FINAL REPORT

to

NATIONAL SCIENCE FOUNDATION

ENGINEERING GEOLOGIC SITE CHARACTERIZATION OF THE GREATER OAKLAND-ALAMEDA AREA ALAMEDA AND SAN FRANCISCO COUNTIES, CALIFORNIA

Grant No. BCS – 9003785

by

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30 December 1991

(*digital version, October, 2005*)

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Engineering Geologic Site Characterization of the Greater Oakland-Alameda Area, Alameda and San Francisco Counties, California[1]

J. David Rogers and Sands H. Figuers[2]

INTRODUCTION

A unique aspect of the October 17, 1989 Loma Prieta earthquake in California's San Francisco Bay metropolitan area was the extensive structural damage and highly variable ground response observed in the greater Oakland-East Bay plain area, approximately 100 kilometers (km) north of the quake's epicenter (shown in Figure 1). Strong motion recorders on Yerba Buena and Treasure Islands registered motions with 250% variance over a separation of 3000 feet. 9850 feet east of Yerba Buena Island, a container wharf at the Port of Oakland recorded peak ground accelerations (PGA) of between 0.27g and 0.29g (horizontal), with up to 0.084g vertical acceleration. 7000 feet east of this wharf, the northern half of the double-decked Interstate 880 Cypress Street viaduct experienced an extensive partial collapse.

The ground amplification effects appear to be ascribable to site geology. The stated purpose of this grant was to retrieve as much unpublished subsurface information as possible in order to create a data base of subsurface information, and correlate the subsurface stratigraphy of the greater Oakland-Alameda area. Information was collected on more than 200 deep wells in the greater East Bay plain, extending from Hayward, north to Richmond (Figure 2). The wells ranged in depth from 120 to 1035 feet below ground surface and were drilled between 1892 and 1991.

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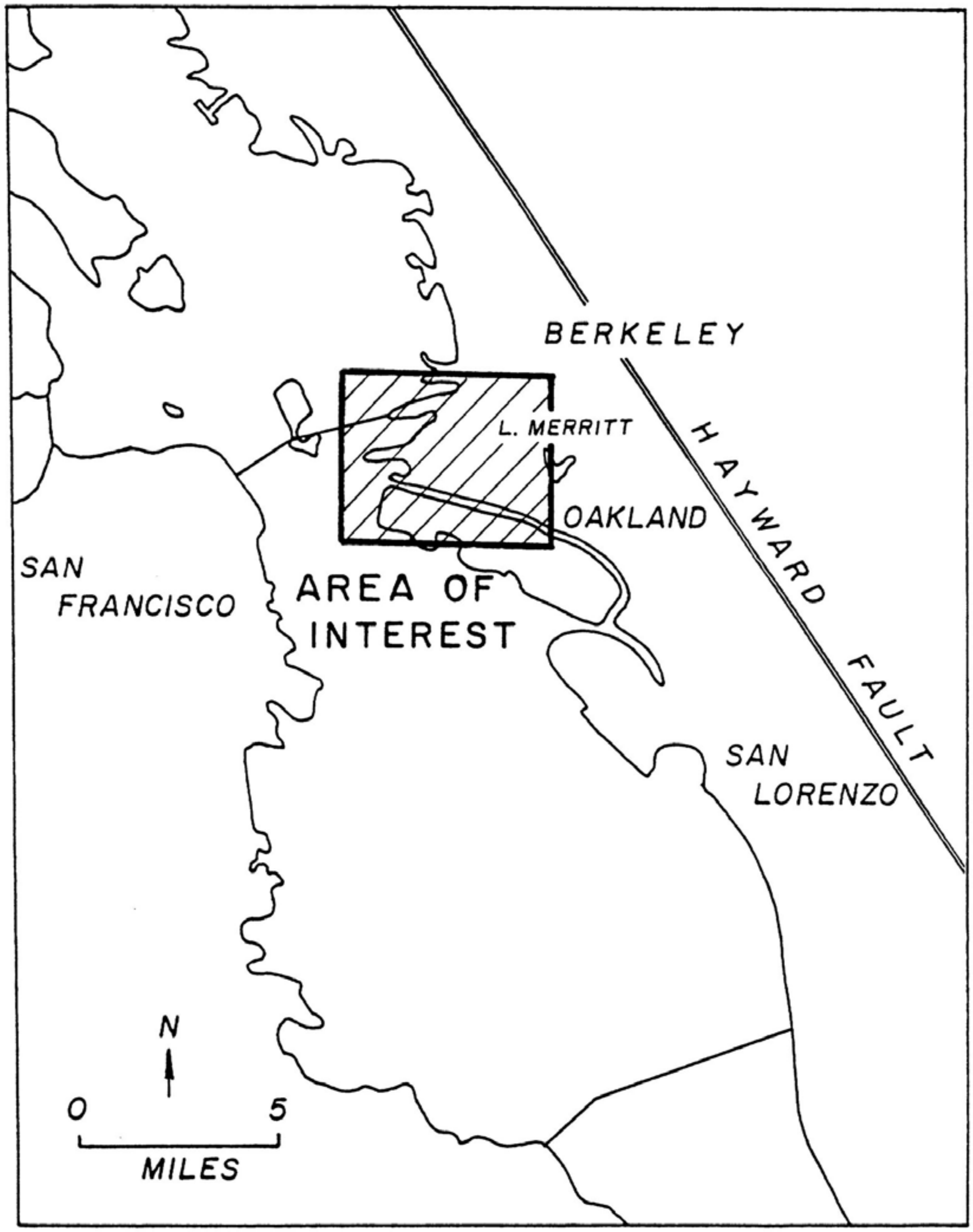


