GEOLOGIC MAPS OF THE SACRAMENTO - SAN JOAQUIN DELTA, CALIFORNIA

By Brian F. Atwater

INTRODUCTION

The Sacramento - San Joaquin Delta, the arm of the San Francisco Bay estuary that reaches into the Central Valley of California, differs from typical coastal-plain deltas in three important respects. First, rather than meeting the ocean individually and directly, all major waterways of this delta discharge via a single constricted outlet into a chain of estuarine bays and straits. Second, in the most common vertical sequence of deposits, peat and mud deposited in tidal marshes and swamps (tidal wetlands) directly overlie alluvium or eolian sand, a sequence recording a landward spread of tidal environments rather than the seaward migration of fluvial environments that is typical of coastal-plain deltas (Cosby, 1941, p. 43; Thompson, 1957, p. 12; Shlemon and Begg, 1975, p. 259; Atwater and Belknap, 1980). Finally, intensive human use has led to a peculiar set of conflicts involving rights to water and responsibilities for flood-control levees (Kockelman and others, 1982).

The accompanying maps (sheets 1-20) bring together several kinds of information that aid in understanding the near-surface geology of the Sacramento - San Joaquin Delta. Chief among these data are the surficial distribution of principal kinds of mappable deposits (map units); the basal elevations of soft peat and mud; approximate limits of autumnal high tides and locations of tidal waterways before agricultural reclamation of wetlands; the location of nontidal waterways, many of whose traces were covered with tidal-wetland deposits within the past 5,000 years and then exhumed in historic time; the location and stratigraphic setting of radiocarbon-dated samples; and the location of 16 of the breaks in manmade levees that have occurred since about 1900. This text, supplemented with tables, a correlation chart, and short explanations of map units and symbols (sheet 21), serves mainly to explain how these various data were assembled. In addition, it describes each map unit, briefly discusses the evidence for Quaternary movement along faults, and discusses use of the maps for determining foundation conditions beneath levees and elevations of land before agricultural reclamation. For cross sections and interpretations of some of the principal map units, the reader is referred to Atwater and Belknap (1980); additional geologic descriptions and interpretations are provided by Cosby (1941) and Shlemon and Begg (1975).

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SKETCH OF DEPOSITIONAL HISTORY

The Sacramento - San Joaquin Delta overlies 5-10 km of sedimentary deposits. Most of this material, including sources and reservoirs of the Delta's natural gas, accumulated in marine environments about 175 million to 25 million years ago (Burroughs, 1967). Younger deposits are generally described as nonmarine (Burroughs, 1967), but some must have formed in shallow seas and estuaries (see maps by C. A. Repenning in Hackel, 1966).

The depositional history of the Delta during the past one million years or so (late Quaternary time) probably reduces to several kinds of cycles imposed by fluctuations in regional and global climate (Shlemon, 1971, p. 430; Atwater and Belknap, 1980, p. 89-92). Greatly simplified, each cycle consists of an episode of deposition and an episode of nondeposition and erosion.

One kind of cycle, ultimately attributable to exchange of water between oceans and large continental ice sheets, results from rise and fall in the level of the sea relative to land. In the Delta the principal known product of sea-level rise is soft peat and mud that have accumulated during the past 7,000 years (p. 9; sheets 3-12, 15-17). This material records a time between major ice ages (an interglacial) when relative sea level rose enough for tidewater to invade the Central Valley and create extensive wetlands like the tule marshes that covered most of the Delta before agricultural reclamation. Similar tidal-wetland deposits probably formed during Pleistocene interglacials but are now scarce or absent (Atwater and Belknap, 1980, p. 100-101); perhaps these deposits disappeared during ice ages, when evacuation of tide water from the Central Valley would have exposed the site of the Delta to erosion by running water and wind and, as agricultural drainage and cultivation do (see Weir, 1950, and Broadbent, 1960), would have promoted decomposition of peat by oxygen and organisms. Another product of relative sea-level change is the silty and clayey Holocene alluvium that lies upstream of the Delta along its principal tributaries, reaches into the Delta as natural levees, and extends beneath parts of the Delta as deposits underlying tidal-wetland deposits (p. 8). Similar alluvium, formed 38,000 to 46,000 ^{14}C years ago (table 1, sheet 21) during a lesser interglacial, lies about 50-90 ft below the present ground surface at parts of Jersey and Bradford Islands (sheet 10) and at Hotchkiss Tract (sheet 14).

A second kind of cycle, out of phase with the first, results from waxing and waning of glaciers in the Sierra Nevada. Episodic glaciation in the Sierra Nevada has long been cited to explain a widespread sequence of alluvial-fan deposits in the northeastern San Joaquin Valley (p. 5). These deposits, probably removed from glaciers by meltwater streams and (or) washed from drift-covered alpine slopes, flank and underlie the eastern margin of the Delta where it borders fans of the Mokelumne and Stanislaus Rivers (sheets 8, 12, 13, 17, and 20). Also attributable to glaciation in the Sierra Nevada are fields of windblown (eolian) sand, the largest of which extends southeastward from an area between Antioch and Bradford Island (sheets 9-11, 14, and 15). The youngest sand in this field was probably swept from glacial-age flood plains of the San Joaquin and Sacramento Rivers during one or more of the episodes of alluviation that produced the Modesto Formation (p. 7).

Still other kinds of cycles may influence deposition by Delta tributaries that head in the unglaciated drainage basins of the Sierra Nevada foothills and the Coast Ranges. Alluvial-fan deposition by these streams is demonstrably episodic in two cases. First, younger alluvium of the Putah Creek fan (sheet 4) reportedly overlies older alluvium having a well-developed buried soil that extends from the head to the toe of the fan (Thomasson and others, 1960, p. 48). A period of nondeposition on the Putah Creek fan thus preceded a time of widespread alluviation. Second, whereas a set of stream-built ridges (former channels labeled 1 on sheet 14) splay across the fan of Marsh Creek, the youngest natural course of the creek (labeled 2 on sheet 14) passively follows a trough rather than building a ridge of its own. This contrast suggests that an episode of little or no widespread deposition has followed a period of aggradation by Marsh Creek. Further, because the inferred episode of virtual nondeposition coincides with the present high stand of the sea, the prominent stream-built ridges of the Marsh Creek fan cannot have resulted primarily from rise in sea level. The cause and timing of alluviation by Coast Range streams are too poorly known, however, to permit correlation with specific climatic or tectonic events. Indeed, judging from available ^{14}C dates (p. 4, 5), episodes of deposition by such streams as Putah and Marsh Creeks may or may not have occurred at the same time from one stream to another; likewise, they may or may not coincide with the major episodes of deposition on fans of the Mokelumne and Stanislaus Rivers.

The site of the Delta during late Quaternary time can thus be likened to a stage on which three related and repetitious plays are presented simultaneously. In one play, wetlands and flood plains appear and expand as tidewater invades from the west, then become sites of erosion after the tide- water retreats. In another play, glacially eroded detritus from the Sierra Nevada builds alluvial fans and, reworked by wind, creates extensive sand dunes. In third, little-understood play, streams draining the Sierra Nevada foothills and Coast Ranges episodically build alluvial fans. Spanish- and English-speaking persons enter during a major incursion of tide water and find most of the stage covered with tules.

METHODS

Criteria for defining and differentiating map units

Differences among the map units on sheets 1-20 take several forms. Some units differ from one another in lithology, others differ in relative age, and still others differ in both. Further, some alluvial-fan deposits may differ from one another primarily in geographic location; unconvinced that sequences of alluvial-fan deposits in the vicinity of the Delta necessarily correlate from fan to fan, I have named most local sequences individually rather than attempting to fit them into a single set of regional units. Finally, the mapped limits of flood plain and tidal deposits depend in part on arbitrary conventions. These various criteria for mapping Quaternary deposits are discussed in the following paragraphs.

