are highly variable throughout the upper 3.8 m of the core (Fig. 4). In general, when LOI 550 °C is high, LOI 950 °C is low to zero, CN ratios are high, gastropod counts are low to zero, and ostracod counts decline. Due to the effect of clay de-watering, LOI 950 °C values less than 4% are considered to be zero carbonate (Dean, 1974). Further, because LOI 950 °C and gastropods are positively correlated for the upper 3.8 m of the core ($r = 0.75$; $p = <0.0001$), we assume that LOI 950 °C values less than 4% in intervals without gastropod counts equate to zero gastropods. For example, no samples were analyzed for gastropods between 260 and 270 cm. However, LOI 950 °C values are <4–6% across this interval, so we infer a near absence of gastropods as well.

In all, there are nine intervals where the CN ratio and LOI 550 °C are high and LOI 950 °C, ostracods, and gastropods are low (Fig. 4). We interpret these nine intervals as periods of increased precipitation/run-off (pluvials) and thus higher relative lake level. Although discussed in detail in the succeeding paragraphs, our proxy interpretations are summarized as follows: 1) high CN ratios coupled with high percent total organic matter (LOI 550 °C) reflect enhanced run-off of terrestrial biomass during wetter climates; 2) low gastropod counts reflect a combination of reduced habitat, longer transport paths from the littoral to the profundal zone, and potentially more corrosive hypolimnion waters during wetter climates/deeper lake; and, 3) low percent total carbonate (LOI 950 °C) reflect a cooler spring–summer epilimnion, diminished primary productivity, enhanced carbonate solubility, and potentially more corrosive hypolimnion waters during wetter climates/deeper lake.

Terrestrial organic matter is characterized by higher $C_{organic}$ to N_{total} ratios than aquatic organic matter (Meyers and Ishiwatari, 1993); thus, we interpret higher CN values as a proxy for enhanced delivery of terrestrial biomass by increased precipitation and run-off into Lower Bear Lake during wetter climates. High percent total organic matter, indicated by high percent LOI 550 °C values, is positively correlated to high CN ratios in the Lower Bear Lake record, suggesting that the high CN ratios result from increased input of terrestrial organic matter, rather than simply a decrease in aquatic productivity. High LOI 550 °C during the proposed pluvial episodes may reflect also higher preservation of organic carbon, as a less shallow lake will more frequently experience periods of anoxic bottom waters.

Bottom water anoxia will also decrease hypolimnion pH and could enhance carbonate dissolution during settling or in-situ post-deposition. The latter factor likely contributes to the decrease in microfossil counts, especially gastropods, as well as lower LOI 950 °C values (percent total carbonate) during times of high CN and high LOI 550 °C values. We contend that a wetter climate also increases Lower Bear Lake's volume at the expense of the littoral habitat for gastropods. As a result, it also lengthens the transport distance between the littoral zone and profundal zone, thereby reducing the number of littoral organisms (i.e., gastropods) transported to the profundal core site during the proposed pluvial episodes.

Wetter Holocene climates may be associated with enhanced high elevation snowfall. Today, even sub-tropical winter storms generate heavy snow at high elevations in the San Bernardino Mountains (Minnich, 1986). It is possible that enhanced alpine snowfall during Holocene pluvial episodes produced more persistent snowpack. More persistent snowpack will generate extended coldwater run-off throughout the melt season, thereby lowering average spring/summer epilimnion water temperatures. In many modern lakes, calcium carbonate precipitation is a seasonal feature of the lake's epilimnion, often temperature and/or productivity related (Thompson et al., 1997; Hodell et al., 1998; Mullins et al., 1998). Cooler epilimnion temperatures during spring/summer phytoplankton blooms may have reduced primary productivity, limiting photosynthetic CO_2 drawdown and thus decreasing carbonate precipitation (e.g., Hodell et al., 1998). A decrease in primary productivity will also cause a decrease in the total contribution of low CN ratio aquatic organic matter. Finally, calcium carbonate solubility increases with lower water temperatures (Mucci, 1983). Cooler epilimnion temperatures would promote higher calcium carbonate solubility and thus decrease LOI 950 °C values as well as gastropod/ostracod production and/or preservation.

In summary, we infer nine intervals of wetter than normal climate in the sediments of Lower Bear Lake during the past 9170 cal yr BP. Of these nine inferred intervals, five are more pronounced based on the co-occurrence of a) near or total absence of gastropods, b) near zero LOI 950 °C values, c) notable CN ratio peaks, and d) notable LOI 550 °C peaks (Fig. 3). The five major pluvial episodes (PE) occurred: (PE-V)9170?–8250, (PE-IV) 7000–6400, (PE-III)3350–3000, (PE-II)850–700, and (PE-I) 500–476 (top of core) cal yr BP. The remaining four minor pluvial episodes are labeled and shown on Figs. 4 and 5.

5. Discussion

5.1. Source to sink

A series of papers by Enzel and others (e.g., Enzel et al., 1989, 1992; Enzel, 1992; Enzel and Wells, 1997) investigate the modern

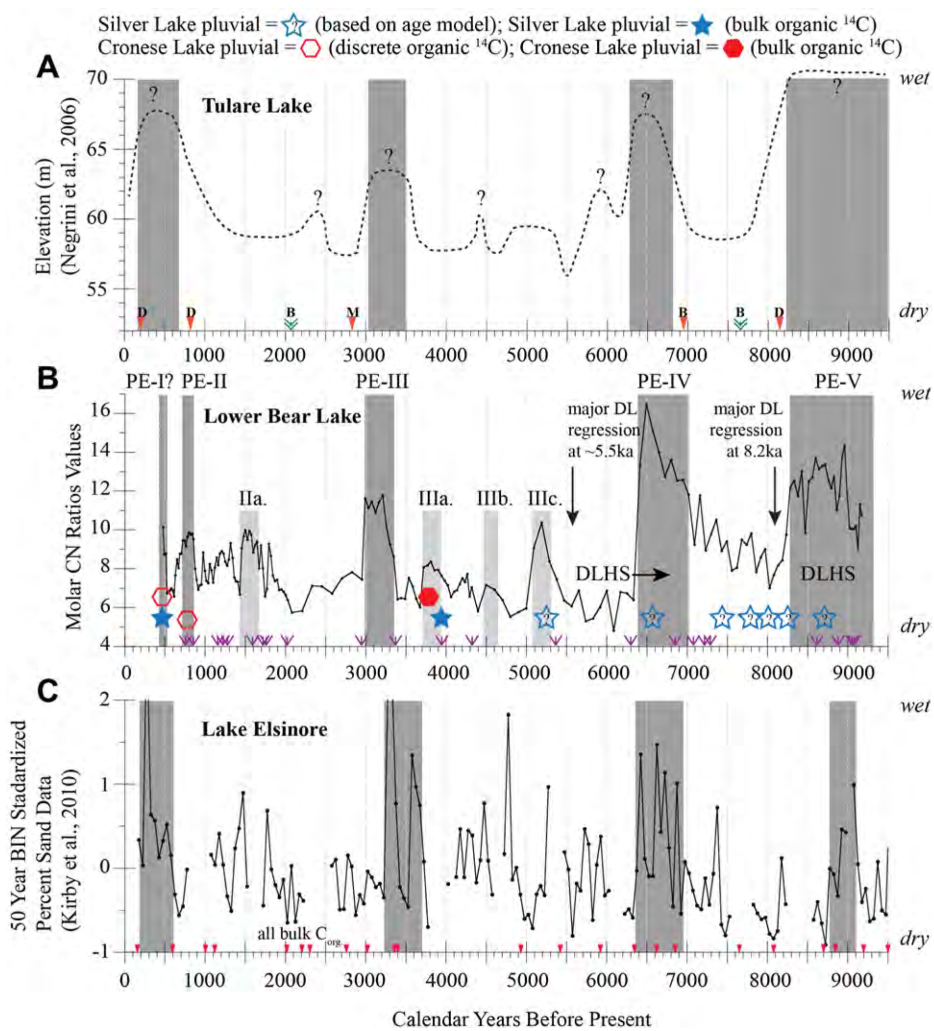

Fig. 5. Lower Bear lake and regional comparisons. A) Tulare lake level reconstruction (Negrini et al., 2006). Question marks denote where absolute highstand elevation is unknown. D = discrete organic ^{14}C age; B = bulk organic carbon ^{14}C age; M = mixed discrete organics ^{14}C age. Solid arrow = age from Negrini et al. (2006) trenches; double-arrow = age from Davis (1999) depocenter core. See Negrini et al. (2006) for Tulare lake age control details. B) Lower Bear lake molar CN ratios with pluvial episodes (PE) labeled. LBL age control depth locations shown by arrows. DL = Dry Lake (Bird et al., 2010), DLHS = Dry Lake highstand (Bird et al., 2010). Dated and inferred Silver Lake highstands shown by symbols (Wells et al., 2003). Dated and inferred Cronese Lake highstands shown by symbols (Drover, 1978; Owen et al., 2007; Miller et al., 2010). C) Lake Elsinore sand record (Kirby et al., 2010). Lake Elsinore age control depth locations shown by arrows.

and modeled Holocene atmospheric conditions necessary to create and maintain lakes in the sink of the Mojave River (Fig. 1). Their work is relevant particularly to the Lower Bear Lake record because the San Bernardino Mountains provide the source of water required to form and maintain Holocene lakes in the Mojave River sink (Fig. 1). Specifically, lakes do not form in the Mojave sink if Lower Bear Lake is dry. An important finding from the Enzel et al. research is that the meteorological conditions necessary to form and maintain Mojave lakes are extreme and anomalous in modern times. Only twice in the 20th century have meteorological conditions produced lakes lasting >12 and ≤18 months duration at the Mojave River's terminal basin, Silver Lake (Enzel and Wells, 1997). These conditions include a significantly southward displaced, winter season polar front jet stream, its associated storm tracks, and moisture transport from the tropical North Pacific. Moreover, these conditions must persist on a near annual (winter season) basis for the duration of the lake's existence. To develop and maintain decadal-to-multi-centennial scale lakes in the Mojave River sink requires atmospheric conditions that generate higher-than-average winter precipitation across the region on a recurring annual basis. Since Lower Bear Lake sits at the headwaters of the Mojave River, the modern conditions that favor lake development in the Mojave River sink will also favor higher discharge into, and rising lake levels, at Lower Bear Lake. Our first objective is to compare and contrast pluvial episode timing and frequency between source (Lower Bear Lake) and sink (lakes in the Mojave River sink).

Two Mojave River sink sites are used for comparison to Lower Bear Lake: Silver Lake and Cronese Lake (Figs. 1 and 5) (Drover, 1978; Wells et al., 2003; Miller et al., 2010). Core sites Sil-M/Sil-N and Pit M (from GSA Data Repository Item, 2003069 [Wells et al., 2003]) contain 11 units described as some form of lacustrine to wet playa environment (Table 2) (Wells et al., 2003). Of these 11 units, only three are dated (Wells et al., 2003). Here, we convert the latter three ^{14}C ages to calendar years before present using the online CALIB program version 6.0.0 to facilitate a direct comparison to Lower Bear Lake and elsewhere (Table 2). Because 8 of the 11 lacustrine facies are bracketed by the two older dates, we constructed a simple linear age model between 3960 and 10,510 cy BP to infer the ages of the undated lacustrine facies (Fig. 3b, Table 2).

Dates from Cronese Lake, 25 km southwest of Silver Lake and fed by the same floods that feed Silver Lake (Enzel, 1992), provide additional insight to the timing of the Holocene lakes in the Mojave River sink (Fig. 1) (Owen et al., 2007; Miller et al., 2010). Like Silver Lake, the ^{14}C ages published in the latter two papers were converted to calendar years before present using the online CALIB Program version 6.0.0 by Kirby (this paper). Owen et al. (2007) and Miller et al. (2010) date discrete organic materials using the AMS ^{14}C method and obtain ages from Cronese Lake centered on 393 ± 25 ^{14}C years (∼470 cy BP) and 820 ± 25 ^{14}C years (∼730 cy BP). An older lacustrine facies from Cronese Lake dates at 3500 ± 180 ^{14}C years (3810 cy BP) based on bulk organic carbon (Drover, 1978 [from Miller et al., 2010 paper]).

A comparison between pluvial episodes in Lower Bear Lake and the lakes in the Mojave River sink indicate some similarities (Fig. 5). Lower Bear Lake PE-I, PE-II, PE-IIIa, PE-IIIc, PE-IV, and PE-V contain possible Mojave correlatives (Fig. 5). Limitations associated with our construction of an over-simplified Silver Lake age model temper our confidence in the absolute timing between source and sink for everything older than 1000 cy BP (Fig. 5). For example, it is odd that there would be a notable Silver Lake and Cronese Lake pluvial episodes correlative to the Lower Bear Lake PE-IIIa event but nothing correlative to the more pronounced Lower Bear Lake PE-III event. One possible explanation for this observation is that the Mojave site dates were measured on redeposited organic matter (i.e., bulk organic carbon). Another possibility is that the bulk organic matter includes materials that incorporated old DIC from the water column during growth. Despite the dating caveats, our source to sink comparison indicates possibly 6 correlative Holocene pluvial episodes between source and sink. Improved age control is required from the Mojave region to link confidently source to sink as well as to determine the durations of the Mojave pluvial episodes, which are likely shorter in length than the Lower Bear Lake pluvials.

5.2. Regional comparisons

Our second objective is to compare the Lower Bear Lake PE record to comparably dated sites across the coastal southwest United States (Fig. 1) (Lake Elsinore, Dry Lake, and Tulare Lake). Dry Lake, located ∼17 km SSE from Lower Bear Lake, is well-dated using discrete organic materials, but of lower resolution than Lower Bear Lake, especially the core section younger than 5500 cy BP (Figs. 1, 4 and 5) (Bird and Kirby, 2006; Bird et al., 2010). A combined sedimentological and geophysical study reveals two early Holocene highstands at Dry Lake (Bird et al., 2010). These two early Holocene Dry Lake highstands are approximately correlative to Lower Bear Lake PE-V and PE-IV. Geophysical data indicate an abrupt termination of the younger of the two early Holocene Dry Lake highstands, perhaps evidenced similarly by the abrupt change in sedimentology in Lower Bear Lake at approximately 265 cm or 6300 cy BP (Figs. 4 and 5).