FIGURE 1 - *Location map showing central San Francisco Bay and the area of interest for the attached study. The I880 Cypress Structure and eastern Oakland Bay Bridge lie within the core of the study area.*

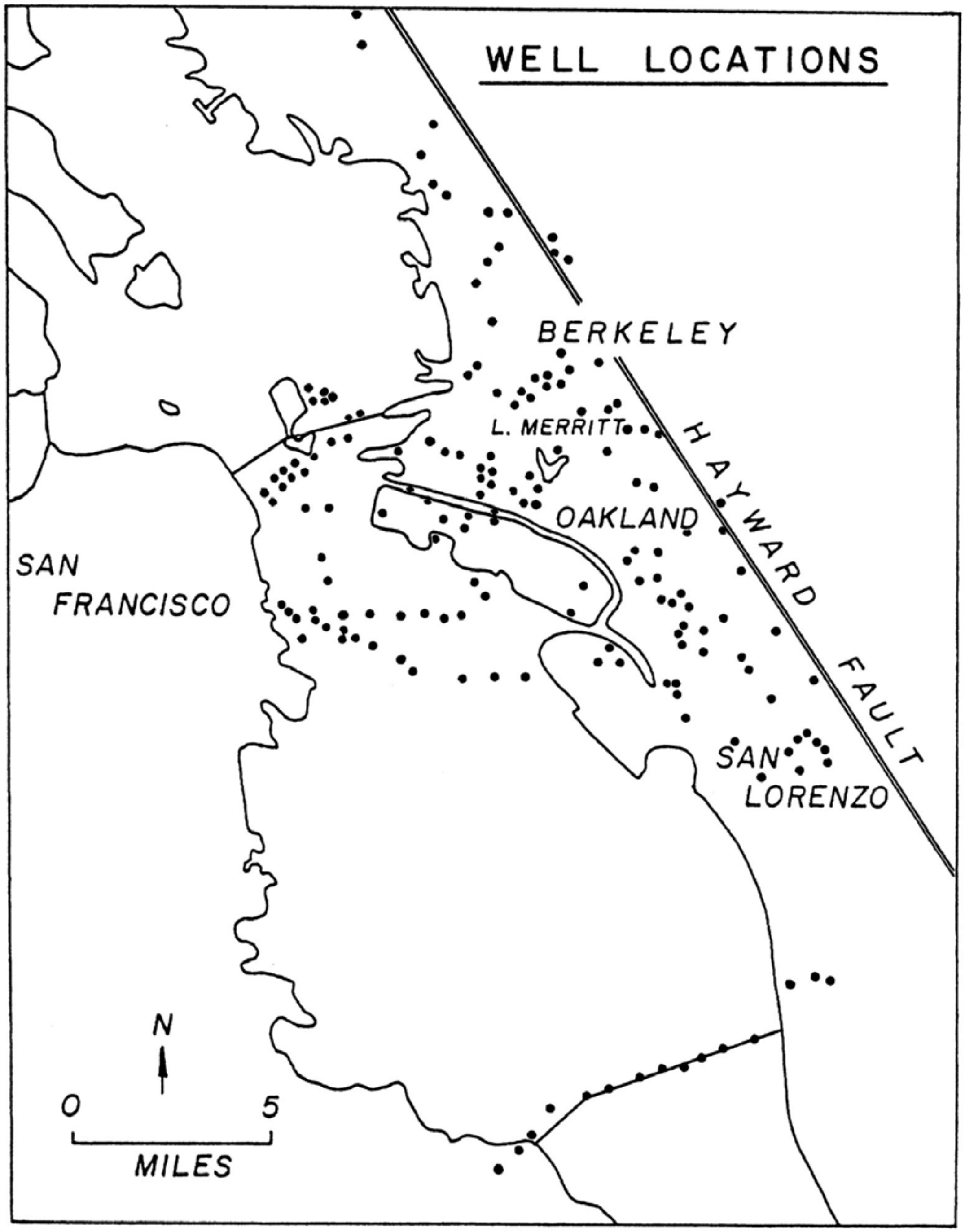


FIGURE 2 – *Map showing the locations of over 200 deep borings and wells utilized in this study. These borings ranged in depth from 120 to 1035 feet below sea level, and extended along the east Bay margin from Hayward north to Richmond.*