Lithologic distinctions separate the principal kinds of map units tabulated on sheet 21 (unindented headings in "Description of map units"). Most lithologic distinctions -- such as that between tidal peat or mud and eolian sand -- result primarily from depositional environment. One, however, reflects provenance: alluvial-fan deposits derived largely from granitic rocks in high parts of the Sierra Nevada (units headed, "...derived from glaciated drainage basins," sheet 21) typically contain more mica and fewer lithic grains than fan alluvium derived from the chiefly sedimentary, volcanic, and metamorphic rocks of the Coast Ranges and Sierra Nevada foothills (the many units headed, "...derived from unglaciated drainage basins," sheet 21).

Demonstrable differences in relative age subdivide several of the lithologic categories of deposits in the vicinity of the Delta. Subdivisions of this sort include the Modesto and Riverbank Formations. Though these units are lithologically indistinguishable where unweathered, the Modesto Formation widely overlies the Riverbank Formation (sheets 8, 12, and 13; Atwater and Belknap, 1980, p. 100), commonly occupies lower positions within series of inset or crosscutting depositional surfaces, and typically bears less strongly developed soils (Marchand and Allwardt, 1981). Similar relative-age criteria justify division of other alluvial-fan deposits into sequences of two or more units, such as younger and older alluvial-fan deposits of Putah Creek.

A problem with using relative-age criteria, however, is how to express degrees of confidence in fan-to-fan correlation between alluvial-fan sequences. The solution I prefer for the Sacramento - San Joaquin Delta and vicinity is to map a single regional set of units on glaciogenic fans and to map several local sets of units on fan deposits derived from unglaciated drainage basins. Glaciogenic units, such as the Modesto and Riverbank Formations, bear regionally correlative soils (Janda and Croft, 1967) and possess a reasonably well-established genetic link with episodic climatic events of regional or global extent (Marchand, 1977); hence they are readily and plausibly correlated from fan to fan. Terrace and fan deposits derived from unglaciated drainage basins, in contrast, commonly bear soils of only local extent and as yet lack a well-demonstrated tie to regional climatic events; fan-to-fan correlation of these deposits is typically conjectural. It is possible, for instance, that the undissected, ridge-forming alluvium of Marsh Creek that bears Brentwood soils (Carpenter and Cosby, 1939; ridges are natural levees of former waterways labeled "1" on sheet 14) formed at the same time as the ridge-forming alluvium that bears Yolo soils (Cosby and Carpenter, 1935) on the fan of Putah Creek. Neither body of alluvium, however, has been dated directly, and the only radiometric date from alluvium of Marsh Creek is 20,465±675 ^{14}C years (UM-2059; table 1, sheet 21), far greater than the 4,000- and 9,000-year bracketing ages (Shlemon and Begg, 1972) for the oldest unit of well-dated alluvium of Putah Creek. In mapping nonglaciogenic alluvial-fan deposits, I have therefore traded the convenience of a single set of relative-age units, such as that used by E. J. Helley (Harwood and others, 1981; Helley and others, 1981) in mapping of the northeastern Sacramento Valley, for the flexibility of multiple sets of units that, however awkward, explicitly allow the possibility of nonsynchronous alluviation by various streams draining areas of contrasting sizes and climates in the Coast Ranges and Sierra Nevada. If synchroneity is later demonstrated, units may of course be combined. On the other hand, future work could also show that map units embracing the fans of several creeks (for example, younger alluvium of Marsh Creek and vicinity) vary in age from fan to fan. The sole excuse for lumping some nonglaciogenic fans together at present is to keep map units at a workable number.

Several arbitrary conventions aid in defining and delimiting flood-plain and tidal units. One convention is to set a minimum thickness of 5 ft for flood-plain and tidal deposits. For peat and mud of tidal wetlands, such a limit is particularly useful because most peaty deposits thinner than 5 ft have been pervasively decomposed, partly desiccated, and locally mixed with buried A horizons of underlying deposits as a result of human-caused drainage and cultivation. Another convention, followed for cartographic simplicity, is to leave unlabeled hundreds of islets of remnant tidal wetland (tule berms). Most of these are underlain by peat and mud, even where nearby farmlands have lost their historic cover of tidal-wetland peat through decomposition, deflation, and other processes described by Weir (1950) and Broadbent (1960). Examples documented by borehole data are shown along Sand Mound Slough in the southwest corner of sheet 11 and along Fourteenmile Slough in the southeast corner of sheet 12. At both localities, the thickness of tidal-wetland deposits equals the difference in elevation between the ground surface of the tule berm, typically about +3 ft according to leveling by Atwater (1980), and the basal elevation of peat or peaty mud plotted beside the borehole symbol(s).

Compilation and presentation of borehole data

Borehole data aid greatly in defining both the boundaries of principal Holocene facies within the Delta and the stratigraphic relations of deposits around its margins. Thousands of boreholes have been drilled and logged as part of engineering and geologic studies of the Delta. For about 1300 of these (table 2, sheet 21) I have abstracted and plotted the basal elevations of two kinds of deposits: peat or peaty mud, most of which probably formed in tidal wetlands, and soft silt or clay that mainly accumulated in tidal waterways but in some areas may have been deposited in nontidal channels or oxbows. For some boreholes I have also supplied brief descriptive logs (abbreviations and symbols explained on sheet 21) in order to justify the location of a nearby contact or show lithologic variation within the mapped unit. For others I show the thickness and stratigraphic position of principal alluvial-fan and eolian units of the fans of Marsh Creek (sheets 10 and 14) and the Mokelumne River (sheets 8 and 12). Finally, I have attempted wherever possible to summarize on the maps the borehole stratigraphy associated with each radiocarbon date listed in table 1 (sheet 21).

Reconstruction of historic and prehistoric hydrologic features

Another aid to mapping of surficial deposits in the Delta and vicinity is knowledge of historic and prehistoric hydrology. For example, excepting a few areas such as the west-central part of Sutter Island (sheet 4; Atwater and Belknap, 1980, p. 95, section C) where natural levees have extended across tidal wetlands, the historic limit of tidal-wetland deposits can be approximated by the historic landward margin of tidal wetlands. Parts of this wetland margin that remained relatively pristine circa 1910 generally plot between the 0- and 5-ft contour on USGS topographic maps of that vintage. This elevation agrees with that of the highest extensive surfaces in remnant wetlands today, located 2.5-3.5 ft above the National Geodetic Vertical Datum (formerly called the U.S. Coast and Geodetic Survey sea-level datum of 1929), according to leveling by Atwater (1980). In general, I have therefore extrapolated the historic margin of tidal wetland into areas already reclaimed for agriculture circa 1910 by plotting it about midway between the 0- and 5-ft contours shown on USGS topographic maps of that vintage. This wetland margin approximates the line of extreme high water during autumn months because peak equinoctial tides rarely exceed elevations of 2.5-3.5 ft under conditions of low river discharge in most of the Delta.

Representing the actual or inferred traces of historic and prehistoric waterways without showing their deposits as map units (sheets 1-21) departs from the usual practice (for example, Cosby, 1941; Allsup and Dudley, 1976; Welch and others, 1976) but highlights paleogeography, denotes as precisely as possible the surficial location of channel deposits, documents a photogeologic contrast between tidal and flood-plain deposits (sheets 15-20), and avoids cluttering the map with labels for units. Traces of waterways were identified in one or both of two ways: using landforms shown on 1:31,680-scale USGS topographic maps surveyed about 1910, and using tonal contrasts on 1:6000- to 1:20,000-scale black-and-white aerial photographs taken since 1965 and 1:24,000-scale USGS orthophoto quadrangles prepared about 1970. Two principal kinds of waterways are shown: tidal and nontidal. The distinction between the two is clear where stratigraphic context requires a tidal origin, as with waterways shown in the southern two-thirds of sheet 11, and where historic elevations require a supratidal origin, as with the many small waterways shown on sheet 20. Further, on aerial photographs and orthophoto maps, the sites of former tidal waterways are generally marked by uniformly light-toned deposits set against darker peat, whereas the sites of nontidal waterways show a combination of light-toned levees and dark-toned peaty channel fill. Distinctions blur, however, where non-tidal waterways historically graded into tidal waterways. As a result, the nature of some waterways is represented in an arbitrary and possibly erroneous fashion.