Lake Elsinore is located ∼76 km SW from Lower Bear Lake (Fig. 1). The Elsinore core is well-dated; however, all of the radiocarbon ages were generated from bulk organic carbon samples, which adds a potential source of error to the core's chronology (Fig. 5) (Kirby et al., 2007, 2010). Despite this dating caveat, the Lake Elsinore sand record indicates wet conditions simultaneously

Table 2
Calibrated age data for Silver lake Sil-M/Sil-N with facies interpretation. Facies interpretations are taken directly from from GSA data Repository Item 2003069 Wells et al. (2003).

Facies depth interval (cm)	Average facies depth (cm)	Calendar years BP	Wells et al. (2003) interpretation	Dating Technique
9–17 cm	16[a]	420	Lake	C-14 (bulk)
55–80 cm	57[a]	3960	Wet playa to lake	C-14 (bulk)
103–120 cm	≈111.5	5349	Lake	Age model
155–164 cm	≈159.5	6572	Intermittent lake?/wet playa?	Age model
185–201.6 cm	≈193.3	7434	Wet playa?/lake?	Age model
201.6–212.8 cm	≈207.2	7788	Lake/wet playa	Age model
212.8–220.4 cm	≈216.6	8028	Lake	Age model
220.4–229.4 cm	≈224.9	8239	Lake	Age model
239.1–247 cm	≈243.05	8702	Intermittent lake?	Age model
269–305.5 cm	≈287	9822	Lake	Age model
312–319 cm	314[a]	10,510	Lake	C-14 (bulk)

≈Based on age model.
[a] Depth of C-14 age from Wells et al. (2003).

across four of the five major Lower Bear Lake PEs (Fig. 5). Lower Bear Lake PE-II is untestable at Lake Elsinore due to a coring gap at the time of PE-II in the Elsinore core (Fig. 4).

Finally, this comparison is extended to Tulare Lake, located 320 km northwest of Lower Bear Lake, but the same distance from the Pacific coast (Fig. 1). The Tulare Lake level record was constructed using a combination of sites and their respective dates (Fig. 5) (Davis, 1999; Negrini et al., 2006). Age control is based on a combination of discrete and bulk/mixed samples (Fig. 5). A comparison of the Tulare Lake level curve to the Lower Bear Lake pluvial episodes indicates similar timing across four of the five major pluvial episodes (Fig. 5) (Negrini et al., 2006).

In all, the comparison between the six sites, which are located across a vast region characterized by varying drainage basins and source waters suggests that the climatological conditions forcing these Holocene pluvial episodes reflect synoptic scale climatological processes and not isolated or microclimatological phenomenon. Moreover, the similarity in timing between the various sites and the major pluvial episodes, despite the range of age control and dated materials, indicates that the age control errors are minor from site to site. We favor the latter statement rather than the alternative conclusion that the apparent coeval pluvial episodes are serendipitously contemporaneous and do not reflect any real spatial and temporal coherence.

5.3. A role for atmospheric rivers

In summary, there is compelling evidence that the Lower Bear Lake major pluvial episodes are temporally coherent across a large region of the coastal southwest United States including the lakes in the Mojave River sink and the south-central Sierra Nevada Mountains (Fig. 1). As a result, it is reasonable to suggest that the large-scale climatological patterns required to maintain lakes in the Mojave River sink, the San Bernardino Mountains, the Los Angeles Basin, and the southern Great Valley (via Sierra Nevada run-off) are associated with changing the frequency of large winter storms that track across a broad region at decadal-to-multi-centennial timescales as originally proposed by Enzel, Ely, and colleagues (e.g., Enzel et al., 1989; Enzel, 1992; Ely et al., 1994; Enzel and Wells, 1997). We build upon their hypothesis through the addition of new and better-dated site comparisons, recent advances in the understanding of atmospheric rivers, and improved knowledge of the ocean–atmosphere dynamics that caused the early 20th century western United States pluvial.

As an analog for the proposed Lower Bear Lake Holocene pluvial episodes, we focus on the early 20th century American west pluvial. This 13-year interval (1905–1917 A.D.) likely represents the wettest sustained conditions across a large portion of the American west over the past 1000 years (Cook et al., 2004, 2011; Fye et al., 2004; Woodhouse et al., 2005). For the coastal southwest United States, specifically, the early 20th century pluvial was a product predominantly of enhanced winter season precipitation (Cook et al., 2011). This event is, therefore, a good candidate for evaluating the ocean–atmosphere conditions requisite for generating anomalously wet winters in the coastal southwest United States for sustained intervals. The early 20th century pluvial was characterized by large, negative winter season 500-hPa height anomalies across the northeast Pacific, similar to the conditions previously proposed (Enzel et al., 1992; Ely et al., 1994; Enzel and Wells, 1997; Cook et al., 2011). Anomalously cool sea surface temperatures characterized most of the central to northeast Pacific during the 20th century American west pluvial (Cook et al., 2011). Both of these conditions are favorable to the formation of large storms, now recognized as atmospheric river storms, or specifically, Pineapple Express AR storms (Newell et al., 1992; Dettinger, 2004; Fye et al., 2004). Notably, sea surface temperature conditions characteristic of El Nino or a warm PDO – both favorable to wetter-than-average winters in the coastal southwest – were not dominant during the early 20th century pluvial (Cayan et al., 1999; Castello and Shelton, 2004; Cook et al., 2011). Future comparisons between Lower Bear Lake and SST records from key sites in the equatorial and northeast Pacific Ocean are required to test the SST forcing hypothesis.

6. Conclusions

We have demonstrated that Lower Bear Lake, in the San Bernardino Mountains of the coastal southwest, experienced several major pluvial episodes over the last 9170 cy BP. These pluvial episodes correspond well (within chronological uncertainties) with pluvials inferred from the lakes in the Mojave River sink, whose source is precipitation (especially wintertime) falling in the San Bernardino Mountains (Fig. 1). In addition, good evidence from several lakes in the coastal southwest US with disparate run-off sources suggest that the climatic conditions that caused the Lower Bear Lake (and Mojave) pluvials were synoptic in nature. We suggest that the proposed pluvial episodes were the result of increased frequency of atmospheric river storms, in particular subtropical Pineapple Express storms, due to persistent atmospheric and SST anomalies in the northeast and/or equatorial Pacific. Our results agree with, and build upon, results from Enzel, Ely and others (Enzel et al., 1989; Enzel, 1992; Ely et al., 1994; Enzel and Wells, 1997). A comparison to high resolution Holocene SST records (sub-centennial scale) are required from the equatorial and northeast Pacific Ocean to test our hypothesis. Our results are particularly significant in the context of global warming, as models suggest that warming could increase the intensity and frequency of AR storms and with it the risks of flooding, landslides, and other geohazards across the study region (Dettinger, 2011).

Acknowledgments

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The Rambla highstand shoreline and the Holocene lake-level history of Tulare Lake, California, USA

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Abstract

The stratigraphy associated with a highstand, wave-cut shoreline and with sites farther out into the lake plain constrain the Holocene lake-level history of Tulare Lake, California, USA as follows: Seven to eight major fluctuations in lake level occurred during the past 11,500 yr. Lake level was generally higher during the early Holocene (prior to ~6000 cal yr BP) peaking in two highstands (65–70 masl) at 9500–8000 cal yr BP and 6900–5800 cal yr BP. Thereafter, it fluctuated at lower amplitude until reaching a major highstand during the most recent millennium between ~750 and 150 cal yr BP. Two lake-level rises of lower amplitude were centered on 3300 and 1600 cal yr BP. At least three, probably brief, lowstands (<58 masl) occurred at: ~9700, 5500, and soon after 3000 cal yr BP. None of the trenches studied penetrated materials as old as the Clovis era, suggesting that the prolific, near surface Clovis shoreline sites found at the southern margin of Tulare Lake are absent at the western margin. An archeological midden of middle to late Holocene age was found near the top of the highstand shoreline feature. This site was probably occupied for much of the Holocene after 5000 cal yr BP, a time interval during which the lake would have been much lower in elevation than that of the site and several hundreds of meters distant from the site.

1. Introduction

Tulare Lake is located in the San Joaquin Valley of central California between the Coast Ranges and the Sierra Nevada (Fig. 1). Over the past few hundred millennia, the surface elevation of Tulare Lake fluctuated by several tens of meters in response to climate variations and to changes in the relative elevation of its spillover sill located near the north end of the lake where the Kings River presently enters the lake (Fig. 1) (Atwater et al., 1986). In this paper, we focus on the Holocene, a sufficiently short time interval for climate change, rather than geomorphic processes, to be the major influence on lake level. That is, during this time interval Tulare Lake behaves primarily as a closed-basin lake system that has not yet appreciably eroded into its spillover sill, a hydrologic barrier built by anomalously large alluvial fan activity during the most recent (MIS2) glacial maximum (Atwater et al., 1986).

The past 15,000–10,000 years is a particularly important time period in the Tulare Lake region. First, the level of this lake may have influenced the distribution of archeological sites. For example, high concentrations of Clovis-aged and younger artifacts are found in an areally restricted, elongate region that is parallel to the southern margin of the lake basin at an elevation of 56–58.5 masl (Riddell and Olsen, 1969; Wallace and Riddell, 1988; West et al., 1991; Fenenga, 1993) (Fig. 1). The location of the associated occupation sites was thus proposed to have been the result of a stable (and low) surface elevation of Tulare Lake for an extended period of time during the "Clovis Drought" of Haynes (1991) at 12,900 cal yr BP and later in the Holocene. Despite the plethora of artifacts, precise dating independent of the presumed ages of projectile point

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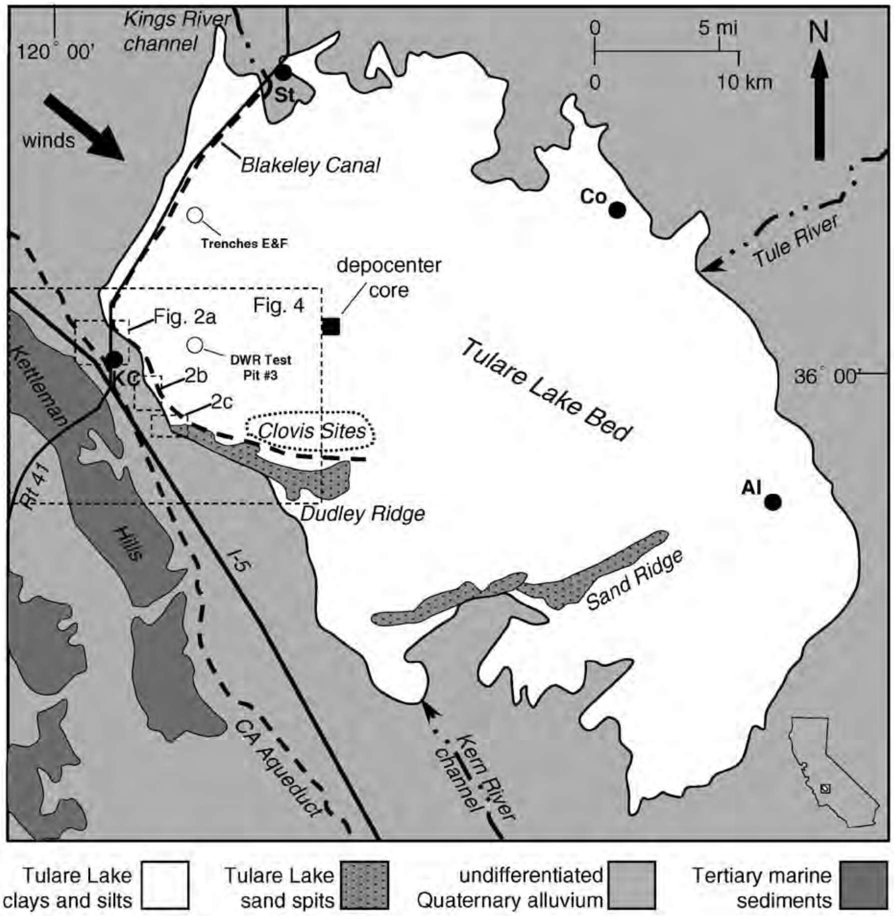

Fig. 1. Generalized geological and landmark map of study area (after Page, 1986). The location of the depocenter core studied by Davis (1999) is indicated by the solid square symbol. The locations of Lake Plain Trenches E and F and DWR Pit #3 are shown as open circles. Locations of communities are shown by the following abbreviations: Kettleman City (KC), Stratford (St), Corcoran (Co), Alpaugh (Al).

types has proven elusive, largely due to agricultural and other historical disturbances that have disrupted or destroyed most of the stratigraphic relationships at these sites. An improved lake-level history will serve as the basis for improved hypotheses regarding the distribution of paleoindian and Native American occupations in the region.

Second, the lake-level history of Tulare Lake is also a potentially important data source toward the understanding of paleoclimatic change in western North America following the most recent ice age. This is particularly true of the south-central California region west of the Sierra Nevada, an area in which few such lake records exist (Davis, 1999; Kirby et al., 2005 and references therein).

Davis (1999) provided an important record of late Quaternary climate for the Tulare Lake region based on the palynology of a depocenter core (Fig. 1). This study included conclusions regarding relative lake levels throughout the Holocene. Here we build on these results with improved constraints on absolute elevations and ages of past lake levels from two trench sites at higher elevations in the basin and mapping of related geomorphic features.

