GEOLOGIC HISTORY OF ELKHORN SLOUGH, MONTEREY COUNTY, CALIFORNIA

A Thesis
Presented to
The Faculty of the Department of Geology
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In Partial Fulfillment
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Master of Science

By
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ABSTRACT

Elkhorn Slough is an elongate, tidally influenced coastal embayment positioned directly adjacent to Monterey Submarine Canyon. Elkhorn Slough presently occupies the western portions of Elkhorn Valley, an abandoned river valley that cuts through the Aromas Sands formation. Elkhorn Valley was eroded during late Pliocene to early Pleistocene time by large rivers that drained the Santa Clara Valley and, at times, the Great Valley of California. This drainage abandoned Elkhorn Valley when its headward region was tectonically disrupted in middle to late Pleistocene time by uplift and tilting along the San Andreas and Zayante Vergeles fault zones. Movement also occurred along the San Andreas fault which resulted in displacement of the headward portions of Elkhorn Valley's drainage to the northwest, and capture of its major tributaries via establishment of the Pajaro River system. Increased precipitation and runoff, which occurred during numerous glacial stages of the late Pleistocene, resulted in smaller scale drainage systems which were competent to scour local tributary channels in Elkhorn Valley.

Borehole data to depths of 29 m below the mouth of Elkhorn Slough reveal a fining upward, transgressive sequence of non-marine to marine sediments. The sediments and microfossils recovered from the boreholes suggest that a channel was cut into Elkhorn Valley during the most recent low stand of sea level 16,000-18,000 years B.P. A high energy tidal inlet existed near the mouth of Elkhorn Slough from approximately 7,000 to 10,000 years ago when rising sea level flooded the incised drainage channel. As sea level continued to rise, the tidal channel was filled with a fining upward sequence of marine sediments.

Core data further suggest that sea water invaded large areas in the western portions of Elkhorn Valley. A quiet water estuary or coastal embayment, larger than the present Elkhorn Slough existed near the mouth of Elkhorn Valley approximately 5,000 years ago. Subsequently, sedimentary infilling of the estuary is characterized by salt marsh habitats expanding gradually and eventually burying intertidal mud banks. Relatively rapid accumulation (1.6 mm/yr) of salt marsh sediment during the past 5,000 years has resulted in isolation of portions of the coastal lagoon such as McClusky Slough.

Past sedimentation rates suggest that had the jetties at Moss Landing harbor not been installed in 1946, Elkhorn Slough would have eventually evolved into a dry alluvial valley dissected by intermittent streams in approximately 2,000 years. Soon after the jetties were installed, however, open marine incursion and erosional scouring occurred, followed by deposition of coarse grained sediments at a rate of 15 mm/yr. Apparently, a state of equilibrium has since been achieved. As long as the jetties are present and relative sea level continues to rise at its present rate, a stable coastal embayment will continue to occupy the western portions of Elkhorn Valley.

ACKNOWLEDGMENTS

Thanks and appreciation are extended to Henry T. Mullins, currently at Syracuse University, for suggesting the research topic, providing invaluable office and field assistance, and for serving as the chairman of my committee. Calvin Stevens and Stephen Janes of San Jose State University are also gratefully acknowledged for participating on my committee and offering constructive criticism during the investigation.

I wish to extend my gratitude to the people who were kind enough to offer their skills and assistance in the identification of the various microfossils that were encountered during this project. Roberta Smith-Everndon and Mike Mullen identified many foraminifera and also assisted by verifying my foraminifera identifications. Thanks also go to Richard Laws who identified the diatoms and Richard Forester who identified the ostracods.

Special thanks and appreciation go to all my field assistants who put up with hours of sometimes undesirable conditions in the marshes of Elkhorn Slough: Ellen Faurot, Richard Rasch, Henry Mullins, Dave Nagel, Tom Verecoutere, Dan Daniels, Mike Reilly, Tim Herrlinger, and Kevin Lohman. Brian Atwater, of the U.S. Geological Survey, aided with valuable suggestions and offered the design for the coring device that was used in the field.

I am grateful to Rob Priceoct, Adalai Goldsmidt, and Rich Fox of the California Division of Transportation (CALTRANS) for their interest and cooperation in allowing me to collect subsurface samples near the mouth of Elkhorn Slough. Thanks also go to Gene Taylor and the Monterey County Flood Control and Gerald Weber for providing me with information on water and exploratory oil wells.

Funds from the David and Lucille Packard Foundation were used for a coring device and three radiocarbon dates and are gratefully acknowledged. I am also indebted to Daniel Belknap of the University of Maine for providing me with important amino acid racemization dates.

I want to also thank all of the Moss Landing Marine Laboratories staff personnel for their time and valued assistance throughout the project, in particular: Preston Watwood, Larry Jones, and Ken Delopst for assisting and designing needed field equipment; Deborah Helms for her excellent typing; Sheila Baldridge, our librarian for her general concern and skills in locating references; and Signe Lundstrom for operating the scanning electron microscope and capturing excellent photographs of Elkhorn Slough foraminifera.

Finally, I want to acknowledge the many hours of editing and typing that were done with such excellence throughout this project by my very close friend Vera Brown.

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INTRODUCTION

Regional Setting

Elkhorn Slough, located in northern Monterey County, California, is an elongate, tidally influenced, coastal embayment which forms an on-land extension of Monterey Submarine Canyon (Martin and Emery, 1967; Figure 1). The main channel of Elkhorn Slough is 11.5 km long and flanked with extensive intertidal mud banks. Its salt marshes, which are the second largest in the state of California, surround the main channel and mud banks and are dissected by numerous tidal channels and ponds (Plate 1).

Elkhorn Slough presently occupies the western portions of the much larger Elkhorn Valley which is approximately 1 km wide with a maximum of 70 m of relief (Plate 2). Elkhorn Valley cuts through the Pleistocene Aromas Sands, which are undifferentiated eolian, marine, and lagoonal deposits (Allen, 1946; Dupre, 1975) and extends approximately 24 km eastward where it gradually disappears as it approaches the Zayante Vergeles and San Andreas faults (Figure 2). An intermittent stream, now located in the axis of Elkhorn Valley, drains into Elkhorn Slough only during the winter months (Gordon, 1979).

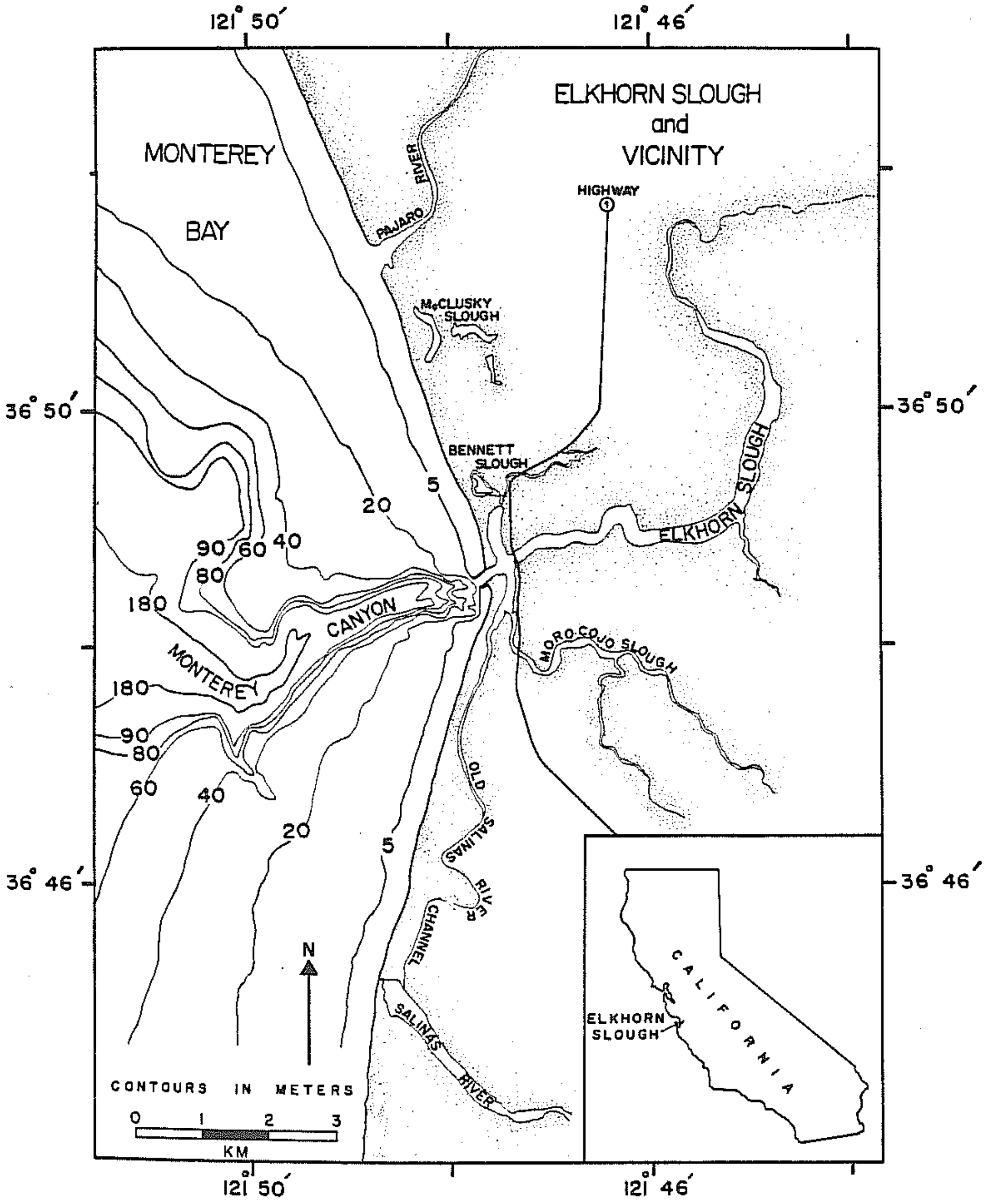


Figure 1. Location map of Elkhorn Slough and central Monterey Bay, California.

Plate 1. Air photograph of Elkhorn Slough taken during a low tide in 1968. Broad mud banks that flank the main channel are visible along with the extensive salt marsh.


McCLUSKY SLOUGH
ELKHORN SLOUGH
MOSS LANDING HARBOR

Plate 2. Air photograph of central Monterey Bay region taken in 1972 showing Elkhorn Valley, Elkhorn Slough, McClusky Slough, and the Salinas and Pajaro River mouths. Elkhorn Valley is outlined with heavy line.


SALINAS RIVER

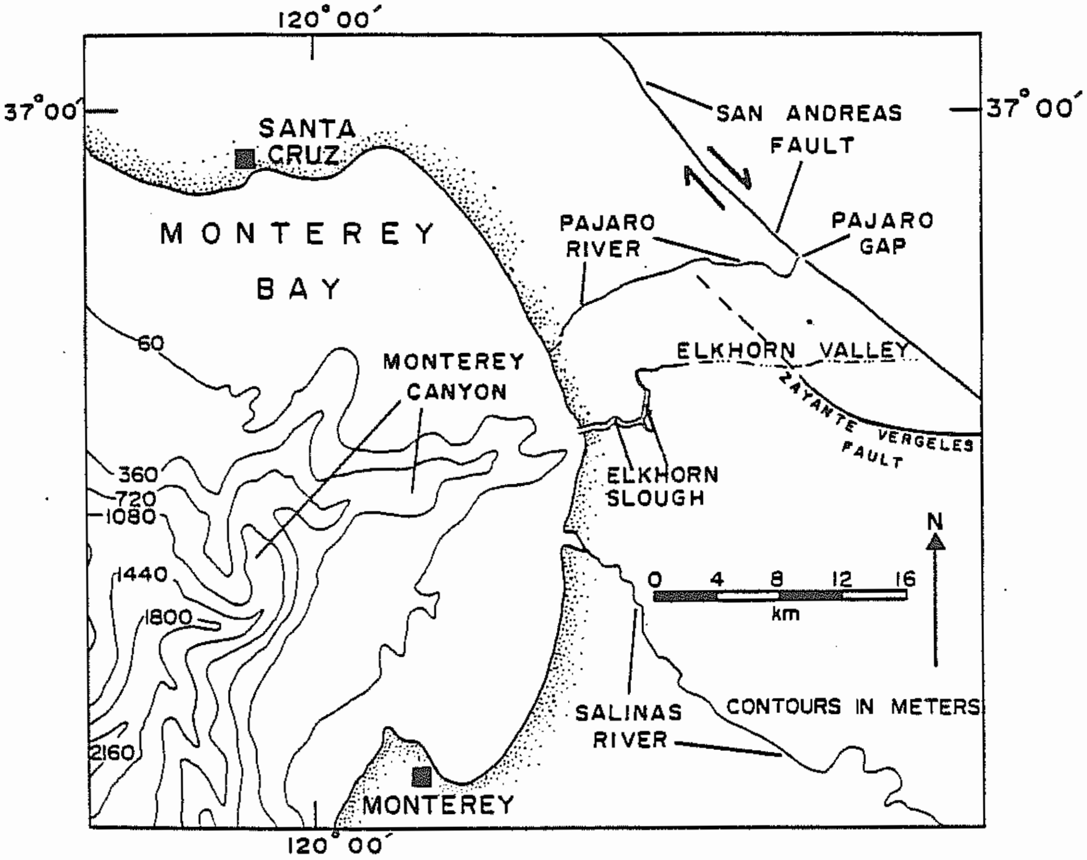


Figure 2. Map illustrating the geographical and geological relationship of Elkhorn Slough and Elkhorn Valley to the Monterey Bay region. Elkhorn Valley had less vertical relief than the western drowned portions and eventually disappears as it approaches the Zayante Vergeles and San Andreas faults; modified after Starke and Howard (1968).

Recent History

The mouth of Elkhorn Slough has changed its position due to both natural and human influences numerous times since the middle 1800's. The change that has had the greatest effect on the physical and biological evolution of Elkhorn Slough was initated in 1946, when the jetties for the Moss Landing boat harbor were installed. The jetties, which are positioned directly in line with the western main channel of Elkhorn Slough (Figure 1; Plate 1), created an open pathway for oceanic waters to enter and exit Elkhorn Slough via tidal processes. Before the installation of the jetties, Elkhorn Slough experienced brackish water conditions with minimal open-ocean circulation (MacGinitie, 1935). Since the jetties were installed, currents at the mouth of Elkhorn Slough commonly achieve velocities as high as 50 cm/sec (1 knot) during flood tides and 72 cm/sec during ebb tides (Clark, 1972).

Recent studies show that salinities in Elkhorn Slough are variable depending on the amount of precipitation, evaporation, and runoff, which fluctuate seasonally. During rainy periods of the winter months, the upper portions of Elkhorn Slough attain estuarine characteristics with salinities as low as 17 parts per thousand (ppt). However, salinities as high as 37 ppt commonly occur in the upper (eastern) portions of Elkhorn Slough during the drier summer months when circulation is minimal and evaporation exceeds precipitation (Broenkow, 1977). In the lower (western) portions of Elkhorn Slough, where there is a greater exchange of oceanic waters, salinities vary less, ranging from approximately 30 to 33 ppt (Broenkow, 1977).

The physical and biological characteristics of Elkhorn Slough for the past 50 to 60 years is well documented. From 1926 to 1935, MacGinitie conducted pioneering ecological studies in the western portions of Elkhorn Slough, and since MacGinitie's (1935) pioneering work, numerous biological studies have been completed or are in progress. However, there have been no previous geological investigations that have concentrated on the origin, evolution, and depositional history of Elkhorn Slough. As a result, there is a lack of understanding on how Elkhorn Slough relates to Elkhorn Valley and the adjacent Monterey Submarine Canyon. Also, no information presently exists on the shallow lithostratigraphy or biostratigraphy, or on paleoenvironmental conditions of Elkhorn Slough. There also have been no previous studies that resolved past accumulation patterns in Elkhorn Slough or described what physical and environmental conditions would be expected now or in the future had humans not interfered with Elkhorn Slough.

Objectives

The objectives of this study are: (1) to determine the origin and subsequent depositional history of Elkhorn Slough; (2) to determine Holocene sedimentation patterns and environmental conditions of Elkhorn Slough; (3) to further the understanding of the evolution of Elkhorn Valley and discuss how it relates to Elkhorn Slough and the

Monterey Submarine Canyon, and (4) to compile all available data into a model that describes the geologic history of Elkhorn Valley and Elkhorn Slough.

METHODS

Field

During April and May of 1981, the California Division of Transportation (CALTRANS) conducted a bridge foundation study along U.S. Highway 1 at the mouth of Elkhorn Slough in which samples from 13 boreholes were recovered. Five were drilled from a barge in the main channel, and six were drilled on land along the margins of Elkhorn Slough (Figures 3 and 4). Unconsolidated sediment samples were taken at approximately 1.5 m intervals to subsurface depths ranging from 15 to 29 m.

In addition to these drill core samples, a hand-driven sediment coring device was used to collect 19 cores up to 7 m long from the marshes and mud banks of Elkhorn Slough and three cores from the marshes of McClusky Slough (Figures 3 and 4). Prior to the collection of the hand-driven core samples, a metal probe was used in determining the relative thickness of unconsolidated sediments beneath the marshes of Elkhorn Slough and to aid in selection of core site locations. This hand-driven sediment corer is capable of collecting up to 7 m long samples with a 3 cm diameter. A minimum of two sub-samples were taken every meter. A transect of eight cores, referred to as the marsh transect, was recovered from the northwest portion of Elkhorn Slough (Figures 3 and 4).

