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Late Quaternary Evolution of the Sacramento-San Joaquin Delta, California

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Abstract

The Sacramento-San Joaquin Delta of central California is the latest of several deltaic systems that have expanded and contracted during late Quaternary time. Subsidence of the ancient deltas apparently continued throughout Quaternary time, downwarping Pleistocene glacial channels and interglacial deltaic sediments to elevations well below a bedrock notch "downstream" toward San Francisco Bay and the Pacific Ocean. Radiocarbon-dated peat indicates that the Holocene transgression reached the western Delta about 10,500 years ago, and that subsidence is continuing, probably localized along a previously unrecognized extension of the Rio Vista Fault under Sherman Island.

Introduction

In the central part of the Great Valley of California a complex of islands and meandering streams ("sloughs") is formed by the intermixing waters of the Sacramento and San Joaquin rivers. This region, called the "Sacramento-San Joaquin Delta" or locally the "California Delta", contains over 200,000 ha. of peat and organic-rich deposits, in the United States second in area only to the Florida Everglades. The Sacramento-San Joaquin Delta, although only 80 km east of the populous San Francisco Bay area, is little known to the geological community, and still less known to the public. Yet preserved within its sediments are remnants of several great deltaic systems and interbedded channels which waxed and waned in response to Quaternary changes in stream regime and sea level. The modern delta is a youthful geological feature, forming during Holocene time, but essentially mirroring the evolution of the earlier deltaic systems.

The general evolution of the late Quaternary Sacramento-San Joaquin Delta is relatively easy to discern, for the sediments record broad alternating sequences of interfingering glacial and interglacial deposits. For detailing its evolution logs of hundreds of water wells and levee borings drilled within the last 30 years in the delta proper or on the adjacent irrigated alluvial terrain are available for analysis. Lithologic and engineering data from the logs make it possible to delimit many subsurface facies, especially basal peat and interdistributary deposits laid down during Holocene time.

Although typically complicated by subsidence, isostatic adjustment and compaction, radiometrically-dated deltaic sediments can provide a first-order indication of the time and rate of sea level rise during the Holocene. Accordingly, a drilling and coring program was set up to obtain samples for radiocarbon assay from the Sacramento-San Joaquin Delta. The 13 dates obtained thus far make it possible to outline the approximate Holocene rise in sea level and to reconstruct the paleogeography in this part of California. Also by dating the deltaic sediments, constructing a sea-level curve, and comparing these data with a synthesis of world-wide curves, it has been possible to identify a general area of probable late Quaternary faulting. This may be not only of academic interest, but also may have increasing relevance for siting of large structures particularly sensitive to geological hazards.

The Delta Environment

The Sacramento-San Joaquin Delta, a roughly triangular-shaped lowland, is approximately delimited by the one-metre contour (Fig. 1). Bounded by Quaternary alluvial fans on its eastern side, the Delta abuts against the Montezuma Hills and the California Coast Ranges on the west or downstream side. Because of this topographic constriction, the Sacramento-San Joaquin Delta has expanded "headward" or to the east, rather than prograding seaward as is characteristic of true coastal deltas. Thus the term "delta", although in common usage, is perhaps a misnomer, for the California version does not have classic deltaic areal geometry nor easily recognizable vertical sequences of prodeltaic, distal bar, or similar facies. In fact, from an environmental standpoint, the Delta resembles more an estuary, or "perimarine" area of Dutch usage (Hageman 1969), where sedimentation is influenced directly by relative sea level changes, but little affected by coastal processes such as longshore drift or storm-driven waves.

The present delta landscape is almost entirely man-made. Since reclamation began, about 120 years ago, over 50 tracts and islands have been brought into intensive cultivation, and traditional spring-season flooding is now reduced or prevented by continual build-up of surrounding natural levees. Owing largely to these practices, many islands of the delta are now 3 to 6 m below sea level and protected from floods only by an intensively maintained levee system. The rate of surface lowering, at least 7 cm/yr, appears to be increasing mainly owing to (1) oxidation of peat after exposure by plowing, (2) burning of peat soils to reduce weeds and insects and to return potash to the soil, (3) wind erosion of loose peat, and (4) local compaction by heavy farm machinery (Weir 1950). In addition to the obvious deleterious environmental effects, this man-induced surface lowering has outlined low, sinuous ridges of silty and sandy old crevasse deposits now standing slightly above the adjacent, non-resistant peat (Davis 1963). Also the removal of surficial peat, in some cases to 3 to 4 m on the western delta islands, has unfortunately made it impossible to date these youthful sediments by radiocarbon, thereby precluding more precise deciphering of the late Holocene tectonic history and relative sea-level changes.