2. Background

2.1. Modern climate

The study area is hot and dry with low velocity winds (Preston, 1981). Mean temperatures in July range from highs of 37–38 °C (98–100°F) to lows of 18–20 °C (64–68°F). In January, they range from highs of 12–13 °C (54–56°F) to lows of 0–2 °C (32–36°F). Mean annual rainfall is in the range of 15–23 cm/yr (6–9 in/yr). Based on on-line climate summary data for the towns of Hanford, Corcoran, and Kettleman City from the Western Regional Climate Center at the Desert Research Institute, January, February, and March are the wettest months, and July and August are the driest. Winds blow predominantly (65% of the time) from the northwest and west-northwest (Fig. 1), with speeds usually between 5 and 25 kmph (3–15 mph). Due to the high temperatures and low precipitation values, evaporation rates of standing water (i.e., lake water) exceed precipitation rates by at least one m/yr (Atwater et al., 1986). Thus, it is clear that local precipitation contributes little to the waters of Tulare Lake at the present time and that most of the water in this basin is provided by streamflow.

2.2. Hydrology

Several major streams feed the Tulare Lake Basin. The largest of these originate in the Sierra Nevada. They are, from north to south, the Kings, Tule, and Kern Rivers (Fig. 1). The much smaller, currently ephemeral streams entering Tulare Lake from the Kettleman Hills do not greatly affect the hydrologic budget and, thus, the surface elevation of Tulare Lake (Atwater et al., 1986). However, they are significant to the geomorphic development of the local study area in that they have formed alluvial fans that protrude into the basin.

Although subsidence due to groundwater pumping has greatly affected the elevation of much of the San Joaquin Valley, the elevation of this study area has subsided less than 0.3 m (1.0 ft) due to groundwater withdrawal (Poland and Davis, 1956; Lofgren and Klausing, 1969; Poland et al., 1975; Galloway and Jones, 1999). Thus, subsidence should not significantly affect the conclusions of this study regarding paleolake levels.

Tulare Lake is currently dry due to stream diversions for agricultural purposes. The bottom of the lake basin sits at an elevation of ~55 masl. Prior to stream diversion, the level of the lake occasionally reached an elevation of 66 masl (216 fasl) during wet years in the nineteenth century (Atwater et al., 1986).

2.3. Geological setting

The San Joaquin Basin has been the site of deposition, predominantly in a marine setting, for more than 100 million years (e.g., Harden, 2003). For the past million or so years, deposition in the San Joaquin Basin has been mainly in a nonmarine setting. During this time, depositional environments have ranged from alluvial fan to lacustrine settings dependent on proximity to source streams around the margins of the basin (Lettis and Unruh, 1991). Lacustrine deposits, primarily found near the center of the basin, are predominantly fine-grained clays and silts but also include sand deposits associated with beaches, spits, and deltas.

The study area is in the vicinity of Kettleman City on the west side of the Tulare Lake Basin (Fig. 1). This area is comprised predominantly of fine-grained sediments deposited subaqueously. Toward the west, between the lake bed and the Kettleman Hills, the lacustrine deposits are overlain and/or intercalated with the deposits of small alluvial fans corresponding to ephemeral stream systems. Several kilometers to the southeast of Kettleman City, a ridge of sand protrudes east-southeast into the southernmost part of the Tulare Lake Basin. The sand deposits are currently being reworked by eolian processes to form dunes and, hence, have been mapped as dune sand (Page, 1986). However, the origin of the sand deposits is likely from a lacustrine environment, probably as a result of the interaction of wind-driven longshore currents in Tulare Lake and outflow from the mouth of the Kern River. These sediments and similar sediments found further to the southeast, are mapped here as sand spits (Fig. 1).

3. Methods

3.1. Mapping

The following mapping resources were used in this study: USGS 7.5 min topographic maps, digital elevation models (DEM), digital orthophotoquads, NAPP aerial photographs, and USDA Soil Survey Maps of Arroues and Andersen (1986). Shaded relief maps were constructed from the DEM data using ArcView™ and Natural Scene Designer™ software.

3.2. Trenching

Two series of trenches were excavated to provide detailed lake-level records in context with the geomorphic features identified in the mapping component of this study. Trenching was conducted with backhoes supplied both by the California Department of Water Resources (DWR) and by Tyack Construction, Inc., of Bakersfield, California. Elevations at trench sites or of shoreline features were either surveyed in from benchmarks or estimated from 7.5′ topographic maps.

Detailed lithologic descriptions were completed by the two primary authors for all of the stratigraphic units exposed in the trenches. The relative elevations of individual stratigraphic columns within each trench were tied to each other via level line. Samples of all stratigraphic units were taken routinely for radiocarbon dating, fossil and mineral identification, and the determination of total organic and inorganic carbon (TOC and TIC) content. Radiocarbon dates were run on shell, bone, charcoal and bulk sediment with high organic content (Table 1). TOC and TIC were determined by the loss-on-ignition method (e.g., Dean, 1974). In addition to the above analyzes, samples were collected and processed for pollen analysis, which yielded no pollen. Instead, lake-level indicators from these and other analyses were placed in context with the previously published pollen data of Davis (1999) from a nearby depocenter core, as well as our new analysis of raw pollen and algae data graciously provided by Dr. Davis from this same core (Fig. 1).

4. Mapping results

4.1. The Rambla highstand shoreline

A prominent wavecut shoreline feature was identified in all of the mapping resources and is evident in the field as a topographic bench (Figs. 2–5). The northern segment of the shoreline appears as relatively closely spaced, parallel

Table 1
Summary of radiocarbon ages

Site	Lab no.	Elevation (masl)	Material	^{14}C age	±	Cal age range BP
DWR test pit #3	Beta-170144	56.9	Organic sediment	2370	40	2682–2331
Lake plain trench E	Beta-170145	56.9	Organic sediment	2410	40	2699–2345
Lake plain trench B	Beta-170148	56.9	Organic sediment	2510	70	2745–2364
Lake plain trench E	Beta-170146	56.9	*Anodonta* sp. shell	2740	40	2925–2759
Lake plain trench D	Beta-170143	56.9	Organic sediment	3340	80	3824–3393
Rambla shoreline trench 2	Beta-170147	63.3	Fish bone	100	50	274- -4
Rambla shoreline trench 2	Beta-170150	63.3	*Anodonta* sp. shell	180	50	303- -3
Rambla shoreline trench 2	Beta-170149	62.0	Gastropod shell	820	40	892–673
Rambla shoreline trench 2	WW-5304	60.9	Organic sediment	5900	35	6795–6645
Rambla shoreline trench 2	Beta-170151	60.9	Organic sediment	6190	40	7241–6974
Rambla shoreline trench 2	WW-5305	60.7	Charcoal	7250	35	8166–7984
Rambla shoreline ditch	Beta-167851	69.8	*Anodonta* sp. shell	2880	40	3157–2879
Rambla shoreline ditch	Beta-167852	69.8	Bone	4360	70	5280–4817
Depocenter (Davis, 1999)	A-5412	53.9	Organic sediment	2030	80	2301–1818
Depocenter (Davis, 1999)	A-5413	52.5	Organic sediment	6770	110	7829–7438
Depocenter (Davis, 1999)	A-5414	51.3	Organic sediment	9100	160	10,675–9739
Depocenter (Davis, 1999)	A-5415	50.4	Organic sediment	9460	220	11,273–10,195
Depocenter (Davis, 1999)	A-5416	48.6	Organic sediment	10,110	350	12,788–10,763

All lake plain samples are from the organic-rich units correlated to Unit 4a from Trench D, which is at an elevation of 56.9 masl. "Beta" dates were processed and run at Beta Analytical, Inc.; "WW" samples were processed at the USGS radiocarbon laboratory of the USGS in Reston, VA, USA and run at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory, Livermore, CA, USA. Radiocarbon ages were converted to calibrated years BP using Calib 5.01 software (Stuiver et al., 2005) and the calibration dataset of Reimer et al. (2004). Calibrated ages are reported as 2 sigma ranges.

contour lines at elevations from 210 fasl (64 masl) to 230 fasl (70 masl) on the Kettleman City 7.5′ USGS topographic map in the western halves of Sections 7 and 18, T22S, R19E (Fig. 2a). The shoreline is also prominently displayed on the DEM of Fig. 4 and on aerial photographs due to its relatively bright signature (e.g., Fig. 5). The northern segment can be traced along a N20W bearing for ~2 km from the eastern end of Kettleman City and from this same point along a S60E bearing for a similar distance. The feature also recurs farther south with a S30E trend, appearing as a ~1.0-km-long segment in the southeast corner of Section 29 on the Los Viejos 7.5′ map (Fig. 2b). Finally, it appears as a 2.0-km-long segment, trending more easterly (S70E) in the southern halves of Sections 3 and 4 of T23S, R19E before it merges with the northern edge of Dudley Ridge (Fig. 2c). The southernmost segment is named "La Rambla" on the topographic map, presumably after its Spanish meaning of "sandy or dry gully." We hereafter refer to related geomorphological features as the "Rambla" slope or shoreline.

In the field, the Rambla shoreline exhibits a discernable slope that interrupts an otherwise flat-lying featureless landscape (Fig. 3a). The surface of the slope contains numerous fragments of gastropods and bivalves including *Anodonta* sp.

A topographic profile of the shoreline was generated across its northern segment using elevations surveyed with a level and stadia rod, supplemented by data on the margins picked from topographic maps (Fig. 3b). The base of the feature is at an elevation of 62.5 masl (205 fasl) and its top is just below 70 masl (230 fasl). This elevation range includes both the elevation of the modern spillover sill (66 masl/210 fasl) and the highest lake-level elevation observed during historical times (67 masl/220 fasl) (Atwater et al., 1986). This observation, in conjunction with the fact that the morphology of the profile is consistent with that of a feature cut by wave action into a uniform slope of unconsolidated sediments (Currey, 1994), indicates a wavecut terrace origin for the Rambla shoreline.

4.1.1. Relationship of Rambla shoreline to Dudley Ridge

Further support for the wavecut origin of the Rambla slope feature is its slightly higher elevation relative to Dudley Ridge (maximum elevation = 67 masl/219 fasl), a feature that we interpret as a sand spit formed in shallow water during Tulare Lake highstands. Dudley Ridge is a ridge of sand that projects southeastward from the Kettleman Hills outward into the Tulare Lake plain (Figs. 1 and 4). Our interpretation that Dudley Ridge originated as a sand spit is supported by the following observations: (a) its linear morphology, (b) its projection out into the lake basin downwind of and normal to the shoreline, and (c) its point of origin from an abruptly eastward jutting spur of the lake basin, a feature that would serve to deflect longshore transport of beach sands basinward.

4.1.2. Relationship of Rambla shoreline to alluvial fans

Fig. 4 is a shaded relief map generated in Natural Scene Designer™ from USGS DEM files corresponding to the Kettleman Hills (NW), Los Viejos (SW), and Dudley Ridge (SE) 7.5′ quadrangles. This map clearly depicts the three main segments of the Rambla shoreline, as well as Dudley

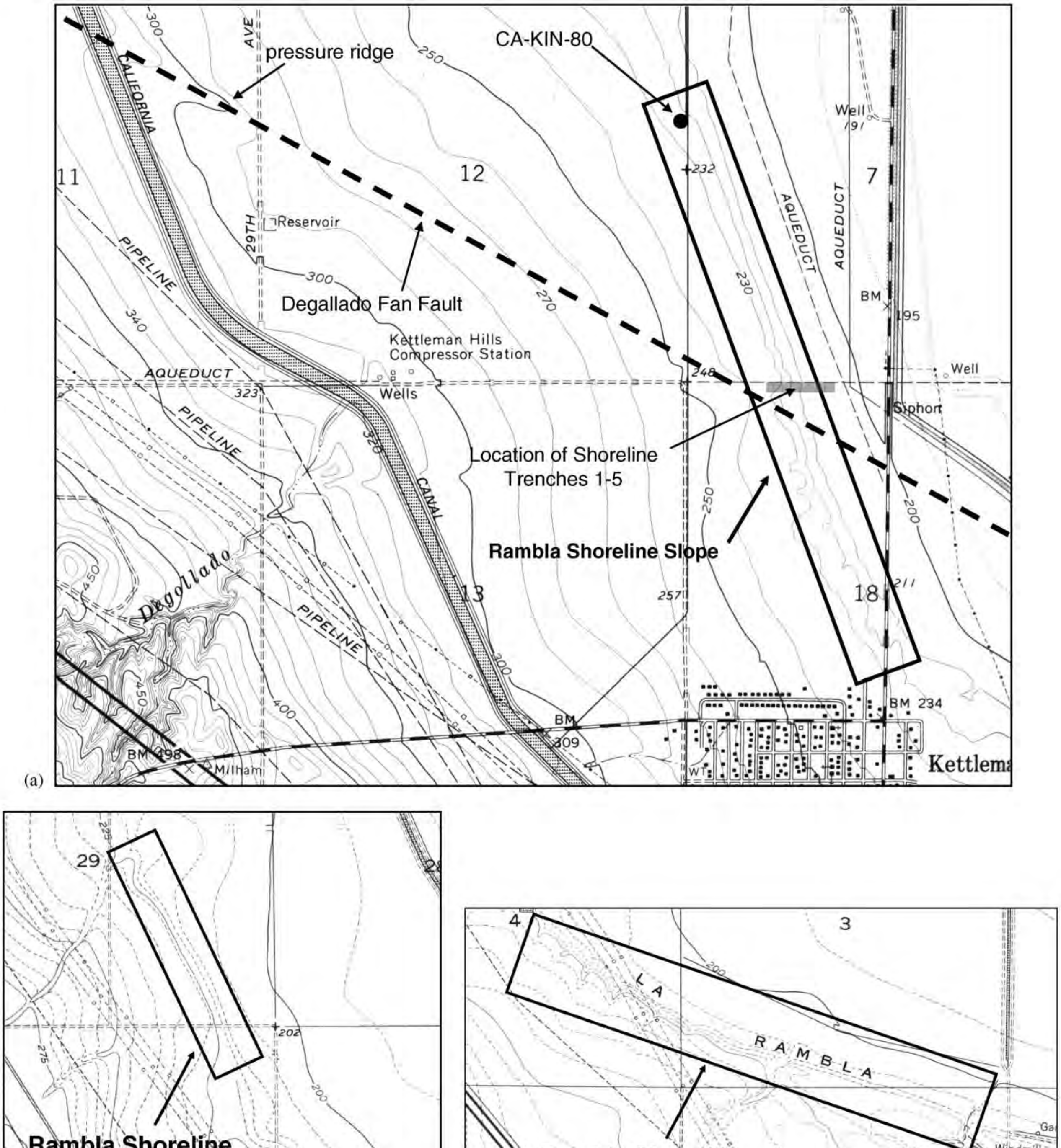

Fig. 2. Portions of 7.5′ topographic maps showing segments of Rambla highstand shoreline feature. (a) Northernmost segment of Rambla shoreline. Location of shoreline trenches 1–5 and archeological site CA-KIN-80, and the trace of the Degallado Fan Fault are also shown. (b) Portion of Los Viejos 7.5′ topographic map showing location of middle segment of Rambla shoreline. (c) Portion of Los Viejos 7.5′ topographic map showing location of southernmost segment of Rambla shoreline.