Location of levee breaks

A break in a manmade levee of the Sacramento-San Joaquin Delta commonly scours a depression that persists as a pond after reclamation of the flooded island or tract. Ponds of this sort, generally elongated normal to the levee, appear on USGS topographic maps of several vintages. Combining the location of mapped ponds with archival descriptions assembled by Thompson (1957, p. 446-509) and U.S. Corps of Engineers (1979, p. 7), present-day oral accounts of eyewitnesses, and photographs of recent breaks, it is possible to show the location and year of 16 levee breaks dating from about 1900 to 1980 (sheets 6, 10, 11, 12, 15). Most of the plotted breaks occurred in the peat lands of the central Delta; nine are shown on the Bouldin Island quadrangle (sheet 15). Study of the primary sources cited by Thompson (1957) would probably permit the plotting of additional breaks in more nearly alluvial parts of the Delta where few scoured depressions were deep or long-lived.

GENERAL DESCRIPTION AND DISCUSSION OF MAP UNITS

Because relative ages are in many cases unknown, Quaternary deposits discussed in the following section are grouped primarily by depositional environment and (or) provenance. Terms and symbols for soils follow Birkeland (1974) and Soil Survey Staff (1975).

Sedimentary rocks and deposits whose environments of deposition have been largely or wholly disarranged

Sandstone, siltstone, claystone, and minor conglomerate and tuff mapped on sheet 14 as bedrock range in age from Late Cretaceous to Pliocene. Similar rocks, most of which originated in marine environments, underlie all of the Delta (for example, Burroughs, 1967). For details about the exposed section, see Brabb, Soneman, and Switzer (1971) and references cited therein.

Alluvial gravel, sand, silt, and clay of the Montezuma Formation form hills with nearly accordant summits about 250 ft above sea level (sheets 6 and 10). These hills constrict the Delta's connection with Suisun Bay and may be bounded by faults west of Rio Vista (Montezuma Hills) on the east and west (Reiche, 1950). The precise age of the Montezuma Formation is unknown but presumed to be Pleistocene because the original top of the unit probably forms the nearly accordant summits. The formation may, however, be partly coeval with unnamed subsurface beds near Collinsville (sheet 9) in which Sarna-Wojcicki, Bowman, and Russell (1979) have identified the Pliocene Lawlor Tuff (approximate age 4.0 million years) and a younger tuff common to the top of the San Joaquin Formation (Pliocene) at Kettleman Hills in the southern San Joaquin Valley.

Alluvial-fan and alluvial-terrace deposits derived from unglaciated drainage basins

These deposits, consisting of clayey silt, silt, sandy silt, and subordinate sand and gravel, are nonarkosic and generally nonmicaceous. Map units are defined chiefly by provenance and relative age. Time-stratigraphic correlation between alluvial sequences of different creeks has not been established. Areas are discussed in counterclockwise order beginning at Putah Creek (sheet 3).

Putah Creek

Older alluvium of Putah Creek is widely but sparsely exposed at the toe of the Putah Creek fan, most commonly in basins between stream-built ridges of younger alluvium. In the Saxon 7.5-minute quadrangle, north of the area of sheet 3, it locally forms hills as much as 5 ft high and 100-1000 ft across, conceivably the remnants of stream-built ridges or an interglacial flood basin similar to Yolo Basin. Older alluvium of Putah Creek bears San Ysidro soils (Cosby and Carpenter, 1935), San Ysidro and Antioch soils (Bates and others, undated), and Riz soils (Andrews, 1972). Its presumed age is Pleistocene.

Younger alluvium of Putah Creek grades from sandy silt and silt of prominent natural levees (these levees chiefly northwest of map area; see Bryan, 1923), on which Cosby and Carpenter (1935) mapped Yolo soils, to clayey silt and silty clay of intervening basins and areas transitional with Yolo Basin, on which Cosby and Carpenter (1935) mapped Capay and Clear Lake soils, respectively. Near Davis, about 15 km north of the northwest edge of the area of sheet 3, this unit includes three superposed members separated by buried A horizons (Shlemon and Begg, 1972). Organic carbon from the lower Ab horizon yields an age of 9,150$\pm$650 ^{14}C years; ages determined from similar material in the upper Ab horizon are 3,890$\pm$200 and 4,330$\pm$180 ^{14}C years (Shlemon and Begg, 1972). According to E. L. Begg, (oral commun. with D. E. Marchand, 1977), the upper Ab horizon correlates with Yolo soils and the lower with Capay soils. If so, the regional significance of the dated Ab horizons near Davis is clouded by the possibility that, in most other parts of the Putah Creek fan, the parent materials of the Yolo and Capay soils of Cosby and Carpenter (1935) are coeval levee and basin facies, respectively, rather than tabular, superposed units.

Montezuma Hills

Older alluvium of Montezuma Hills and vicinity forms slightly to moderately dissected fans on northeast flank of Montezuma Hills. Presumably it was derived from the Montezuma Formation. The dissection displayed by this unit suggests deposition before the Holocene rise in sea level.

Younger alluvium of Montezuma Hills and vicinity floors valleys graded to late Holocene sea levels. Locally it may include detritus from Sacramento River floods. Carpenter and Cosby (1934) mapped Yolo and Capay soils on this unit.

Antioch

Older alluvium of Antioch and vicinity forms dissected surfaces, most of whose soils have well-developed Bt horizons (chiefly Ambrose and Antioch soils of Carpenter and Cosby, 1939). This alluvium underlies eolian sand of the Modesto Formation and is therefore regarded as Pleistocene.

Intermediate alluvium of Antioch and vicinity forms thin (thickness 3-8 ft) patches of silt that overlie older alluvium of Antioch and vicinity (for example, annotated locality along E. 18th St., sheet 9). Locally the intermediate alluvium abuts eolian sand of the Modesto Formation, and locally it lies 20-25 ft above Holocene alluvium and tidal-wetland deposits. The deposit bears Zamora soils (Carpenter and Cosby, 1939), which here lack Bt horizons. Possibly it is coeval with eolian sand of the Modesto Formation, whose deposition may have temporarily raised local base levels for small streams passing through the site of eastern Antioch.

Younger alluvium of Antioch and vicinity floors valleys apparently graded to Holocene high sea levels.

Marsh Creek

Older alluvium of Marsh Creek and vicinity forms as many as four terraces near the apex of the Marsh Creek fan (sheet 14). Most of these terraces are littered with subangular cobbles of chert derived from the Franciscan Complex at Mount Diablo. The exact number of original surfaces is uncertain because, although I have no proof, faults may have broken some terraces. This unit was mapped as Corning soils by Carpenter and Cosby (1939).

Younger alluvium of Marsh Creek and vicinity forms fans of Marsh, Kellogg, and Sand Creeks. Near the apex of the Marsh Creek fan (sheet 14), it generally consists of 5-15 ft of overbank silt overlying channel sand and gravel; sand and gravel diminish down the fan. The unit also grades into and includes gray silt and clay deposited in near-sea-level flood basins and ephemeral lakes among preexisting eolian deposits of the Modesto Formation at the toe of the Marsh Creek fan. The lacustrine deposits locally contain shells of freshwater gastropods, including Stagnicola sp. (John Hanley, written commun., 1979). The unit overlies eolian sand of the Modesto Formation in lower reaches of the fans of Sand Creek (for example, NW 1/4 sec. 1, T. 1 N., R. 2 E.) and Marsh Creek (for example, NE. 1/4 sec. 7, T. 1 N., R. 3 E.).