Cite
Weir 1950

The delta tidal range is normally less than one metre, but present river flood stage can exceed two

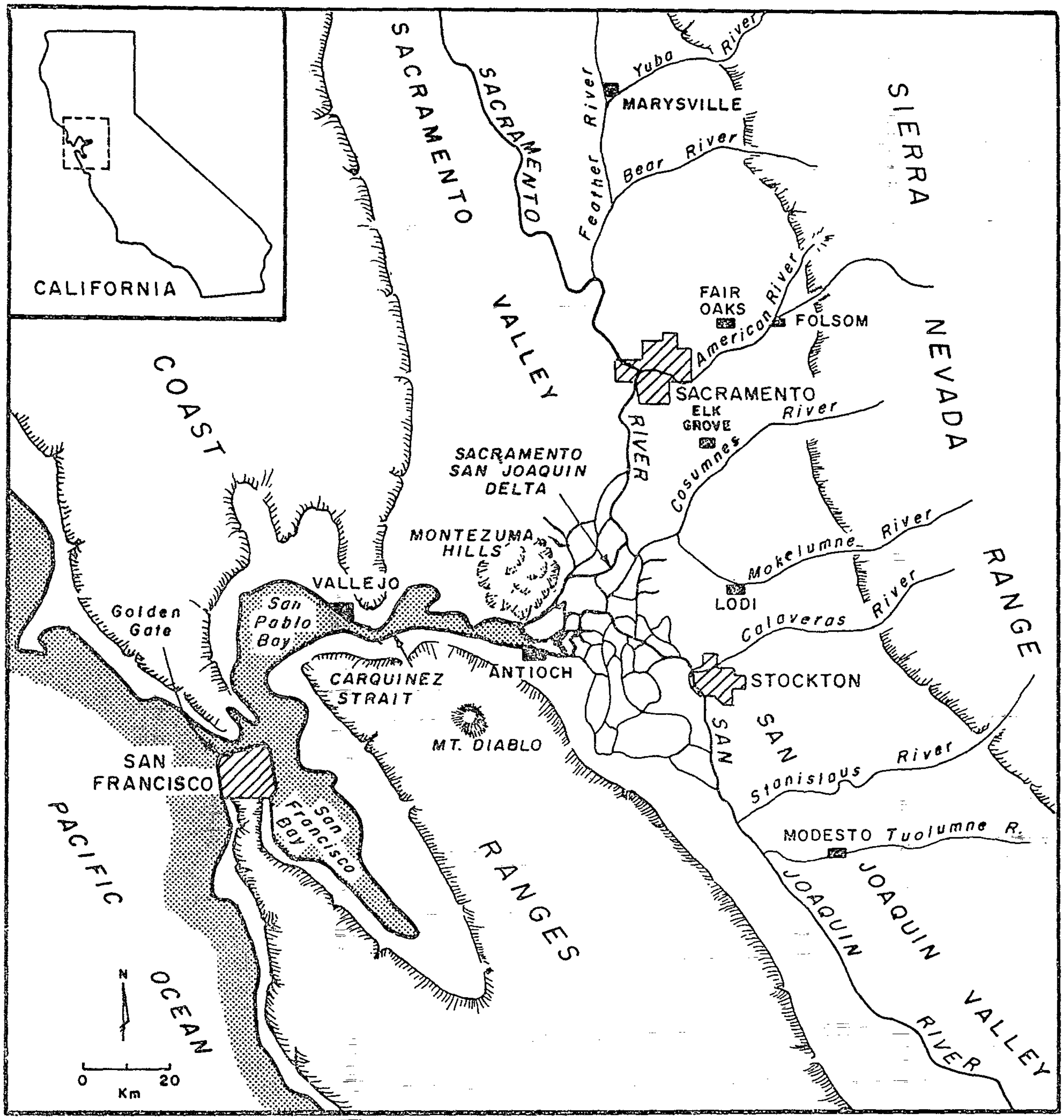

FIG. 1. — The Sacramento-San Joaquin Delta, central California.

metres. The water is fresh, although a saline wedge penetrates into the western islands during low discharge in August and September. The hydrologic and sedimentologic egimes, before reclamation, gave rise to a vegetational pattern of dense "tule" or bulrush *(Scirpus lacustris)* on the now reclaimed islands, with fringing willows and other woody plants on the slightly higher natural levees. Borings reveal that the delta peat is composed primarily of *Scirpus lacustris* overlying a thick accumulation of fibrous reeds, mainly *Phragmites communis* (Cosby 1941). The maximum thickness of peat is 18 m, under Sherman Island logs indicates that re-entrants of mixed peat and (Fig. 2) in the western part of the delta, thinning to the east. Analysis of water well and levee boring organic-rich silt and clay, 12 to 15 m below sea level, extend "upstream", generally underlying the modern Sacramento, San Joaquin, and Mokelumne rivers (Fig. 1: Shlemon 1971, p. 431). Ancient crevasse and splay deposits are common, especially along the margins of the delta, but lithologic data from borings are thus far too sparse to permit a detailed three-dimensional portrayal of these features.