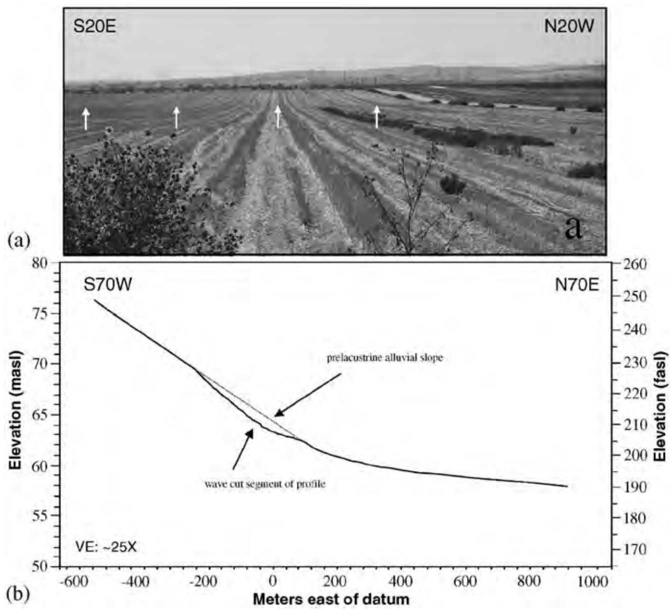

Fig. 3. (a) Photograph of northernmost segment of Rambla shoreline (view to SW). Kettleman Hills in the background. Base of steepest-slope portion of shoreline is indicated by arrows. (b) Topographic profile of Rambla shoreline. Feature is clearly eroded into pre-existing, uniform alluvial slope consistent with morphology discussed in Currey (1994). Profile runs through area of Trenches 1–5 (Fig. 2a). Vertical exaggeration ~25 × .

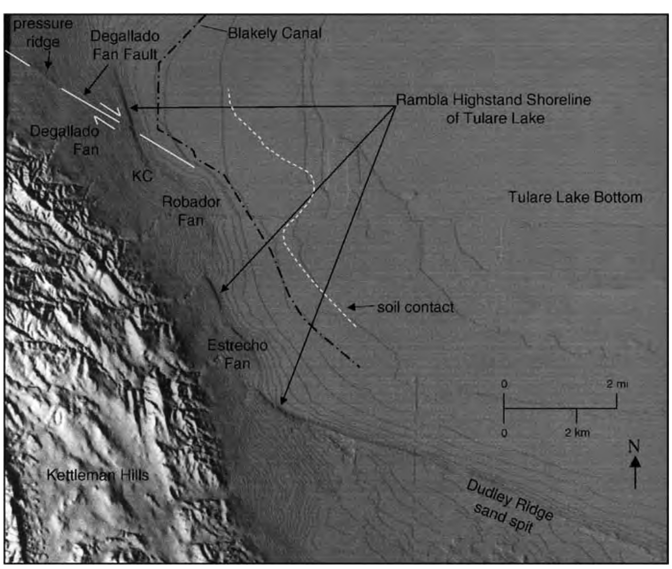

Fig. 4. Digital elevation model of study area and associated geologic features discussed in text. Degallado Fan fault is depicted in segments rather than a continuous line to avoid concealing evidence for its existence (the pressure ridge and offset shoreline). Soil contact is after Arroues and Andersen (1986). This contact separates lake bottom soils to the east from soils with coarser uppermost layers. Deflection of this contour basinward shows that alluvial fans extend farther out into lake basin than is apparent from the DEM alone.

Ridge. It also clearly illustrates the relationship of the Rambla shoreline feature with two prominent alluvial fans protruding into the Tulare Lake Basin from the Kettleman Hills. The larger fan is presently supplied by a stream occupying Arroyo Robador and the smaller fan is supplied by the Arroyo Estrecho stream. Both fans extend into the lake plain, especially the Robador Fan, as revealed by the eastward extension of lobes of soil types containing relatively coarse-grained materials (e.g., soil #126 of Arroues and Andersen, 1986) well out into the Tulare Lake Basin beyond the fan terminus suggested by the DEM image (Figs. 4 and 5).

Both the Robador and Estrecho alluvial fans are, for the most part, younger than the Rambla shoreline because their sediments have either covered or eroded much of this feature, resulting in the dissection of the shoreline into its three major segments. On the other hand, portions of the alluvial fans may have been active prior to one of the highstands that formed the Rambla shoreline. This is evidenced by two relatively subtle subsegments of the two more northerly segments, which show a deflection of the shoreline around the north end of the two alluvial fans (Fig. 4).

4.1.3. Relationship of Rambla shoreline to the Degallado fan fault

In Fig. 4, an elongate, N55W trending ridge cuts across the alluvial slope ~1.5 km north of the termination of Arroyo Degallado. This feature can also be observed on the USGS Kettleman Hills 7.5′ topographic map as deflected elevation contours in the northeast corner of Section 11, T22S, R18E, where it underlies the California Aqueduct. A slight right-lateral offset of the northern segment of the Rambla shoreline is almost exactly on trend with the aforementioned ridge. Based on these two observations, we interpret the ridge to be a local transpressional ridge due to recurrent right-lateral, strike-slip faulting. The fault is named the Degallado Fan fault because it transects the alluvial fan associated with Arroyo Degallado. The Rambla shoreline likely was developed prior to the latest slip events on this fault that apparently offset the shoreline several meters.

Although the Degallado Fan Fault passes within 100 m south of the shoreline trenches (Fig. 2a), no evidence of deformation was observed in any of the trenches. Thus, the fault zone must be localized to within a few tens of meters of its map trace.

4.2. "190 ft" Clovis shoreline

As discussed above, previous workers have suggested a stable shoreline of Tulare Lake based on the ubiquitous occurrence of Clovis-aged artifacts and Pleistocene megafauna in an elongate region parallel to the margins of the lake basin, north of Dudley Ridge at an elevation of 56–58.5 masl (185–192 fasl) (Fig. 1). Because much of the study area is located within this elevation range, particularly in the vicinity of the Blakeley Canal (Fig. 1), we investigated the possibility that this shoreline projected into the study area.

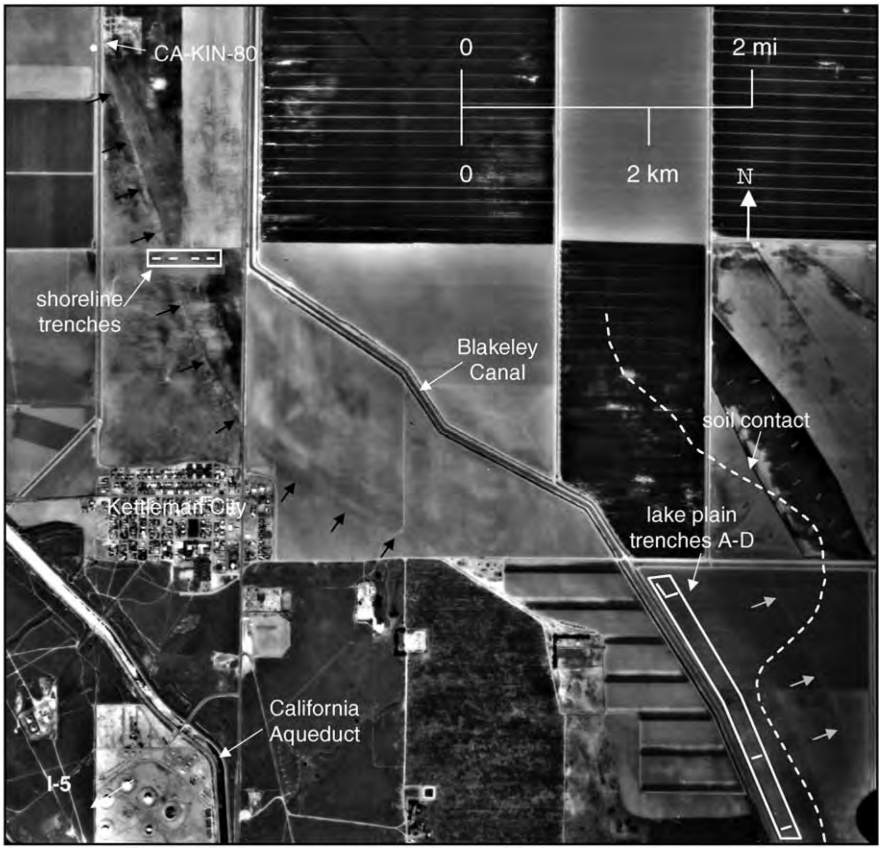

Fig. 5. Portion of NAPP 6915-254 aerial photograph showing main project area. Locations of all shoreline trenches and lake plain trenches A–D lie within rectangular regions outlined in white. Northern segment of Rambla shoreline is depicted by black arrows drawn perpendicular to shoreline. Gray arrows in SE corner of photo delineate a possible shoreline at the ~190 ft elevation associated with the abundant Clovis occupations found at the lake margin just north of Dudley Ridge (Fig. 1). Because this feature cuts through the alluvial fan margin indicated by the deflection in the soil contact (see text and Fig. 4), it, instead, must be much younger than the latest Pleistocene age of Clovis occupation.

We found no compelling evidence for such a shoreline in the mapping phase of this investigation. Several whitish streaks, similar to the signature of the Rambla shoreline, are observed in the aerial photographs at or near this elevation (e.g., see feature delineated by light gray arrows in the SE corner of Fig. 5). However, these features cut across the toe of the Robador fan, as defined by the outer contact of Soil Type #126 (Figs. 4 and 5), the last basinward soil with a relatively coarse-grained uppermost layer (Arroues and Andersen, 1986). If these are shoreline features, then they are clearly younger than the late Holocene sediments deposited by this fan and are too young to be associated with the hypothesized Clovis-aged lake-level stand. If a Clovis-aged shoreline exists in this area, then it would likely lie beneath the sediments of the alluvial fans emanating from the Kettleman Hills.

5. Trenching results

5.1. Relationship of trench locations to mapping results

The subsurface portion of the study was conducted in three areas. The first area consisted of five trenches (Trenches 1 through 5, heretofore referred to as the "shoreline" trenches) that were excavated in the vicinity of the northernmost segment of the Rambla shoreline feature (Fig. 2a). These trenches were typically 10 m-long and 2 m-deep. The elevations covered varied from 60 to 70 masl. Of these, all but Trench 1 were below the top of the wave-cut shoreline feature. Trench 1 was excavated into the sediments above the shoreline that represent the substrate materials, perhaps covered by a thin veneer of lacustrine beach deposits. Trenches 2 through 5 were dug into and just below the steepest slope of the shoreline to recover a potential record of lake sediments deposited at these high elevations during highstands. In addition, we inspected ~2.0 m of section exposed in a road-side ditch near the northernmost extent of the Rambla shoreline in order to discern the geological context of archeological site CA-KIN-80 (Gardner, 2003; Gardner et al., in press) that was exposed in the side of this ditch (Fig. 2a).

The second area was composed of four trenches (A–D) excavated into the toe of the Robador fan where the purported 190 ft (58 m) Clovis shoreline is possibly buried by a thin veneer of younger alluvial sediments at the toe of the fan (Figs. 4 and 5). Trenches A and D were located near the axis of this fan. Trench A was oriented parallel to the fan axis (perpendicular to potential shorelines) and Trench

D was oriented perpendicular to Trench A. Trenches B and C were oriented perpendicular to the shoreline but near the southern edge of the Robador Fan.

The third area contains Trenches E and F and DWR Test Pit #3 that were dug farther out into the lake basin (Fig. 1 and Gardner, 2003). These excavations, along with the trenches from the toe of the Robador fan, are referred to as the "lake plain" trenches. Collectively, they were investigated to provide a deep lake context for the stratigraphy associated with the trenches from the other two areas.

5.2. Stratigraphy above the Rambla shoreline: distal alluvial fan sediments?

Trench 1, which was dug into the sediments above the Rambla shoreline, could not be entered due to the uniformly sandy nature of its sediments and the associated danger of trench collapse. Three samples were collected from the edge of the trench down to a depth of 45 cm below ground surface. All three samples were well-sorted, very fine sands and silts with a color of 2.5Y 5-6/2. No lacustrine fossils (e.g., fish bones or *Anodonta* sp. shell) were found in the trench spoil. Inspection of the trench spoil and visual inspection down into the trench from the surface suggest that the top 45 cm of sediment is representative of the entire 2 m of section in the trench. Also, the deposits were observed to be massive in nature (i.e., no bedding). We interpret these sediments to have been deposited in a distal alluvial fan setting as sheet wash or perhaps eolian sediments.

5.3. Stratigraphy of the Rambla shoreline trenches: three Holocene highstands

The lacustrine sediments of the Rambla shoreline feature were deposited during a period that included three major highstands of Tulare Lake separated by intervals of nondeposition. The stratigraphy is described below and is summarized in Fig. 6. This composite stratigraphy is based primarily on a detailed description of Trench 2, the deepest trench containing the thickest section. The stratigraphy in Trenches 3, 4, and 5, which exposed sediments down to only Unit 7, were consistent with that described below.