Twelve surface grab samples were also collected from tidal channels, mud banks, and salt marshes of Elkhorn Slough. Grab samples

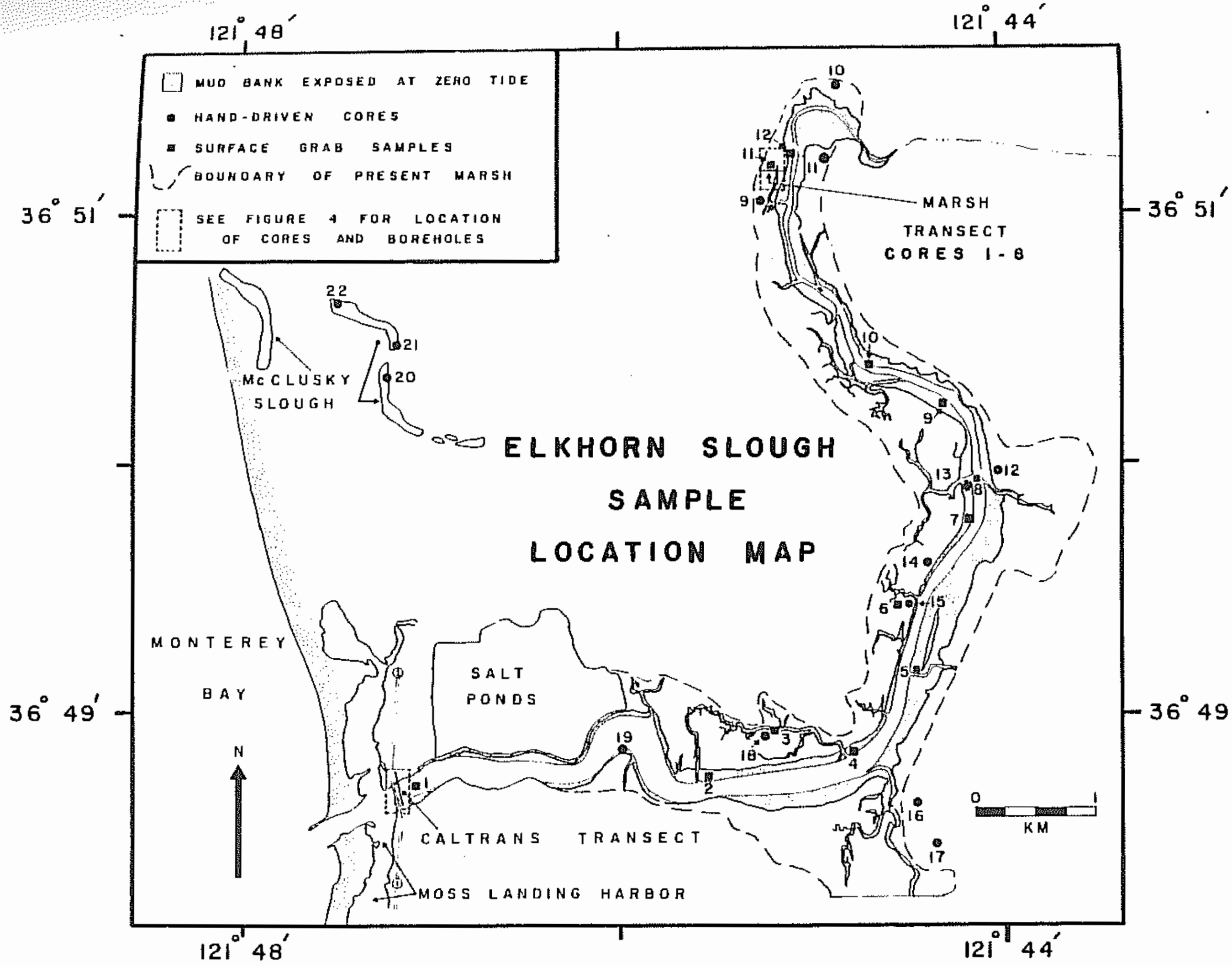
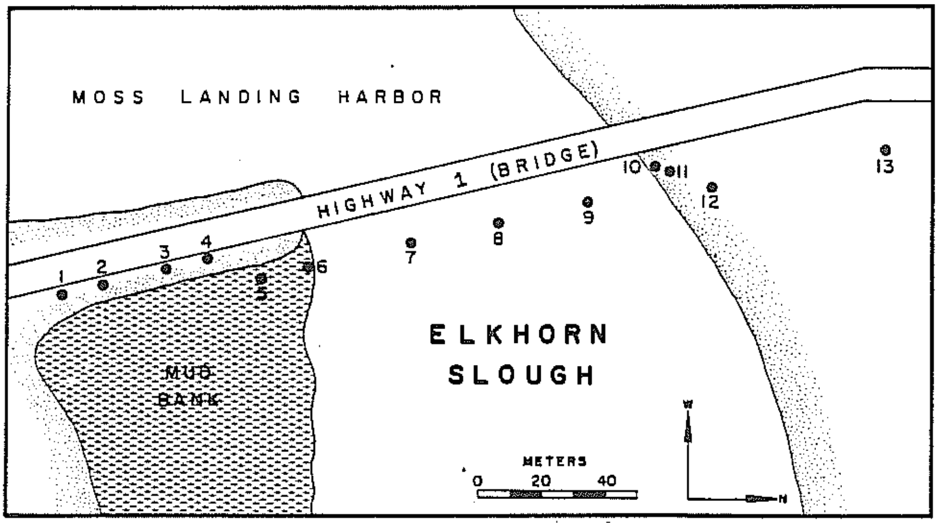
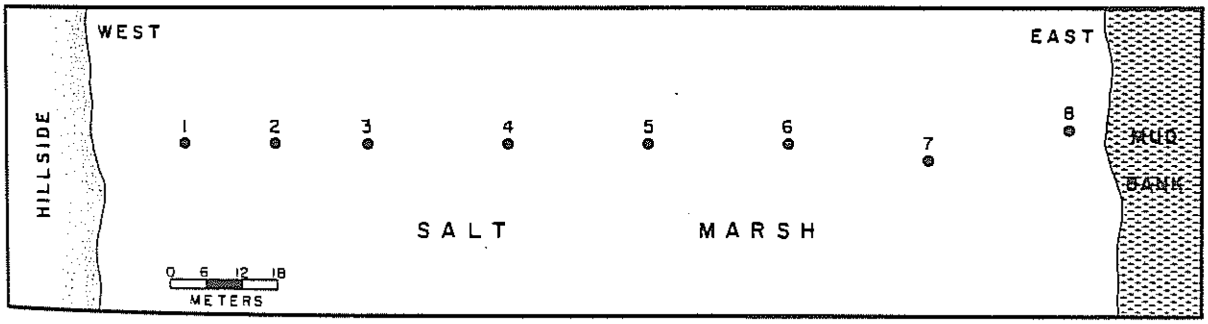


Figure 3. Location map of CALTRANS transect, marsh transect, hand-driven cores, and surface grab samples collected from Elkhorn Slough and McClusky Slough. See Figure 4 for location of the CALTRANS boreholes and marsh cores 1-8.



CALTRANS TRANSECT

A



MARSH TRANSECT

B

Figure 4. Location map of boreholes taken at the mouth of Elkhorn Slough (A) and hand-driven cores of the marsh transect (B).

were put immediately in a rose bengal-methanol solution to stain living foraminifera.

Laboratory

The grain size of samples obtained from the CALTRANS boreholes was determined by standard sedimentologic procedures outlined in Folk (1974). All surface grab samples, samples obtained from CALTRANS, and the hand-driven core samples were split into 30 gram sub-samples. These sub-samples were washed through U.S.A. standard seives numbers 120 and 230, dried, and analyzed for benthic foraminifera, mollusc fragments, ostracods, diatoms, and plant remains. Foraminifera were separated from sandy samples by floating in carbon tetrachloride.

Five amino acid racemization dates were determined for a single genus of foraminifera, *Elphidium* spp. Approximately 50 mg of sample were picked by hand from five sediment samples obtained from the CALTRANS boreholes. Three carbon-14 dates were also determined by Geochron Laboratories in Cambridge, Massachusetts, one on mollusc fragments recovered from the base of borehole 11, approximately 21 m below sea level, and the other two from salt marsh peats recovered in core 8, at 275 cm and 635 cm subsurface (Figures 3 and 4).

RESULTS

Elkhorn Slough

Lithostratigraphy. Quantitative grain size analysis reveals a fining upward sequence almost to the surface below the mouth of Elkhorn Slough to depths of 29 m subsurface (Figure 5). Along the southern margin of Elkhorn Slough, the base of the section consists of gravelly sand deposits overlain by a thick muddy sand unit, with numerous silt lenses. The contact between the gravelly sand and muddy sand deepens to the north (Figure 5), while the muddy sand unit is overlain by silt and clay units which extend laterally across the entire section. Along the southern margin of Elkhorn Slough the sequence is capped by a thin sandy unit containing abundant shell fragments. The shaded areas of sand and silt on the north and south sides of Elkhorn Slough above mean lower low water represent road fill (Figure 5).

Most of the sediments beneath the marshes of Elkhorn Slough are blue gray and light to dark brown, organic-rich clays. *Salicornia* root mat is present below the subsurface of the salt marsh for 1 to 2 m. Dark brown and black peat also is common, but less abundant than the clays, and often it occurs in discrete beds.

Below the marshes of Elkhorn Slough, peat is most abundant along the margins of the slough, gradually decreasing towards the present main channel (Figure 6). Other examples of this are detected in cores 9, 10, 11, and 18 which are located along the distal margins of the

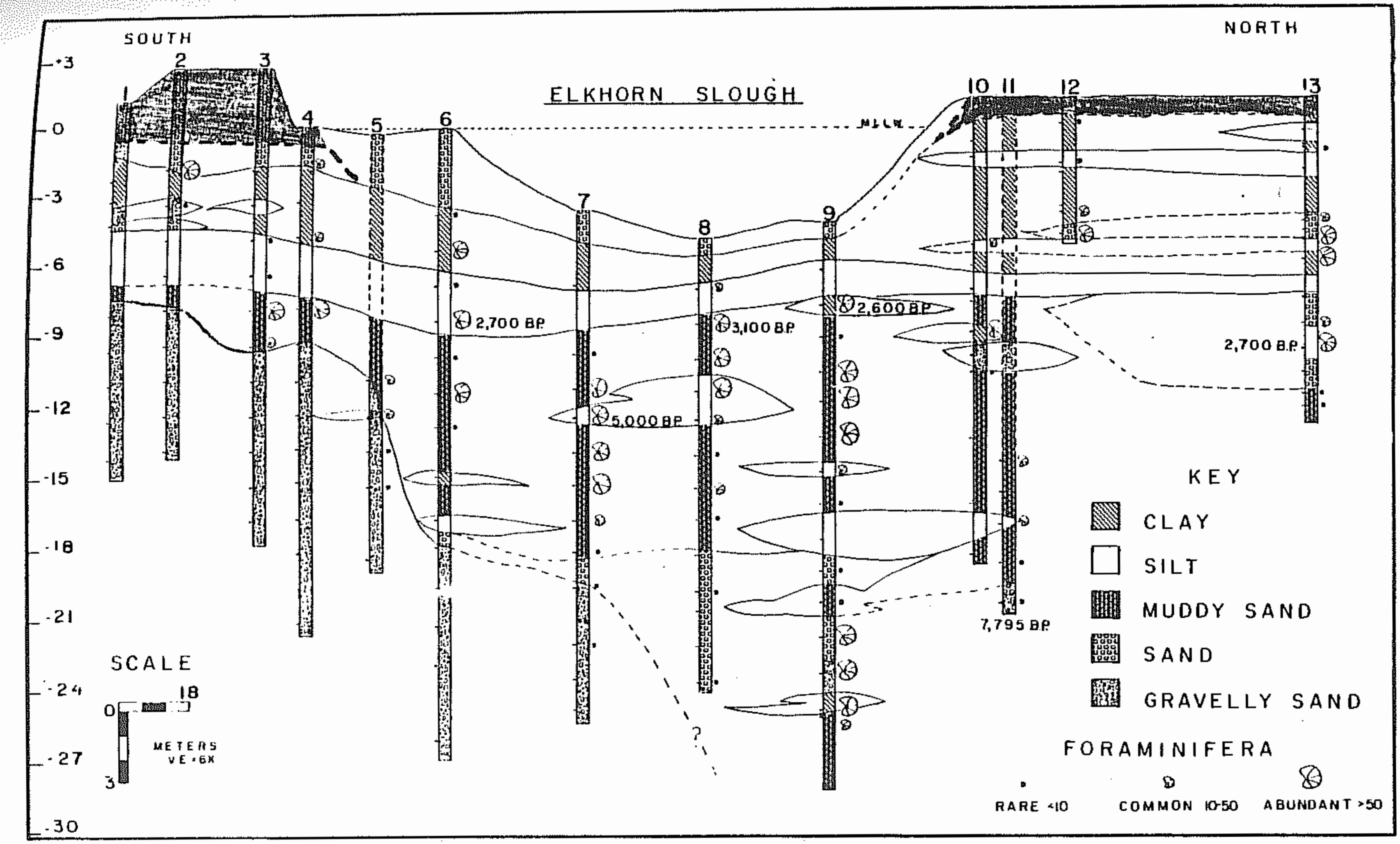


Figure 5. Lithostratigraphic cross section across mouth of Elkhorn Slough along CALTRANS transect illustrating a fining upward sequence and general relationships of subsurface units. The relative abundance per 30 gram of sample of foraminifera and age estimates also are shown. The contact between the clay and sand beds at the top of the section is interpreted to be an unconformity initiated in 1946 when the jetties for the Moss Landing harbor were installed. Shaded areas at the top of the section represent road fill.

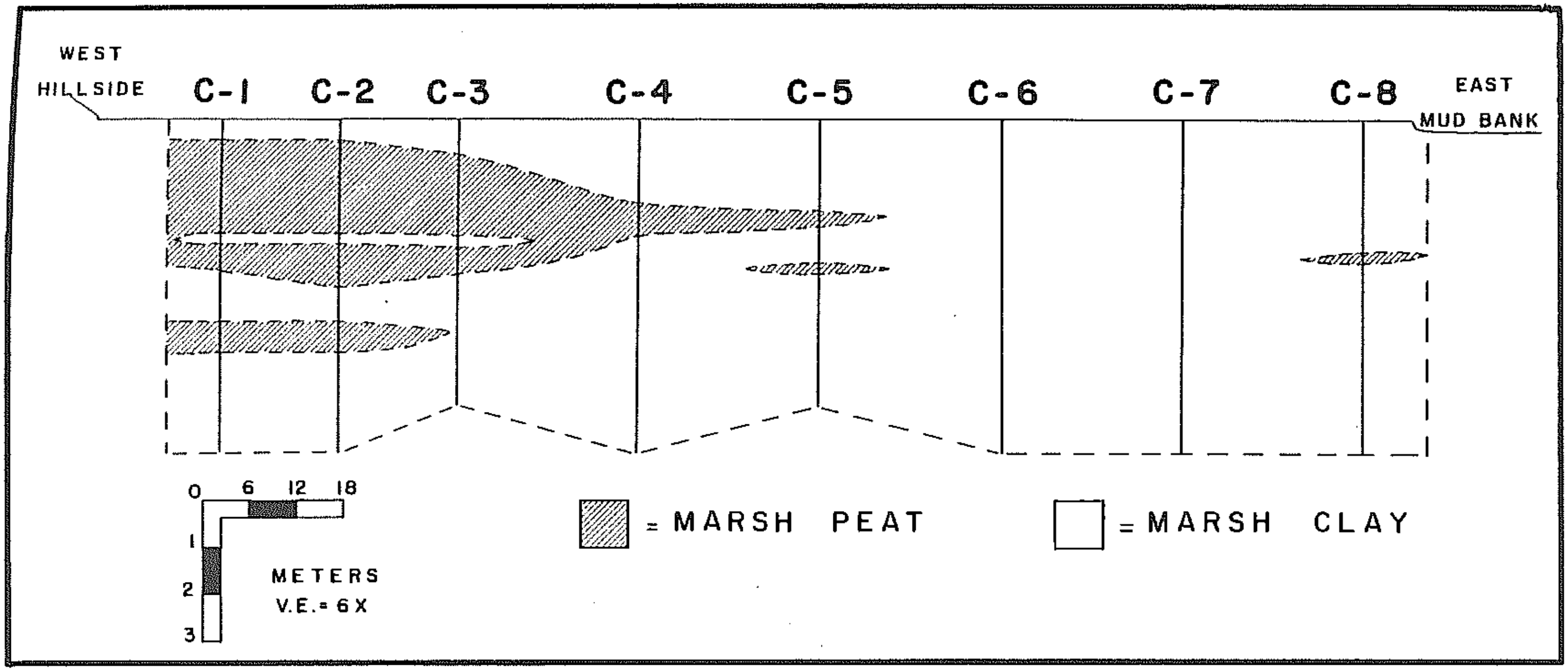


Figure 6. Subsurface cross section of Elkhorn Slough along the marsh transect illustrating relative abundance of marsh clay and peat. See Figure 4 for the location of cores 1-8.

slough (Figure 3) and consist almost entirely of dark brown to black peat (Figure 7). In contrast, cores 12, 14, and 15 are all located relatively close to the present main channel and contain mostly blue gray and brown clay (Figure 7). Similar lithostratigraphic subsurface units also are present beneath McClusky Slough (Figures 1 and 3). However, the ratio of abundance of clay to peat is the opposite from the subsurface of Elkhorn Slough. Beneath McClusky Slough, dark brown and black peat is the most abundant material. Brown and blue gray clays, which are the dominant subsurface component of Elkhorn Slough, are very rare beneath the first 5 m of McClusky Slough (Figure 7).

Foraminiferal Paleoecology. Fossil and living foraminifera and other organisms in Elkhorn Slough were recovered from surface grab samples taken from subtidal channels, mud banks, and the salt marsh (Figure 3). A total of 12 genera of foraminifera were identified from grab samples. The distribution of microfossils found in all the grab samples is given in Appendix 1. Only five species, Ammonia beccarii, Elphidium spp., Quinqueloculina sp., Rosalina sp., and Trochamina inflata were living at the time of collection. A variety of species of Elphidium present in the surface grab samples and many subsurface samples will be referred to as Elphidium spp.

Three different assemblages of microfossils were found to be associated with the three modern "sub-environments": (1) salt marsh; (2) mud bank; and, (3) subtidal channels (Figure 8). The subtidal channels and mud banks have similar assemblages of benthic foraminifera that sharply contrast with salt marsh assemblages. For

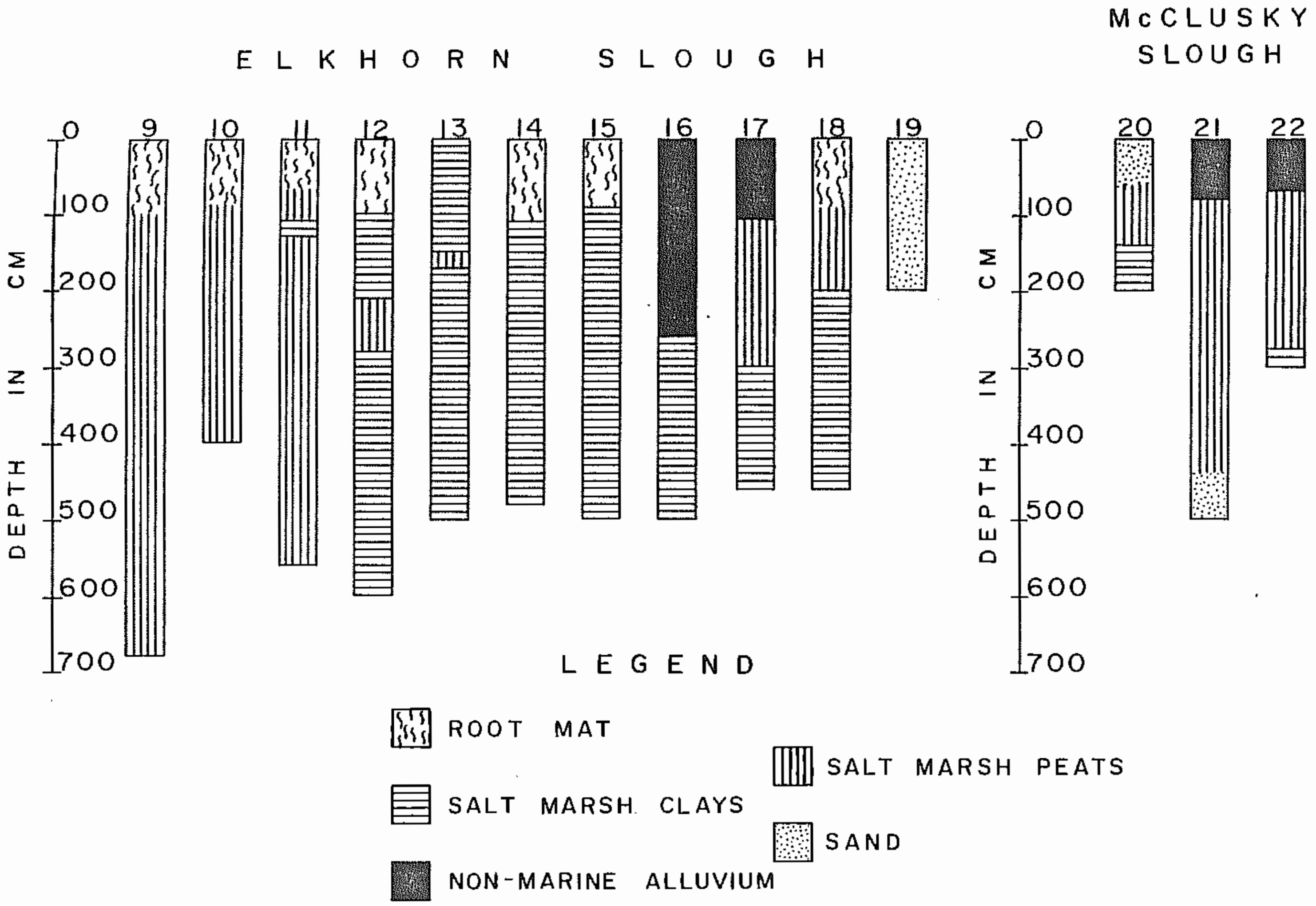


Figure 7. Elkhorn Slough and McClusky Slough hand-driven cores illustrating general subsurface lithologies. See Figure 3 for location of hand-driven cores.