GEOLOGIC FRAMEWORK

The modern Sacramento-San Joaquin Delta is but the latest delta that has developed in central California since at least late Cretaceous time. Information about the early deltas and their interbedded gravel-filled channels has been derived mainly from analysis of logs of oil and gas wells, hundreds of which have been drilled in the immediate area (Safanov 1962). Recognizable precursors of the present delta probably developed in early Quaternary time when continual uplift and faulting within the Central Coast Ranges outlined the broad structure of the Central Valley of California and San Francisco Bay (Fig. 1). Throughout late Pleistocene time, several deltas had

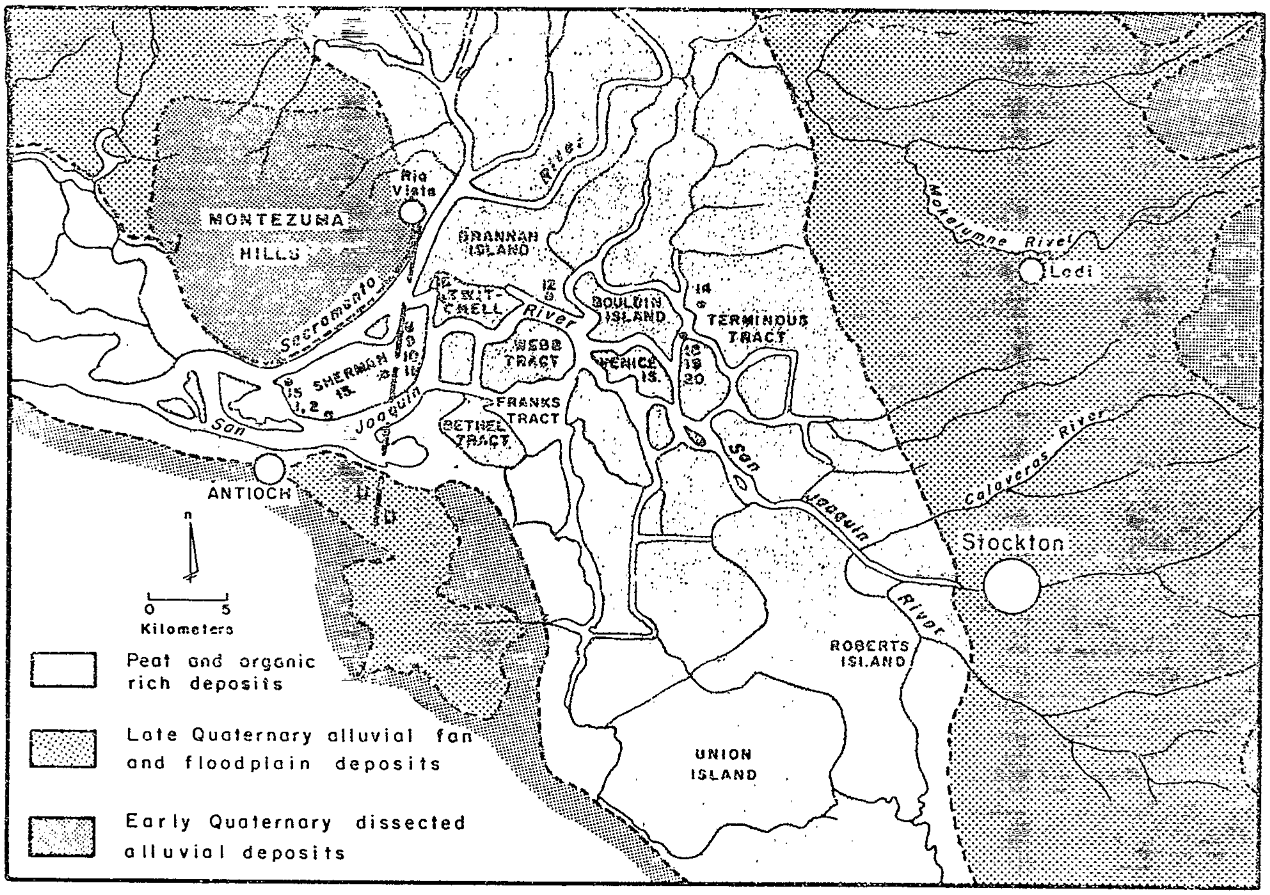

FIG. 2.—Quaternary geology of the Sacramento-San Joaquin Delta, and location of radiocarbon-dated samples (Table 1 and Fig. 4).

waxed and waned, each apparently formed during a glacio-eustatically controlled high stand of sea level. In Holocene time, a rise in sea level resulted in an eastward transgression from the San Francisco Bay area, including thalassostatically-controlled sedimentation and the expansion of the Sacramento-San Joaquin Delta to its approximate present position.

Quaternary Setting

The early Quaternary evolution of central California, particularly the San Francisco Bay area, has been outlined by Taliferro (1951), Louderback (1951), Howard (1951), and Christensen (1966). In general, by onset of the Quaternary an ancestral Sacramento River had cut across the rising Coast Ranges and entered the sea at the present Golden Gate (Fig. 1). Subsidence and faulting of San Francisco Bay continued throughout at least the Pleistocene, etching out the broad structural pattern upon which were superimposed glacio-eustatic fluctuations of the sea.