5.3.1. First highstand

Unit 1 is a very well-sorted, fine sand consisting of subangular to subrounded grains of granitic minerals (e.g., quartz and feldspar with minor hornblende). Based on its lithology and its stratigraphic position below Unit 2, we interpret Unit 1 to represent a transgressive shore facies characterisitic of a beach deposit. Unit 2 is a relatively thick, massive, olive-gray colored clay layer. Fe-oxide staining occurs toward the top of this unit. It is likely to have been deposited under relatively deep water but the Fe-oxide staining in the top of the unit suggests that it was near the surface of the lake soon after deposition. Post-depositional exposure of Unit 2 to near surface conditions is consistent with the overlying Unit 3, an upward-coarsening sand layer that is interpreted to represent a regression at the end of the highstand corresponding to Unit 2. A sample of charcoal collected 7 cm above the base of Unit 3 yielded an age of 7250 ± 35 ^{14}C yr BP (7984–8166 cal yr BP).

5.3.2. Second highstand

Unit 5 represents the next interval of high lake. It is another massive clay that lies above an organic-rich, sandy clay (Unit 4). Two bulk, organic-rich sediment samples collected from the middle of Unit 4 were dated by two different radiocarbon facilities at 6190 ± 40 ^{14}C yr BP (6974–7241 cal yr BP) and 5900 ± 35 ^{14}C yr BP (6645–6795 cal yr BP). Unit 4 is interpreted as a marshy environment present when the water was still fairly shallow before the transgression indicated by Unit 5. The presence of organic-rich layers immediately below deeper water clays was also observed by Atwater et al. (1986) in cores from the Tulare Lake Basin. Unit 5 contained 1.0-cm-wide, sand-filled mud cracks that suggest lake level subsequently lowered to the point where Unit 5 was exposed subaerially. A return to overall shallower water conditions is also suggested by the gradual coarsening of grains beginning in Unit 6 and continuing up through Unit 7. Unit 7, nearly a meter thick, may even have been deposited subaerially as part of a distal alluvial fan, but the presence of articulated *Anodonta* sp. shell toward the top of Unit 7a and clay layers in Unit 7b suggest that Tulare Lake was at or above the elevation level of Unit 7 (61.3–62.1 masl) for at least a portion of its deposition, and was filled with cool, fresh water. Gastropod shell from within 10 cm of the top of Unit 7 yielded an age of 820 ± 40 ^{14}C yr BP (673–892 cal yr BP).

5.3.3. Most recent highstand

The third and final highstand observed in the Rambla shoreline trenches commenced with the top of Unit 7b and peaked during the deposition of Units 8 and 9, which are relatively fine-grained and clay-rich. Unit 10 is relatively coarse-grained but contains bones of Sacramento sucker (*Catostomus occidentalis*), a species commonly found in pools of clear, cool streams, lakes and impoundments (Page and Burr, 1991). This unit also contains *Anodonta* sp. shells., some of which are articulated. *Anodonta* sp. is a molluscan genus that favors muddy river bottoms (though they may be found in sands as well) or lakes with a high trophic level, but with some kind of current, and a diversity of fish that can be used in its reproductive cycle (Chamberlin and Jones, 1929). Together, these factors suggest that Unit 10 may also have been deposited in a lake and that the lake at this time was cool and fresh with some current. The uppermost unit, Unit 11, consists entirely of silt-sized grains partially cemented with calcium carbonate. Its environment of deposition is undetermined, though it is

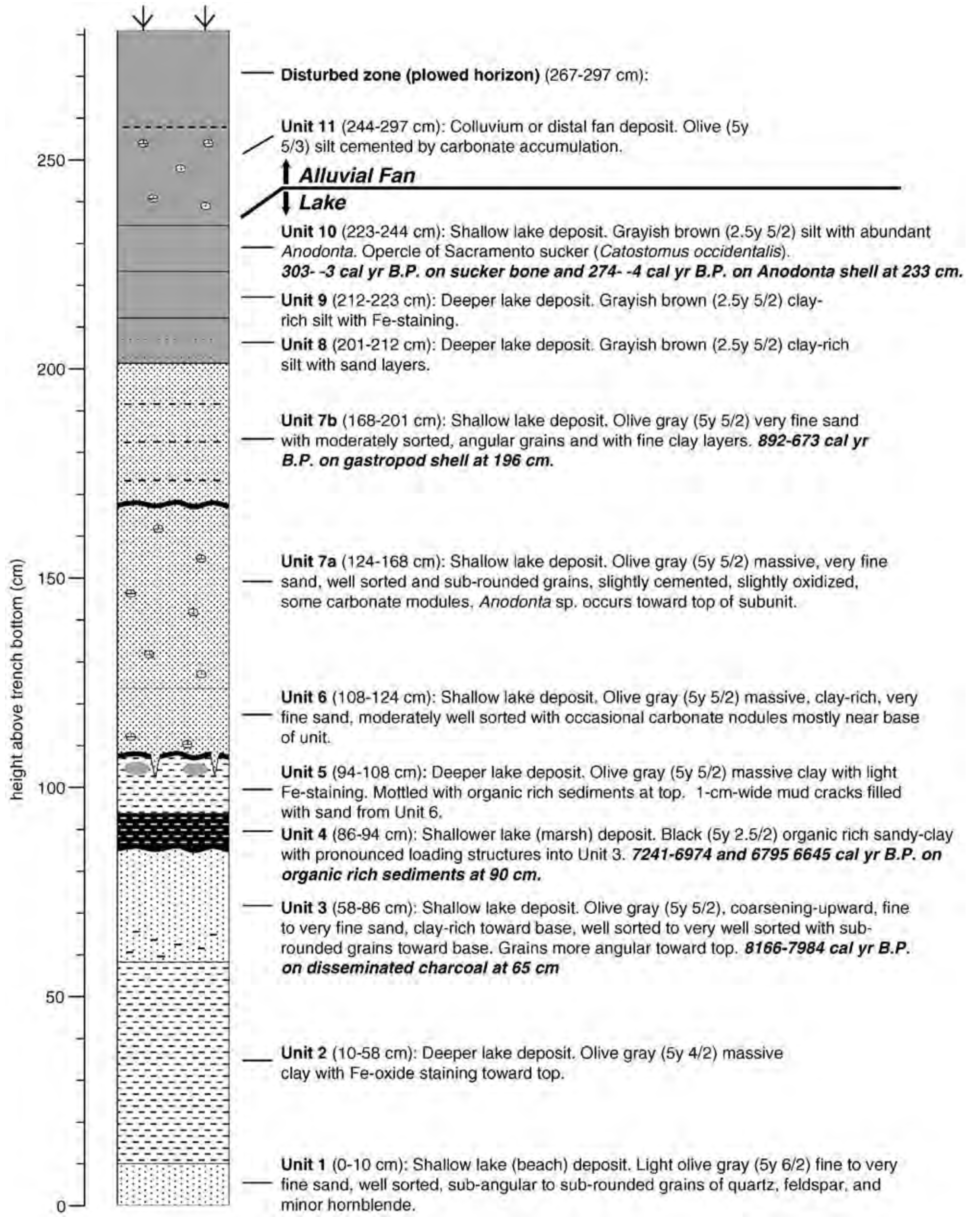

Fig. 6. Stratigraphic description of units from Trench #2 dug into the slope segment of the Rambla shoreline wave-cut feature. Depth is measured relative to bottom of trench. Elevation at top of trench is 63 masl (206 fasl). Radiocarbon ages are shown in bold italics (also see Table 1). Unit 2, Unit 5, and Units 8–10 are interpreted to be deposited under relatively deep water (i.e., below wave base). Bold, wavy lines indicate dessication events.

not inconsistent with the distal alluvial fan environment favored for the sediments of Trench 1 (see above). The presence of discontinuous carbonate accumulation is indicative of incipient soil development. The lack of a well-developed soil is consistent with a young age for the most recent transgression, as suggested by the bounding radiocarbon ages shown near the top of Fig. 6. The lower bounding age is from near the top of Unit 7 (Section 5.3.2); the upper bounding age is constrained by radiocarbon dates of $180\pm50\,^{14}$C yr BP (−3–303 cal yr BP) and $100\pm50\,^{14}$C yr BP (−4–274 cal yr BP) from sucker bone and *Anodonta* sp. shell, respectively. These latter samples were collected from the middle of Unit 10. The top 30 cm of Unit 11 exhibits mixing and gouging of the sediments, probably due to agricultural tilling.

5.4. Stratigraphy of the Rambla shoreline ditch exposure (site CA-KIN-80)

At the archeological site CA-KIN-80, 190 cm of section was exposed in a ditch 1 km north-northwest of the shoreline trenches (Figs. 2a and 7). All but the top 30 cm of the sediments in this exposure consist of a massive, poorly sorted, very fine sand unit with abundant clasts of *Anodonta* sp. shell and charcoal (Fig. 8). A continuous 4.0-cm-thick, medium- to coarse-grained sand layer ran

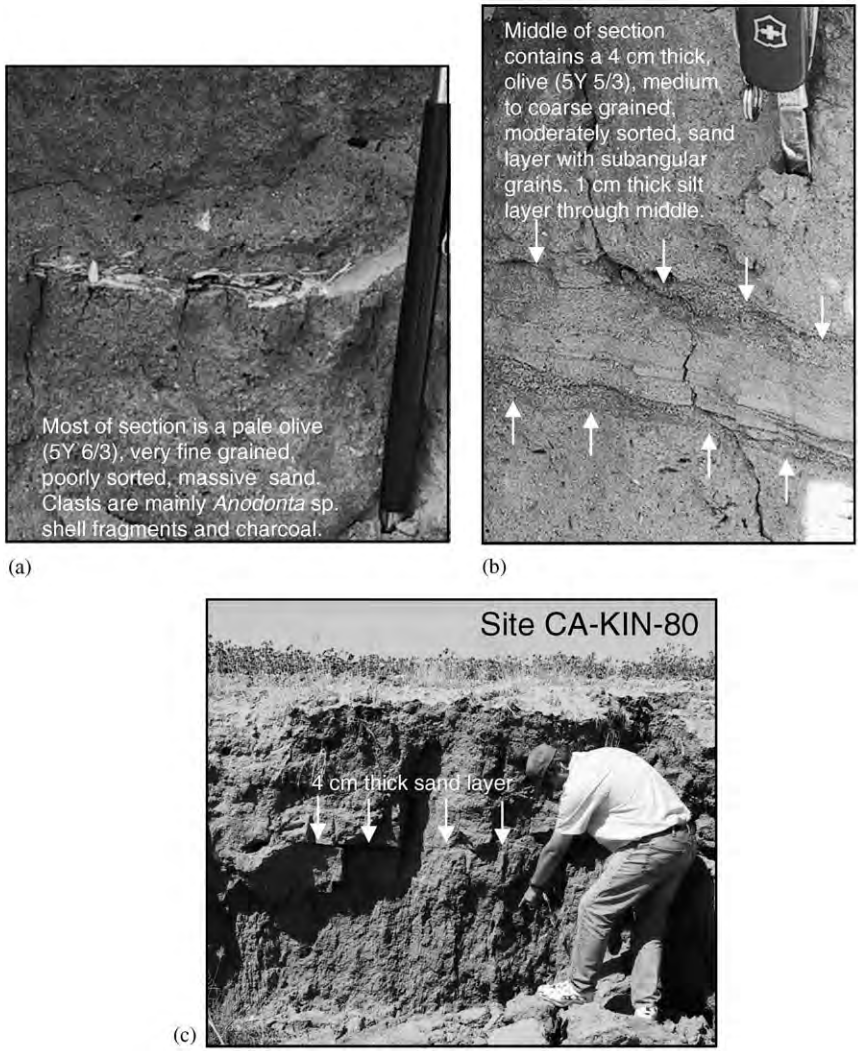

Fig. 7. Stratigraphy of CA-KIN-80 site: (a) 190 cm thick section is principally composed of poorly sorted, massive, very fine sands with abundant fragments of charcoal and *Anodonta* sp. shell. Upper 50 cm of this unit is in till zone; (b) continuous, 4-cm-thick medium to coarse sand found at 82–86 cm below the surface; and (c) photograph of entire section (R. Yohe for scale).

through the exposure ~85 cm below the surface. A fragmentary human distal metacarpal was found near the base at 177 cm (Gardner, 2003; Gardner et al., in press). The bone was dated at 4360 ± 70 ^{14}C yr BP (4817–5280). A shell fragment from 106 cm below ground surface yielded an age of 2880 ± 40 ^{14}C yr BP (2879–3157).

The Rambla shoreline is not well defined this far north and a major concrete irrigation canal separates this exposure from the main shoreline feature. Thus, the spatial relationship of the CA-KIN-80 stratigraphy relative to that of the Rambla shoreline trenches is unclear. With the exception of Trench 1, the deposits of the CA-KIN-80 exposure are generally coarser than those seen in the top 2 m of any of the trenches discussed previously. This suggests that the stratigraphy of the CA-KIN-80 exposure fits in with that of the top of the shoreline. If this is true, then much of the sedimentation responsible for the alluvial fan deposits in Trench 1 were deposited during the past 5000 years. This, in turn, implies that the present geomorphic expression of the Rambla shoreline has been formed by relatively recently wave erosion, perhaps in association with the uppermost transgression found in Trench 2, an event that occurred within the past ~700–900 cal yr BP (Fig. 6).

Except for the one through-going sand layer described above, the CA-KIN-80 sediments exhibited no bedding. This observation, combined with the ubiquitous presence of shell fragments and charcoal and, of course, the human bone fragment, all point towards the CA-KIN-80 sediments as an archeological midden. Given this interpretation and the aforementioned two radiocarbon dates, the midden was occupied at least intermittently throughout most of the Holocene after ~5000 cal yr BP. The sand layer running through the middle of the outcrop may represent a flooding event that occurred sometime between 1500 and 2000 cal yr BP based on the stratigraphic position of this sand layer relative to those associated with the two radiocarbon dates from this locality.