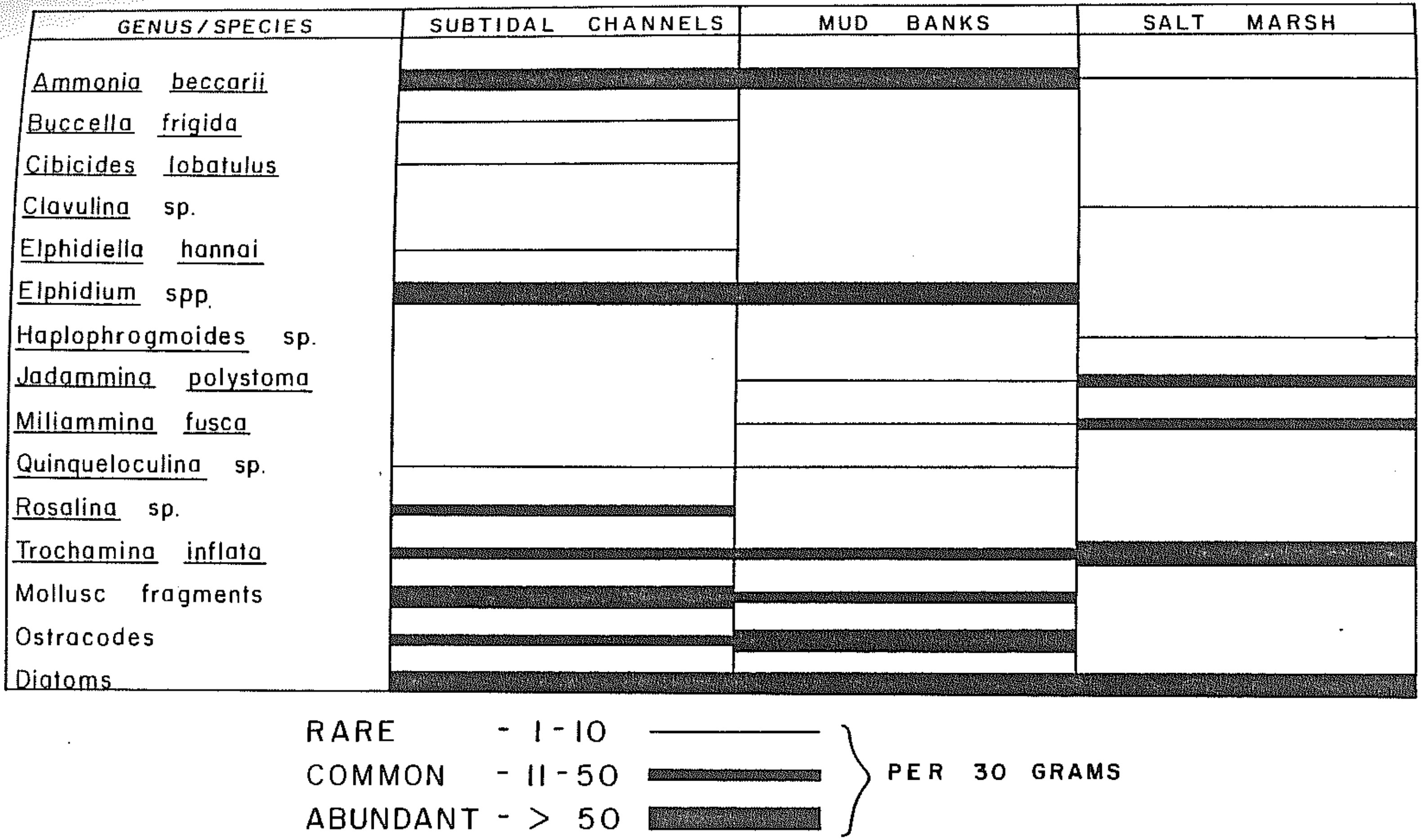


Figure 8. Relative abundance of benthic foraminifera, mollusc fragments, ostracods, and diatoms characteristic of various modern environments of Elkhorn Slough collected from 12 grab samples. See Figure 4 for locations of grab samples and Appendix 1 for a complete list of the distribution of microfossils recovered.

example, Ammonia beccarii, Elphidium spp., and ostracods are not present on the surface of the salt marsh environments, but are abundant and common on the surface of both subtidal channels and mud banks. Other foraminifera such as Jadammina polystoma and Miliammina fusca are common on the salt marsh environments but are rare to nonexistent on the surface of mud banks and subtidal channels (Figure 8; Plates 3-8).

Two different assemblages of microfossils observed in surface grab samples are also present in subsurface units of Elkhorn Slough. One assemblage characterized by the abundance of Trochamina inflata, the presence of Haplophragmoides sp., Miliammina fusca and Jadammina polystoma and the complete absence of Ammonia beccarii, Elphidium spp., and ostracods will be called the "marsh assemblage" because of its strong similarity to the microfauna found on the modern day salt marsh. The other fossil assemblage contains abundant Ammonia beccarii, Elphidium spp. and ostracods, common mollusc fragments and Trochamina inflata, and rare Miliammina fusca and Jadammina polystoma. Because of the similarity this fossil assemblage has with the microfauna encountered on modern day mud banks, it will be referred to as the "mud bank assemblage".

Core samples (Figures 9 and 10) from the northern portions of Elkhorn Slough indicate that only marsh assemblage of microfossils are present beneath the outer portions of the salt marsh. However, Figure 9 shows that a fossil mud bank assemblage occurs toward the center of the marsh transect which gradually expands eastward toward the axis of the main channel. Cores 12, 14, and 15 also demonstrate that in areas

Plate 3.
1. *Jadammina polystoma* Bartenstein and Brand, ventral view, x200.
2. *Jadammina polystoma* Bartenstein and Brand, dorsal view, x192.
3. *Jadammina polystoma* Bartenstein and Brand, apertural view, x228.
4. *Haplophragmoides* sp., side view, x160.
5. *Haplophragmoides* sp., side view, x232.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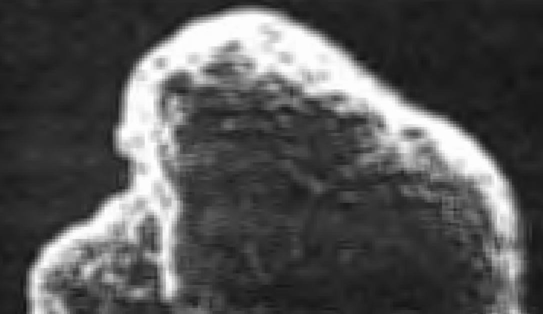
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Plate 4.
6. <u>Trochamina inflata</u> Montagu, ventral view, x155.
7. <u>Trochamina inflata</u> Montagu, apertural view, x175.
8. <u>Trochamina inflata</u> Montagu, dorsal view, x150.
9. <u>Clavulina</u> sp. ?, side view x257.

Plate 5. 10. *Miliammina fusca* Brady, side view, x154.
11. *Quinqueloculina* sp., side view, x126.
12. *Quinqueloculina* sp., side view, x259.
13. *Quinqueloculina* sp., apertural view, x294.

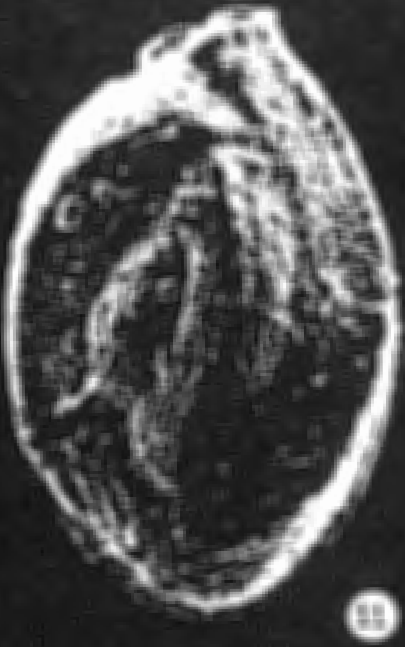

Plate 6.
14. *Elphidium* sp., side view, x 252.
15. *Elphidium* sp., side view, x194.
16. *Elphidium* sp., apertural view, x258.
17. *Ammonia beccarii* Cushman, ventral view, x238.
18. *Ammonia beccarii* Cushman, dorsal view, x206.

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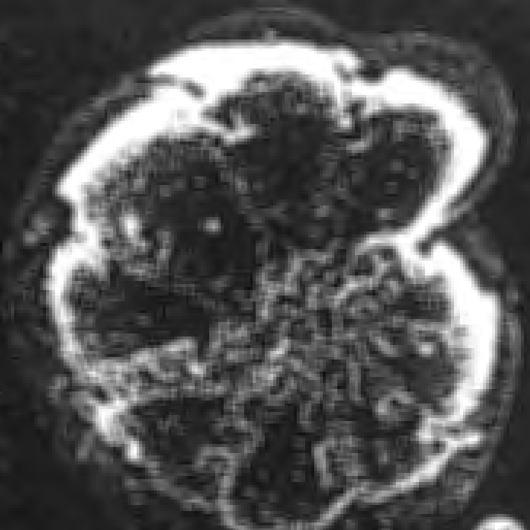

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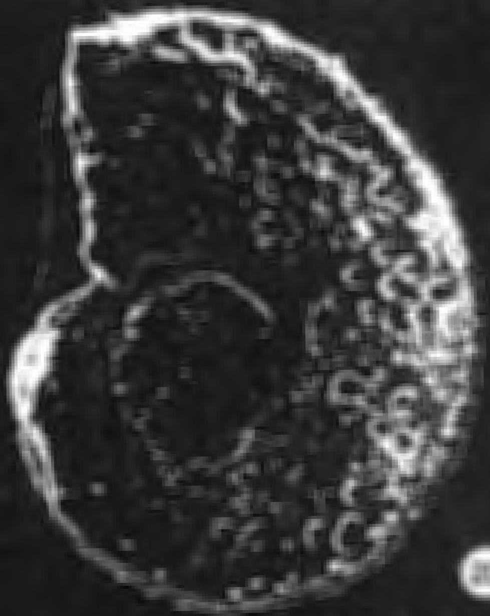
Plate 7. 19. *Elphidiella hannai* Cushman and Grant, side view, x112.
20. *Cibicides lobatulus* Walker and Jacob, ventral view, x282.
21. *Cibicides lobatulus* Walker and Jacob, ventral view, x288.
22. *Cibicides lobatulus* Walker and Jacob, dorsal view, x239.



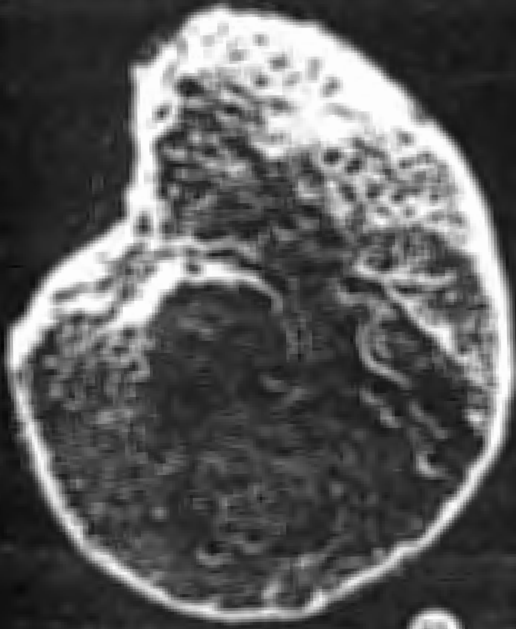


Plate 8. 23. *Rosalina* sp., ventral view, x184.
24. *Rosalina* sp., dorsal view, x179.
25. *Bucella frigida* Cushman, ventral view, x284.
26. *Bucella frigida* Cushman, dorsal view, x239.

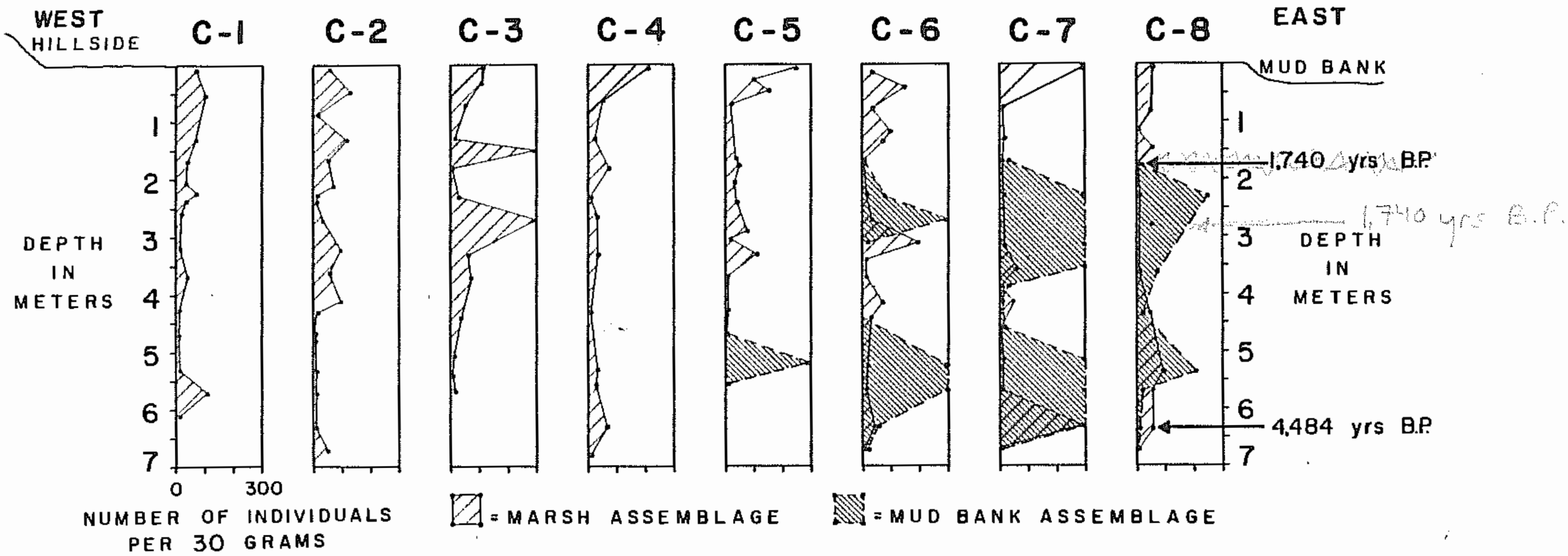


Figure 9. Subsurface cross section along the marsh transect (Figure 4) showing the relative abundance of "marsh assemblage" and "mud bank assemblage" microfossils. See Figure 8 for modern distributions.

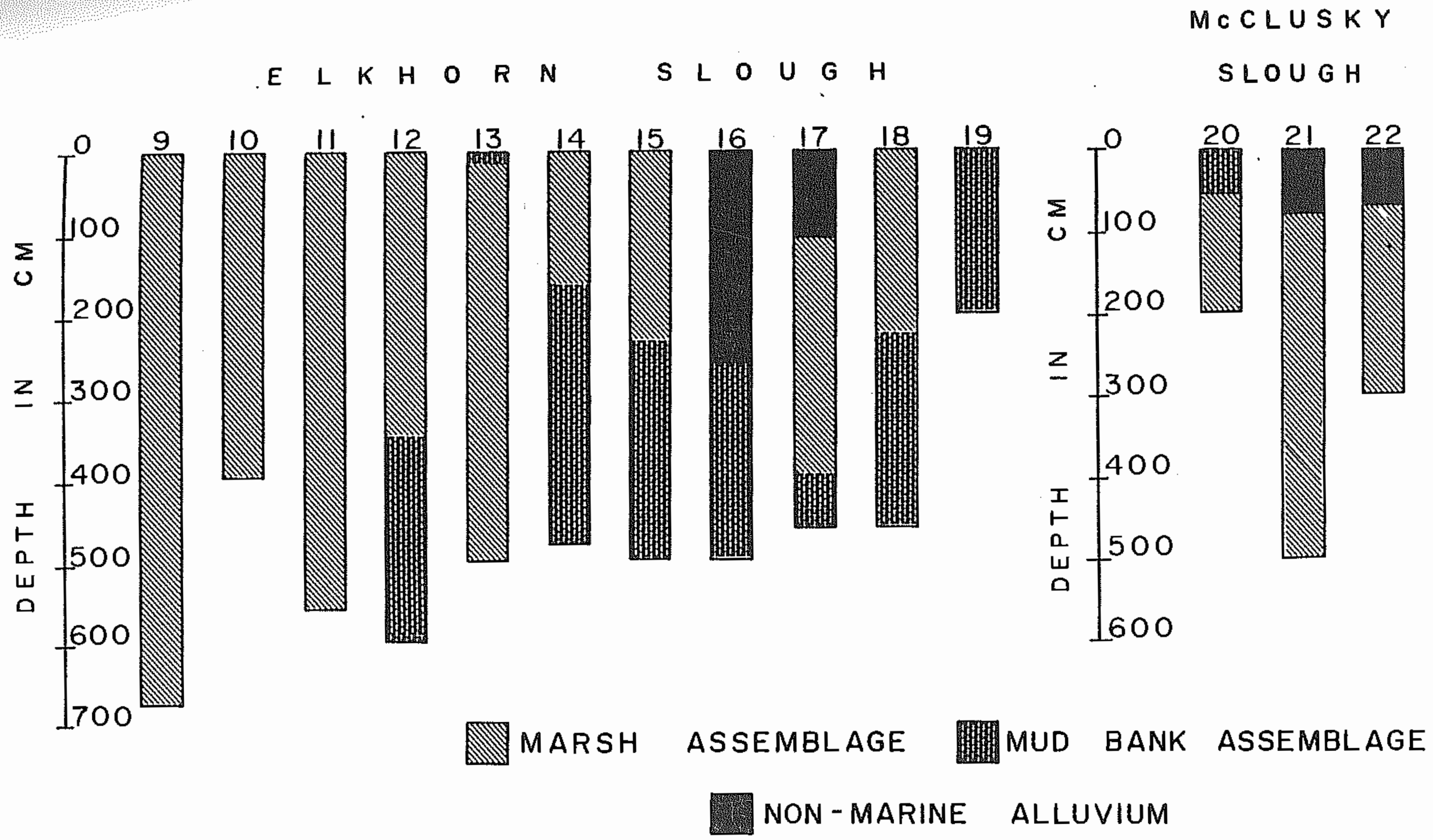


Figure 10. Schematic illustration of Elkhorn Slough and McClusky Slough hand-driven cores depicting subsurface distribution of "marsh assemblage" and "mud bank assemblage" microfossils. See Figure 8 for modern distributions.

immediately adjacent to the present main channel, mud bank assemblage of microfossils are abundant in the subsurface (Figure 10). Core 19, taken directly on an intertidal mud bank which fringes the present main channel, consists entirely of mud bank assemblage. Core 13 is an exception to this trend in that it was also taken on a mud bank (Figure 3) but consists of marsh assemblage from 16 to 430 cm subsurface (Figure 10).