The age of younger alluvium of Marsh Creek and vicinity is probably plural. The map unit possibly includes one or both bodies of buried Marsh Creek alluvium having late Pleistocene ^{14}C ages: (1) sand beneath Jersey Island (sheet 10) bracketed between San Joaquin River alluvium dated 38,000-46,000 ^{14}C years (table 1) and eolian sand whose minimum age is about 10,000 years (see "eolian deposits" below); and (2) gravelly deposits at the head of the fan (sheet 14) containing charcoal dated 20,465±675 ^{14}C years (UM-2059, table 1). Another part of the map unit definitely post-dates eolian sand of the Modesto Formation because of stratigraphic superposition. This part of the unit contains at least two noncoeval subdivisions. The older, associated with prominent channel ridges (former waterways labeled 1 on sheet 14) and bearing Brentwood and Rincon soils (Carpenter and Cosby, 1939), may have formed in latest Pleistocene or early Holocene time. The younger, associated with the most recent courses of Marsh Creek (existing and former waterways labeled 2 on sheet 14) and largely bearing Sorrento soils (Carpenter and Cosby, 1939), is probably of late Holocene age.

Corral Hollow and Brushy Creek

Alluvium of creeks from the Corral Hollow drainage to Brushy Creek was deposited chiefly by the Corral Hollow drainage (Tracy and vicinity, sheets 19 and 20), Mountain House Creek (sheet 18), and Brushy Creek (sheet 18). I have not studied this alluvium in the field. It bears Ambrose, Herdlyn, Pescadero, Rincon, and Sorrento soils of Cole and others (1943), and it probably ranges in age from Pleistocene to Holocene.

Calaveras River

Alluvium of Calaveras River and vicinity was deposited by Calaveras River, Bear Creek, and several lesser streams between the Mokelumne and Stanislaus Rivers (sheets 13 and 17). Locally it appears to crosscut and may overlie a young part of the Modesto Formation on the Mokelumne fan in the vicinity of Micke Grove Park (sheet 13; sec. 25, T. 3 N., R. 6 E.; Marchand and Atwater, 1979). Its western boundary is very uncertain in nature and location; contact relations with the Modesto Formation and Holocene flood-plain deposits along this boundary are unknown.

Alluvium of Calaveras River and vicinity was divided by Marchand and Atwater (1979) and Atwater and Belknap (1980, p. 84) into two relative-age units, the younger of which was interpreted by these authors to thin westward and veneer the older unit on much of sheets 13 and 17. Here I combine them because the younger unit is commonly thinner than 3 ft and its typical contact with the older unit could be interpreted as the base of a thick A horizon. The alluvium bears Capay, Landlow, and Stockton soils of Cosby and Carpenter (1937) and Landlow and Stockton soils of Retzer and others (1951).

Alluvial-fan deposits derived from glaciated drainage basins

Silt, sand, and minor gravel deposited by major rivers of the Sierra Nevada are largely arkosic and commonly micaceous. The principal fan deposits of these rivers, particularly rock-flour-like silt and very fine sand (Arkley, 1962; Janda and Croft, 1967; Marchand, 1977), record principal episodes of Pleistocene glaciation in the Sierra Nevada. Marchand (1977) correlates these deposits with large-ice-volume (even-numbered) stages of the marine oxygen-isotope record.

Arkosic fan deposits east of the Delta can be assigned to the Modesto and Riverbank Formations by correlation with the "recent" and "late Pleistocene" deposits, respectively, of Arkley (1959, p. 13). Arkley's units, given their present formational names by Davis and Hall (1959), have been widely mapped on fans of major Sierra Nevada rivers in the northeastern San Joaquin Valley (Janda and Croft, 1967; Marchand and Allwardt, 1981) and eastern Sacramento Valley (Shlemon, 1972; Harwood and others, 1981; Helley and others, 1981). Delineation of the Modesto and Riverbank Formations on sheets 2, 5, 8, 12, and 13 generally follows Marchand and Atwater (1979), Atwater and Marchand (1980), and Atwater and Belknap (1980, p.

94) except in the naming of subdivisions of these formations.

Riverbank Formation

The Riverbank Formation, undivided, forms low rises surrounded and partly veneered with Holocene alluvium on sheets 4 and 8. In addition, it underlies the Modesto Formation in boreholes and ditch exposures on sheets 8, 12, and 13 (Atwater and Belknap, 1980, p. 100). It is not subdivided as on sheets 1, 2, and 5 because partial to complete burial obscures degree of dissection and geomorphic position. Soils developed on the Riverbank Formation, undivided, on sheets 4 and 8 are the Glann soils of Cole and others (1954) and the Rocklin soils of Cosby and Carpenter (1937).

In many places east of the Delta the Riverbank Formation can be divided into an older and a younger unit. The older unit of the Riverbank Formation forms moderately dissected surfaces on sheets 1, 2, 4, and 5. Its contact with the younger unit on sheet 5 is marked by contrasts in degree of dissection and generalized elevation of the land surface as surveyed for the 1910 edition of the Bruceville quadrangle. Though equated by Atwater and Marchand (1980) with the middle unit of the Riverbank Formation (as defined by Marchand and Allwardt, 1981), this correlation now seems too speculative to be retained. The provenance of the unit is unknown; possibly it was deposited in large part by American River, but foresets near the intersection of Interstate Highway 5 and Lambert Road dip northward (sheet 5). Cole and others (1954) mapped most of this unit as San Joaquin and Alamo soils.

The younger unit of the Riverbank Formation forms a slightly to moderately dissected surface having a more northwesterly strike and slightly lower elevation than the contiguous surface formed by the older unit of the Riverbank Formation on sheet 5. Marchand and Atwater (1979) and Atwater and Marchand (1980) equated this unit with the upper (youngest) unit of the Riverbank Formation (as defined by Marchand and Allwardt, 1981). It was deposited chiefly by the Cosumnes and (or) Mokelumne Rivers, and it bears San Joaquin and Alamo soils of Cole and others (1954) and Rocklin soils of Cosby and Carpenter (1937).

Modesto Formation

The Modesto Formation forms fans of the Mokelumne River (sheets 8, 12, and 13) and Stanislaus River (sheets 17 and 20). It overlies the Riverbank Formation and underlies Holocene tidal-wetland deposits (Atwater and Belknap, 1980, p. 100). Its average thickness is 10-15 ft on the fan of the Mokelumne River (sheets 8, 12, and 13) and probably greater on the fan of the Stanislaus River. On these fans the lithology in top 5 ft of the Modesto Formation allows subdivision into three main units:

(1) Loose, ridge- or mound-forming fine sand generally thicker than 5 ft (on maps, represented by denser pattern of dots). This sand, probably eolian, displays a somewhat radial distribution on the Molekumne River fan (Marchand and Atwater, 1979) that suggests derivation from radiating distributaries of the fan rather than the more remote sources tapped by the Antioch-Oakley-Bradford Island dune field (see discussion of eolian deposite below). It correlates by geomorphic position and degree of soil development with the upper member of the Modesto Formation, whc approximate age is 9,000 to 14,000 years according Marchand and Allwardt (1981 p. 60-61). Soi developed on this unit are the Hanford loamy sand Cosby and Carpenter (1937) and Delhi soils of Retz and others (1951).