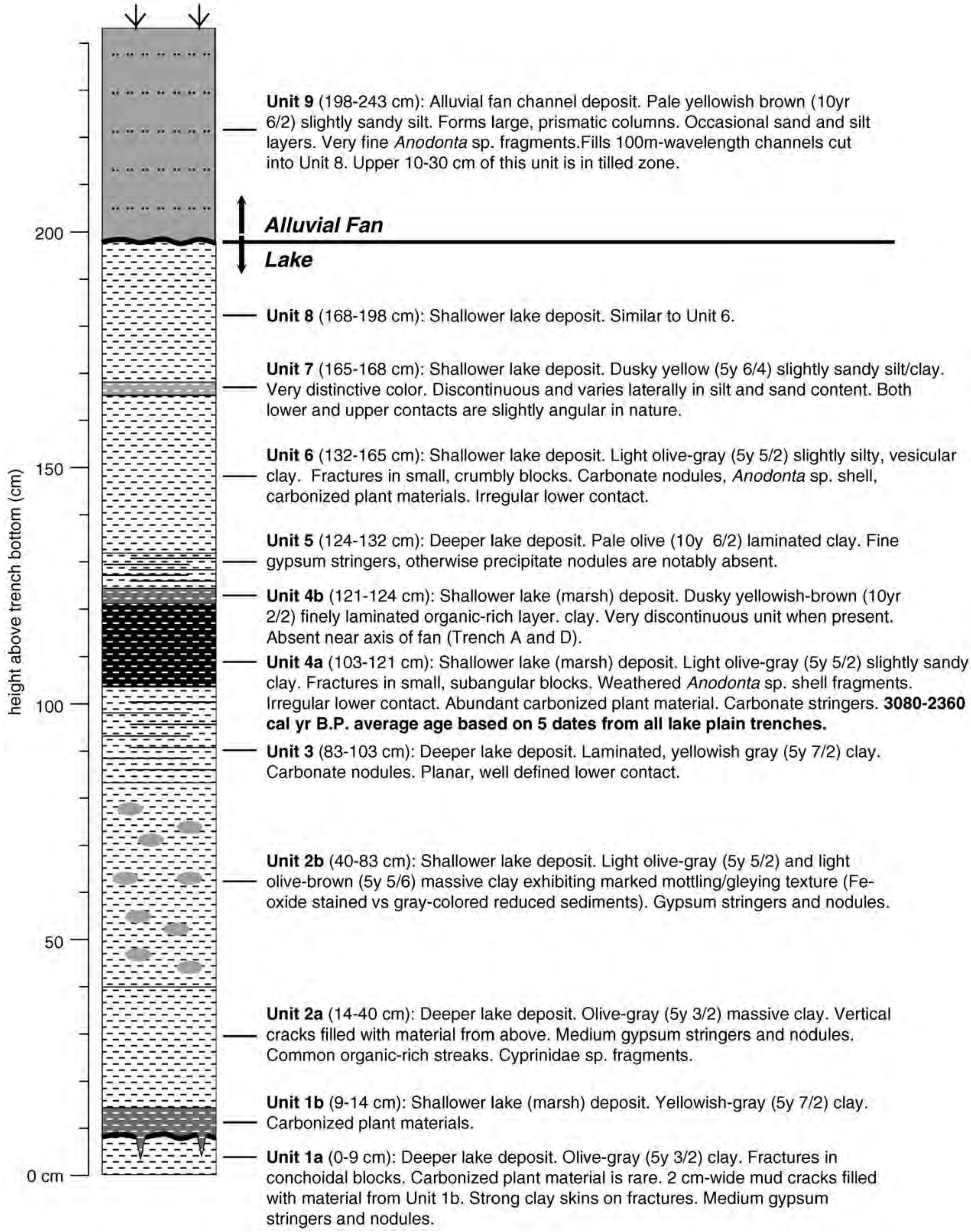

Fig. 8. Stratigraphic description of units from lake plain Trenches A–D at distal end of Arroyo Robador alluvial fan (Fig. 4). Depth is measured relative to bottom of trench. Elevation at top of trench is 58 masl (190 fasl). Radiocarbon ages are shown in bold italics (also see Table 1). Units 1a, 2a, 3, 5, 7, and 8 are interpreted to be deposited under relatively deep water. Unit 9 is interpreted as a channel deposit associated with the progradation of the Arroyo Robador alluvial fan onto the lake plain. Bold, wavy lines indicate dessication events.

5.5. Stratigraphy of the lake plain trenches: deep lake facies

The stratigraphy in all of the lake plain trenches at the toe of the Robador fan (Fig. 4) was divided into nine correlative units. All but the top unit were clay-rich and contained fossils of aquatic fauna consistent with a freshwater lacustrine environment (Fig. 8). We therefore interpret that these deposits accumulated predominantly in quiet water under the surface of Tulare Lake. A discontinuous, organic-rich clay horizon in the middle of the section (~120 cm below surface) suggests at least one interval of shallower water, perhaps a marsh-like environment (Fig. 8). Furthermore, there is abundant evidence throughout the section of soil development (ped structures, clay skins on ped surfaces, vesicles), perhaps due to intermittent subaerial exposure. The common occurrence of vertical and polygonal drying cracks and gleying supports this hypothesis.

The uppermost unit in the lake plain trenches, Unit 9, was relatively coarse-grained and occupied broad, shallow, west-to-east trending channels (Figs. 8 and 9). This unit most likely represents alluvial deposition at the toe of the Robador fan. The top 30 cm of this uppermost unit shows the highly irregular lower boundary and disruption of sedimentary structures that is characteristic of agricultural tilling.

Not surprisingly, the stratigraphy farther out into the lake plain (Trenches E and F and DWR Pit #3; Fig. 1) was nearly identical to that of the lacustrine units from Trenches A through D. All units were clays. Stringers and nodules of gypsum (identified using X-ray diffractometer) were common in these units. As with the stratigraphy near the toe of the Robador fan, an organic-rich layer was often present (see Unit 4 in Fig. 8), although it was at a relatively shallower depth (~70 cm below the surface as opposed to 120 cm). In both cases the organic-rich units are found above units with relatively abundant *Anodonta* sp. shells, some of which were articulated. The total organic carbon content in this unit was 13% by mass, the highest measured in this study.

Fig. 9. Basal contact of alluvial silts near top of section in lake plain trenches from near the Blakeley Canal. Everything below this contact is interpreted to have been deposited in a lacustrine or marsh environment rather than in an alluvial fan setting.

The ~50 cm difference in depth between the organic-rich unit from the more basinward sites and that of Trenches A through D is easily explained by the additional ~50 cm of alluvial fan deposits found in these trenches. These deposits are not found in Trenches E and F and DWR Pit#3 because these sites are beyond the extent of the alluvial fans from the Kettleman Hills.

5.6. Summary of age control

The radiocarbon data are summarized in Table 1. In all trenches, radiocarbon dates from deeper units yielded older dates and, in the two cases where different materials were dated from nearly the same stratigraphic horizon, the radiocarbon analyses yielded consistent results from different materials. The organic-rich unit from Trenches A through F has consistent ages from both organic-rich sediment and shell. Also, the uppermost transgression in Trench 2 from the shoreline trenches has consistent dates from both fish bone and shell. Finally, the organic-rich sediments of Unit 4 in Trench 2 yielded the same date from two different laboratories.

Radiocarbon ages were converted to calibrated years using the Calib 5.0.1 software (Stuiver et al., 2005). In all cases, the 2-sigma distribution option was used in the conversions. In the case of a converted specific date, the range of dates within the 95% confidence window is reported (e.g., Table 1).

Only one horizon (Unit 4) is dated in the lake plain trenches. Its age (3609–2331 cal yr BP) is based on the full range of five calibrated ages from that unit corresponding to four different trenches (first five dates in Table 1). The average and standard deviation calculated from the five calibrated ages is 2810 ± 470 cal yr BP. The ages of the rest of the lake sediments in this section are estimated using the 0.038 cm/cal yr sedimentation rate for Tulare Lake bottom sediments of this age (referred to as the Chatom Silt by Atwater et al., 1986; Davis, 1999). The resultant oldest and youngest ages of the lake sediments in this section are ~5800 and ~550 cal yr BP, respectively.

6. Holocene lake-level history of Tulare Lake

6.1. Post-glacial to 10,700 cal yr BP: erosional event followed by aggradation

A large gap in the late Quaternary Tulare Lake records of Atwater et al. (1986) and Davis (1999) indicates an erosional event at the end of the Pleistocene. This event ended with the onset of deposition of lake bottom sediments at 11,800 cal yr BP (Davis, 1999). An abrupt change at ~10,700 cal yr BP from anomalously high to more typical sedimentation rates was interpreted by Davis

(1999) to represent a change from a rapid infilling of the lake associated with fan dam aggradation to an environment more typical of a geomorphically stable lake system influenced primarily by climate change.

6.2. 10,700–7800 cal yr BP: two early Holocene highstands

This interval consists of two highstands, the latter of which reached the maximum shoreline elevation of ~70 masl (Fig. 10). Evidence for these two highstands includes two peaks of pelagic algae (*Botryococcus* sp. + *Pediastrum* sp.) in the depocenter core (Fig. 1) which were interpreted by Davis (1999) to suggest open, deep water. The younger of the two peaks is coeval with the oldest highstand clay (Unit 2) found in the high shoreline trenches of this study (Figs. 6 and 10). The basal, well-sorted sand of this trench (Unit 1) was likely deposited in a beach setting during the transgression leading to the younger of these two early Holocene highstands.

The younger highstand lasted for ~1200 or more years, based on the thickness of Unit 2 and the typical deposition rates (~0.04 cm/^{14}C yr = 0.038 cm/cal yr) of Tulare Lake bottom sediments reported by Atwater et al. (1986) and Davis (1999). This event ended with the regression below 61 masl represented by Unit 3 of the shoreline trenches, an upward-coarsening sand deposit. Oxidation stains in the upper part of Unit 2 are consistent with lake-level fall soon after its deposition. A radiocarbon age on disseminated charcoal at the base of Unit 3 indicates that this regression began at 8000–8100 cal yr BP (Fig. 10). This date, the 1.2 kyr duration of Unit 2, and the 9000 cal yr BP age of the older pelagic algae peak of Davis (1999) suggest that the lowstand between the two early Holocene highstands was a short-lived event.

6.3. 7800–5500 cal yr BP: lowstand followed by a middle Holocene highstand

In the record from the shoreline trenches, the time interval from 7800 to 5500 cal yr BP begins with a fall in lake level below 61 masl represented by the upward-coarsening sand of Unit 3 (see above). Unit 3 is ~1200 yr younger than the overlying Unit 4 (Figs. 6 and 10). Given this age difference and the interpretation of Unit 4 as a transgressive, shallow water deposit, lake level must have fallen below the elevation of the contact between these units during the time interval from 7800 to 7000 cal yr BP.

Beginning with the deposition of Unit 4, the lake rose above 61 m for at least 500 years, the time interval required for the deposition of Unit 5, a deepwater clay unit, at the sedimentation rate typical of Tulare Lake bottom sediments (Atwater et al., 1986; Davis, 1999). Mudcracks are

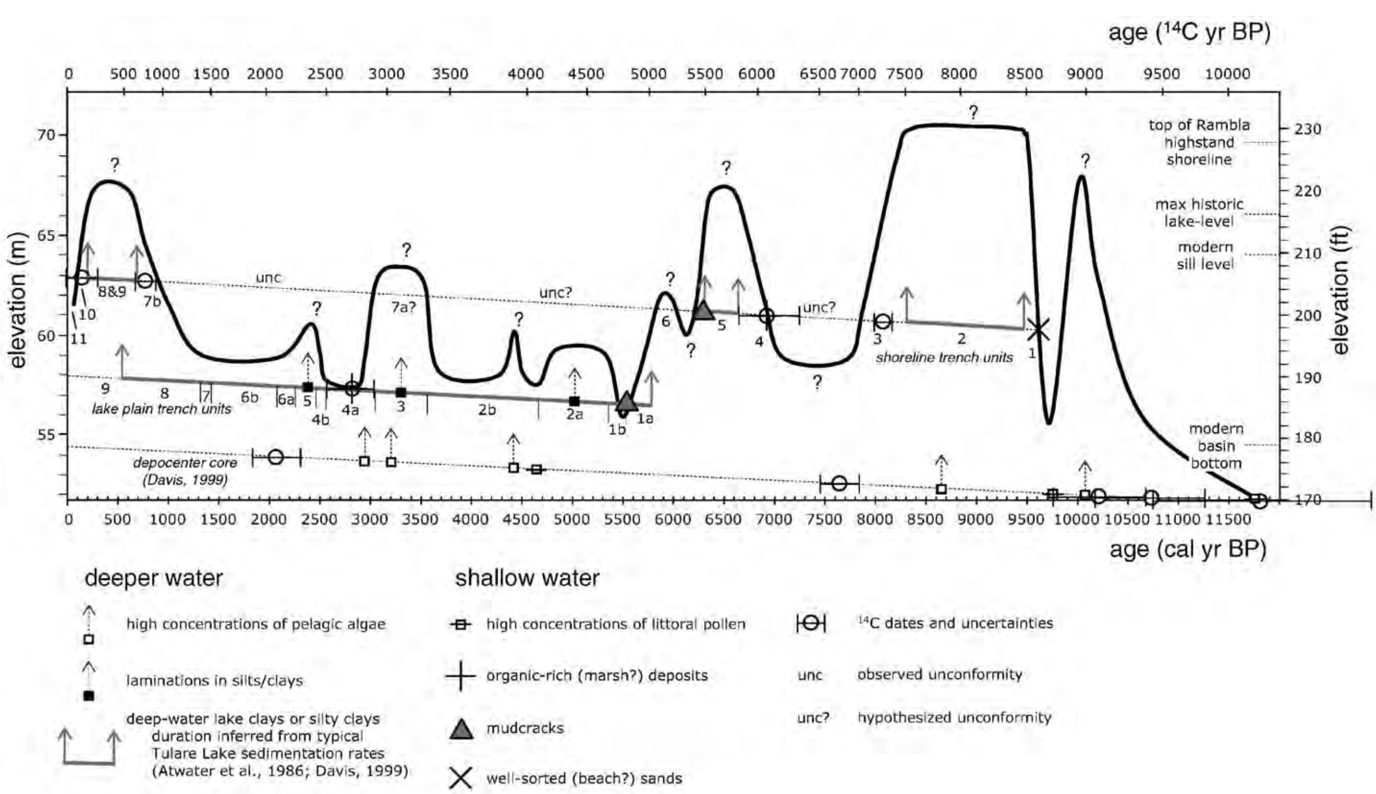

Fig. 10. Holocene lake-level history of Tulare Lake based on data from shoreline and lake plain trenches of this study (Figs. 5–9) and the depocenter core pollen record of Davis (1999). Lake level through time is indicated by bold line. The uncertainties shown for radiocarbon dates are the range of calibrated dates within the 95% confidence window except for date in Unit 4 of shoreline trenches which shows standard deviation calculated for the first five calibrated dates in Table 1.