Cores 16, 17, and 18 (Figure 3) demonstrate that microfossill mud bank assemblages occur in areas distal to the present main channel. Cores 17 and 18 are similar to cores 12, 14, and 15 (Figure 10) in that mud bank assemblages are overlain by marsh assemblages. However, at core 16 the top few meters of sediment were probably disturbed by agricultural purposes which resulted in the removal of marsh assemblage (Figure 10). The alluvium that now overlies the mud bank assemblage in core 16 is completely devoid of marine indicators.

Fossil foraminifera and other microfossils also were found in the boreholes at the mouth of Elkhorn Slough (Figure 3; Plates 3-10) except for borehole 1, which is located on the south end of the CALTRANS transect (Figure 5). The gravelly sand is the only unit that does not contain foraminifera, ostracods, or diatoms, although some mollusc fragments are present in the top portions of this unit. The distribution of the foraminifera and other microfauna and microflora recovered in the boreholes is given in appendix 3.

The number of genera of foraminifera in all boreholes at the mouth of Elkhorn Slough is relatively low, which is typical of estuarine marsh environments (Brandy and Arnal, 1960; Murray, 1973).

Plate 9.
27. Globigerina sp., side view, x35.
28. Florilus basispinatus Cushman and Moyer, side view, x35.
29. Florilus basispinatus Cushman and Moyer, side view, x145.
30. Florilus basispinatus Cushman and Moyer, apertural view, x273.

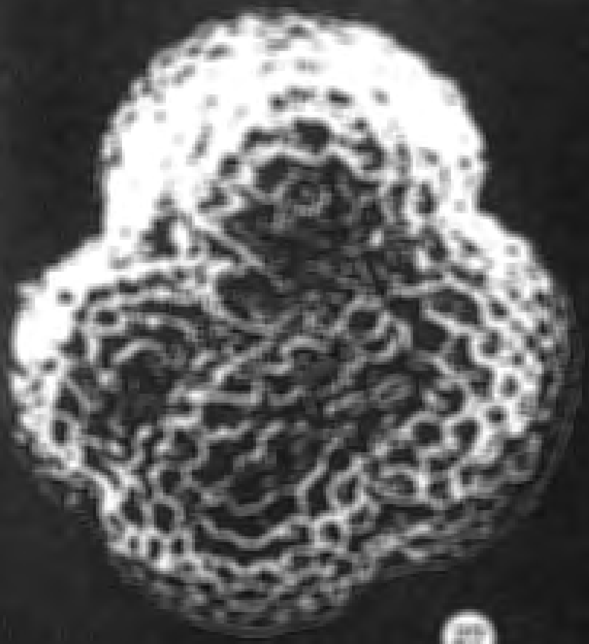


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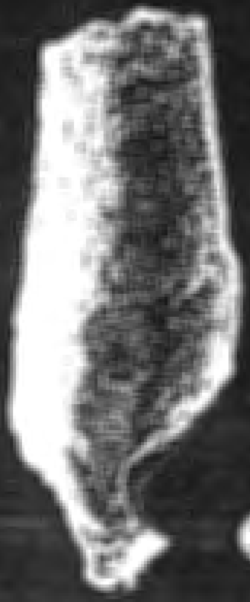
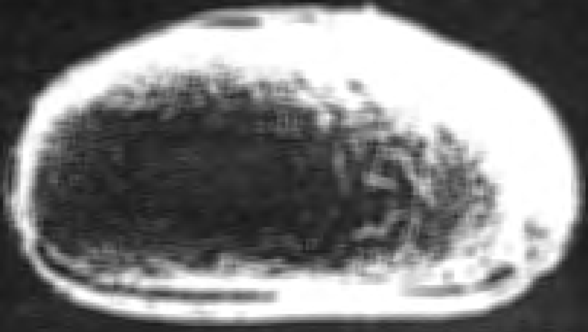
Plate 10. 31. *Buliminella* sp., side view, x273.
32. *Bulimina* sp., side view, x336.
33. *Bolivina* sp., side view, x150.
34. Ostracod *Cyprideis beaconensis*, x83





There are, however, twice as many genera present in these samples as in marsh samples from Elkhorn Slough and McClusky Slough. Elphidium (the dominant genus) make up at least 55 to 97 percent of the total population of foraminifera recovered from 11 out of 12 boreholes at the mouth of Elkhorn Slough (Table 1, Appendix 4).

The average number of genera of foraminifera recovered from each borehole sample is approximately three. However, near the base of borehole 9 (Figure 5), nine different genera have been identified from two samples. The only other sample recovered from the entire study area that has as many as nine genera of foraminifera is surface grab sample #1 (Figure 3). The borehole samples also are similar to surface grab sample #1 in that they both consist of coarse sand and contain abundant shell fragments and ostracods (Table 2).

Ostracods and diatoms are abundant in surface grab samples and subsurface samples recovered throughout the study area (Appendices 1-5). Ostracods have been identified in surface grab sample number 12 and three samples taken from cores 5, 6, and 8 of the marsh transect (Appendix 5, Figure 3). Diatoms have been identified in samples from boreholes 6 and 8 and Elkhorn Slough marsh cores 1, 2, and 12 (Appendix 5, Figure 3).

McClusky Slough

McClusky Slough (Figure 1) is a small isolated fresh water marsh that has no marine influence. Water samples taken from McClusky Slough showed 0.0 ppt salinity, and there are no fossil or living

	Borehole											
Species	2	3	4	5	6	7	8	9	10	11	12	13
Elphidium spp.	55	92	72	97	83	93	86	81	97	75	67	71
Ammonia beccarii	14	0	4	1	9	3	1	7	3	10	27	22
Elphidiella hannai	10	1	0	1	1	3	3	4	0	5	0	0
Trochamina inflata	2	7	24	0	6	0	8	1	0	0	0	7
Other foraminifera	19	0	0	1	1	1	2	7	0	10	6	0

Table 1. The four most common species of foraminifera (in percent of total population) recovered from all borehole samples at the mouth of Elkhorn Slough. See Appendix 4 for the other foraminifera present.

	Main Channel Surface Grab Sample 1	Borehole 9 17.5 m	19 m
Ammonia beccarii	240	14	15
Bucella frigida	2	4	1
Buliminella sp.		3	10
Cibicides lobatulus	5	3	7
Elphidiella hannai	8	10	21
Elphidium spp.	300	98	110
Florilus basispinatus		3	4
Globigerina bulloides		4	3
Haplophragmoides sp.	5		
Quinqueloculina sp.	3	2	3
Rosalina sp.	11		
Trochamina inflata	29		
Shell fragments	A	R	A
Diatoms	A	C	C
Ostracods	A	A	A
Grain Size	Gravelly Sand	Sand	Gravelly Sand

Table 2. Comparison of microfossil and grain size present in the main channel (surface grab 1) with samples from borehole 9 at 17.5 m and 19 m subsurface. R = rare (<10); C = common (10-50); A = abundant (>50); per 30 grams of sediment.

foraminifera, or any other marine organisms present in the first 65 centimeters of the subsurface. Yet, fossil marine foraminifera, diatoms, and ostracods are present at greater subsurface depths in three cores collected from marshes of McClusky Slough (Appendix 2).

McClusky Slough is similar to Elkhorn Slough in that the generic diversification of foraminifera is low relative to open ocean samples (Bandy, 1963). Only four species make up the entire population found in all three cores. Haplophragmoides sp. comprising 73 percent; Miliammina fusca, 14 percent; Trochamina inflata, 8 percent, and Jadammina polystoma, 5 percent (Plates 3, 4 and 5). Also, the same species of diatoms and ostracods found in both subsurface and surface samples from Elkhorn Slough are present, but in less abundance beneath McClusky Slough.

Accumulation Rates

The results of five amino acid racemization dates determined for hand-picked species of Elphidium and one radiocarbon date determined from mollusc fragments at the base of borehole 11 are shown in Figure 5 and Table 3. Two other radiocarbon dates for salt marsh peat samples recovered in core 8 of the marsh transect are also given (Table 3).

Rates of accumulation near the mouth of Elkhorn Slough were approximately 2.8 mm/yr between 8,000 and 5,000 years ago (Figure 11). The rate of accumulation gradually slowed to 1.7 mm/yr at approximately 5,000 years B.P. and to 1.1 mm/yr for approximately the

Borehole	Depth (m) below sea level	Age Estimates
9	7.5	2,600 ± 800 years B.P.
6	8.6	2,700 ± 800 years B.P.
8	8.7	3,100 ± 900 years B.P.
13	9.3	2,700 ± 800 years B.P.
7	12.3	5,000 ± 1,200 years B.P.
11	20.5	7,795 ± 240 ^{14}C years B.P.

Marsh Core	Depth (cm) below marsh surface	Age Estimates
8	275	1,740 ± 130 ^{14}C years B.P.
8	635	4,845 ± 195 ^{14}C years B.P.

Table 3. Results of amino acid racemization dates and radiocarbon dates determined for various samples recovered from Elkhorn Slough. See Figures 6 and 10 for subsurface locations.

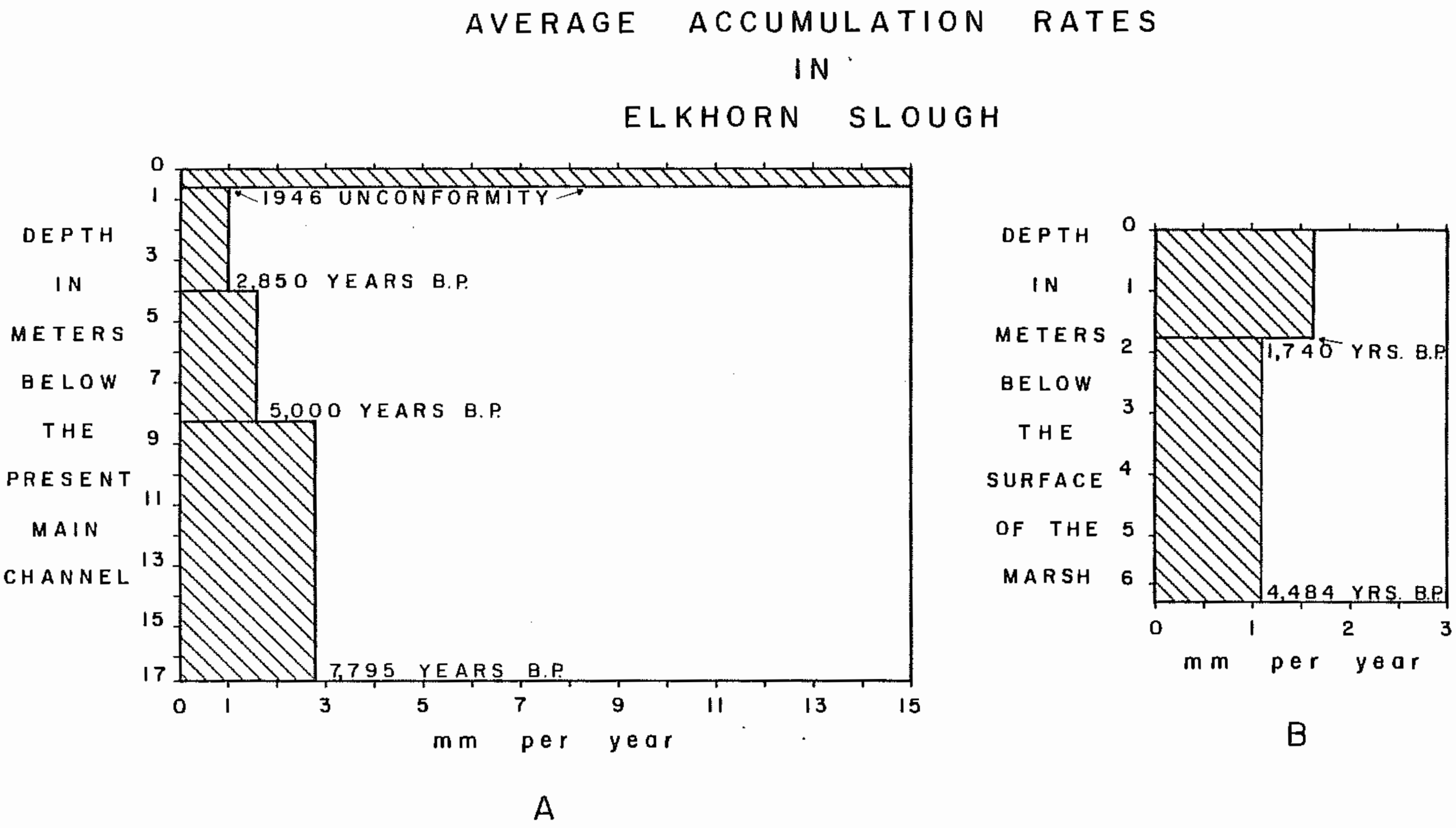


Figure 11. Average rates of Holocene accumulation in Elkhorn Slough at the mouth of the present main channel (A) and at the east end of the marsh transect (B).

last 3,000 years. After a period of scouring that occurred shortly after the jetties for the Moss Landing Harbor were installed in 1946, sedimentation rates increased to 15 mm/yr at the mouth of Elkhorn Slough.

Figure 12 shows a plot of the average accumulation rates that occurred near the mouth of Elkhorn Slough during the past 8,000 years. The curve in Figure 12 closely resembles sea level curves for the past 8,000 years (Atwater, 1979; Neumann, unpublished sea level curve), and it appears that the rate of Holocene sea level rise may have influenced the rate of deposition that occurred near the mouth of Elkhorn Slough. As sea level rose more rapidly from 8,000 to 5,000 years B.P. at approximately 3 mm/yr (Atwater _et al_., 1979), accumulation rates in the main channel were also the greatest at 2.8 mm/yr. As sea level slowed to approximately 1.4 mm/yr from 5,000 years ago to present (Atwater _et al_., 1979), sedimentation rates at the mouth of Elkhorn Slough also slowed by a comparable margin (Figure 12).

Accumulation rates at the eastern end of the marsh transect during the past 5,000 years differ from that at the mouth of Elkhorn Slough. The rate of accumulation in this area increased from 1.1 mm/yr from approximately 5,000 to 2,000 years B.P. to nearly 1.7 mm/yr during the past 2,000 years (Figure 11).

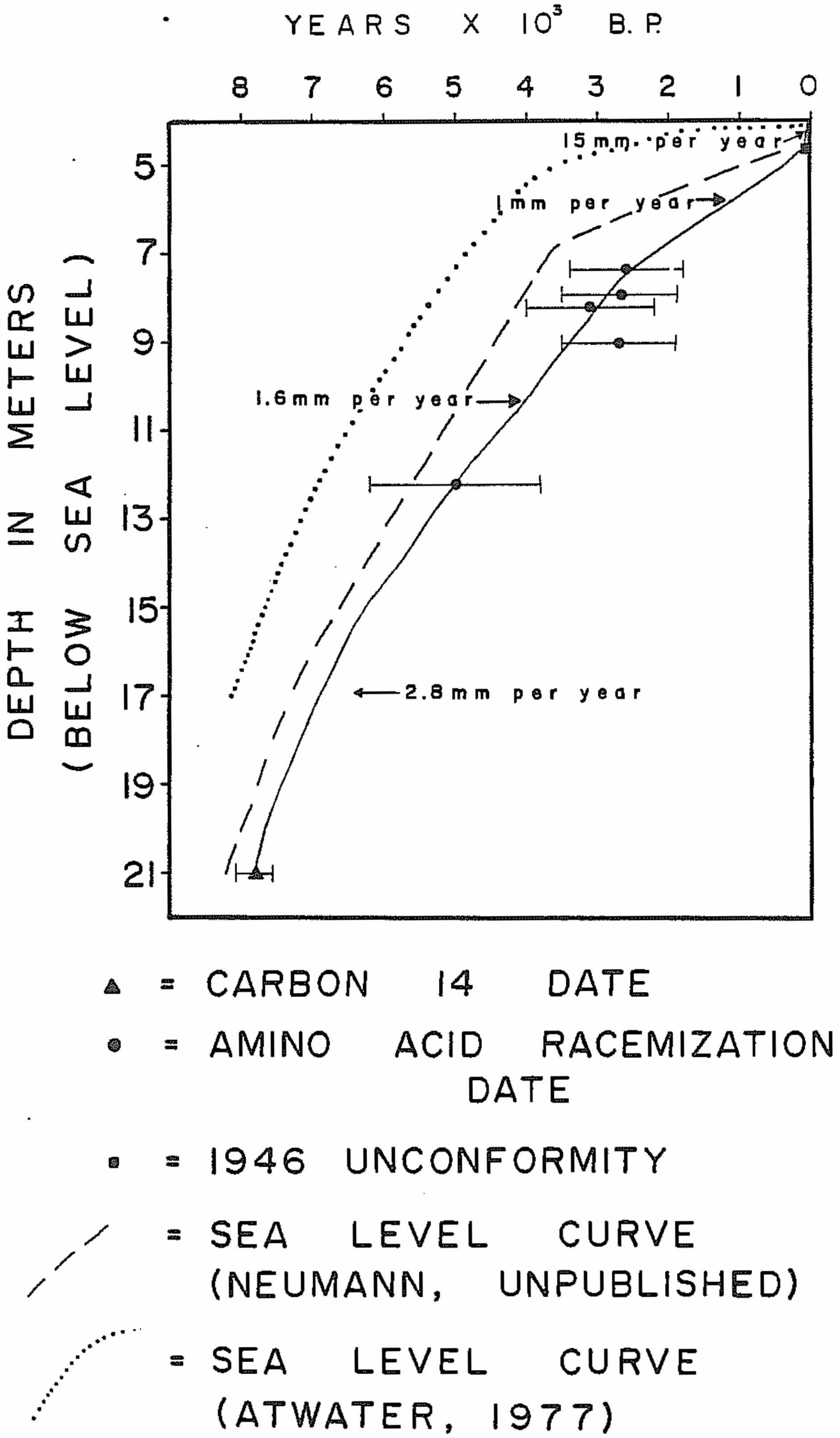


Figure 12. Average accumulation rates that occurred at the mouth of Elkhorn Slough during the past 8,000 years (solid line).

DISCUSSION

Geologic History

Oligocene to Early Pleistocene. Elkhorn Valley and Elkhorn Slough have an obvious and important relationship with the Monterey Submarine Canyon. These features have an equally important, but more obscure, relationship with an older, buried canyon that was eroded in the central Monterey Bay region between Cretaceous and Miocene time (Martin, 1964; Martin and Emery, 1967; Greene and Clark, 1979). In order to more fully understand the origin and significance of Elkhorn Valley and Elkhorn Slough, it is necessary to discuss these canyons.

The Monterey Bay region of central California encompasses a geologically complex portion of the continental margin. The entire region is located on a major structural feature known as the Salinian Block, which is an allochthonous terrain bounded on the northwest by the San Andreas fault zone and on the southeast by the San Gregorio and Nacimiento fault zones (Figure 13; Greene, 1977b; Mullins and Nagel, 1981; Nagel and Mullins, 1983). Tectonic uplift of smaller structural areas within the Salinian Block occurred numerous times in the Monterey Bay region throughout the Tertiary (Greene and Clark, 1979). One such event was the uplift of a large land mass, referred to as the Ben Lomond-Gabilan Block, that occurred along the Zayante-Vergeles fault in the middle to late Oligocene (Clark and Rietman, 1973; Greene and Clark, 1979).