(2) Ridge-forming, loose, poorly sorted fine coarse sand and sandy silt thicker than 5 (represented on maps by more open pattern of dots These deposits commonly grade down section into medi to coarse sand. They cover most of the middle reach of the fans and locally extend to the toes. Thou chiefly or wholly fluvial, they may be partly eoli at top. Typically they overlie compact, unweather silt locally plated with calcium carbonate similar the silt of unit (3) and probably continuous with th silt; this sequence is also displayed in the ty section of the Modesto Formation (Marchand a Allwardt, 1981, p. 53-55). Like unit (1), the loo material above the silt correlates with the upp member of the Modesto Formation. The deposits be Hanford soils (typical phases) of Cosby and Carpent (1937) and Dinuba (deep phases) and Hanford soils Retzer and others (1951).

(3) Compact, well-sorted silt and very fine sa overlain by less than 5 ft of looser, more poor sorted silty sand and sandy silt like that of unit ((unstippled areas on maps). This two-tiered alluvi is most common in low-lying areas, particularly ne the toes of the fans. Soils developed on it -- Dinu (shallow phases) and Fresno soils of Retzer and othe (1951) and Hanford (calcareous-subsoil phases Merced, and Stockton soils of Cosby and Carpent (1937) -- locally contain Bt horizons, and the Fres and Stockton soils include a hardpan that is typical cemented with calcium carbonate and silica and plat at the top with 1-5 mm of these precipitates. T tiers were previously interpreted by Marchand a Atwater (1979), Atwater and Belknap (1980, p. 100 and Marchand and Allwardt (1981, p. 55) as t superposed units, the loose sandy deposits belongi to the upper member of the Modesto Formation, and t silty hardpan beneath belonging to the lower membe According to the model of these authors, a soil with hardpan first developed in fine-grained facies of t lower member of the Modesto Formation, then w largely stripped during deposition of the upp member. Three problems afflict this model. Firs the hardpan of the Fresno and Stockton soils might attributed instead to ground water, the calci carbonate being precipitated at the capillary frin of a high water table and hence unrelated to so formation. Indeed, high water tables historical coincided with the principal areas of calcareo "subsoil" on the Mokelumne River fan (compare Stear and others, 1930, pl. 8, with Cosby and Carpente 1937). Second, a predominance of silt and abundan of alkali typify fan-toe areas in which the soi formed on the Modesto Formation have Bt horizon Because the parent material of these soils contains much as 15 percent clay (e.g., Arkley, 1959, p. 1 and because clay moves more readily in a soil profi if dispersed by sodium (Birkeland, 1974, p. 112 soils like the Fresno may develop Bt horizons mo rapidly than the Hanford soils, whose parent materi is relatively poor in clay and whose waters a relatively poor in sodium. Third, assuming contamination of the dated sample, availab radiocarbon-age control suggests that the pare material for many Fresno soils may indeed be as you

as that of many Hanford soils. Specifically, the only published ^{14}C age pertaining to the time of formation of Fresno soils indicates, for the toe of the Tuolumne River fan, a parent material younger than 42,400±1000 years (USGS-429; Marchand and Allwardt, 1981, p. 57). If, as argued by Marchand (1977), the lower member of the Modesto Formation correlates chiefly with oxygen-isotope stage 4 (73,000-61,000 years old using the time scale of Hays and others, 1976) and the upper member formed about 14,000-9000 years ago (Marchand and Allwardt, 1981, p. 60-61), then the limiting ^{14}C age suggests that many or all Fresno soils have formed on the upper member of the Modesto Formation.

Pending further study, it thus seems best to use map units that allow the possibility of a short hiatus between the compact silt and the looser, sandier deposits that commonly overlie it on the middle and lower reaches of glacial-outwash fans of the Modesto Formation. If the hiatus is indeed short, then the lower member of the Modesto Formation may generally project well beneath the toes of these fans rather than forming the extensive fan-toe surfaces mapped by Marchand and Atwater (1979), Atwater and Belknap (1980), and Marchand and Allwardt (1981).

Eolian deposits

Eolian deposits, undivided, are mapped where uncertainty about relative age prevents assignment to either of the two units described below. Near Pittsburg Point (sheet 9), they formed a ridge leveled by man since the Collinsville (now Antioch North) quadrangle was surveyed in 1906-1907; and in borehole logs on sheet 14 they denote sand from which buried soils might have been removed by erosion accompanying deposition of overlying eolian deposits.

The unit, older eolian deposits, serves as a catch-all for windblown sand in the following settings:

(1) A U-shaped ridge, probably a barchan, about 10 ft high in 1906-1907, now partly removed and sectioned by an excavation for a parking lot and factory near Sixth Street Park in Antioch (south-central part of sheet 9). This deposit displays a Bt horizon about 5 ft thick with 10YR hue (Munsell system). Probably it correlates with youngest part of the Riverbank Formation. It was not differentiated from contiguous alluvial-fan deposits by Cosby and Carpenter (1939), who mapped Ambrose soils on the ridge.

(2) An 8-ft bed overlying a buried soil formed in micaceous silt and underlying about 45 ft of younger eolian sand near the base of a natural river bluff 2.4 km east of the Antioch Post Office (sheet 9). This deposit displays a Btb horizon about 3 ft thick with 10YR hue. Possibly the soil is a stripped version of the soil near Sixth Street Park, or perhaps it is younger and coeval with the lower member of the Modesto Formation (as defined by Marchand and Allwardt 1981).

(3) Deposits buried by younger dune sand between Oakley and Brentwood (sheet 14). Btb horizons 1-3 ft thick with 10YR hue suggest correlation with the buried eolian unit in the river bluff.

(4) Surficial deposits about 4 km south of Hood (sheet 4). The Bt horizon developed in these deposits has a 7.5YR 4/4 color, the redness perhaps attributable in part to an abundance of lithic grains in parent material. The thickness of the B horizon is unknown. Probably the deposit overlies alluvium of the Riverbank Formation. Its age relative to other older eolian deposits is not known. Cole and others (1954) mapped the deposit as "Oakley sand"; perhaps they overlooked the presence and redness of the Bt horizon.

Eolian deposits of the upper member of the Modesto Formation form a large dune field fanning eastward and southeastward from Antioch (sheets 9-11, 14, and 15), a smaller field between Hood and Walnut Grove (sheets 4 and 5), and isolated hills in central parts of the Delta (sheets 7, 11, and 12). Deposits belonging to this unit are present also on fans of the Mokelumne and Stanislaus Rivers (sheets 8, 12, 13, and 20), but represented there with dense stippling rather than a separate label in order to emphasize local provenance. Lithic grains form about 5-10 percent of the deposit in Hood-Walnut Grove field, presumably reflecting a Sacramento River source. Isolated sand bodies at Rindge Tract (sheet 12) and Bouldin Island (sheet 11), in contrast, are almost purely arkosic, implying a San Joaquin River source. The intermediate composition of sand of the Antioch-Oakley-Bradford Island field suggests mix of detritus from Sacramento and San Joaquin Rivers; further, long axes of linear and parabolic dunes in this field indicate eastward and southeastward transport from an area between Antioch and Bradford Island. Though generally thinner than 5 ft between Hood and Walnut Grove (Cole and others, 1954) and locally removed by agricultural leveling in this area, eolian deposits of the upper member of the Modesto Formation commonly 20-40 ft thick near Antioch, Oakley, and Bradford Island.