The first Quaternary deltas are thought to have formed in interglacial times when the Sacramento-San Joaquin Delta grew headward or to the east during high stands of sea level (Shlemon 1971). With successive glaciations in the adjacent Sierra Nevada, ancestral channels of the Mokelumne River cut a direct course to the then lowered sea levels, carrying basal gravels and overlying sands into the delta. Gravel-filled channels and "oxidized" alluvial fan sediments have been traced to about 95 m below present sea level on the eastern side of the delta (Fig. 3). This depth is less than the − 116 m bedrock "notch" of the Pleistocene Sacramento River at the Golden Gate, about 80 km "downstream" from the delta (Trask and Rolston 1951; Carlson *et al.* 1970). However, the maximum depth to bedrock in the intervening Carquinez Strait, only 32 km west of the delta, is − 40 m, well above the oldest, recognizable Mokelumne River channel. The Pleistocene Mokelumne River channels also diverge vertically downstream, the longitudinal profile of the older ones seemingly "bowed down" (Fig. 3). Therefore, apparently, the Mokelumne River channels and interbedded deltaic sediments subsided to the present depth, or alternatively, Pleistocene uplift in the San Francisco Bay area has raised bedrock channels far above original levels. Based on the presence of a well-defined scarp bordering the east side of the Montezuma Hills (Fig. 2), a fault was inferred to offset Pleistocene deltaic and channel sediments under Sherman Island (Fig. 2; Shlemon 1971, p. 435). Because there is no offset of the Delta surface, the fault was thought pre-Holocene in age. Now, however, from the areal distribution and depth of radiocarbon-dated sediments, it appears that there was also movement on this fault in Holocene time. In essence, the Quaternary evolution of the Sacramento-San Joaquin Delta was governed primarily by an alternating sequence of glacial and interglacial sediments superimposed on regional subsidence and complicated by periodic faulting.

Holocene Evolution

The effect of the Holocene world-wide sea rise on the Sacramento-San Joaquin Delta has been appreciated only recently. Previous investigations generally assumed that the 18-20 m thickness of peat was

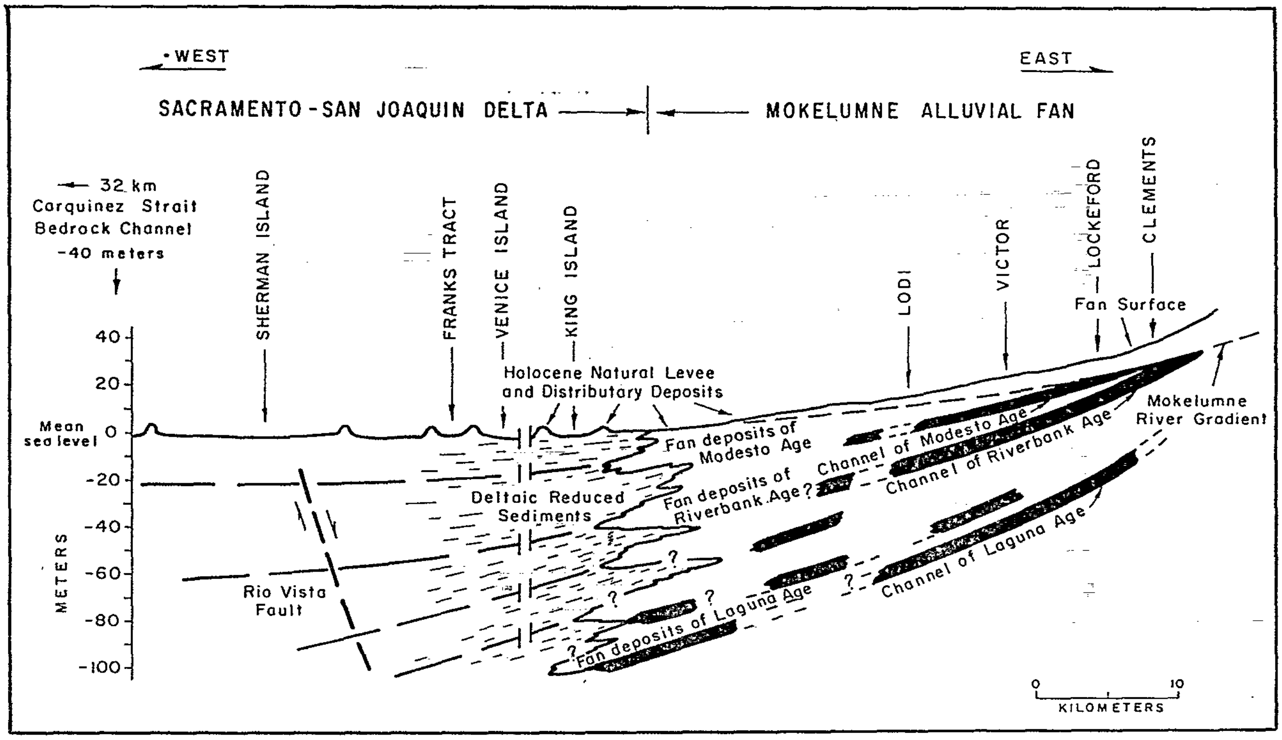

FIG. 3. — Interfingering interglacial deltaic and glacial channel deposits.

due to "sedimentary processes" whereby floating peat mats settled out in deep water (Dachinowski-Stokes 1936); or totally to "geologic subsidence", in which the peat developed at or near sea level, building up during a long period of regional subsidence (Cosby 1941; Stearns *et al.* 1930). There is truth in both hypotheses, for floating peat mats are still seen on a few small unreclaimed islands, and the regional geologic framework indicates continuous subsidence along the west side of the Central Valley of California in general (Safanov 1962; Wahrhaftig and Birman 1965), and in the Sacramento-San Joaquin Delta in particular (Shlemon 1971).