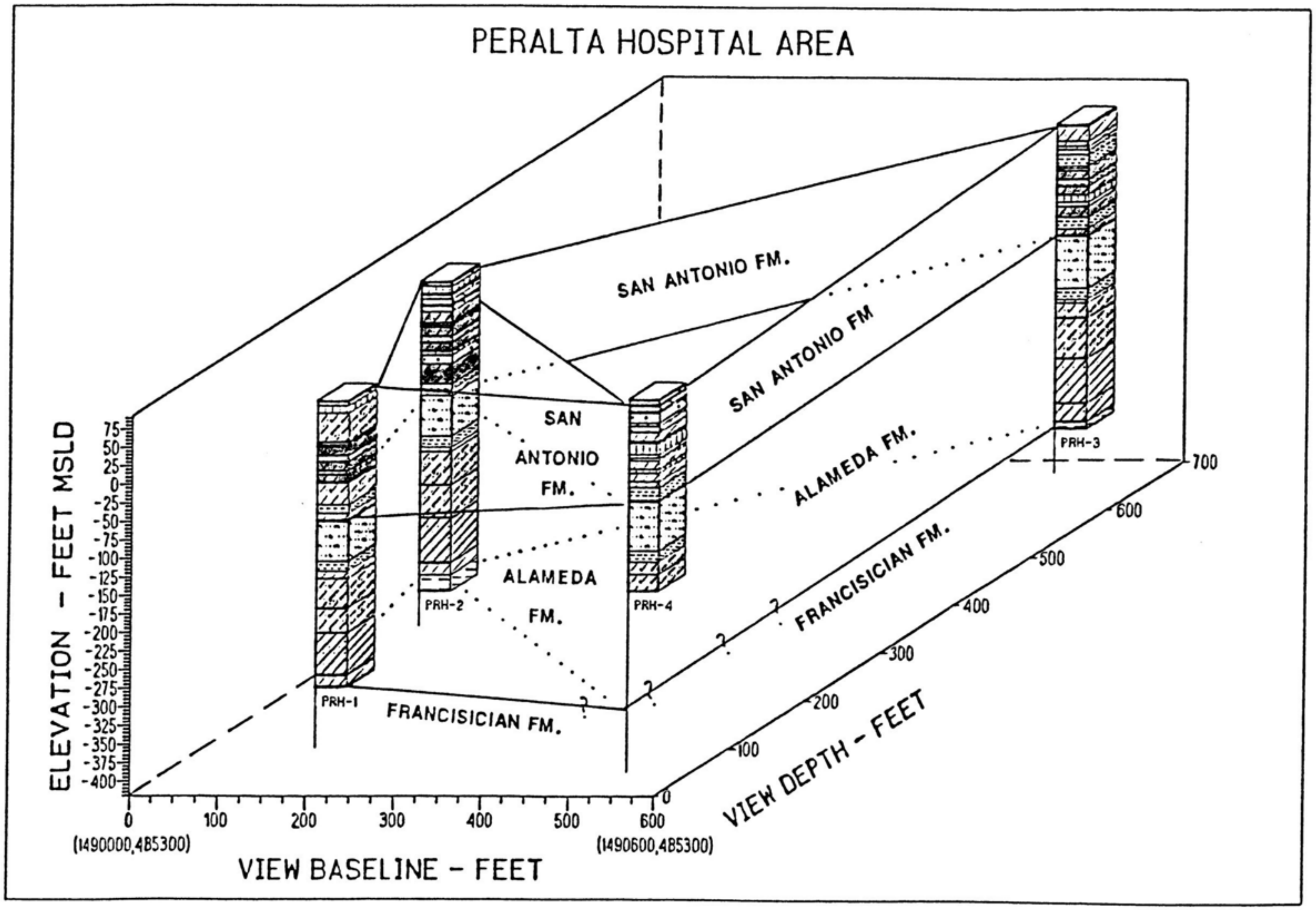


FIGURE 3 – *An example of the geologic database manipulations that were made utilizing GTGS. The example shown is a stratigraphic fence diagram that allows detailed cross-hole correlations of the subsurface data. All collar locations were input with the California Plane Coordinate System.*

To handle this volume of information, all of the engineering and geologic data were entered into a computer data base *(GTGS* of Berkeley, CA). The data base was configured to be compatible with the existing U.S. Geological Survey well data base at Menlo Park, CA. This systems allows for easy manipulation of data and rapid generation of well logs, maps, cross sections and fence diagrams, as presented in Figure 3. These maps have provided the first detailed look at the area's regional geologic framework that, when combined with detailed site-specific subsurface data, will enable a better understanding of both past and future site response variances.

OBSERVED LEVELS OF SHAKING DURING THE LOMA PRIETA EARTHQUAKE