In the Antioch-Oakley-Bradford Island field, eolian deposits of the upper member of the Modesto Formation widely underlie alluvium of Marsh Creek and tidal-wetland and tidal-waterway deposits. Near and within historic margins of tidal wetlands, dune crests are marked by light tone on aerial photographs (finely stippled areas, sheets 10, 11, 14, and 15), by high ground that historically rose above surrounding wetlands (hence Sand Mound Slough, sheets 10 and 11), and by patches of high ground exhumed historically by decomposition and deflation of peat. Historically supratidal sand bears Oakley sand of Carpenter and Cosby (1939), Cosby (1941), and Cole and others (1954). Exhumed sand mounds typically bear Piper soils of Cosby (1941). Stage II and III calcium carbonate in Piper soils implies high water table related to Holocene sea-level rise because, on a single sand mound at Bradford Island (sheet 10), Oakley sand occupies the historically supratidal crest and Piper soils the historically tidal and subtidal flanks (Carpenter and Cosby, 1939); moreover, carbonate cementation in some Piper soils evidently postdates the digging of several aboriginal burials (Cook and Elsasser, 1956, p. 33-34).

The age of upper Modesto dune sand lies between limiting ^{14}C dates of about 40,000 and 10,000 years. The maximum limiting age is determined at Jersey Island and Hotchkiss Tract (sheets 10 and 14), where dune sand overlies alluvium of Marsh Creek that in turn overlies San Joaquin River alluvium having ^{14}C ages of 38,000-46,000 years, and at Bradford Island (sheet 10), where dune sand overlies oxbow-lake(?) mud with a ^{14}C age of about 42,000 years (table 1). A minimum limiting age is approximated by ^{14}C dates on the oldest peat or mud covering sandy alluvium of the combined Sacramento and San Joaquin Rivers between Antioch and Bradford Island. Using peat, this limiting age is 7,000 ^{14}C years; using mud it is 10,000-11,000 ^{14}C years (table 1; Shlemon and Begg, 1975). The actual age range of dune sand in the upper part of the Modesto Formation in the Antioch-Oakley-Bradford Island field is probably far more restricted than 10,000-40,000 years B. P. Perhaps it is as narrow as 10,000-14,000 years B. P., in rough accord with the age inferred by Marchand and Allwardt (1981, p. 60-61) for alluvial-fan facies of the upper member of the Modesto Formation. Alternatively, the age range may be slightly broader than for these alluvial-fan deposits; perhaps depositional episodes in which major Sierran rivers failed to spread aggrate their fans nonetheless caused enough overbank deposition on the trunk-stream flood plains to trigger eolian deposition near Antioch.

Eolian deposits of the upper member of the Modesto Formation bear Delhi and Piper soils of Welch (1977), Nazar and Swearinger (1975), and Paul Nazar and Charles Swearinger (unpub. mapping, 1975-1976). The mapping of Welch, Nazar, Swearinger, and their colleagues extends the known surficial distribution of these deposits to areas in which dunes have been partly or wholly exhumed since soils mapping of the 1930's.

Alluvium of supratidal flood plains of the San Joaquin River, Sacramento River, and principal tributaries

Holocene deposits of natural levees, flood basins, and active and abandoned channels of the Sacramento and San Joaquin Rivers consist mainly of firm silty clay, micaceous silt, and micaceous sand with low organic content (less than 5 percent; Andrews, 1972, p. 98) and A/C soil profiles. Typical colors range from dark gray (5Y 4/1) to yellowish brown (10YR 5/6). Near the Sacramento River they are readily differentiated into natural-levee and basin facies (see below).

The unit, alluvial-floodplain deposits, undivided, is mapped chiefly on a time-transgressive flood plain of San Joaquin River. Part of this floodplain was historically covered with tidal-wetland peat but is now largely exhumed (for example, Jones Tract and much of Woodward, Victoria, Union, and lower Roberts Islands, sheets 15, 16, 18, and 19). The remainder was historically supratidal (Lathrop, Paradise Cut, and vicinity, sheets 19 and 20). Deposits of the exhumed flood plain appear to truncate and (or) lap onto the southeastern part of the Antioch-Oakley dune field near Orwood Tract (sheet 15). Commonly they yield down section into 40-60 ft of sand, much or most of which is possibly coeval with the upper member of the Modesto Formation; this fining-upward sequence is found in boreholes along the Mokelumne Aqueduct at Woodward Island and Jones Tract (East Bay Municipal Utilities District, unpub. data). The exhumed flood plain includes small unmapped bodies of peaty mud thicker than 5 ft in abandoned channels and interdistributary basins, some of which have been mapped as Ryde silty clay loam by Welch and others (1976 and unpub. data) but are not differentiated on the maps accompanying this report.

The undivided unit also includes local bodies of reddish-brown overbank alluvium of probable historic age, both along the San Joaquin River south of Stockton (sheets 15 and 19; Ramada soils of Retzer and others, 1951) and along the Cosumnes River (Columbia-over-Sacramento soils of Cole and others, 1954).

Natural-levee deposits consist of sand, silt, and silty clay, chiefly dark grayish brown (10YR 4/2) to yellowish brown (10YR 5/6). These deposits are mapped only on broad natural levees and crevasse splays of Sacramento River and its distributaries but are present also in immediate vicinity of historic and prehistoric nontidal channels shown in areas of undivided flood-plain alluvium. The contact with adjacent basin and tidal deposits commonly grades across tens to thousands of feet; probably the levees formed the interface between rapidly flowing and nearly standing water (Brice, 1977, p. 19). Locally levee deposits overlie peat and peaty mud, as along Sutter Slough at west end of Sutter Island Cross Road and at a crevasse splay east of the head of Steamboat Slough (sheet 4; Atwater and Belknap, 1980, fig. 4, section C); at the second locality, a 1910±55 ^{14}C year age (table 1) of peat immediately beneath the crevasse-splay deposits implies that the splay deposits predate hydraulic mining. The unit also includes reddish-brown alluvium of probable historic age and, along manmade levees, underlies unmapped spoils from clamshell dredges and mule-drawn scrapers (Dutra, 1976).

Flood-basin deposits are firm to stiff (unconfined shear strength 2-4 kg/cm^2 by pocket penetrometer) silty clay, clayey silt, and silt, commonly with $CaCO_3$ nodules and locally with black, slightly metallic, fine-sand- to granule-size spherules (Mn and(or) Fe oxides). Colors are very dark gray (10YR 3/1) to dark gray (N6/0), locally variegated and mottled in hues of 5Y to 7.5YR. The deposits formed in supratidal reaches of basins flanking the Sacramento River (for example, Sacramento and Yolo Basins, sheets 1-4) and in interdistributary basins not necessarily above high-tide levels but probably cordoned off from tidal waters by supra-tidal natural levees (for example, Merritt and Randall Islands, sheet 4). Native vegetation was dominated by *Scirpus acutus* ("tule" of Bryan, 1923, p. 43). The deposits grade laterally into peaty mud and mud of tidal wetlands of Yolo Basin, Sutter Island, and Pierson District (sheets 1 and 4). Contacts with tidal-wetland deposits in cores are locally abrupt but commonly grade through mud that forms angular aggregates 0.1-2.0 mm in diameter, a granular structure attributable to occasional desiccation. Locally the deposits are veneered with silty, reddish-brown alluvium of historic age. The natural sedimentation rate in late Holocene time, judging from a ^{14}C age of 2940±140 on basin deposits about 8 ft below historic surface of a flood basin near Sacramento (table 1), is less than rate of relative sea-level rise in San Francisco Bay (roughly 15 ft in past 3000 years; Atwater and others, 1977) but not inconsistent with the possibility that rise in base level caused much of the late Holocene aggradation in near-sea-level flood basins of the Sacramento River. The unit was mapped as Sacramento and Columbia-over-Sacramento soils by Cosby and Carpenter (1935), Cosby (1941), and Cole and others (1954).