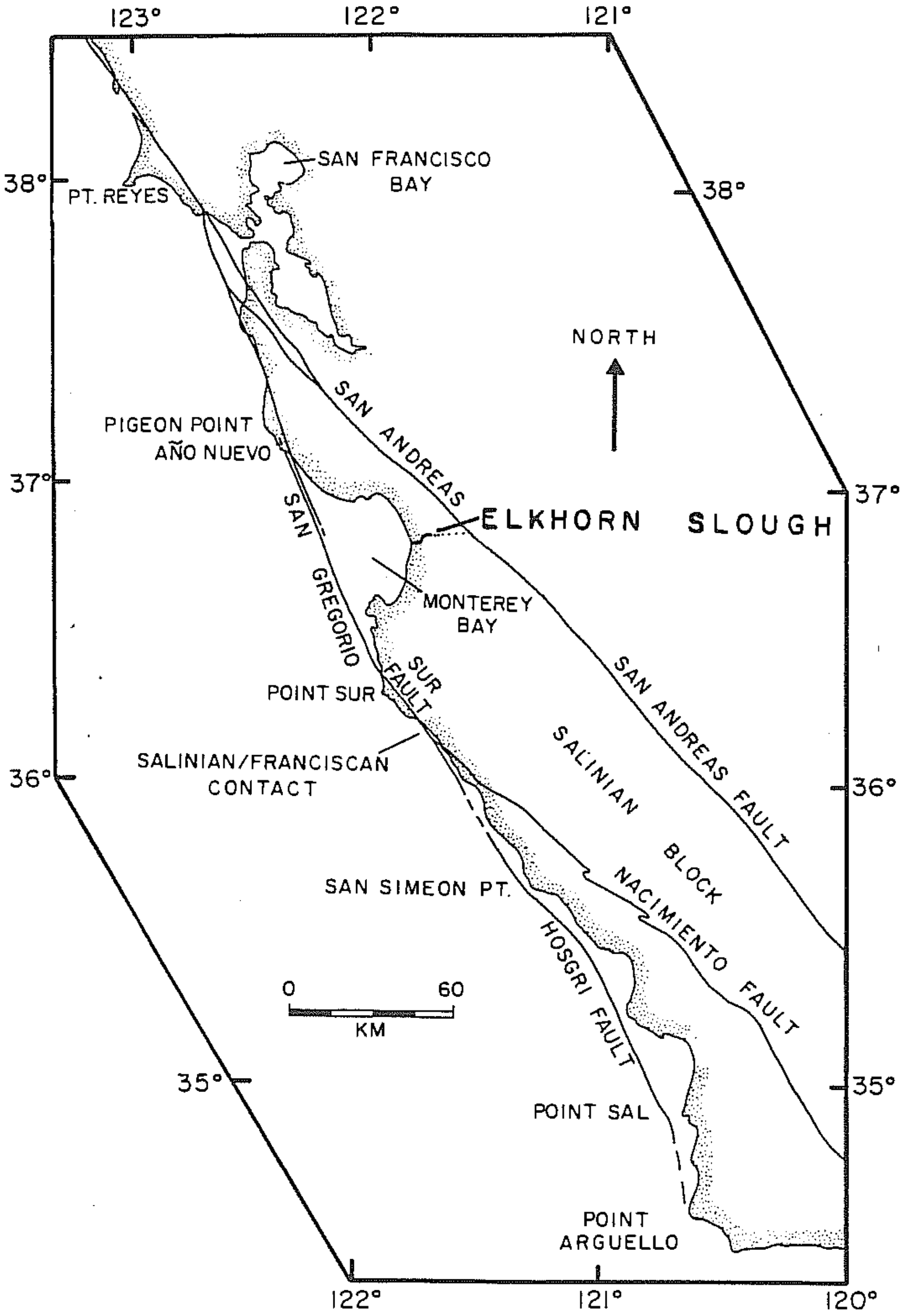


Figure 13. Map illustrating the relationship of Elkhorn Slough and central Monterey Bay to the Salinian Block; modified from Nagel and Mullins (1983).

A large slope off the Ben Lomond-Gabilan Block drained to the southwest during the late Oligocene, and subaerial erosion removed most Paleogene sediments that may have overlain the Cretaceous Salinian basement (Greene, 1977b). The late Oligocene is also the time of the lowest known stand of relative global sea level (Vail et al., 1977) which probably played an important role in the exposure of Paleogene sediments. Martin and Emery (1967) referred to the resultant erosional surface, described from Salinas Valley well log data, as the "Elkhorn erosion surface." Starke and Howard (1968) and Hoskins and Griffiths (1971) also have reported the existence of this erosional surface in the Monterey Bay region (Figure 14).

Relief on the Elkhorn erosion surface was well established by early Miocene time when a canyon was cut into granitic basement of the southwest- tilted Ben Lomond-Gabilan Block, presumably by subaerial river erosion. The canyon was probably formed between late Cretaceous and early Miocene time, because it is incised into Cretaceous basement and filled with middle Miocene sediments (Martin, 1964; Starke and Howard, 1968; Greene, 1977b). The filled canyon, often referred to as the Pajaro Gorge, was then buried with upper Miocene, Pliocene, and early Pleistocene sediments (Figure 14; Martin, 1964; Starke and Howard, 1968).

According to Martin (1964) and Greene (1977a) the present Monterey Submarine Canyon was formed in the late Pliocene or early Pleistocene by both subaerial river erosion and submarine erosion. Nagel (1983) pointed out, from offshore seismic evidence, that a major period of scouring and canyon formation occurred during one or more

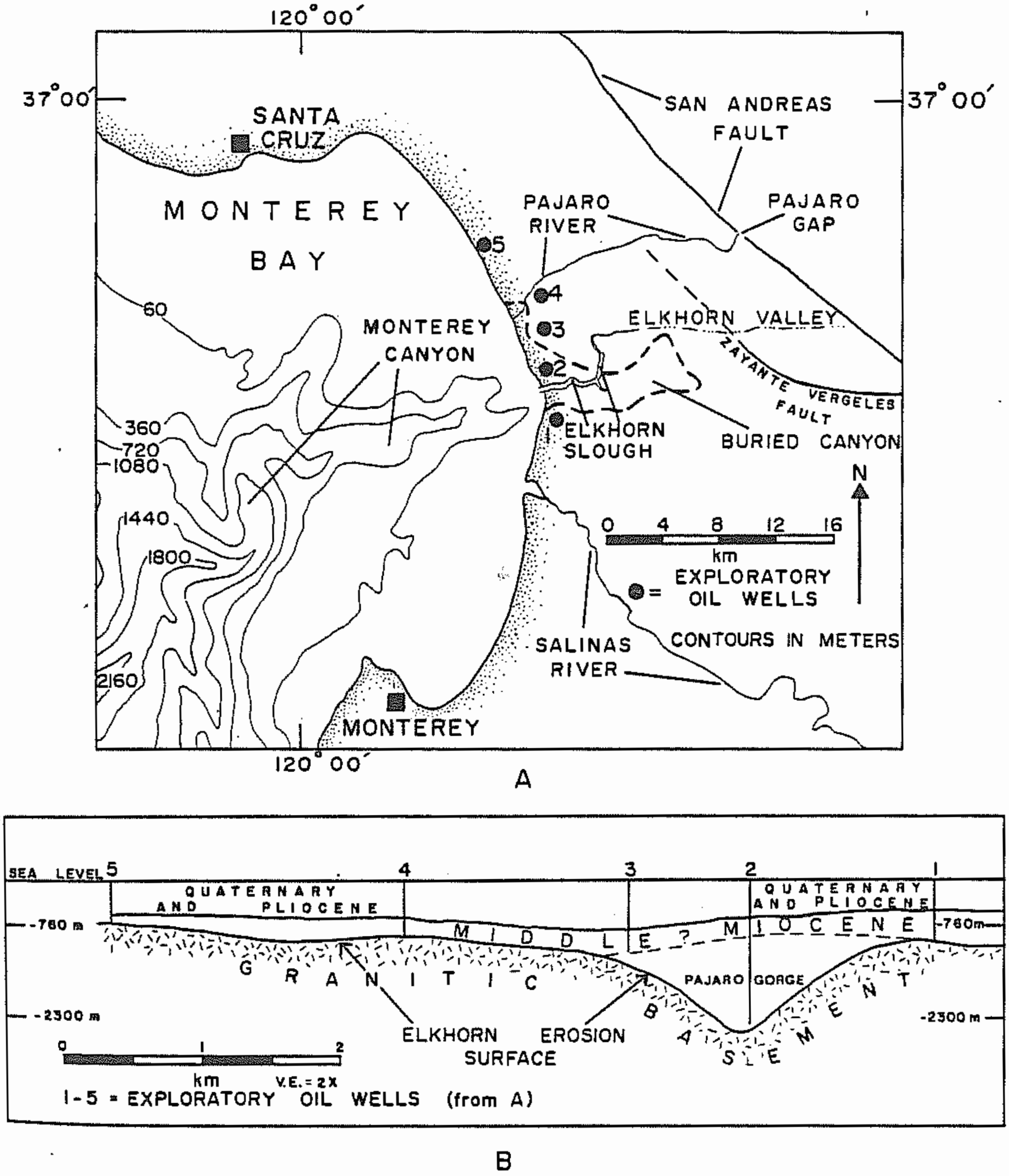


Figure 14. Map showing the relationship of buried canyon (Pajaro Gorge) to Monterey Submarine Canyon and Elkhorn Slough (A). Geologic cross section illustrating Elkhorn erosion surface and size of Pajaro Gorge (B); modified after Starke and Howard (1968).

low stands of sea level in the Monterey Bay region during the late Pliocene and early Pleistocene. These data suggest that the Pajaro Gorge was completely filled and covered, possibly for as long as 10 to 15 million years, before the exhumation of the modern Monterey Canyon.

It is not accidental that the headward reaches of Monterey Submarine Canyon and the mouth of Elkhorn Valley are directly above and aligned with the Pajaro Gorge (Figure 14). Compaction of thick sediment deposits in Pajaro Gorge is thought to have caused a geographically low region which directed large rivers toward central Monterey Bay (Martin, 1964; Martin and Emery, 1967) that may have aided in the initial formation of the Monterey Submarine Canyon by subaerial scouring of its headward portions during sea level lowstands.

Elkhorn Valley was most likely formed during this time, eroded by rivers directed toward central Monterey Bay. Much of Elkhorn Valley cuts through undifferentiated eolian and lagoonal deposits of the Aromas Sands. This formation was deposited during relative lowstands of sea level and now extends offshore more than 10 km from the mouth of the Pajaro River (Greene and Clark, 1979). Seismic reflection data from Monterey Bay suggest that the Aromas Sands are of late Pliocene to early Pleistocene age (Greene and Clark, 1979) and therefore predate, or are contemporaneous with, the formation of Elkhorn Valley.

Early Pleistocene to Late Pleistocene. Seismic activity, tectonic uplift and subsidence, offset of major structural and lithologic units and dramatic changes in climate occurred in the

Quaternary Period in the Monterey Bay region and have been responsible for the formation of lakes, dams, and the changing of courses of major rivers (Griggs, 1973; Jenkins, 1974; Greene and Clark, 1979). It remains unclear, however, where some of the more significant rivers originated, particularly those that may have scoured of Monterey Submarine Canyon and Elkhorn Valley, and how they reached the central Monterey Bay region. A working hypothesis, previously suggested by a number of workers (LeConte, 1891; Branner, 1907; Snyder, 1913; Beard, 1941; Allen, 1946; Baldwin, 1963; Martin, 1964; Martin and Emery, 1967; Jenkins, 1974), is that periodically during the Pleistocene, large scale drainage possibly from the Santa Clara Valley, joined at times with drainage from the Great Valley of California, emptied into Monterey Bay at the head of Monterey Canyon (Figure 15). Evidence supporting this hypothesis comes from the absence of a submarine canyon off the Golden Gate and the presence of a submarine canyon off central Monterey Bay, where present-day drainage enters the Pacific Ocean, plus the fact that Elkhorn Valley is positioned directly landward of the head of Monterey Submarine Canyon. Many submarine canyons worldwide show a close relationship to land rivers and drowned river valleys, and there is growing evidence that subaerial erosion plays an important role in the initial genesis of submarine canyons (Shepard, 1981).

Other evidence that large scale drainage periodically discharged through Elkhron Valley comes from numerous well preserved stream terraces that line the valley at elevations of 18, 24, and 60 meters (Allen, 1946; Baldwin, 1963; Dupree, 1975). Presently, a small

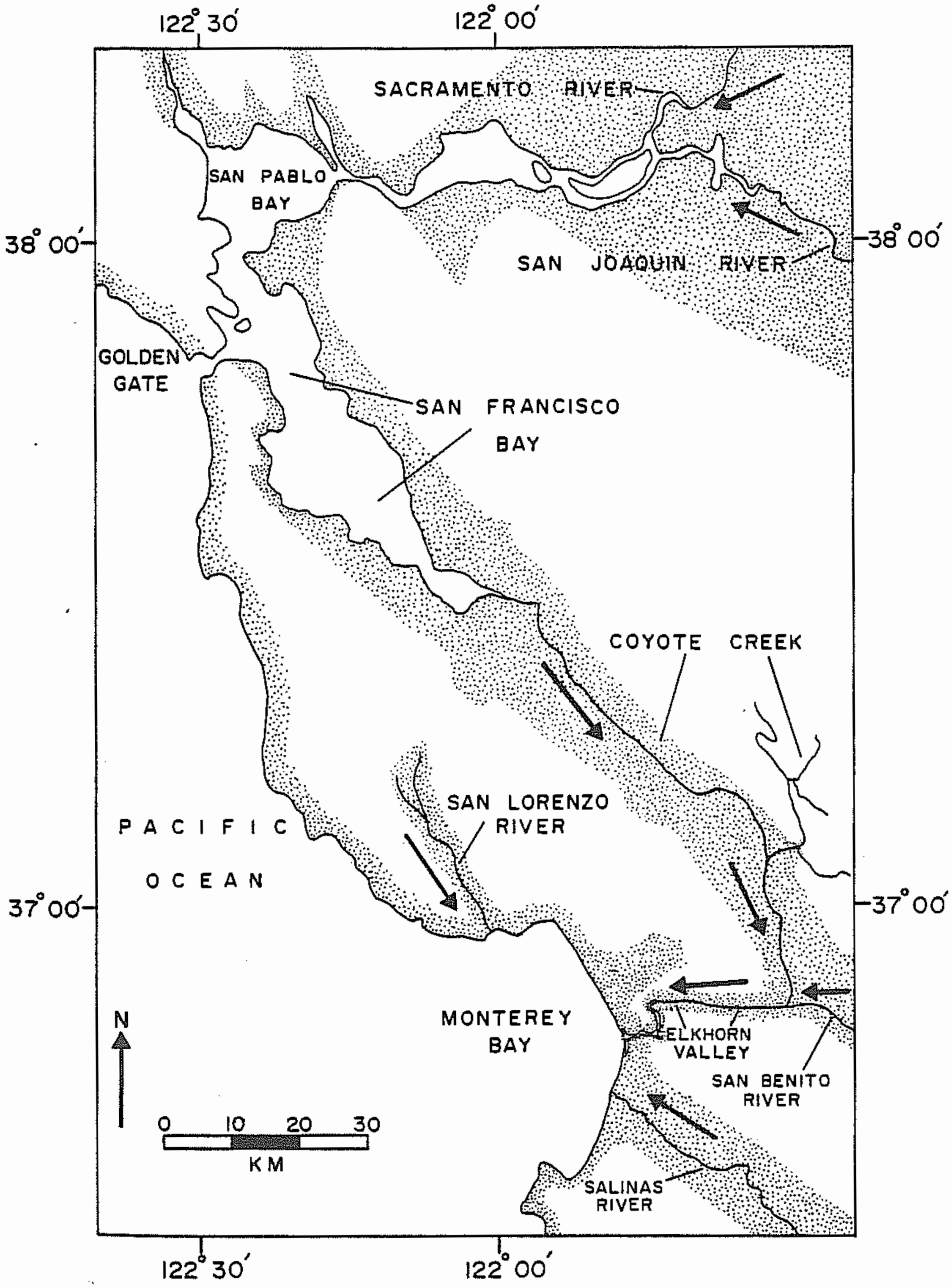


Figure 15. Large rivers that may have periodically emptied into Monterey Bay via Elkhorn Valley during Pleistocene time may have originated in the Santa Clara Valley and the Great Valley of California. Stippled areas represent lowlands and valleys.

intermittent stream, incapable of forming stream terraces at such elevations, flows through the geographically "oversized" Elkhorn Valley into Elkhorn Slough. The large size of Elkhorn Valley, approximately 1 km across and 70 meters deep, also suggests that the valley could have accommodated a much larger flow of water. Menard (1960) and Normark (1970) described a very extensive submarine fan that is present in the adjacent deep sea at the mouth of the Monterey Canyon system. Menard (1960) computed that the volume of material eroded from the continental slope and shelf amounts only to about one-tenth of the sediment deposited in the deep-sea fan adjacent to Monterey Canyon and concluded that most of the fan sediment must have been eroded and transported to the continental margin by subaerial rivers.

A similarity between fresh water fishes found in the Sacramento-San Joaquin drainage system and streams tributary to San Francisco and Monterey Bays also supports the hypothesis that the Great Valley of California periodically drained into Santa Clara Valley and ultimately into Monterey Bay (Branner, 1907; Snyder, 1913; Baldwin, 1963; Moyle, 1976). Both the Pajaro River, which presently drains into Monterey Bay, and Coyote Creek, which presently drains into south San Francisco Bay (Figure 16) contain nearly the same species of fresh water fishes found in the Sacramento-San Joaquin system (Snyder, 1913; Moyle, 1976). This indicates that there were periodic connections of these drainage systems, and according to Moyle (1976) these connections occurred as early as late Pliocene-early Pleistocene. The other two major tributaries of Monterey Bay, the

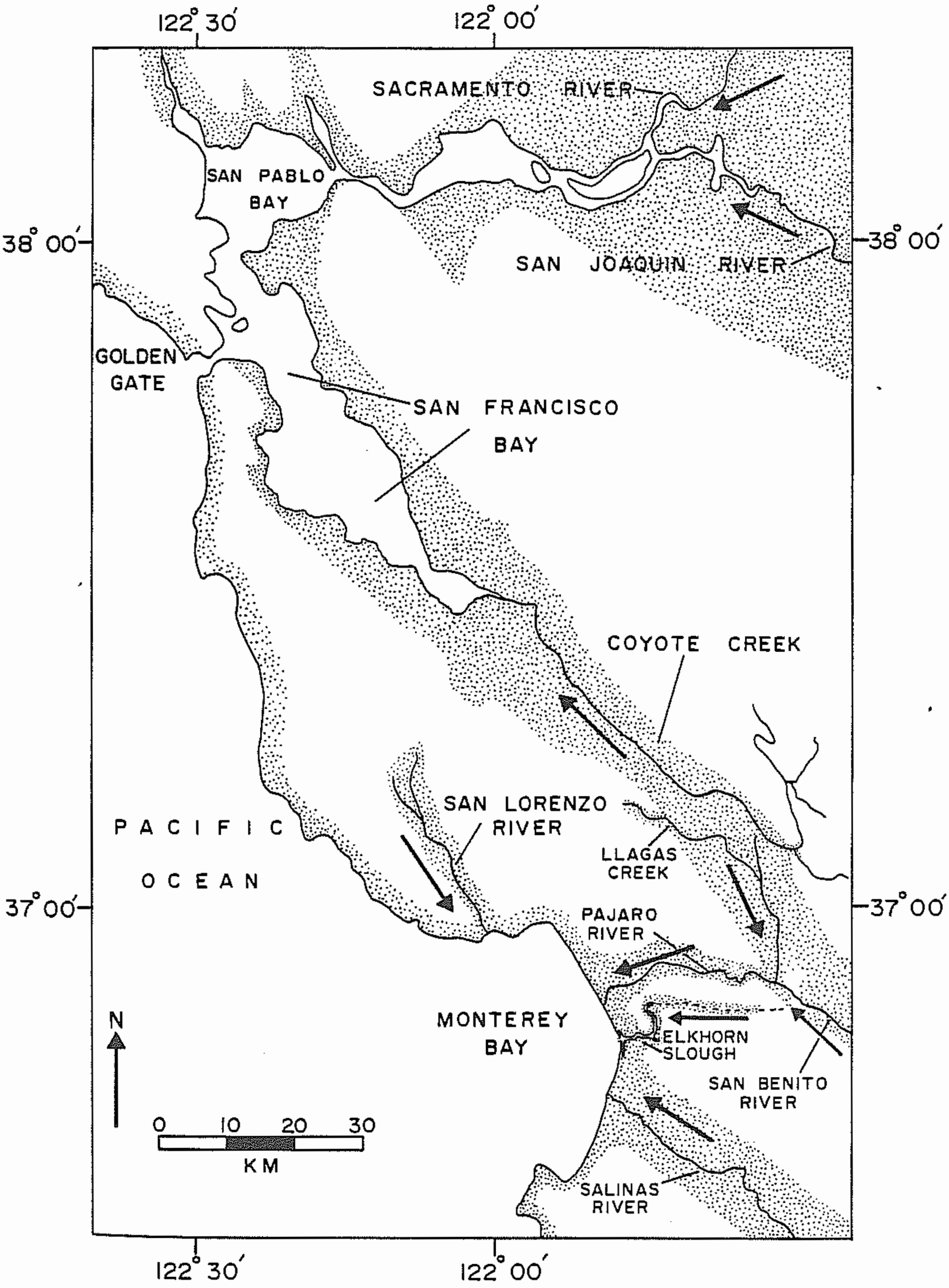


Figure 16. Map of central California illustrating the present direction of flow of major river systems. Stippled areas represent lowlands and valleys.