The Loma Prieta earthquake occurred at 5:05 p.m. local time on Tuesday October 17, 1989. The quake's hypocenter was approximately 18 km beneath the Santa Cruz Mountains, between San Jose and Santa Cruz. Recent studies suggest that the quake occurred on an unnamed splay of the San Andreas fault system, and that the basal rupture was bimodal, lasting only 6 seconds. *A Richter magnitude* (M) of 7.1 was eventually assigned to the event. Maximum recorded site response was approximately 15 seconds 95 to 105 km to the north, in San Francisco and Oakland.

The Interstate 880 Cypress Structure was located on the west side of Oakland's downtown area, about 60 miles from the quake's epicenter. Strong motion records recovered from five structures in the Oakland-Alameda area showed peak ground acceleration (PGA) values of between 0.18g and 0.29g, as presented schematically in Figure 4. *Ground amplification* effects were very apparent when evaluating adjacent strong motion records. For instance, the recorder on Yerba Buena Island, situated near bedrock on colluvial blow sands, measured a PGA value of 0.06g. The station on hydraulic sand fill, only 3000 feet away, registered 0.16g before its record was obliterated by massive ground disturbance (due to liquefaction). In downtown Oakland, *vertical accelerations* of between 0.04 and 0.16g were measured, also suggestive of local ground amplification.