Deposits of tidal environments

Peat and mud of tidal wetlands and waterways form soft, generally carbonaceous deposits having low bulk density (1.1-1.5 g/cm^3 wet). They are shown where generally thicker than 5 ft and more extensive than about 1 km^2 in 1980; otherwise the underlying unit is mapped. Tidal peat and mud are also present, but not generally labeled, on numerous islets of tidal wetland (tule berms in local vernacular). Locally the unit underlies unmapped sand, silt, and clay deposited historically by clamshell dredges (Thompson, 1957; Dutra, 1976) or by water flowing over or through manmade levees (Cosby, 1941, p. 36). The fundamental cause of deposition of the tidal peat and mud is relative rise in sea level (Gilbert, 1917 pl. IV; Cosby, 1941, p. 43; Shlemon and Begg, 1975; Atwater and Belknap, 1980).

Deposits of tidal wetlands are chiefly peat and peaty mud. Organic matter is decomposed in part (typically hemic in the classification of McKinzie, 1974) but generally retains epidermal remains of roots and rhizomes, particularly those of Scirpus acutus and Phragmites australis, also those of Distichlis spicata in near-surface deposits of Browns Island (sheet 9). Organic content is highest (50-70 percent loss on ignition; California Department of Water Resources, unpub. data for boreholes drilled 1956-58, table 2) in the central and south-central Delta, lower in southernmost and northern areas where peaty mud is typically intercalated with mud in layers 1-10 cm thick (Cosby, 1941; Atwater and Belknap, 1980). The maximum thickness is currently about 50 ft and the maximum known age 6805±350 ^{14}C years before present, both at Sherman Island (sheets 9 and 10). Peat or peaty mud comprise typical parent materials of Correra, Venice, Staten, Egbert, Ryde, Burns, and Roberts soils of Cosby (1941) but cover less total area than these soils because of decomposition and deflation of peat during the past 40 years. The map symbol for the unit is queried where peat possibly formed in supratidal, interdistributary wetlands or in closed basins dammed by natural levees of tidal waterways.

Deposits of tidal waterways are chiefly clay (south-central areas) and silt (southernmost and northern areas) with low (less than 10 percent) organic content. Locally they are sandy, particularly along a major prehistoric channel at Sherman Island (sheet 10). Typically they form the present-day land surface along historic and prehistoric tidal waterways, particularly on point-bar sides of meanders; also they commonly underlie tidal-wetland deposits along point bars. Generally they give a lighter photographic tone than adjacent tidal-wetland deposits. Most were mapped chiefly as Ryde soils by Cosby (1941).

Deposits of manmade environments

Sand, locally laminated, and subordinate silt, clay, and peat, have been deposited as hydraulic-dredge soils during attempts to widen, straighten, and (or) deepen the Sacramento and San Joaquin Rivers. Most of these of the mapped spoils between Cache Slough (sheet 6) and Collinsville (sheet 9) were emplaced between 1913 and 1927 (Jones, 1942; Thompson, 1957, p. 175). These include loose sand mistaken for natural, presumably prehistoric strand-line deposits by Wilshire and others (1978, p. 300 and 303); the sand, banked against Montezuma Hills 2-3 km southwest of Rio Vista City Hall (sheet 6) at elevations up to 50 ft (as much as 35 ft above peak recorded flood stage at Rio Vista; Jones, 1942), is continuous with similar sand at similar elevations farther southwest covering areas mapped as tidal wetland in 1906-1908 (Jersey and Rio Vista 7.5-minute quadrangles, editions of 1910) and hence must have been deposited during the 20th century. The unit roughly corresponds to "made land" of Cosby (1941, p. 38).

FAULTS WITH QUATERNARY DISPLACEMENT

The Sacramento-San Joaquin Delta provides few of the usual clues of Quaternary displacement along faults. Telltale landforms such as scarps and sag ponds would probably have been concealed by wetland vegetation in the pristine delta and, in any case, have probably been obliterated by leveling and lowering of cultivated peat. Below ground, an abundance of channel cuts and fills affords a nontectonic explanation for abrupt stratigraphic changes between boreholes.

The only fault with demonstrable Quaternary offset in the immediate vicinity of the Delta is the Antioch fault (sheet 9). This fault was identified in upland areas by Burke and Helley (1973), who report right-lateral displacement of railroad tracks, sidewalks, and other manmade structures in Antioch. Subsequent trenching by the California Department of Water Resources (1978, trench T-64) confirms the inference of Burke and Helley (1973) that the fault extends into Tertiary rocks southeast of Antioch. Northwestward the fault may extend across the San Joaquin and Sacramento Rivers, perhaps stepping northeastward to the linear southwestern front of Montezuma Hills (Burke and Helley, 1973; Jennings, 1973). Conclusive evidence concerning this possibility has yet to be published.

Not shown on sheets 6 and 10 is the Rio Vista fault of Reiche (1950), inferred by him to follow the linear southeastern front of the Montezuma Hills southwest of Rio Vista. The high accordant summits of the Montezuma Hills and the likely Pleistocene age of the deposits that form these hills indeed suggest Quaternary uplift, perhaps localized at linear margins of the hills. Nevertheless, the linear scarp near Rio Vista might also have been cut by the Sacramento River. Although he reports about 100 ft of vertical displacement of Pleistocene deposits across the alleged fault, presumably evidenced by borehole data, Reiche (1950) gives no reason to rule out abrupt facies change as an alternative. The existence of the Rio Vista fault of Reiche (1950) thus seems insufficiently proven.

Also omitted from sheet 10 is a normal fault proposed by Shlemon (1971) as a possible boundary between tectonically subsiding parts of the Delta and stable or uplifted areas to the west. Noting that the bedrock sill at Carquinez Strait, located about 40 km seaward of the Antioch Bridge (sheet 10), lies at a higher elevation than many Quaternary deposits beneath the Delta, Shlemon (1971) inferred that one or more normal faults cross the western part of the Delta, perhaps in the vicinity of Sherman Island (sheet 10). Such a fault would be analogous with the San Joaquin fault zone of Herd (1979), in which one or more normal faults apparently downdrop the west-central San Joaquin Valley relative to adjacent parts of the Coast Ranges. A sill opposite Montezuma Hills provides new and local evidence for the fault proposed by Shlemon (1971). Judging from borehole logs of the California Department of Transportation (unpub. data 1964-1970; see also Atwater and Belknap, 1980, p. 95, section I), at least 100 ft of stiff, light brown silt and sand of unknown but presumably late Cenozoic age underlies gray clay, silt, sand, and gravel of late Pleistocene age at a widespread, subhorizontal unconformity at elevations of -100 to -115 ft beneath the new Antioch Bridge (line of boreholes crossing San Joaquin River at eastern edge of sheet 9 and extending northward one-third of the way across Sherman Island). East of the bridge, in contrast, boreholes drilled to -150 ft beneath Bradford Island and beneath the east half of Jersey Island (sheet 10) indicate a predominance of alluvium that is typically gray, locally soft, probably late Pleistocene in age (B. F. Atwater, unpub. data, 1978). Though open to many interpretations, this contrast could reflect movement along a fault passing somewhere between eastern Jersey Island and the new Antioch Bridge, with the stiff silt and sand beneath the bridge being Pliocene or lower Pleistocene "bedrock" uplifted relative to upper Pleistocene deposits on the east.

Although local stratigraphy may thus support Shlemon's (1971) hypothesis of a Quaternary fault in the vicinity of Sherman Island, there is little reason to accept Shlemon and Begg's (1975) inference of spectacular Holocene displacement along such a fault. Comparing relative sea levels in other parts of the world with ^{14}C ages and elevations of carbonaceous deposits beneath Sherman Island, these authors propose 30-50 ft of vertical fault displacement, west side upthrown, between 7,000 and 10,000 years ago. The dated material allegedly uplifted (samples GX-2578 and W-744, table 1) may, however, have formed well above coeval sea level in an active or abandoned river channel because, judging from all available descriptions, the material contains neither the roots and rhizomes of tidal-wetland plants nor any other diagnostic evidence of tidal conditions. If the dated material indeed formed above coeval sea level, then its elevation provides only an upper limit for that sea level; hence the material need not have been uplifted to be consistent with low-latitude sea levels elsewhere in the world.