Salinas and San Lorenzo Rivers, also contain fishes found in the Sacramento-San Joaquin River system, although similarity of their assemblages is not quite as complete as that of the Pajaro River and Coyote Creek (Snyder, 1913; Moyle, 1976). Fishes probably intermixed with these two rivers when converging lowland connections existed in the Montery Bay area (Branner, 1907; Moyle, 1976). Further support that the drainage from the Sacramento-San Joaquin systems possibly connected with the Santa Clara Valley drainage comes from the presence of non-marine alluvial and eolian deposits that underlie the Holocene estuarine deposits of San Francisco Bay (Atwater et al., 1977). These and other deposits indicate that this area has alternated between marine and fresh water conditions numerous times during the Pleistocene, in response to glacioeustatic sea level fluctuations (Atwater et al., 1977; Ross, 1977; Wagner, 1978). During low stands of sea level it may have been possible for Great Valley drainage to flow southward, through the valley now occupied by San Francisco Bay, into the Santa Clara Valley and ultimately into Elkhorn Valley (Figure 15). It should be noted that the present marine waters of San Francisco Bay, which act as a barrier to any mixing of fresh water fishes between the Great Valley and Santa Clara Valley, flooded and submerged the valley only 11,000 years ago (Atwater et al., 1977).

As previously mentioned, the greater part of the Santa Clara Valley presently drains north to the San Francisco Bay via Coyote Creek (Figure 16). An alluvial fan which spreads out across the entire width of the Santa Clara Valley is the only barrier that presently separates the watershed that drains the north end of Santa

Clara Valley from the southern end (Allen, 1946; Jenkins, 1974). The south end of Santa Clara Valley presently drains into Monterey Bay via Llagas Creek and the Pajaro River (Figure 15). However, there is sedimentologic evidence that Coyote Creek has shifted its course to the south several times in the Pleistocene, especially during the constructional phases of the fan (Branner, 1907). Therefore, during times when Coyote Creek flowed to the south, the entire Santa Clara Valley, and possibly the Great Valley of California (during low stands of sea level) would have drained south into Elkhorn Valley and Monterey Bay (Branner, 1907; Howard, 1951; Jenkins, 1974).

The headward portions of Elkhorn Valley near the San Andreas fault were disrupted by uplift and tilting that took place at the north end of the Gabilan Range in the middle to late Pleistocene (Martin, 1964; Jenkins, 1974). According to Martin (1964) other central Monterey Bay drainages were affected by this event. Only a short insignificant stream occupied the Salinas Valley in the earlier Pleistocene, but the tilting of the Gabilan Range caused the drainage pattern of the Salinas River to assume its present course and length (Martin, 1964).

Contemporaneously, or shortly after, tectonic movements occurred near the headward portions of Elkhorn Valley, major portions of its drainage system were displaced by movement along the San Andreas fault (Figure 17; Baldwin, 1963; Martin, 1964; Jenkins, 1974). The Pajaro River (formerly Coyote Creek) presently takes an unusual right angle turn as it crosses the San Andreas fault at the Pajaro Gap (Figure 17). From the mouth of the San Benito River to the Pajaro Gap, the

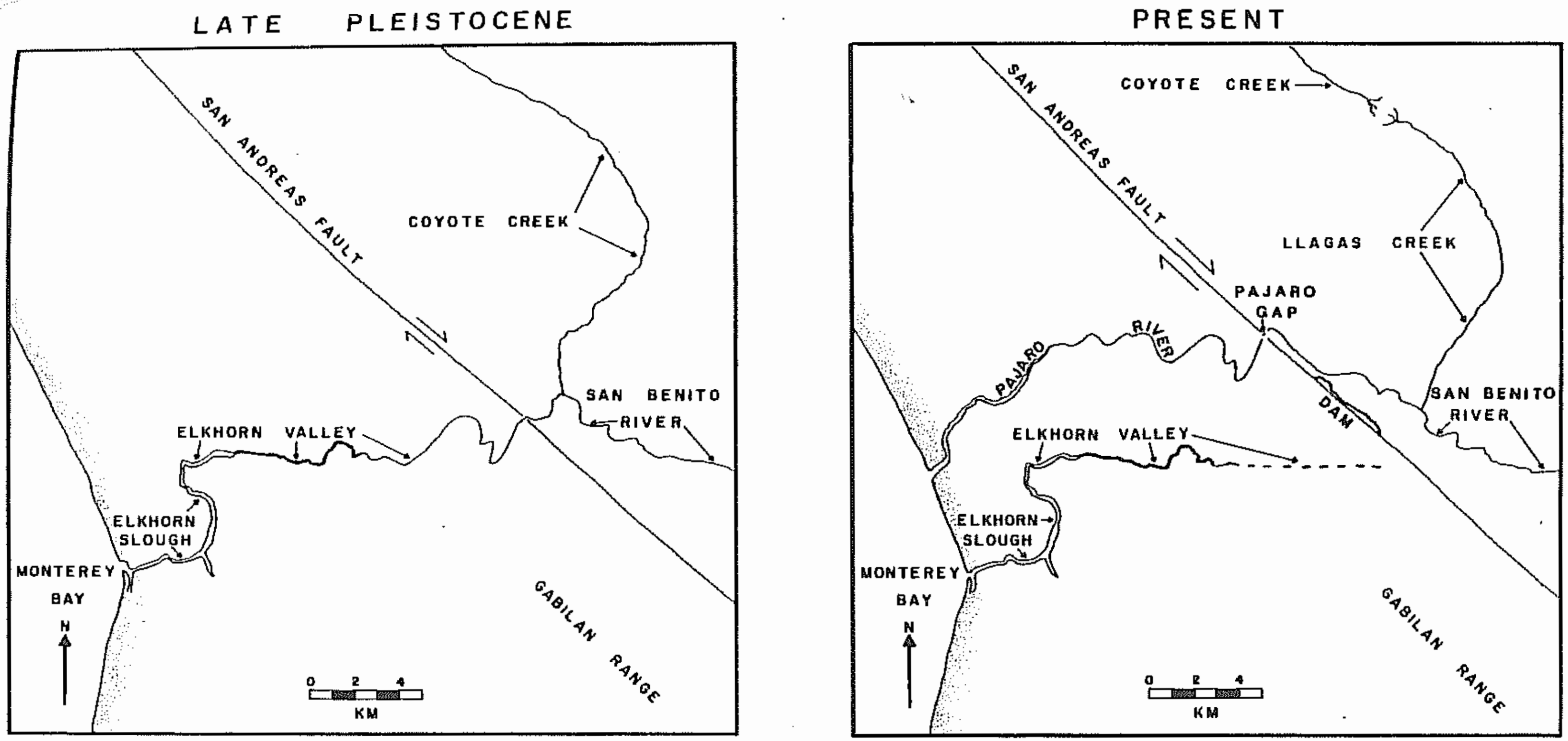


Figure 17. During the late Pleistocene the Santa Clara Valley may have drained into Monterey Bay via Elkhorn Valley and Coyote Creek. The Pajaro River system was established when major portions of Elkhorn Valley's drainage system were displaced to the north by movements along the San Andreas fault; modified from Martin (1964) and Jenkins (1974).

Pajaro River appears to be offset by approximately 8 km in a right-lateral sense, from a southerly course to its present northwesterly direction (Figure 17). According to Beard (1941), major headward tributaries of the Elkhorn Valley drainage were captured by the San Benito River, which was also displaced northward with the Pajaro River system at this time.

If displacement along the San Andreas fault was constant at 6 cm/yr (Atwater, 1970), it would have taken approximately 150,000 years for the Pajaro River to have migrated approximately 8 km north to its present position. Jenkins (1974) suggests that as the Pajaro River was being displaced by right lateral movement away from the headward positions of Elkhorn Valley, a dam formed 100,000 years ago as the system passed in front of a higher range of Purisima hills. The result of the dam was the formation of a large body of water that occupied the southern Santa Clara Valley. A portion of the body of water, referred to as Lake San Benito, drained through Elkhorn Valley although headward portions probably were partially destroyed by this time (Jenkins, 1974).

It appears that both the Pajaro and Salinas Rivers were not in existence during the early Pleistocene (except possibly as small coastal streams) and unlike Elkhorn Valley, had little bearing on the genesis of the headward portions of the Monterey Submarine Canyon (Beard, 1941; Martin, 1964). Furthermore, periodic drainage into the Pajaro River from Coyote Creek and possibly from central California must have continued to the late Pleistocene (less than 100,000 years ago) after northward displacement of the Pajaro River in order to account for the intermixing of fresh water fish species between these otherwise isolated drainage basins.

Late Pleistocene through Holocene. Many coastal valleys of California were incised by streams and rivers when low stands of sea level occurred during the Wisconsin glacial period (10,000-60,000 years B.P.; Dupre, 1975; Lohmar et al., 1980). During the most recent low stand of sea level, which occurred approximately 16,000 to 18,000 years ago (Milliman and Emery, 1968; Bloom et al., 1974; Beard et al., 1982), the western portion of Elkhorn Valley, where Elkhorn Slough is now located, was incised by river erosion to at least 30 m below present sea level. During this time, most of the sediment from Elkhorn Valley was deposited at or near the present shelf break, and as a consequence the sedimentary record of this event in the present coastal region is poorly preserved (Dupre, 1975). However, as a result of the most recent rise in sea level, previously incised coastal valleys in the Monterey Bay region were filled by a transgressive sequence of non-marine and marine sediments. Dupre (1975) characterizes these sediments as a mega-fining upward sequence of coarse-grained braided stream deposits to finer grained estuarine deposits.

The shallow stratigraphy at the mouth of Elkhorn Slough clearly shows this infilling episode. The absence of marine fossils from the gravelly unit beneath Elkhorn Slough indicates that this unit was deposited by rivers when sea level was rising. The very top portions of the gravelly unit contain some angular shell fragments which indicate that the upper portion could represent a high energy transitional river-to-marine environment. The boundary between the non-marine gravelly sands and marine sands/muddy sands above (Figure 4) may reflect a portion of the outline configuration of a late Pleistocene river channel.

Data collected from around the world suggest that sea level was 100 to 130 m lower during the last late Pleistocene low stand of sea level than today (Curry, 1964; Milliman and Emery, 1968; Shackelton and Opdyke, 1973; Dillon and Oldale, 1978). It is likely that increased precipitation and runoff during glacial stages (Fairbridge, 1972), temporarily renewed a significant drainage system in Elkhorn Valley competent to remove sediment and scour a channel. If the late Pleistocene drainage system incised its channels to near base level, the entrenched system would have easily reached the headward portions of the adjacent Monterey Submarine Canyon, which presently occur in water as shallow as 30 m.

As sea level rose rapidly at the close of the Pleistocene, marine waters flooded the incised channel that connects Elkhorn Valley with the headward portions of Monterey Canyon. Approximately 8,000 years B.P., relative global sea level was still 15 to 17 m lower than today (Atwater _et al_., 1977; Neumann, unpublished sea level curve), and a significant portion of continental shelf was still exposed. Marine waters flooded the incised river channel below the present mouth of Elkhorn Slough approximately 8,000 years ago when the base of the channel was at least 21 m lower in elevation than today (Figure 5). The depositional environment most likely experienced strong currents from marine waters funneling into and out of the late Pleistocene entrenched channels.

Between 8,000 and 10,000 years ago, a high energy tidal inlet developed similar to the marine environment that presently exists at the mouth of Elkhorn Slough. Both modern surface grab samples and samples recovered from boreholes at the mouth of Elkhorn Slough (Table 2; Appendix 4) are typical of open shelf, normal marine salinities (Lankford and Phleger, 1973) and were probably transported up and into the drowned channel by tidal action.

It is probable that a network of drainage channels was incised in other adjacent low areas of western Elkhorn Valley 4,000 to 5,000 years ago and that these entrenched channels connected Monterey Canyon with Elkhorn Slough as the valley was inundated by the rising sea. Marine microfossils recovered from the north end of the CALTRANS transect (Figure 5), Elkhorn Slough cores, and McClusky Slough cores (Figure 3) all indicate that marine waters flooded into these areas and created an estuary or embayment much larger than the present Elkhorn Slough-Moss Landing harbor system. From approximately 2,000 years ago to as recently as 1908 or 1946, extremely quiet water conditions existed near the present mouth of Elkhorn Slough as indicated by the presence of estuarine clays at the top of the fining upward sequence (Figure 5).

A fining upward sequence very similar to those described by Dupre (1975) and that which exists below the present mouth of Elkhorn Slough, is also present below the lower Salinas Valley and the Pajaro Valley. The base of the sequence below the Salinas Valley is composed of sand and gravels (Manning, 1963; Tinsley, 1975) that are probably generically equivalent to the sands and gravels below Elkhorn Slough. Above the sands and gravels in the Salinas Valley is a clay layer that contains a microfaunal assemblage indicative that shallow marine, estuarine conditions have been obtained from portions of the clay unit (Simpson, 1946; Tinsley, 1975). A nearly identical assemblage has also been obtained from the silts and clays beneath the mouth of Elkhorn Slough (Appendix 3). Manning (1963) has suggested that the gravelly sand layer and the clay layer beneath the Salinas Valley are late Pleistocene to early Holocene in age, which correlates well with the Elkhorn Slough sequence (Figure 5). Drill hole data from the Pajaro Valley and at the mouth of the Pajaro River also indicate that a similar sequence of gravel and finer grain sediments make up the Holocene alluvial fill, although direct evidence is still needed to confirm an estuarine origin of these sediments (Muir, 1972).

Many estuaries and coastal lagoons on both the west and east coasts of North America were formed in the early Holocene when rising sea level flooded incised drainages cut during the Wisconsin glacial period (Biggs, 1978; Atwater et al., 1979; Lohmar et al., 1980). According to Tinsley (1975), after the Salinas River incised its pre-Wisconsin valley fill during the last glacial period, sea level rose faster than the Salinas Valley could re-alluviate itself, resulting in the formation of a large, shallow estuary that extended inland as far north as the city of Salinas (Tinsley, 1975). Estuarine sediments beneath the Salinas River were eventually buried by younger river sediments deposited by the Salinas River (1975). Elkhorn

Valley, however, lacks a drainage basin of sufficient size to have filled Elkhorn Slough as rapidly as the Salinas River and probably Pajaro River filled in the estuaries that once occupied the western portions of their valleys. Sedimentation rates during the Holocene in the Salinas Valley were as high as 5.5 mm/yr (Tinsley, 1975) which is greater by a factor of two to three times that in the marshes (1.6 mm/yr) or main channel (2.8 mm/yr) or Elkhorn Slough (Figure 11).

Portions of the fining upward sequence below the mouth of Elkhorn Slough are shallower compared to equivalent sequences that exist below the mouth of the Salinas and Pajaro Rivers. These stratigraphic differences can be explained by the smaller drainage basin that feeds Elkhorn Valley since the headward portions of this system were disrupted and displaced northward. The river or stream draining Elkhorn Valley during the last lowstand and early rise in sea level was less competent than the Salinas and Pajaro Rivers and therefore not as able to incise its valley as deep as these adjacent valleys. Elkhorn Valley may have approached base level further out on the continental shelf, perhaps in the headward portions of Monterey Submarine Canyon (Figure 1).

Microfossils recovered from the marshes of both Elkhorn and McClusky Sloughs also indicate that a quiet water, estuarine depositional environment existed in these areas as early as 5,000 years ago. The most common foraminifera recovered from the marshes (Figure 8) are all commonly found living in salt marsh environments on the Pacific coast of North America (Phleger, 1970; Murray, 1971). The diatoms identified in the marshes of Elkhorn Slough (Appendix 5) are also typical brackish water, shallow benthic species common on intertidal salt marshes and on mud banks in San Francisco Bay (Laws, 1983). Ostracod data indicate that 2,000 to 5,000 years ago brackish water conditions with salinities possibly as low as 5 ppt existed in the upper portions of Elkhorn Slough. The absence of abundant non-marine ostracods further suggests that the upper portions of Elkhorn Slough during middle to late Holocene were not influenced by regular stream input. Groundwater seepage and flow from the Salinas River, when it discharged north of Elkhorn Slough, are the likely contributors of fresh water.

In the shallow subsurface of Elkhorn Slough, organic-rich clays, peats, and marsh assemblage microfauna are most abundant farthest from the present main channel and gradually decrease as the main channel is approached. This suggests that salt marsh plants (such as Salicornia virginica) have been accumulating in areas more distal to the present main channel for a longer time compared to areas more proximal to the present main channel. The lithostratigraphy (Figure 6) and biostratigraphy (Figure 9) of the marsh transect demonstrate this and show how the spatial distribution of salt marsh and mud banks in Elkhorn Slough have evolved during the last 5,000 years. Approximately 4,000 to 5,000 years ago a salt marsh existed at the base of the hillside in the area of the marsh transect, but was approximately half its present size (Figures 6 and 9). During this time a broad mud bank extended out toward the main channel where cores 5, 6, 7, and 8 are located (Figure 4). In only approximately 4,500 years the salt marsh expanded more than 50 meters toward the main channel burying older mud banks (Figure 18). Peats below McClusky Slough contain a salt marsh assemblage of microfauna very similar to fossil microfauna recovered from Elkhorn Slough, which suggests that this area was also occupied by a salt marsh that was probably part of the Elkhorn Slough system. If the upper 70 cm of sediment in McClusky Slough were deposited at a rate similar to the rate of deposition that occurred on the salt marsh in Elkhorn Slough for the past 3,000 years (1.6 mm/yr), then marine waters would have been cut off from McClusky Slough as recently as 500 years ago.

For the past 5,000 years, different hydrographic and sedimentologic processes have occurred at the western end of Elkhorn Slough compared with the subtidal channel near the mouth of the slough. The subtidal channel has received abundant sediment from the numerous small tributaries, particularly the intermittent stream at the head of Elkhorn Slough, whereas the mud banks and salt marshes have had less opportunity to receive sediments because of their intertidal positions. Figure 11B also shows that the upper 7 m of sediment at the east end of the marsh transect did not accumulate at a constant rate. Figure 8 shows that the depositional environment changed with time at this location from mud bank to salt marsh. It is likely that the vegetation on the salt marsh was able to trap sediments brought in from the rising tides more rapidly than the smooth surfaces of the mud banks. The different rates of accumulation may also be a result of recent agriculture that has taken place on the adjacent uplands.