The disparity between established empirical predictions of peak ground acceleration with epicentral distance and those observed in the Oakland area during the Loma Prieta earthquake are shown in Figure 5 [from Joyner and Boore (1988) and Shakal, et al (1989)]. The accelographs located closest to the collapsed Cypress Structure were 5000 feet and 7500 feet west and east-southeast of the viaduct, respectively. The records from these stations plot more than two standard deviations from the accepted mean relationship (Figure 5). This is known to be a result of damping of seismic waves in older, more consolidated geologic materials, commonly referred to as *"bedrock".*

GROUND ENHANCEMENT EFFECTS

Shortly after the Loma Prieta main shock a group of seismologists from Lamont-Doherty Geological Observatory working with portable seismic arrays developed under the auspices of the National Center for Earthquake Engineering Research (NCEER) and the Incorporated

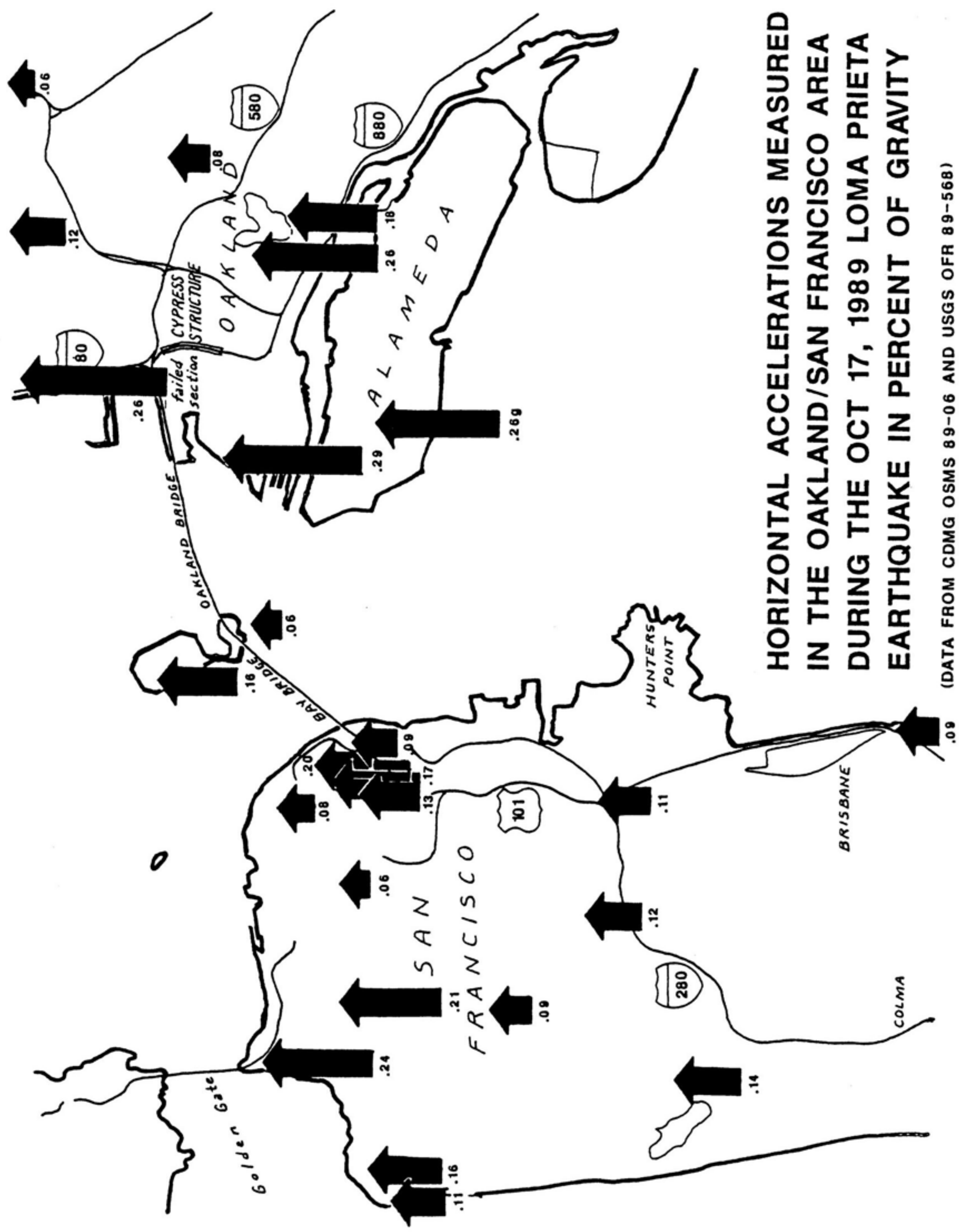


FIGURE 4 - *Weighted vectors depicting peak horizontal accelerations during the Loma Prieta earthquake from raw strong motion data recorded on State and Federally-owned accelographs. The failed portion of the I-880 Cypress Structure is delineated in west Oakland.*