To determine the age of peat and thereby partially reconstruct the Holocene history of the Sacramento-San Joaquin Delta, a drilling and sampling programme was organized. Continuous cores were obtained from seven borings along a transect from Sherman Island on the west to Terminous Tract on the east (Fig. 2). About 180 m of core samples were obtained and 11 samples selected for radiocarbon dating. The dates, their ranges, and the elevations of the samples are shown in Table 1. Shown also are data for peats collected and dated by the U.S. Geological Survey (W-744; W-794). Samples collected for dating were usually taken in the middle of a peat bed, and in some cases several were obtained from the same bore hole. Where possible samples were taken at similar depths in different holes in order to "calibrate" the age-depth relationship between islands (e.g., UCD 14, 15, and 16; Table 1). The basal peat under Sherman Island in the western Delta (UCD 11) was sampled particularly for verifying well log records of peat thickness in this area and for comparing the resultant data with a previously reported assay by the U.S. Geological Survey (USGS W-744; no. 2; Table 1). Except for near-surface samples (UCD 18-20), obtained from Devil's Island, a small unreclaimed tract (Fig. 2), the peat and organic-rich sediments were taken from about − 6 m or deeper, in order to avoid contamination from contemporary rootlets, and to remain within the phreatic zone. Field inspection of the 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. Some samples, however, taken

TABLE 1. — Radiocarbon ages and ranges, Sacramento-San Joaquin Delta. (Laboratory data from Geochron Laboratories, Inc. (GX), and U.S. Geological Survey (USGS).)

Lab No.	Location and no. (Figs. 2 and 4) (UCD)		Depth (m)	C-14 years B.P.	Material	cm/yr
GX-2932	Devil's Is.	(18)	-0.9	800 ± 170	peat	.1
GX-2933	Devil's Is.	(19)	-2.4	2,420 ± 140	peat	.099
GX-2934	Devil's Is.	(20)	-4.0	3,575 ± 260	peat	.11
GX-2581	Terminus Is.	(14)	-6.1	3,315 ± 150	peat	.18
GX-2582	W. Sherman Is.	(15)	-6.1	3,900 ± 140	peat	.16
GX-2583	Twitchell Is.	(16)	-6.1	3,090 ± 190	peat	.2
GX-2575	Sherman Is.	(8)	-9.1	4,340 ± 195	peat	.2
GX-2579	Andrus Is.	(12)	-9.1	4,675 ± 200	peat	.2
USGS W-794	W. Sherman Is.	(1)	-10.1	6,600 ± 250	organic silt	.15
GX-2576	Sherman Is.	(9)	-12.2	6,635 ± 320	peat	.18
GX-2577	Sherman Is.	(10)	-15.2	6,805 ± 350	peat	.22
GX-2578	Sherman Is.	(11)	-17.0	10,475 ± 500	organic clay	
USGS W-744	W. Sherman Is.	(2)	-17.7	10,690 ± 300	organic silt	

near island levees, may be slightly depressed in elevation, owing to local loading by "mineral sediments" placed on natural levees. These dated samples, therefore, provide only an approximate time for the Holocene transgression in the Sacramento-San Joaquin Delta. As shown in Table 1, the deepest basal peats underlying Sherman Island in the western delta are about 10,500 years old, essentially delimiting the Pleistocene-Holocene boundary in this part of California. With the continuing Holocene transgression, basal peats formed at progressively higher elevations as the delta expanded to the east.

Comparison with World-Wide Sea Level Curves
Many curves purport to show the depth and rate of the Holocene rise in sea level. There was a relatively rapid rise of the sea from about 12,000 to 6,000 radiocarbon years before present. Questionable, however, is the amplitude and wavelength of presumed oscillations from about 6,000 years ago to the present. Were there fluctuations above present sea level ("hypsithermal")? What were the possible effects of isostatic adjustment on glacio-eustatic shorelines? These and a host of related problems are still unresolved, although an increasing body of knowledge is presently available (see, for example, Curray *et al.* 1970; and Newell and Bloom 1970).

Often a Holocene sea level history is deduced solely from a few dated organic sediments, a curve drawn connecting age-depth points, and extrapolations made about rates of sea level rise for the entire region. Unfortunately, little concern may be given to possible errors stemming from modern carbon contamination, local tectonism or compaction, or post-depositional transportation of the dated sediments. Despite these shortcomings, it is still quite instructive to plot an apparent Holocene transgression for a particular location, then compare the result with curves from many other places in the world. Significant deviation of the local age-depth plot may then be analyzed for possible *effect of* tectonic, hydrologic, or even man-induced influence. This is illustrated in Figure 4, where a "calibration envelope" enclosing the maximum oscillatory points of 15 curves from presumed tectonically stable areas (Curray and Shepard 1972), is compared with the 13 radiocarbon ages and ranges available thus far from the Sacramento-San Joaquin Delta.