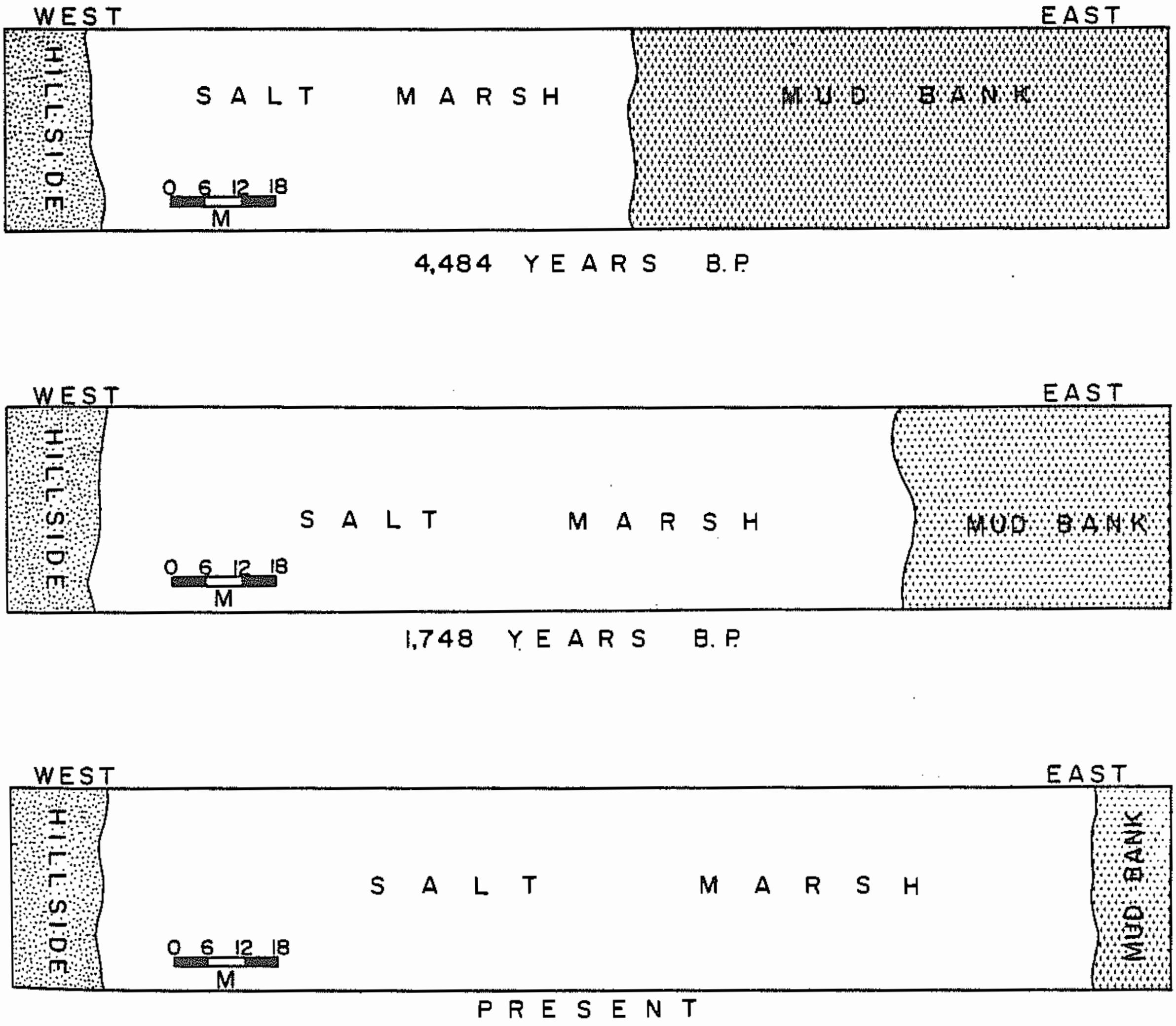


Figure 18. Schematic map view of the marsh transect showing the migration of salt marsh habitats over broad intertidal mud banks during the past 4,484 years.

Historical Times and Human Influences. Since the mid-1800's, Elkhorn Slough as well as the Salinas and Pajaro Rivers have shifted their coastal positions due to both natural and human influences. The Salinas and Pajaro Rivers once shared the same mouth located approximately 4 km north of Moss Landing (Blake, 1853). During the latter 1800's the Salinas River continued to discharge north of Moss Landing, but separate of the Pajaro River (Figure 19). Due to a series of winter storms in 1909, the Salinas River changed its course to its present position, approximately 8 km south of Moss Landing (Gordon, 1979; Figure 19). The position of the new river outlet was maintained by local farmers who reclaimed most of the Old Salinas River channel for agriculture (Gordon, 1979). Elkhorn Slough remained a tributary to the Old Salinas River channel until 1946, when the jetties for the Moss Landing boat harbor were installed (Figure 18). After installation of the jetties, the Old Salinas River mouth, previously kept open by tidal action, rapidly infilled with sand (Gordon, 1979).

As the energy of the depositional environment gradually decreased near the mouth of Elkhorn Slough during the past 8,000 years, rates of sedimentation also decreased until the system was dramatically interrupted by human influence in 1946. After the jetties were installed in 1946, tidal currents scoured the clay layer at the top of the Holocene fining upward sequence in the main channel. This scouring was followed by a period of rapid accumulation (15 cm/yr) of sand with abundant mollusc fragments that presently caps the sequence (Figure 5). Present rates of accumulation at the mouth of Elkhorn

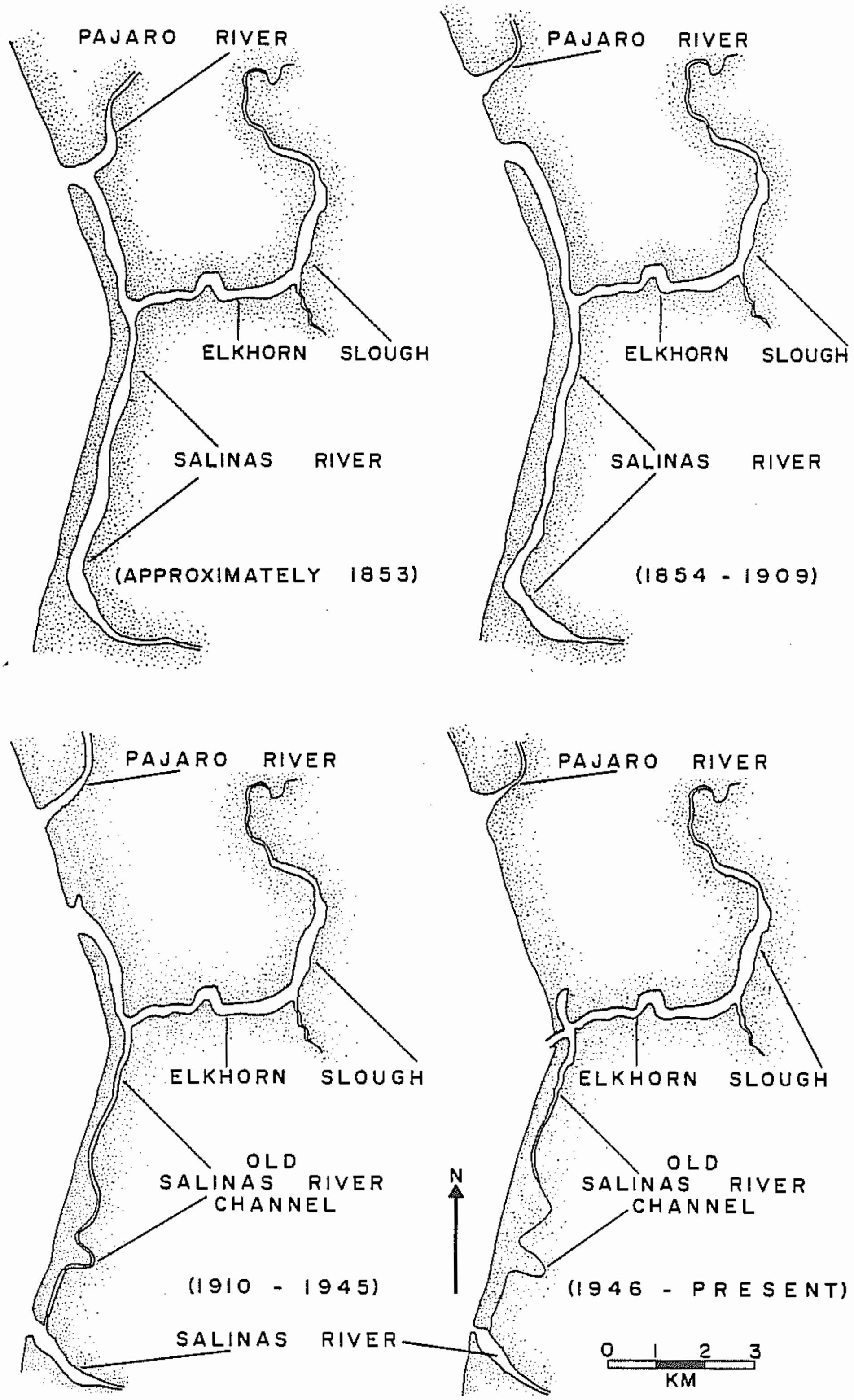


Figure 19. Maps showing various coastal positions of the mouths of Elkhorn Slough and the Salinas and Pajaro Rivers since the middle 1800's to the present.

Slough have not been determined, although it is likely that a state of equilibrium has been achieved.

Core 13 may demonstrate that because of human influence, sedimentologic trends that have been occurring naturally in Elkhorn Slough for the past 5,000 years have been interrupted. Core 13 is an exception to the general infilling trend because it was recovered from a mud bank that fringes the main channel (Figure 3) but contains only marsh assemblage of microfauna (Figure 10). At the site of core 13, instead of salt marsh taking its natural course of encroaching out and over the mud banks, it was most likely cut back allowing the older mud bank to expand westward, where the salt marsh once recently existed.

Future Fate of Elkhorn Slough. If the jetties for the Moss Landing harbor had not been installed in 1946, Elkhorn Slough would have evolved into a dry alluvial valley dissected by an intermittent stream similar to other sloughs (Struve Slough) in the area. The salt marsh would have continued to expand at the expense of mud banks, and the main channel would shallow and eventually disappear. The mouth of Elkhorn Slough and the Old Salinas River channel would have continued to migrate as it did for the last 100 years prior to the installation of the jetties. Dry alluvial conditions may have occurred in most areas within the next 2,000 years if sea level continued to rise at its present rate and accumulation rates of the last 2,000 years also would remain constant. For as long as sea level remains near its present relative position and the Moss Landing harbor is maintained, Elkhorn Slough will remain a subtidal embayment surrounded by salt marshes. Scouring will continue to deepen portions of the main channel and tidal creeks, and in some areas (Core 13, Figure 3), mud banks will expand. Relative sea level and human influence will continue to be the most important long-term factors regarding the future environmental and physical conditions of Elkhorn Slough.

CONCLUSIONS

The origin of Elkhorn Valley and the headward portions of Monterey Submarine Canyon are related to an older buried canyon called the Pajaro Gorge eroded in the late Oligocene . Compaction of thick middle Miocene and Pliocene sediments deposited in Pajaro Gorge caused topograpic lows which directed large river systems toward central Monterey Bay. These river systems, which drained the Santa Clara Valley and at times the Great Valley of California, eroded Elkhorn Valley and the present headward portions of Monterey Submarine Canyon in the late Pliocene/early Pleistocene.

The upper (eastern) reaches of Elkhorn Valley were disrupted in the middle to late Pleistocene by uplift and tectonic tilting that occurred toward the north end of the Gabilan Range near the San Andreas fault. Approximately 150,000 to 300,000 years ago the Pajaro and San Benito Rivers, which once fed directly into Elkhorn Valley, were displaced to the north along the San Andreas fault and eventually established the present Pajaro River drainage system.

Increased precipitation and runoff which occurred during the late Pleistocene glaciation, created temporary streams and rivers in Elkhorn Valley that were competent enough to remove sediment and scour channels. During and shortly after the most recent low stand of sea level (16,000 to 10,000 years ago) a stream/river system was established in Elkhorn Valley and scoured a channel at least 30 m below present sea level. As sea level rose rapidly at the close of the Pleistocene, marine waters flooded the incised channel creating a high energy tidal inlet that had an open connection with the ocean.

Infilling of the main channel eventually impaired direct connections with the ocean, and the energy of the depositional environment was gradually reduced. A quiet water estuary or coastal lagoon existed in the western portion of Elkhorn Valley from approximately 5,000 years ago to as recently as 1946. Intermittent streams that have drained Elkhorn Valley during the last 5,000 years have not supplied sufficient sediment to infill Elkhorn Slough as rapidly as the Salinas and Pajaro Valley estuaries were infilled by their respective streams. The most common pattern of sedimentary infilling that occurred during the last 5,000 years was the expansion of salt marsh habitats at the expense of intertidal mud banks. As Elkhorn Slough gradually infilled, its size diminished when areas distant to the present main channel such as McClusky Slough, were cut off from marine influences.

The dominant human influence on Elkhorn Slough are the jetties for the Moss Landing harbor which interrupted sedimentary infilling trends that have been occurring naturally for the last 5,000 years. Instead of Elkhorn Slough evolving towards brackish, fresh water and eventually dry alluvial conditions as it was doing prior to the installation of the jetties in 1946, scouring occurred, and Elkhorn Slough has become a stable tidal embayment that experiences near-normal marine salinities. If direct human influence had not occurred, the main channel would have infilled, and the salt marsh environments would have continued to rapidly expand. Within approximately 2,000 years marine influences would have been entirely cut off, and most of Elkhorn Slough would have evolved toward dry alluvial conditions. Other areas may have resembled McClusky Slough, attaining fresh water conditions before being completely re-alluviated.

During the late Pleistocene, before any human influence was introduced in the area, the western portions of Elkhorn Valley, like San Francisco Bay, probably alternated between marine embayments and non-marine alluvial and fluvial conditions as a result of numerous glacioeustatic sea level fluctuations. Elkhorn Slough may represent only one of many other tidal embayments and estuaries that occupied the western portions of Elkhorn Valley in Late Pliocene/Pleistocene time during relatively high stands of sea level.

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APPENDICES

	Main Channel		Mud Bank							Tidal Channel	Marsh	
	1	8	2	4	5	7	9	10	12	3	6	11
Ammonia baccarii (Cushman)	240	8		53	42	5	>300	>300	>300	35		
Bucella frigida (Cushman	2	>300								1		
Cibicides lobatulus (Walker and Jacob)	5											
Clavulina sp.											2	
Elphidiella hannai (Cushman and Grant)	8											
Elphidium spp.	300	>300		9	10		53	26	>300	9		
Haplophragmoides sp.	5						6				1	
Jadammina polystoma Bartenstein and Brand)			3	5							8	4
Milliamina fusea (Brady)				7			1	11		1	17	7
Quinqueloculina sp.	3							10		2		
Rosalina sp.	11									3		
Trochamina inflata (Montagu)	29		27	5	3		5	2	50	34	52	50
Shell Fragments	A	A		R	R	R	R	R	A	C		
Gastropods		A					C					
Ostracods	A	A	A	A	R	A	A	A	A	R		
Diatoms	A	R	A	A	C	R	A	A	C	C	A	C
Foram Fragments	A	A	R	C			C	A		R	R	R

Appendix 1. The occurrence of microfauna recovered from 30 grams of sediment from 12 surface grab samples. See Figure 3 for their locations. R = rare, <10; C = common, 10-50; A = abundant, >50; per 40 grams.

Appendix 2. The distribution of microfauna recovered from the hand-driven cores taken in Elkhorn Slough. See Figure 3 for their locations. R = rare, <10; C = common, 10-50; A = abundant, >50; per 30 grams.

CORE 1

Sample Depth in Cm

	7	22	53	130	170	206	222	235	260	315	365	422	450	478	507	532	570	623	650
Ammonia beccarii (Cushman)																			
Elphidium spp.																			
Haplophragmoides sp.	4		6	3		4		2											
Jadammina polystoma (Bartenstein and Brand)																			
Milliammina fusca (Brady)																			
Trochamina inflata (Montagu)	64		95	63	39	33	72	34	12	17	19	12	4	2		10	105	1	
Shell fragments																			
Diatoms	A	R	C	C	C	C	C	C	C	C	C	C	C	C	A	C	C	A	A
Ostracods																			
Foram fragments													A	A	A				

CORE 2

Sample Depth in Cm

	6	20	42	85	130	165	207	223	234	270	274	320	360	410	430	450	462	480	528	570	630	670
Ammonia beccarii (Cushman)																						
Elphidium spp.																						
Haplophragmoides sp.					30	5	28	1	2	13	11	42		8	2							
Jadammina polystoma (Bartenstein and Brand)	3		6	3			10															
Milliammina fusca (Brady)			7		3	4						2										
Trochamina inflata (Montagu)	48	1	110	5	80	45	21	9	8	21	243	48	46	87	4		2		3	13	7	43
Shell fragments																						
Diatoms	C	R	A	C	A	C	C	A	A	A	A	C	A	A	A	A	A	A	A	A	R	A
Ostracods																						
Foram fragments	C		C		C	C	A	R		A	A	C	R	C					C			C

	CORE 3 Sample Depth in Cm												
	30	70	128	150	178	233	270	330	370	440	505	540	568
Ammonia beccarii (Cushman)													
Elphidium spp.													
Haplophragmoides sp.		36	4	150		8	200						
Jadammina polystoma (Bartenstein and Brand)	2	4											
Milliammina fusca (Brady)													
Trochamina inflata (Montagu)	104	11	13	>300	1	14	>300	57	63	29	10	1	17
Shell fragments													
Diatoms	R?	C	A	C	C	A	A	A	R	C	R	A	C
Ostracods													
Foram fragments	A	A		A		C	A	R	R			R	A

	CORE 4 Sample Depth in Cm												
	30	60	130	182	230	265	330	430	468	529	554	630	680
Ammonia beccarii (Cushman)													
Elphidium spp.													
Haplophragmoides sp.	68			72			10						1
Jadammina polystoma (Bartenstein and Brand)	2	4			1					1		2	
Milliammina fusca (Brady)													
Trochamina inflata (Montagu)	213	43	21		6	31	28	6	18	27	24	63	6
Shell fragments													
Diatoms	A	C	C	R	A	R	C	A	A	C	C	A	C
Ostracods													
Foram fragments	C	R	A			R	C		A		A		

CORE 5

Sample Depth in Cm

	5	25	47	72	130	164	174	206	240	287	306	330	370	430	470	520	558
Ammonia beccarii (Cushman)																111	
Elphidium spp.																176	
Haplophragmoides sp.		6	28				39				9						
Jadammina polystoma (Bartenstein and Brand)	3		7				2	1	1								
Milliammina fusca (Brady)																	
Trochamina inflata (Montagu)	243	86	98	18		38		26	36	78	2	108	3	2			8
Shell fragments																	
Diatoms	R	R	C	A	A	A	C	C	A	A	C	C	R	R	A	C	A
Ostracods																C	
Foram fragments	A	A	A				C	R	A	C	C	A				R	A

CORE 6

Sample Depth in Cm

	15	40	77	117	134	167	230	270	310	338	368	415	440	528	567	630	670
Ammonia beccarii (Cushman)						1	21	60	12					>300	>300	8	1
Elphidium spp.							53	230						>300	>300	33	12
Haplophragmoides sp.	4		7						46		6	5					
Jadammina polystoma (Bartenstein and Brand)	4																
Milliammina fusca (Brady)									1								
Trochamina inflata (Montagu)	29	143	31	87	68		14	33	146	7	8	57	16	18	10	41	2
Mollusc fragments						R	A	A	C	R			R	C	C	A	
Diatoms	C	R	C	C	C	A	A	A	A	C	C	A	C	C	A	A	C
Ostracods						A	A	A	A	R		R	R	A	A	A	R
Foram fragments	R	C		R	R		C	R	C			C	R	C	C	C	
Gastropods						R	A	A	R			R		C	R	R	