found at the top of Unit 5. These are filled with Unit 6, a coarsening-upward sand. We interpret this sequence to represent a brief recession after the deposition of Unit 5 that was followed by a similarly brief return to high enough lake levels to allow the deposition of Unit 6. The latter deposit, a transgressive sand, then represents a terminal recession that ended an overall high lake-level interval in the middle Holocene that spanned from ~7000 to 5500 cal yr BP. The younger age limit is inferred from the estimated age of the top of Unit 1a, the lowest unit from the lake plain trenches (Figs. 8 and 10). Unit 1a is a blocky, gray clay deposit much like that of Unit 5 in the shoreline trenches. The age of the bottom of Unit 1a could not be estimated because it was below the bottom of its trench. Its uppermost age, however, was estimated at ~5500 cal yr BP based on linear extrapolation downward at 0.038 cm/cal yr from the calibrated radiocarbon date in an overlying unit. The top of Unit 1a contains mudcracks similar to those found in Unit 5 of the shoreline trenches. In this case, they represent a brief fall of Tulare Lake below the level of the lake plain trenches at the end of the middle Holocene highstand.

6.4. 5500–1000 cal yr BP: low amplitude lake-level fluctuations

The record over this time period is mostly constrained by alternating lithologies in the lake plain trench sediments and the pollen record from the depocenter core of Davis (1999). Unit 2a (5400–4700 cal yr BP), Unit 3 (3600–3000 cal yr BP), and Unit 5 (2500–2300 cal yr BP) from the lake plain trenches are, for the most part, laminated, devoid of gleying structures (mottled mixtures including Fe-oxide stained sediments), and contain relatively few carbonate nodules. This suggests deeper water relative to the elevation of these units (57–58 masl). Because these features are more prominent in Units 3 and 5, we hypothesize that Tulare Lake was higher during the time periods corresponding to these units, perhaps above the level of the shoreline trenches (62–63 masl). This hypothesis is supported by prominent peaks in pelagic algae concentration that were found in the depocenter core (Davis, 1999) at approximately the same time as the probable age for Unit 3 (Fig. 10). The most likely corresponding deposit from the shoreline trenches is Unit 7a, a well-sorted, very fine sand that was likely a shallow water lake deposit, perhaps in a beach environment. This unit is separated from an almost identical Unit 7b by an angular unconformity. Unit 7a, the lower unit, differs from Unit 7b in that it is cemented weakly with a carbonate cement and contains abundant Fe-staining. Thus, it was probably exposed at the surface for a significant period of time prior to the deposition of Unit 7b.

A likely lowstand event that corresponds to the unconformity between Units 7a and 7b from the shoreline trenches is suggested by a dramatic drop in pelagic algae concentrations in the depocenter core (Davis, 1999) and a coeval, ubiquitous organic-rich marsh deposit (Unit 4) found in all the lake plain trenches (Fig. 8). The age of Unit 4 (~2800 cal yr BP) is approximately the same as that of the correlative event in the depocenter core (Davis, 1999).

6.5. 1000 cal yr BP to present. High lake levels and incursion of alluvial fans onto the lake plain

During the past 1000 years, the surface of Tulare Lake rose above 63 m and stayed there long enough to deposit shoreline trench Units 7b, 8, 9, and 10. Units 8 and 9, together, comprise 22 cm of clay-rich silts. Presuming the typical sedimentation rate for Tulare Lake bottom sediments (~0.04 cm/yr), these units alone represent approximately 500 years of deposition. Given the upper and lower limits of the dates below and above these units (Table 1), this highstand must have commenced no later than 670 cal yr BP (1280 AD) and ended no earlier than 290 cal yr BP (1660 AD). Historical records show the lake rising to a level above the shoreline trenches several times in the nineteenth century (Atwater et al., 1986). Thus the upper part of Unit 10 was likely to have been deposited up until the time of irrigation-related stream diversion.

The trench sites in the toe of the Arroyo Robador alluvial fan (Figs. 4 and 8) began to receive alluvial deposits (Unit 9 channel deposits) sometime between 600 and 500 cal yr BP (1350 and 1450 AD). The timing of local alluvial fan progradation thus appears to be coeval with the lake-level rise described in the previous paragraph. This suggests that the climate change responsible for lake-level rise is not just restricted to the headwaters of the major Sierran rivers that feed Tulare Lake, but also reflects increases in the discharge of local streams.

7. Lake depth and marsh extent evidenced by selected algae, and marsh and aquatic plant pollen

The interpretations based mainly on the stratigraphic record that were presented in the previous section (Figs. 10 and 11a) are supplemented by additional examination of the pollen and algae record (Figs. 11b–d) that are based on raw data graciously provided by Owen Davis from his original data set (Davis, 1999). These data provide information regarding the water level, stability, and water chemistry of the marsh/lake from the basin bottom. First, Fig. 11b shows a ratio of the two most abundant algae, *Pediastrum* sp. and *Botryococcus* sp. These algae are characterized by very different water chemistry. Whereas *Pediastrum* sp. is found flourishing under more oligotrophic (fresh water) conditions, *Botryococcus* sp. is found under eutrophic (organic-rich water) conditions (Cohen et al., 2000). Thus, the ratio of *Pediastrum* sp. to *Botryococcus* sp. (Fig. 11b) is an indicator of water freshness. Second, shifting marsh composition as reflected in the relative predominance of sedge (Cyperaceae) and cat-tail (*Typha* spp.) pollen indicate changes in both water chemistry and stability of the marsh water level (Wigand, 1987; Cohen

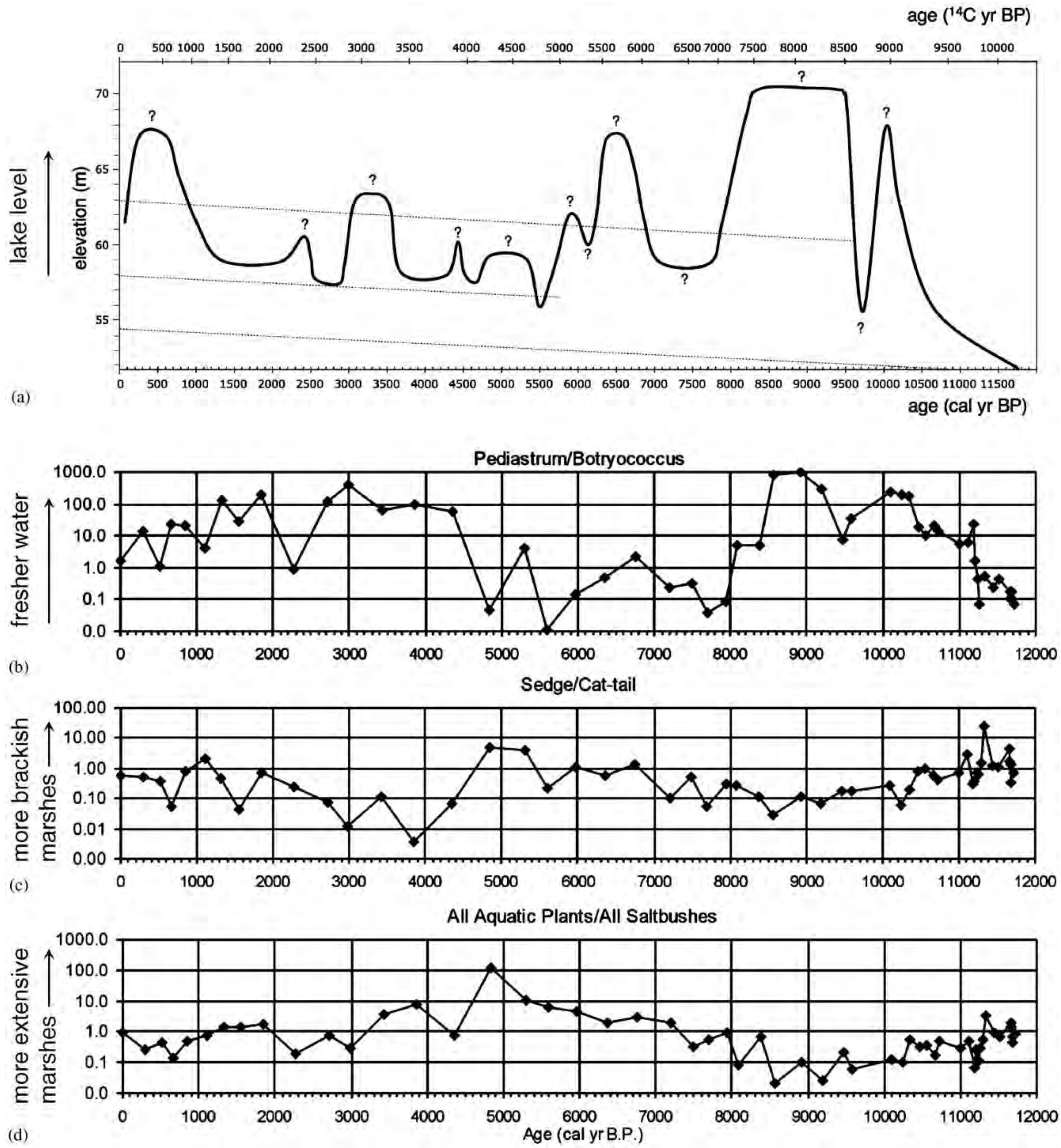

Fig. 11. Weighted ratios of major aquatic algae, and littoral, aquatic and terrestrial plant pollen reflecting lake and marsh dynamics in the Tulare Lake Basin. These are compared with the lake-level record reconstructed from stratigraphic trenches near Kettleman City. The ratios are weighted to reflect not only their relative proportions to other algae or pollen types, but also to reflect their abundance relative to the total terrestrial pollen abundance for each sample.

et al., 2000). Specifically, a higher ratio of sedge to cat-tail (Fig. 11c) implies marshes with relatively brackish waters. Finally, the proportion of aquatic plants relative to saltbushes (all Chenopodiaceae) reveals information regarding the extent of marsh in the Tulare Lake Basin with respect to the surrounding saltbush dominated basin slopes and flats (Fig. 11d).

In the early Holocene (11,000–8000 cal yr BP), increased abundance of *Pediastrum* sp. relative to *Botryococcus* sp. corresponds well overall to deeper lake intervals (Figs. 11a and b) after a period of time characterized by shallow marshes and/or ponds as indicated by all of the floral indicators including relatively high concentrations of both emergent and littoral aquatic plants. Maxima in the sedge/

cat-tail and aquatic plants/saltbush ratios in conjunction with a minimum in the *Pediastrum/Botryococcus* ratio infer a maximum extent of brackish water marshes in the middle Holocene (~5000 cal yr BP) after a gradual expansion of brackish water marshes starting at ~9000 cal yr BP (Figs. 11b–d). At their peak, organic production in these marshes would have been high as evidenced by maxima in absolute values of *Botryococcus* sp. The timing of maximum marsh extent coincides with overall low lake levels as indicated by the trench stratigraphy (Figs. 11a–d).

While the marsh was under expansion, a relative maximum in the *Pediastrum/Botryococcus* ratio from 7000 to 6500 cal yr BP, suggests that water conditions became slightly more oligotrophic. This supports the presence of a deeper lake as indicated by quiet water clay deposits found in the shoreline trenches, although the algae signal is subtler than one would expect given the >65 masl lake depth constrained by the trench data.

The return to fresher waters after the maximum marsh event commenced at ~4000 cal yr BP, according to all floral indicators (Fig. 11b–d). A spike in cat-tail (low sedge/cat-tail ratio) at ~4000 cal yr BP indicates a spurt of freshwater marsh expansion that likely is associated with a significant lake-level rise. This timing is a few hundred years earlier than the increase in lake level inferred from the trench stratigraphy (Figs. 10 and 11). The floral data also diverge from the trench stratigraphy in that the former suggests a fresh water event (high *Pediastrum/Botryococcus* ratio) from ~2000 to 1200 cal yr BP that is not seen unambiguously in the trench stratigraphy. These discrepancies will perhaps be reconciled by improved dating of both records. For example, the shoreline trenches contain a meter of fine-grained sediments between radiocarbon dates of ~7000 and 800 cal yr BP (e.g., Unit 7 of Fig. 6). As suggested in Fig. 10 at least some of these deposits may represent shallow water deposits at this high elevation and, because their age control is poorly constrained, some of these sediments could easily have been deposited during the 2000–1200 cal yr BP highstand indicated by the algae data.

The algae data is consistent with the high lake levels for most of the past several hundred years as inferred from the trench data (Fig. 11). Two peaks in the *Pediastrum/Botryococcus* ratio suggest that the highest lake levels occurred in two phases, one centered at ~800 cal yr BP and the other at ~250 cal yr BP.