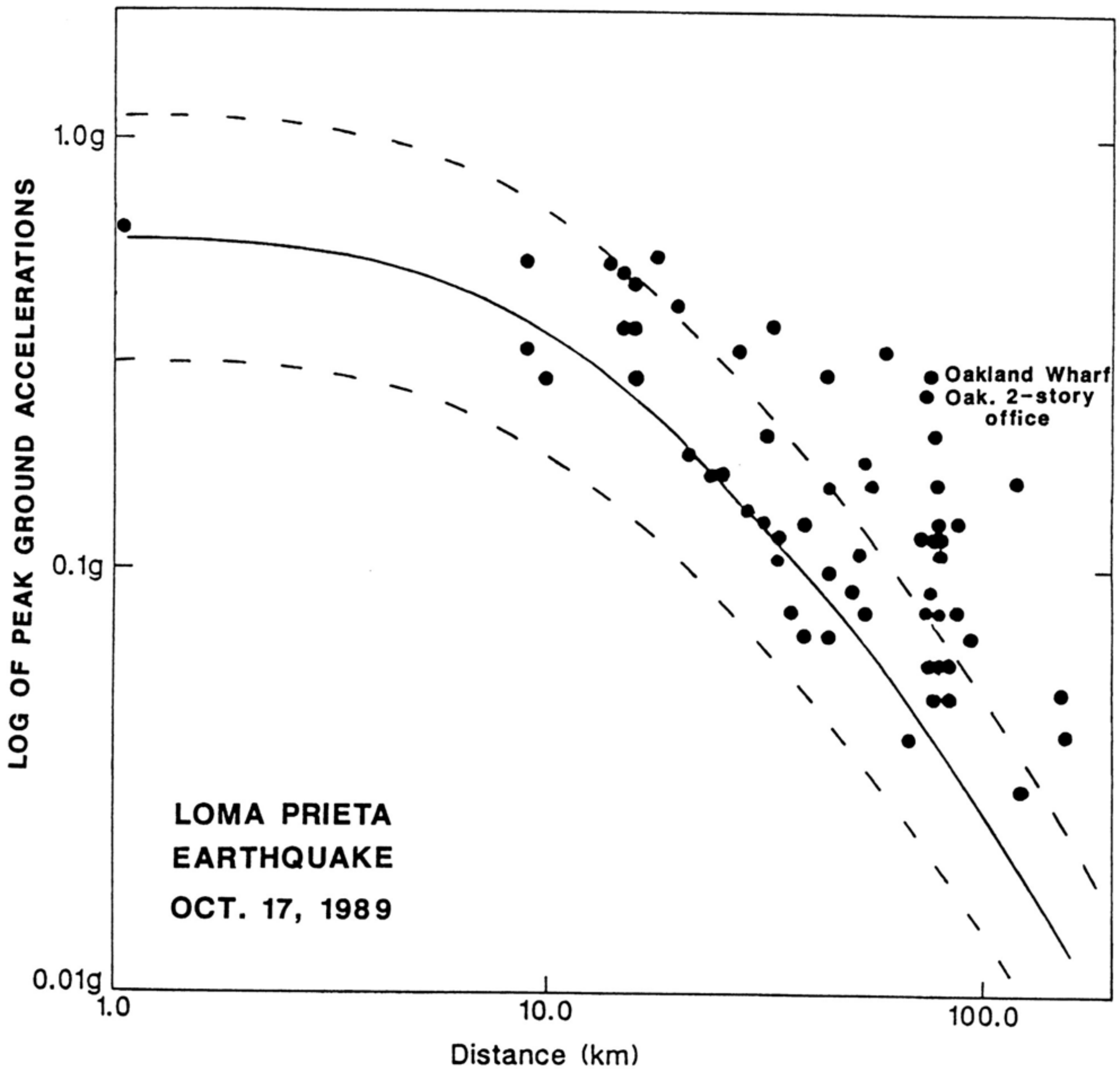


FIGURE 5 - *Peak horizontal accelerations values plotted versus distance from causative fault for the 1989 Loma Prieta earthquake on the Joyner-Boore attenuation curves. The solid line represents the mean while the dashed lines represent one standard deviation. The structures in Oakland plot more than two standard deviations above the mean.*