Except for samples from the small unreclaimed Devil's Island (UCD 18, 19, 20; Fig. 2), the eight youngest points in the Sacramento-San Joaquin Delta, if connected, would approximate oscillations similar in amplitude and wavelength to the short period theoretical fluctuations postulated by Fairbridge (1961). However, comparing the delta data with the envelope of world-wide curves (Fig. 4) shows that the youngest dated sediments occur some 5 to 10 m lower in elevation than expected and that the approximately 10,500-year-old peats underlying the western part of the Delta are about 15 m higher than anticipated. Also, although having a "break-in slope" about 6,000 years ago, a plot of the Holocene transgression in the Sacramento-San Joaquin Delta would be generally less steep than reported elsewhere. In part this anomalous age-depth relationship may reflect local post-depositional loading of peat, and/or Holocene tectonism in the western part of the Delta. Of course, too, the dated peats do not indicate exact paleo-sea levels, for the original vegetation may have grown a few metres above or below mean tide. Thus the radiocarbon dates from the Sacramento-San Joaquin Delta are only approximate indicators of the Holocene rise in sea level for this part of California. Nevertheless, the apparent age-depth disparity, compared with world-wide curves, calls attention to areas of possible tectonism heretofore unrecognized.

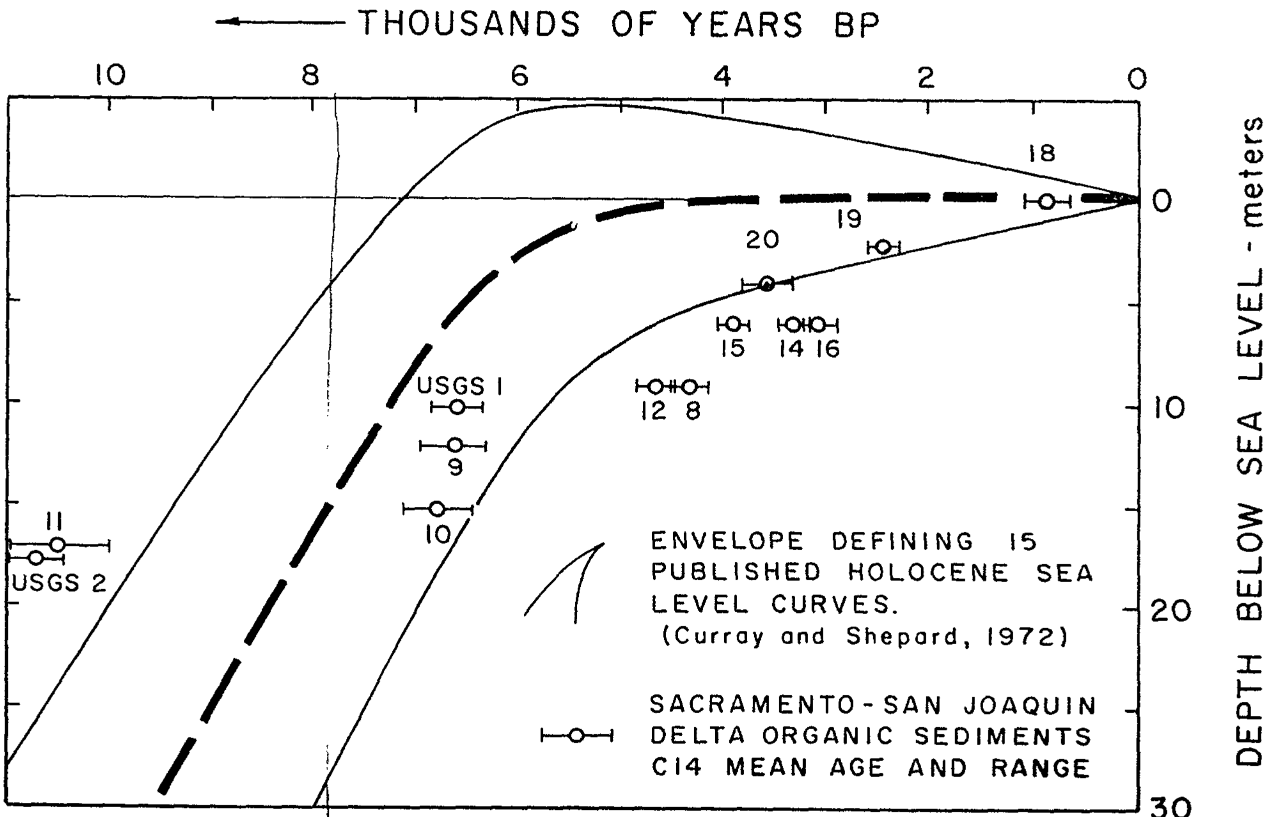

FIG. 4.—Radiocarbon age and depth of Sacramento-San Joaquin Delta sediments compared with a "calibration envelope" of world-wide Holocene sea level curves. Sample locations shown in Figure 2.