Also deserving qualification is the Holocene tectonic subsidence that Shlemon and Begg (1975) inferred from relative sea-level data. Again comparing relative sea levels elsewhere in the world with elevations and ^{14}C ages of organic deposits from the Delta, these authors observe that five samples (GX-2575, -2579, -2581, -2582, and 2583, table 1) seem too low for their age. Without disputing the likelihood of widespread Holocene tectonic subsidence in the Delta, it is important to note that at least three of the samples (GX-2575, -2579, and -2583) may have subsided primarily because of compaction of underlying peat, whose thickness in one locality is 24 ft (table 1). Such compaction, known to distort sea-level data in New England (Bloom, 1964; Kaye and Barghoorn, 1964), seems likely from the accordionlike shortening of vertical roots and general flattening of rhizomes in middle Holocene peat of the Delta that I have seen in cores, ditches, and clamshell-dredge spoils. These compacted organs were apparently overlooked by Shlemon and Begg (1975, p. 262), whose "field inspection of cores showed no evidence of crushing of reeds, the permanent saturation of peat and clay below the water table apparently maintaining pore pressure and preventing significant compaction."

USES OF THE MAPS

Some of the data presented on the accompanying maps may be useful in assessing hazards to foundations of manmade levees and in locating boundaries of land subject to private ownership and public easement. Nevertheless, these maps provide little of the precision and detail normally required in engineering design and boundary determination.

Foundation hazards

Several of the hazards to manmade levees in the Delta stem from physical properties of materials on which the levees rest (Josselyn and Atwater, 1982). One such hazard is failure under static loads: soft peat and mud beneath a levee may flow or rupture under either pressure from flooding channels or the weight of the levee itself (Wright, undated, p. 10; U.S. Corps of Engineers, 1979, p. 6; California Department of Water Resources, 1981, p. 7). Another, more hypothetical hazard involves cyclic loads: though the 1906 San Francisco earthquake caused no certain damage to levees, it is conceivable that loose, water-saturated silt and sand beneath levees might lose their shear strength (liquefy) if shaken by a strong earthquake (Kearney, 1980).

Failure under static loads

One aspect of failure under static loads that the maps partly address is subsidence of peat land behind levees. This subsidence effectively adds to the hydraulic head of channels, thereby increasing both the static loads on levees and the cost of reclaiming a flooded island or tract (California Department of Water Resources, 1975; U.S. Corps of Engineers, 1979). Assuming continued subsidence of peat land at historic rates, the magnitude and extent of future subsidence can be predicted from the thickness and distribution of peat, as shown by Newmarch (1980). Sheets 1-20 supply two kinds of data that could be used to refine Newmarch's estimates. First, the contact between tidal and nontidal deposits on sheets 4-12, 15, and 16 reasonably approximates the outer limit of land subject to substantial subsidence in the near future. This contact, defined as the present-day limit of peat and peaty mud thicker than 5 ft, is based largely on recent soils surveys, borehole logs, and aerial-photograph interpretations that were unavailable to Newmarch (1980) when he undertook his study. Second, by locating nontidal channels, exhumed sand dunes, and basal peat and mud, the maps define an ancient land surface that should prove helpful in extrapolating thickness of peat into areas having little or no borehole data. This surface, upon which tidal deposits of the Delta rest, is far simpler to project than the thickness of tidal deposits, which varies also with modern topography and may change with time. Basal elevations of peat thus provide bench marks from which the thickness of peat can be determined and extrapolated with the aid of up-to-date topographic maps at any time in the future.

Another aspect of failure under static loads addressed by the maps is the possibility that proximity to former channels triggers levee breaks. Speculating that "some areas where old channels intersect the levees may have been filled with weak construction materials," the California Department of Water Resources (1981, p. 7) recently flagged former channels as "potential weak spots." Sheets 6, 10-12, and 15, however, show little or no correspondence between breaks and former channels, implying that proximity to historic channels has played little or no role in causing the levee breaks identified on these maps.

Sheets 1-20 provide few details, however, concerning the thickness and physical properties of materials beneath manmade levees. Though the maps summarize some of the subsurface data from past foundation studies, they report only the basal elevation of peat and peaty mud beneath levees, not the thickness of these materials. Furthermore, in the interest of cartographic simplicity, I have extended a 5-ft-thickness contour for soft peat and mud -- the contact between tidal deposits with various eolian and alluvial units -- from subsided peat land to adjacent levees as if the same section of peat were missing in both places. This procedure understates the thickness of peat beneath levees; whereas farmland has lost peat by decomposition and deflation (Weir, 1950), many levees may rest on a complete, if somewhat compressed, historic section. Finally, my twofold division of soft materials beneath levees -- into peat and peaty mud of tidal wetlands and mud of channel environments -- commonly oversimplifies lateral and vertical variation in physical properties of these materials. In particular, some sections of peat and peaty mud for which I report only a basal elevation contain distinct interbeds of mud and sand. Sheets 1-20 thus provide only general guides to the Holocene stratigraphy discovered in past foundation studies; for details, the interested reader must consult primary sources, most of which are on file with the California Department of Water Resources (table 2).

Failure under cyclic loads

The maps delineate several kinds of deposits that might be susceptible to liquefaction. Chief among these deposits are well-sorted sand and silt formed in tidal and nontidal channels during Holocene time. Liquefaction of Holocene channel deposits probably caused the reported damage to railroad bridges across Old River (sheet 15) and San Joaquin River (sheet 17) in 1906 (Youd and Hoose, 1978). If, as seems likely, many of the Holocene channel deposits elsewhere in the Delta resemble those that liquefied in 1906, then the vicinities of channels shown among floodplain levee, and tidal-wetland deposits deserve special attention in studies of liquefaction potential. Probably meriting similar attention is eolian sand, some of which is described by Underdahl and Wood (1977, p. 11) as "especially susceptible to liquefaction." The maps show eolian deposits to be present at or just below the surface in most areas of former tidal wetland west of Old River and in many such areas east of San Joaquin River.

Boundary determination

Elevations of tidal wetlands before reclamation typically influence the limits of public ownership and easements after reclamation (Briscoe, 1979). The most important cadastral elevations in tidal wetlands and waterways are two tidal datums, mean low water (MLW) and mean high water (MHW). Land lying below MLW is generally owned by the public; land between MLW and MHW can be owned privately but rarely without public easements for activities such as fishing and navigation; and land above MHW is generally unencumbered by such easements (Briscoe, 1979).

The edge of tidal channels and the limit of autumnal high tides as shown on sheets 1-20 outline the probable distribution of tidal wetlands of the Delta in A. D. 1850. To my knowledge this is the first large-scale, Delta-wide delineation of historic margins of wetlands; unlike marshes around San Francisco Bay (Nichols and Wright, 1971), wetlands of the Delta were not carefully surveyed before reclamation, probably because tules and willows standing 10-15 ft high prohibited efficient plane-table work.

None of the mapped margins of Delta wetland, however, necessarily correspond to MHW, MLW, or any other elevation having precise cadastral significance. Furthermore, even if assumed to approximate the historic line of MLW, margins of wetland indicated by tidal channels may be mislocated on the maps by hundreds, even thousands of feet. For those channels evidenced solely by extant or relict waterways on archival USGS plane-table surveys, errors have doubtless arisen from registration to modern maps and from inaccuracies in the old maps themselves. Likewise, for channels evidenced by tonal contrasts on modern aerial photographs, errors may arise from manual transfer between photograph and map and from the possibility that light-toned channel deposits exposed on subsided, leveled farmland are thousands of years old and thus mark a waterway whose course later migrated. Problems such as these render the historic data on sheets 1-20 ill-suited for precise cadastral work.

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