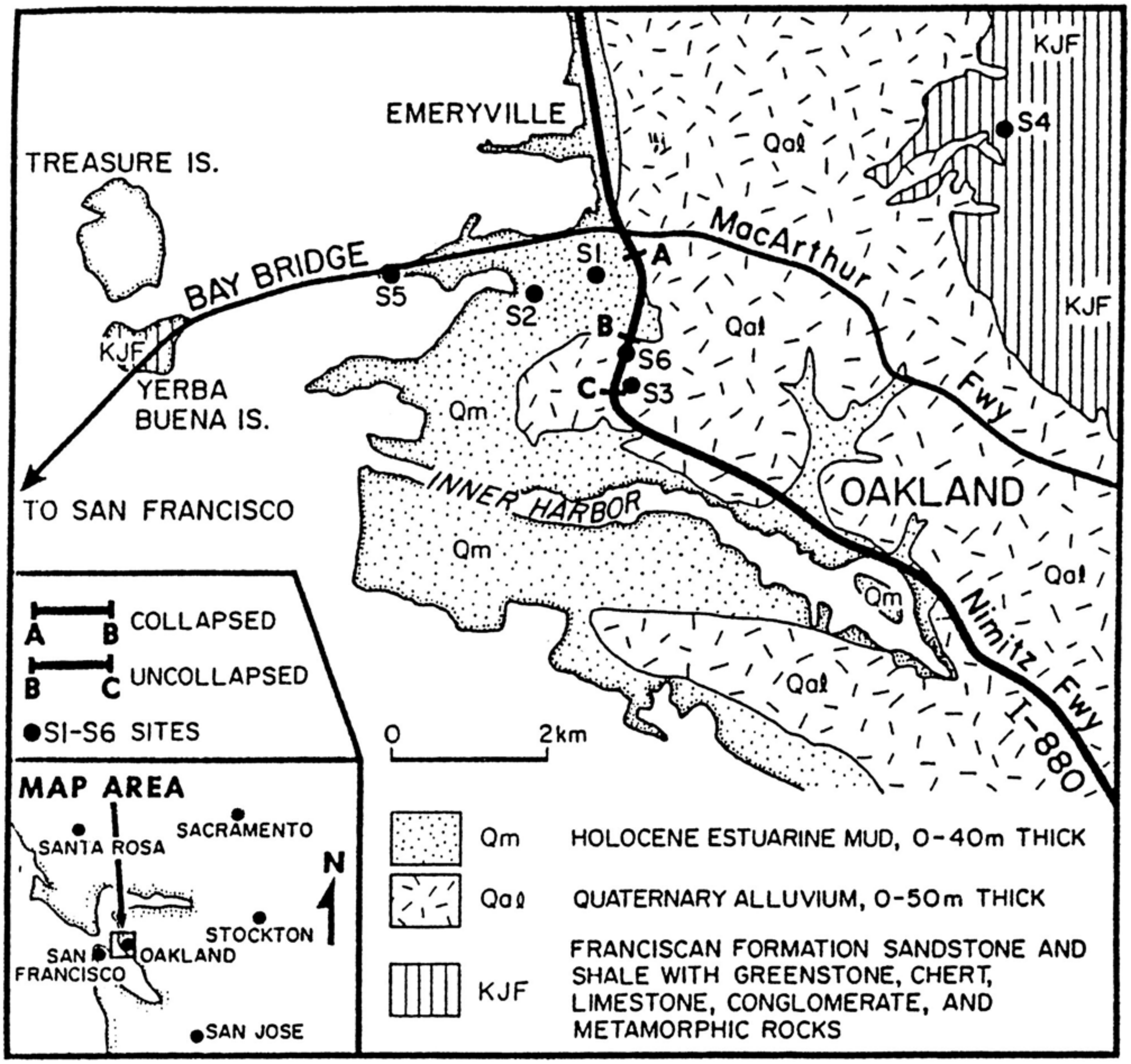


FIGURE 6 – *Map showing the locations of the IRIS aftershock array in Oakland following the 1989 Loma Prieta quake. Surficial geology is taken from Borcherdt and Gibbs (1976). The six seismographs were distributed upon bedrock sand, fill/bay mud and key structures