Holocene Paleogeography. The changing Holocene paleogeography of the Sacramento-San Joaquin Delta was broadly controlled by the rising sea, transgressing eastward from San Francisco Bay. As shown in Figure 5, the sea reached the western part of the present delta about 10,500 years ago forming approximately 8,200 ha of deltaic terrain. As transgression continued, the deltaic area increased to about 28,000 and 36,000 ha respectively, some 6,500 and 3,500 radiocarbon years ago. These values are approximations only because they do not reflect possible effects of local tectonism or regional subsidence. Consequently, the area of deltaic deposits, especially before about 6,500 years ago, may have been substantially greater than shown.

Radiocarbon-dated peats in adjacent San Francisco Bay indicate that sea level there reached its present position about 5,000 years ago (Lajoie 1972). This would similarly be the expected time for maximum areal extent of the Sacramento-San Joaquin Delta. However, from Figure 4, the 5,000 year old basal peat is about 9 m below present sea level, and deltaic expansion appears to have increased steadily to the pre-reclamation period, about 120 years ago. This continued growth of the Delta may indicate, alternatively, (1) uninterrupted regional subsidence and local compaction, (2) a Holocene sea stand higher than the present, or (3) peat formation several metres above sea level. Of these three hypotheses, subsidence and related local compaction appears most plausible to explain continued deltaic expansion within the last 5,000 years, for similar phenomena occurred in the Delta throughout much of Pleistocene time (Shlemon 1971), and are observed in Holocene sediments in San Francisco Bay (Helley *et al.* 1972, p. 29).

Late Quaternary Tectonism

The area immediately west of the Sacramento-San Joaquin Delta is tectonically active (Sharp 1973; Burke and Helley 1973), but there are no faults having surficial expression across the Delta, nor would such be likely to be preserved in marsh and estuarine terrain. However, numerous faults cut Tertiary sediments underlying the Delta; indeed, many Delta gas fields are developed in fault-bounded structures (Safanov 1962; Edmonson 1965). Two main lines of evidence suggest that tectonism probably continued into the Holocene.

First, as noted, the bedrock channel of the Carquinez Strait, west of the delta (Fig. 3), is over 40 m higher in elevation than Pleistocene channels of the Mokelumne River. This relationship, *per se,* suggests late Quaternary relative uplift of the Carquinez Strait and subsidence of the Delta, possibly localized under Sherman Island (Shlemon 1971; Fig. 3). Second, although requiring further data for verification, the age and depth of dated deltaic sediments, compared with other curves depicting the Holocene transgression, suggest possible periodic displacement along one or more faults under Sherman Island and possibly west of the delta. The relative movement appears similar to that which displaced the older Mokelumne River channels; that is, the entire delta has been subsiding in Holocene time complicated by periodic uplift of the Carquinez Strait and western Sherman Island.

The probability of Holocene-age displacement of deltaic sediments is also indirectly suggested by a fault