CORE 7

	Sample Depth in Cm															
	30	73	130	170	230	270	317	345	378	415	460	515	532	568	630	670
Ammonia beccarii (Cushman)				3	11		>300	>300	2	3	3	>300	>300	8	250	
Elphidium spp.				25	>300	16	>300	>300	29	3	14	>300	>300	20	>300	3
Haplophragmoides sp.	30														15	
Jadammina polystoma (Bartenstein and Brand)	5															
Milliammina fusca (Brady)																
Trochamina inflata (Montagu)	>300	4	17	3	14	179	16	60	5	47	2	17	12	11	280	1
Mollusc fragments				C	C	C	A	A	R	C		C	C		C	R
Diatoms	R	R	C	A	A	C	A	A	A	A	R	C	A	R	A	C
Ostracods			R	A*	A*	C	A*	A*	C	A*	C	A*	A*	C	A*	C
Foram fragments					C	C	A	A	C			A	A		A	
Gastropods	C			C	A	R	R	C	R	C		C			R	

CORE 8

	Sample Depth in Cm												
	30	78	115	145	178	240	325	355	435	535	568	635	678
Ammonia beccarii (Cushman)						29	2	8	3	61	2	1	
Elphidium spp.					3	218	32	64	18	147	17	1	
Globigerina bulloides (d'Orbigny)											1		
Haplophragmoides sp.	5	3		3					4	1	1		
Jadammina polystoma (Bartenstein and Brand)	3												
Milliammina fusca (Brady)													
Trochamina inflata (Montagu)	49	48		52		4	3	1	48	95	54	60	
Mollusc fragments					R	A	C	A	A	R	R	R	
Diatoms	C	A	C	A	A	A	A	A	C	A	A	C	A
Ostracods					A	A	C	A	C	R	R	C	
Foram fragments	A	C				C	C	C	R	A	R	R	
Gastropods						A	C	A	C				

CORE 9

Sample Depth in Cm

	20	66	153	259	315	341	380	395	445	510
Ammonia beccarii (Cushman)										
Elphidium spp.										
Haplophragmoides sp.						69				
Jadammina polystoma (Bartenstein and Brand)						24				
Milliammina fusca (Brady)	3									
Trochamina inflata (Montagu)			4			3			2	
Shell fragments										
Diatoms			C		C			A	R	R
Ostracods										
Foram fragments					A					

CORE 10

Sample Depth in Cm

	25	80	130	170	230	260	325	368	430	465	530	565	615	658
Ammonia beccarii (Cushman)														
Elphidium spp.														
Haplophragmoides sp.	3		3				5		2	1				
Jadammina polystoma (Bartenstein and Brand)														
Milliammina fusca (Brady)														
Trochamina inflata (Montagu)	14													
Shell fragments		R						R						
Diatoms	R		C	R		R	R		R	R				
Ostracods		C		C				C						
Foram fragments	R						R							

	CORE 11									
	Sample Depth in Cm									
	4	30	70	130	180	222	275	318	352	378
Ammonia beccarii (Cushman)										
Elphidium spp.										
Haplophragmoides sp.				16	15	27	26			12
Jadammina polystoma (Bartenstein and Brand)	13		1	5	2	6	1			1
Milliammina fusca (Brady)				11	1					
Trochamina inflata (Montagu)	51	13		43	80	8	3			6
Shell fragments									R	
Diatoms	C	C		A	A	C	A	A	A	C
Ostracods										
Foram fragments	C	A		C	A	A	R	C	C	A

	CORE 12													
	Sample Depth in Cm													
	17	70	135	170	220	270	295	320	325	350	383	428	478	530
Ammonia beccarii (Cushman)												30	>300	
Elphidium spp.												>300	>300	7
Haplophragmoides sp.	60		7	7			2	3			3			
Jadammina polystoma (Bartenstein and Brand)	14		1											4
Milliammina fusca (Brady)	9			2										
Quinqueloculina sp.														
Trochamina inflata (Montagu)	179		23	29		10	9				120	60		35
Shell fragments								C				C	C	
Diatoms	C	A	C	C	A	R	R			C	C	A	A	C
Ostracods												C	A	
Foram fragments												C	C	C
Gastropods														C

CORE 13

Sample Depth in Cm

	2	16	55	125	154	183	235	307	355	430	475
Ammonia beccarii (Cushman)	20										
Elphidium spp.	32										
Haplophragmoides sp.							20			2	1
Jadammina polystoma (Bartenstein and Brand)											
Milliammina fusca (Brady)											
Quinqueloculina sp.		2									
Trochamina inflata (Montagu)	2	8			11		60			12	1
Shell fragments											
Diatoms		C	A	R	A		C	R		R	R
Ostracods	C										
Foram fragments											

CORE 14

Sample Depth in Cm

	20	80	115	165	230	280	330	370	430	470
Ammonia beccarii (Cushman)				49	18	22	3	>300	36	>300
Elphidium spp.				147	65	55	6	>300	78	>300
Haplophragmoides sp.	8		6					5	2	4
Jadammina polystoma (Bartenstein and Brand)	1		1							
Milliammina fusca (Brady)		10								
Trochamina inflata (Montagu)	52		86	4			1	38	7	34
Shell fragments				R	R	A		C	C	C
Diatoms	R		R	C	R	R	R	C	C	C
Ostracods				*A	*A			*A	*A	*A
Foram fragments			A	R				C	R	C
Gastropods				R	A	C		C		C

* >300

	CORE 15													
	Sample Depth in Cm													
	12	48	75	115	133	158	230	270	330	370	430	470	530	570
Ammonia beccarii (Cushman)							30	>300	20	52	35	39		67
Elphidium spp.							65	>300	52	55	74	53	43	92
Haplophragmoides sp.	5								2	2	1	1	8	27
Jadammina polystoma (Bartenstein and Brand)	11				2				10		2	2	2	5
Milliammina fusca (Brady)	203				2									1
Trochamina inflata (Montagu)	43				16			8	33		9	14	12	114
Shell fragments							C	R	R	A	R	C		R
Diatoms	C		C	R	C		C	C	C	C	C	C	C	C
Ostracods							A	A		C	C	C	C	C
Foram fragments									A	R	R	R	R	C
Gastropods							C	R				R		

	CORE 16					CORE 17			
	Sample Depth in Cm								
	100	200	300	400	500	50	120	240	450
Ammonia beccarii (Cushman)			>300		101				>300
Elphidium spp.			>300	54	>300				>300
Haplophragmoides sp.					2		1		
Jadammina polystoma (Bartenstein and Brand)							2		
Milliammina fusca (Brady)								2	
Trochamina inflata (Montagu)				12	29		8	53	12
Shell fragments			C	C					R
Diatoms			R	C	R		R	R	R
Ostracods			A	C	A				A
Foram fragments			R		R				R
Gastropods			C		C				R

	CORE 18								CORE 19			
	Sample Depth in Cm											
	11	33	70	130	170	270	317	340	30	70	130	170
Ammonia beccarii (Cushman)						29			>300	292	240	94
Elphidiella hannai									20		3	
Elphidium spp.						130	43	18	>300	>300	>300	>300
Haplophragmoides sp.	22				45	56	19	8	2			
Jadammina polystoma (Bartenstein and Brand)	28	5				4			1	3		
Milliammina fusca (Brady)		>300			2				1	3		
Quinqueloculina									9	6		
Trochamina inflata (Montagu)	21	250	1			130	68	32	64	29		
Shell fragments							R	C	A	C	C	A
Diatoms		C	R		R	A	A	C	R	R	R	R
Ostracods						C	A	A	A	A	C	A
Foram fragments					A	C	R		R	R	R	
Gastropods							R	C				

Species	Depth in Cm										
	30	70	80	130	180	230	280	320	370	400	450
Haplophragmoides sp.	0	3	226	25	38	2	0	8	40	4	3
Jadammina polystoma	0	0	19	1	2	0	0	0	2	0	0
Milliammina fusca	0	0	0	0	0	0	0	0	56	0	12
Trochamina inflata	0	0	0	0	2	0	1	4	30	0	3
Diatoms	0	R	C	A	C	0	0	C	C	0	C
Ostracods	0	0	0	0	0	0	0	0	R	0	0

Appendix 3. The distribution of foraminifera, diatoms, and ostracods recovered in McClusky Slough from cores 20, 21, and 22. R = rare (<10; C = common (10-50); and A = abundant (>750); per 30 grams.

Appendix 4. The distribution of microfauna recovered from the CALTRANS boreholes. R = rare, <10; C = common, 10-50; A = abundant, >50; per 40 grams.

BOREHOLE 2

Sample Depth in Meters

	3.0	4.5	6.0	7.5	9.0	10.4	12.0	13.3	14.8	16.3
Ammonia beccarii (Cushman)		18								
Bolivina sp.										
Bucella frigida (Cushman)		3								
Buliminella sp.										
Cibicides lobatulus (Walker and Jacob)		10								
Elphidiella hannai (Cushman and Grant)		11	1							
Elphidium spp.		69								
Florilus basispinatus (Cushman and Moyer)		5								
Globogerina bulloides (d'Orbigny)		5								
Haplophragmoides sp.		1								
Quinqueloculina sp.										
Trochamina inflata (Montagu)	1	1								
Shell fragments	R		R	R	R					R
Diatoms	R	C	C	R						
Ostracuds										

BOREHOLE 3

Sample Depth in Meters

	3.0	4.5	6.0	7.5	9.0	10.4	12.0	13.3	14.8	16.3
Ammonia beccarii (Cushman)										
Bolivina sp.										
Bucella frigida (Cushman)										
Buliminella sp.										
Cibicides lobatulus (Walker and Jacob)										
Elphidiella hannai (Cushman and Grant)					1					
Elphidium spp.						99	6			
Florilus basispinatus (Cushman and Moyer)										
Globogerina bulloides (d'Orbigny)										
Haplophragmoides sp.										
Quinqueloculina sp.										
Trochamina inflata (Montagu)			1	3	4					
Shell fragments						C	C			
Diatoms			C	C	C					
Ostracods										

	BOREHOLE 4												BOREHOLE 5				
	Sample Depth in Meters																
	1.5	3.2	4.7	7.6	9.0	10.6	12.0	13.5	15.7	16.5	19.5	21.5	10.5	12.0	13.3	15.0	18.0
Ammonia beccarii (Cushman)	3			2									1				
Bolivina sp.																	
Bucella frigida (Cushman)																	
Buliminella sp.																	
Cibicides lobatulus (Walker and Jacob)																	
Elphidiella hannai (Cushman and Grant)														1			
Elphidium spp.	22			74									44	18	3	3	
Florilus basispinatus (Cushman and Moyer)																	
Globigerina bulloides (d'Orbigny)													1				
Haplophragmoides sp.																	
Quinqueloculina sp.																	
Trochammina inflata (Montagu)	1		31														
Shell fragments	C			A									C			R	
Diatoms	C	C	C	C									C	C	C	R	
Ostracods																	

	BOREHOLE 6														
	Sample Depth in Meters														
	3.7	5.1	6.6	8.1	9.6	11.0	12.6	14.5	16.2	16.5	17.6	19.3	21.0	22.5	26.0
Ammonia beccarii (Cushman)		37	2	1		10									
Bolivina sp.															
Bucella frigida (Cushman)															
Buliminella sp.			1												
Cibicides lobatulus (Walker and Jacob)						1									
Elphidiella hannai (Cushman and Grant)		1													
Elphidium spp.		191	8	139	3	119	2								
Florilus basispinatus (Cushman and Moyer)															
Globigerina bulloides (d'Orbigny)					2										
Haplophragmoides sp.		1													
Quinqueloculina sp.															
Trochammina inflata (Montagu)	6	26		3		2									
Shell fragments	R			R	R	R		C	C	A	A				
Diatoms	C	C	C	C	C	C	C	A	A	A	A				
Ostracods			R												

BOREHOLE 7

Sample Depth in Meters

	3.2	6.0	7.5	8.7	10.2	11.5	13.0	14.4	15.8	18.2	19.7	21.0
Ammonia beccarii (Cushman)			8	10	4	3	2					
Bolivina sp.												
Bucella frigida (Cushman)					3		1					
Buliminella sp.			1									
Cibicides lobatulus (Walker and Jacob)					3							
Elphidiella hannai (Cushman and Grant)			7			5						
Elphidium spp.		5	>300	236	50	48	19	2	2	3		
Florilus basispinatus (Cushman and Moyer)					1							
Globigerina bulloides (d'Orbigny)						2	2					
Haplophragmoides sp.												
Quinqueloculina sp.						1						
Trochamina inflata (Montagu)				2		1						
Shell fragments		C	A	C	C	A	A	C	C	C	R	
Diatoms	C	C	C	C	C	C	C	C	C	C	C	
Ostracods				R	R	R						

BOREHOLE 8

Sample Depth in Meters

	2.1	3.6	5.0	6.4	7.6	9.1	10.5	12.0	13.3	14.6	15.6	17.1	18.6
Ammonia beccarii (Cushman)	3			2									
Bolivina sp.													
Bucella frigida (Cushman)			1				2	2					
Buliminella sp.													
Cibicides lobatulus (Walker and Jacob)													
Elphidiella hannai (Cushman and Grant)			7			5							
Elphidium spp.	35	138	64	88	31	8	17	1		1			3
Florilus basispinatus (Cushman and Moyer)													
Globigerina bulloides (d'Orbigny)			2	2									
Haplophragmoides sp.													
Quinqueloculina sp.			2	1									
Trochamina inflata (Montagu)	12				21								
Shell fragments		A	C	R	R	R	C		C	C	R	R	R
Diatoms	C	C	C	C	C	C	C	C	C	C	C	C	C
Ostracods		C	R	R									

	BOREHOLE 9															
	Sample Depth in Meters															
	2.0	3.5	4.8	6.3	7.5	9.0	10.5	11.8	13.3	14.8	16.0	17.4	19.0	20.5	20.8	23.6
<u>Ammonia beccarii</u> (Cushman)		2	1	1	4	4						14	15	21	11	
<u>Bolivina</u> sp.																
<u>Bucella frigida</u> (Cushman)								1				4	1			
<u>Buliminella</u> sp.											1	3	9	8		
<u>Cibicides lobatulus</u> (Walker and Jacob)		2			1							3	7	2		
<u>Elphidiella hannai</u> (Cushman and Grant)		1		1	2	2						10	21	4		
<u>Elphidium</u> spp.		>300	7	50	70	117	12	8			3	98	110	99	5	
<u>Florilus basispinatus</u> (Cushman and Moyer)				1							1	3	4	4		
<u>Globigerina bulloides</u> (d'Orbigny)					1							4	3	2		
<u>Haplophragmoides</u> sp.																
<u>Quinqueloculina</u> sp.										1		2	3	4		
<u>Trochamina inflata</u> (Montagu)						1										
Shell fragments		A	R	R		C		R		C	C	R	A	A	C	R
Diatoms		C	C	C	C	C	C	C	C	C	C	C	C	C	R	R
Ostracods		C			R	R						A	A			

	BOREHOLE 10												BOREHOLE 11				
	Sample Depth in Meters																
	1.8	2.5	6.2	7.0	8.0	8.6	9.8	10.8	11.5	14.4	17.0	19.0	15.3	16.5	18.0	20.0	21.0
<u>Ammonia beccarii</u> (Cushman)							2						3		1		
<u>Bolivina</u> sp.																	
<u>Bucella frigida</u> (Cushman)																	
<u>Buliminella</u> sp.															1		
<u>Cibicides lobatulus</u> (Walker and Jacob)													2				
<u>Elphidiella hannai</u> (Cushman and Grant)															1		1
<u>Elphidium</u> spp.			14				52		11				9		16	1	2
<u>Florilus basispinatus</u> (Cushman and Moyer)																	
<u>Globigerina bulloides</u> (d'Orbigny)															1		
<u>Haplophragmoides</u> sp.																	
<u>Quinqueloculina</u> sp.																	
<u>Trochamina inflata</u> (Montagu)																	
Shell fragments							C		C				A	R		A	A
Diatoms						C							C				C
Ostracods																	

	BOREHOLE 12						BOREHOLE 13													
	Sample Depth in Meters																			
	1.0	2.7	3.2	4.6	4.8	5.7	1.5	2.0	2.1	3.2	5.2	5.6	6.1	7.0	8.6	9.5	10.5	11.5	12.7	13.0
Ammonia beccarii (Cushman)		1		2	20	17		1			3		171				2			
Bolivina sp.		1				2														
Bucella frigida (Cushman)																				
Buliminella sp.		1				1														
Cibicides lobatulus (Waker and Jacob)				1																
Elphidiella hannai (Cushman and Grant)																1				
Elphidium spp.	1	3		3	9	82		3			10		228			11	>300		3	3
Florilus basispinatus (Cushman and Moyer)		1																		
Globogerina bulloides (d'Orbigny)								1												
Haplophragmoides sp.																				
Quinqueloculina sp.																				
Trochamina inflata (Montagu)														54						
Uvigerina sp.						1														
Shell fragments																				
Diatoms	R							R	R	R			C	R	C					
Ostracods				C																

Diatoms:

Core 1
450 cm subsurface

Cocconeis placentula*
Epithemia turgida
Navicula peregrina*
Rhopalodia gibberula
Amphora ovalis
A. granulata
Gomphonema ventricosum
Fragillaria construens*
F. tabulata*
Navicula pygmeae
N. salinarum
Nitzschia granulata +
N. salinarum
N. accuminata
Paralia sulcata
Rhopalodia gibba
Suriella striatula +
Cymbella muelleric*
Cymbella spp.
Epithemia sorex
Stauroneis spp.
Rhoicosphenia curvata
Hyalodiscus scoticus +
Campylodiscus echeneis +

Core 2
470 cm subsurface

Surirella striatula*
Nitzchia granulata*
Navicula peregrina
Rhopalodia gibberula
Campylodiscus echeneis*
Azhnanthes wellsiae
Thalassiosira decipieus
Paralia sulcata
Hyalodislus scoticus*

Core 12
210 cm subsurface

Gyrosigma batticum*
Navicula salinarum*
N. circumtexta
N. pygmeae
N. multica
Fragillaria tabulata
F. ulna
Amphora granulata
Cymbella mexicana
Nitzchia circumsuta
N. punctata
N. sigma
N. sigmaformis
N. levidensis
N. granulata
N. obtusa
N. accuminata
Rhopalodia gibberula
Paralia sulcata
Surirella striatula
Epithemia sp.
Melosira moniliformis
Achnanthes haukiana
A. wellsiae
Campylodiscus echeneis
C. clypeus*
Cocconeis placentula
C. scutellum*

Borehole 8
10 m subsurface

Actinoptychus splendeus
Campylodiscus echeneis

Borehole 8
5 m subsurface

Actinoptychus splendeus

Ostracods:

Core 5
525 cm subsurface

Cyrpideis beaconensis

Core 6
630 cm subsurface

Cyprideis beaconensis

Core 8
325 cm subsurface

Cyprideis beaconensis *
Cypridopsis vidua
Candona sp.

Surface Grab #5

Cyprideis beaconensis *
Perissocytheridea meyerabichi
Trachyleberis sp.
Loxoconch sp.
Megacythere sp.

Appendix 5. Species list for diatoms and ostracods recovered from various surface and subsurface sediment samples through the study area. See Figure 3 for sample locations. * denotes species that are most common and + denotes diatoms that were recovered from Core 1, 514 cm subsurface.