8. Implications for Holocene climate change

As discussed previously, the geomorphological "fan dam" component of control on the level of Tulare Lake (Atwater et al., 1986) is likely to operate on a time scale much greater than 10^3–10^4 yr; thus, the Holocene lake-level history of Tulare Lake should primarily be a record of climate change in the drainage basin. Because the greatest source of recharge results from precipitation in the headwaters of the Kings, Kaweah, Tule, and Kern Rivers, the lake-level curve in Fig. 10 should be mostly dependent on precipitation change in the central and southern Sierra Nevada.

The principal results, based on both the trench stratigraphy and the floral analyses presented herein and in Davis (1999), are summarized as follows. There were seven to eight discernable fluctuations in the surface elevation of Tulare Lake over the past 11,500 yr (i.e., one per ~1500 yr). At least three of the highstands, and possibly as many as five, surpassed the 60–63 masl elevation of the shoreline trenches (Figs. 10 and 11a). Because the Rambla shoreline modifies the surface of the Robador alluvial fan, at least one of these Holocene highstand events was likely to have risen as high as the top of this shoreline feature (~70 m).

Lake level was generally higher during the early Holocene (prior to ~6000 cal yr BP). The oldest, well constrained highstand ended ~8200 cal yr BP and may have lasted for >1000 years. The age of a subsequent, briefer middle Holocene highstand peaked at 6500 cal yr BP. Two middle- to late-Holocene highstands possibly rose to the elevation of the shoreline trenches and lasted from 4000 to 2700 cal yr BP and 2000–1200 cal yr BP, respectively, the latter based principally on the pollen and algae data shown in Fig. 11b–d). The youngest highstand lasted for a period of several hundred years ending ~100 cal yr BP and may have peaked twice near 800 and 250 cal yr BP. Alluvial fan progradation into the lake as far out as the lake plain trenches commenced approximately at the same time as the youngest highstand. At least three major lowstands (<58 masl) occurred, probably of relatively short duration. The ages of the lowstands are centered at the following times: ~9700, 5400, and 2600 cal yr BP.

In a general way, the Tulare Lake record reflects the climatic pattern of the Holocene derived from other records in the intermontane western US. That is: (1) a moist early Holocene prior to ~8500 cal yr BP; (2) a dry middle Holocene; (3) a moist Neopluvial period between ~4500 and 2800 cal yr BP followed by a strong drought; (4) an episode of wetter, though late spring or summer shifted rainfall between ~1900 and 1100 cal yr BP; and (5) two episodes of wetter climate during the last 1000 cal yr BP (Wigand and Rhode, 2002).

More regionally, the major climate events inferred from the Tulare Lake record are compared to those of other records from localities in the southwestern US (Fig. 12). These records are more or less proximal to the southern Sierra drainage source for Tulare Lake. Included in this comparison are lacustrine records from Lake Elsinore (Kirby et al., 2005), pluvial Lake Mojave (Enzel et al., 1992), and a combined record from Owens and Pyramid lakes (Benson et al., 2002). The records in Fig. 11 are portrayed in a manner to focus on events associated with high precipitation/evaporation (P/E) ratios (black bars) to facilitate comparison with the Lake Mojave pluvial history. Pluvial Lake Mojave was, for the most part, an ephemeral playa lake during the Holocene; thus, its record is mainly

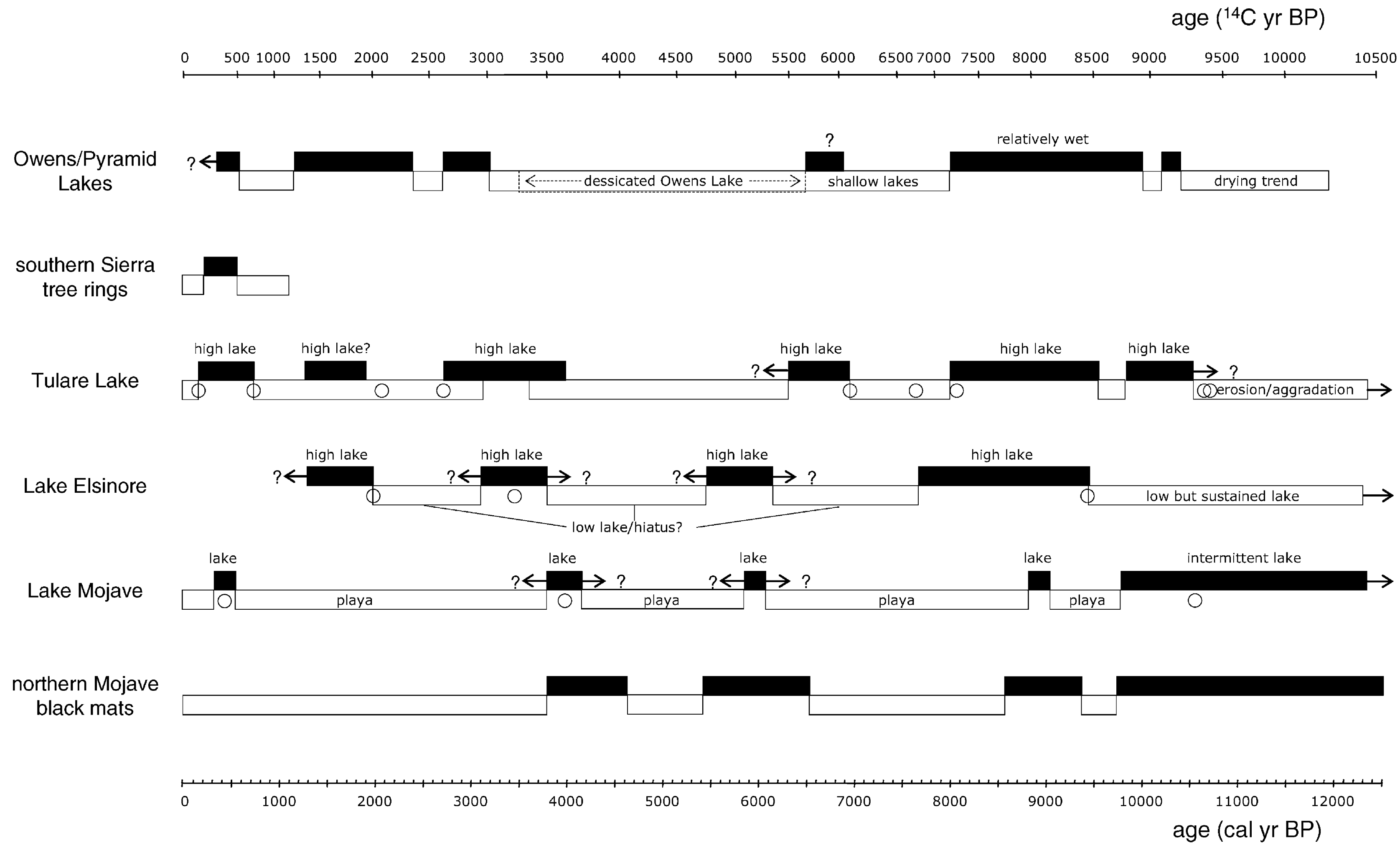

Fig. 12. Representative Holocene climate records from the southwestern US. Wet events were emphasized because of the clipped nature of the Mojave record with respect to dry climates (see associated discussion in text). The records are arranged by the location of their respective precipitation source areas. From top to bottom, they represent regions progressively southward and/or eastward. Owens/Pyramid record is after Benson et al. (2002) and Benson (2004). The tree ring record is based on a reprocessing of the Graumlich (1993) record by Benson et al. (2002). Lake Elsinore record is after Kirby et al. (2005) and Lake Mojave record is after Enzel et al. (1992) and Wells et al. (2003). Black mats record reflects major peaks where ^{14}C age probability is >0.01 as calculated by Wigand (2003) using results from Mehringer and Warren (1976), Mehringer and Sheppard (1978), and Quade et al. (1998). Radiocarbon dates are represented by open circles on the records with sparse age control.

sensitive to climate events with enough effective moisture to leave a record of lacustrine sediments. Fig. 11 also includes a record of precipitation based on tree rings from the source area of Sierran streams feeding Tulare Lake (Graumlich, 1993; Benson et al., 2002) and a record showing relatively high (< 0.01) ^{14}C age probabilities for spring (aka, black) mats (from Quade et al., 1998; Wigand, 2003). In all cases, the definition of relative conditions applies only for the Holocene. That is, for all records that extend back into the Pleistocene, high P/E conditions shown here are, in fact, low P/E conditions when compared to conditions in the Pleistocene.

In the earliest part of the Holocene ($>$10,000 cal yr BP), the records are somewhat inconsistent. Tulare Lake probably exhibited high lake levels only toward the very end of this period when the concentration of pelagic algae peaked in the record from the depocenter core of Davis (1999). This is similar to the conditions and timing exhibited in the Pyramid/Owens lakes record. In contrast, the pluvial Lake Mojave and spring mat records reflect relatively wet conditions for most of the early Holocene up to 9000–8500 cal yr BP. Lake Elsinore, which shows evidence for a sustained but low level lake during this time period, seems to fall somewhere in between.

Relatively wet conditions are indicated by all records from ~10,000 to 8000 cal yr BP and perhaps a few hundred years later than that for Owens Lake based on precise dates on nearshore tufas at relatively high elevations (Bacon et al., in press). These conditions are represented by one, relatively short-lived lacustrine episode in Lake Mojave. All other lacustrine records point to long-lived lakes at perhaps their deepest Holocene levels.

One brief wet episode, observed in all of the records, punctuates an otherwise dry interval that lasted for at least a few thousands of years in the middle Holocene after ~7500 cal yr BP. The maximum age of this wet episode in the Tulare Lake record is constrained at ~7000–6400 cal yr BP by two radiocarbon dates from the shoreline trenches (Fig. 6 and Table 1). The thickness of clay-rich deposits associated with this highstand suggests that the lake persisted for at least several hundreds of years. Prominent features in proxies that indicate higher lake levels for 300–500 years appear at the end of the third climatic interval of Benson et al. (2002; see also Benson, 2004), approximately at the same time as the Tulare Lake highstand. The records from Lake Mojave, Lake Elsinore and the spring mat record also show this feature but at a slightly younger age. In the former two cases, these younger ages are based on linear interpolations between far-removed radiocarbon ages. Further dating of the Elsinore and Mojave records are thus required in order to test the regional correlatibility of this event, an event which potentially corresponds with a dramatic shift to wetter climate at ~6500 cal yr BP (~5500 ^{14}C yr BP) observed from the Plateau of eastern Washington to the northern Mojave Desert in records of paleovegetation, spring peats, and drowned trees (Wigand and Rhode, 2002). Although its initial dramatic increase declined somewhat after a few decades, the effects of this wet event lingered for several hundred years, before drier conditions returned.

All the lacustrine records in Fig. 11 exhibit a middle Holocene dry interval centered at ~5000 cal yr BP. The end of this interval varies between 4000 and 3000 cal yr BP. In the Pyramid/Owens record, this boundary marks the onset of a late Holocene interval characterized by overall wetter conditions. This result is consistent with a plant macrofossil study of Little Lake, California, by Mehringer and Sheppard (1978) and the results of several other studies summarized in Benson et al. (2002). The three other lacustrine records in Fig. 12, however, suggest a return to wetter conditions several hundred years sooner.

The exact duration of the event varies from record to record, but the Pyramid/Owens, Tulare Lake, and Lake Elsinore records all point to wetter conditions during a time interval centered around ~2000–1600 cal yr BP. Notably, this event is missing in the Lake Mojave and Northern Mojave black mat records.

With the exception of the black mat records, all of the records in Fig. 11 for which there is coverage show a wetter period during the past 1000 years. At Tulare Lake, this event commences as much as a few hundred years earlier than the rest of the records. However, if one averages the age of this event over all of the records, the timing is consistent with that of the Little Ice Age (e.g., Ruddiman, 2001).

9. Implications for paleoindian sites around Tulare Lake

In theory, Clovis-aged shorelines built on the alluvial fans originating in the Kettleman Hills would have provided an ideal habitat along the western margin of Tulare Lake. The sandy deposits of the alluvial fans may have provided a well-drained living surface on the margins of a large lake with abundant food resources and materials for manufacturing shelters, as well as for making matting, basketry, and clothing. However, both sets of trenches investigated herein, including those dug into the Rambla highstand shoreline feature, contained younger lacustrine sediments. Hence, any such ideal habitats for Clovis-aged occupations are either buried by younger deposits in this area or have been eroded.

Clovis-age deposits (or, more likely, an unconformity representing an erosional surface at this time) would be found approximately 1 m deeper than the bottom of Rambla shoreline Trench 2. Accessing this horizon would thus require a trench ~3.5 m deep. The correlative horizon in the lake plain trenches would be encountered at a depth of ~5 m or more. Thus the surface elevation at the lake plain trench locality would have been at an elevation of ~53 masl, significantly below the 56–58.5 masl elevation proposed for the surface of Tulare Lake during the Clovis occupation (Riddell and Olsen, 1969; Wallace and Riddell, 1988; West et al., 1991; Fenenga, 1993). This implies that this location would have been submerged under a lake or marsh and that the shoreline at this time would have lain considerably further inland and has since been covered by younger fan deposits from the Kettleman Hills.

The occupants of archeological site CA-KIN-80 likely lived on top of the Rambla highstand feature for a time period that started as early as 5000 cal yr BP and ended as late as ~1000 cal yr BP. Notably, the elevation of the surface of Tulare Lake would typically have been ~10 m lower than CA-KIN-80 for most that time interval (Fig. 10). This would have required a walk of at least a few hundred meters to access the lakeshore. It is apparent, therefore, that these Native Americans opted to live at CA-KIN-80 for reasons other than immediate proximity to the lake, perhaps such as the superior vantage point, more abundant breezes and fewer insect pests offered at the top of the Rambla shoreline.

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