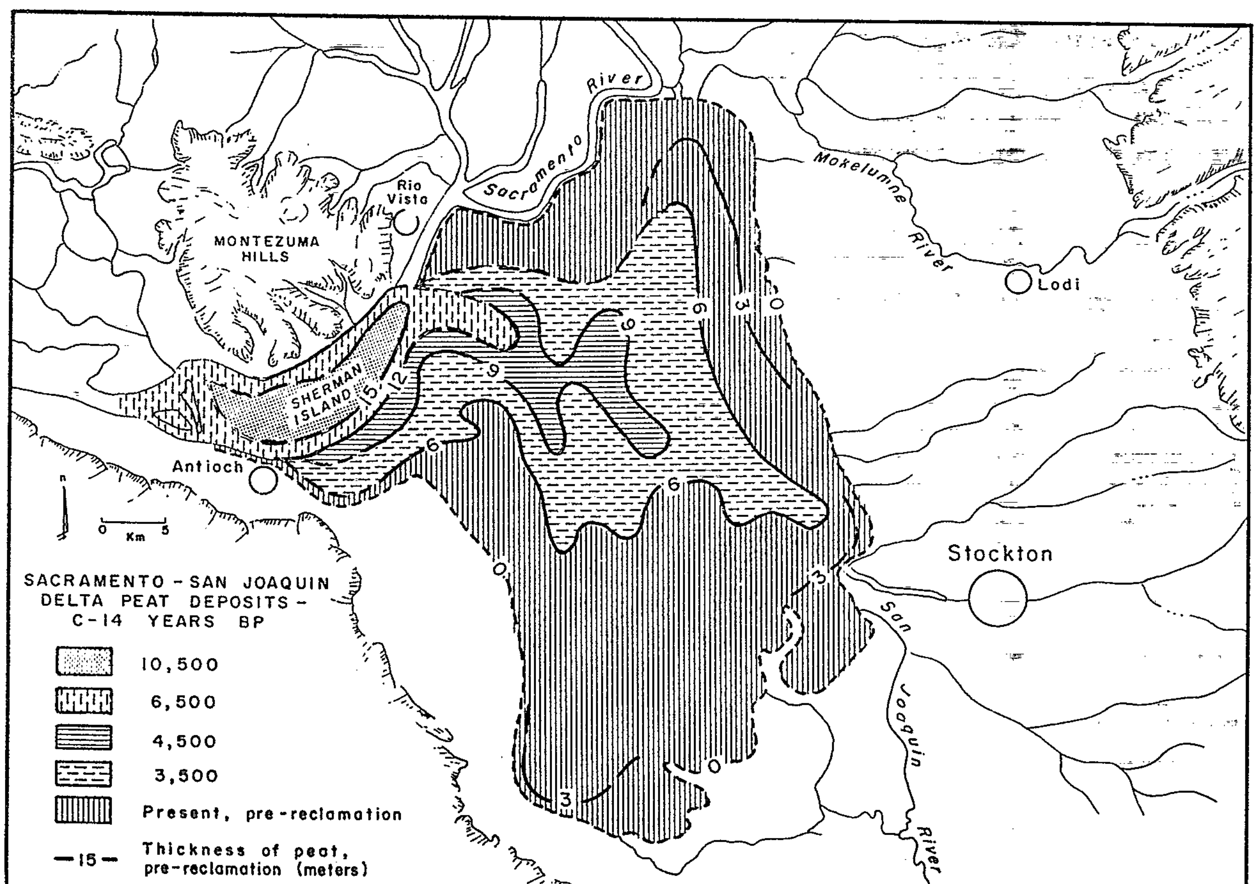

FIG. 5. — Thickness, approximate age of peat, and Holocene growth of the Sacramento-San Joaquin Delta.

scarp bounding the eastern side of the Montezuma Hills near Rio Vista (Fig. 2). The fault dips steeply, and displaces about 30 m of Pleistocene sediments (Reiche 1950, p. 1529).

Projecting the Rio Vista Fault about 2 km southward places it directly through Sherman Island (Fig. 2). The inferred fault offsetting pre-Holocene sediments underlying Sherman Island (Fig. 3) may therefore be the Rio Vista Fault or part of a related system. Most Holocene displacement along the inferred fault seemingly occurred between about 10,000 and 7,000 years ago. This is suggested by the depths of the approximately 10,500 year old basal peats west of the fault (USGS 2 and UCD 11; Table 1) occurring well above the age-depth plot of the Curray and Shepard curves (Fig. 4). However, younger samples, even from the same borings, for example USGS 1 and UCD 9 and 10, consistently lie below the mean of the sea level curves. Thus, although requiring more data for confirmation, the cumulative vertical departure of the dated peats from the mean of the Curray and Shepard curves (Fig. 4) suggests that possibly 10 to 15 m of periodic displacement has occurred under Sherman Island during Holocene time. As also shown by the age-depth relationship of the peat (Figs. 2 and 4; Table 1), it appears that since about 7,000 years ago the entire delta has been generally subsiding. However, in view of the tectonic history of the area it is conceivable that there may have been pauses in this subsidence and possibly even local uplift east of the projected Rio Vista Fault. Although conjectural, continuing movement of the Rio Vista Fault might be responsible for the recent swarm of low-magnitude earthquakes localized near Antioch (McEvilly and Casady 1967; Fig. 1). In summation, the precise times, apparent periodicity, and absolute magnitude of regional subsidence and displacement along one or more inferred faults in the western Delta are still unknown, but perhaps can be ascertained more conclusively with additional radiometric assay of peat.

Recognizing and dating possible late Quaternary tectonism in the Sacramento-San Joquin Delta is of academic interest, primarily for understanding better contemporary rates of subsidence and related geological processes. It is also increasingly relevant to regional planning, because, as in most delta terrain, faults have little if any surficial expression. In particular, the technique of identifying areas of possible active faults by dating sediments and comparing sea level curves may be applicable to other deltaic areas of the world, especially where there is concern for siting large structures, such as nuclear power plants and pumping stations, or for routing canals and other engineering works sensitive to geological hazards.

SUMMARY

The Sacramento-San Joaquin Delta of central California expanded and contracted throughout Quaternary time, responding primarily to glacio-eustatic fluctuations and to climatically-controlled changes in the hydrologic regimen of traversing streams.

Pleistocene channels are traced to about 95 m below present sea level under the Delta, but the bedrock notch at Carquinez Strait, the western drainageway, is 40 m higher in elevation. This relationship suggests late Quaternary subsidence of the Delta, probably localized along one or more faults under and immediately to the west of Sherman Island. In Pleistocene time, interbedded glacial channel gravels and sands, and interglacial deltaic sediments were superimposed on the subsiding trough.

The rising sea reached the western part of the present Delta about 10,500 radiocarbon years ago. However, age-depth points of radiometrically-dated peat, compared with an envelope enclosing world-wide curves, suggests that subsidence continued into Holocene time, complicated by periodic displacement of the Rio Vista Fault under Sherman Island.

The late Quaternary evolution of the Sacramento-San Joaquin Delta, as outlined, is still only partially known. The rate and time of the Holocene transgression, however, may be estimated more precisely by additional radiometric assay of the extensive organic deposits. Additional dating may also call attention to potential faults and other geological hazards heretofore unrecognized.

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