to measure ground enhancement effects (taken from Hough, et al., 1990).*

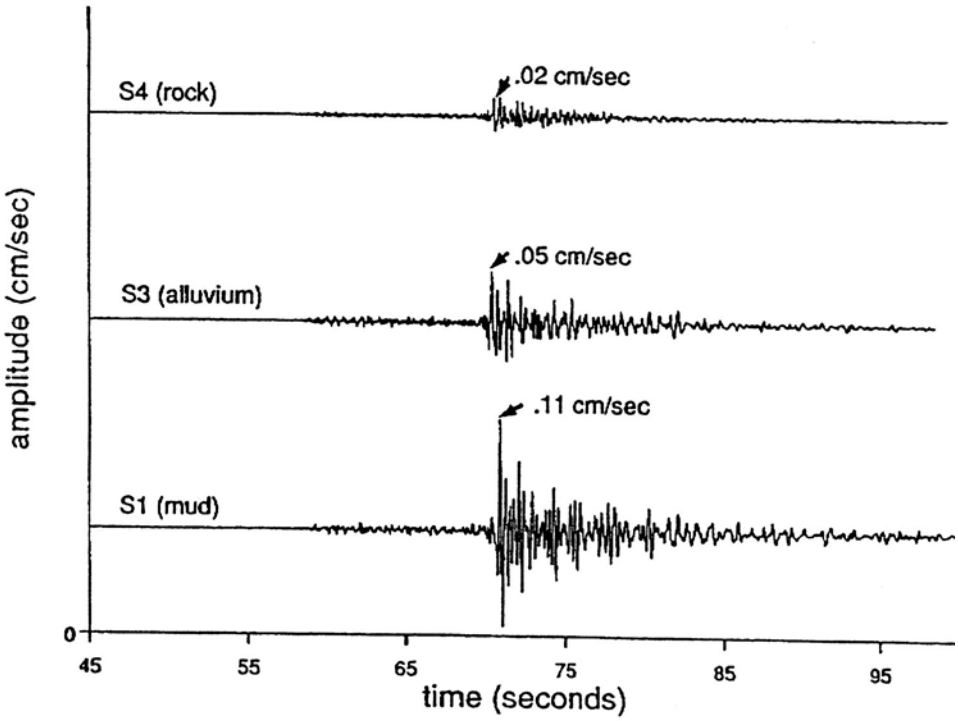


FIGURE 7 – *Comparison of north-south horizontal motion components recorder in a M 4 aftershock. Amplification on the alluvial and bay mud sites is apparent (taken from Hough, et al., 1990).*

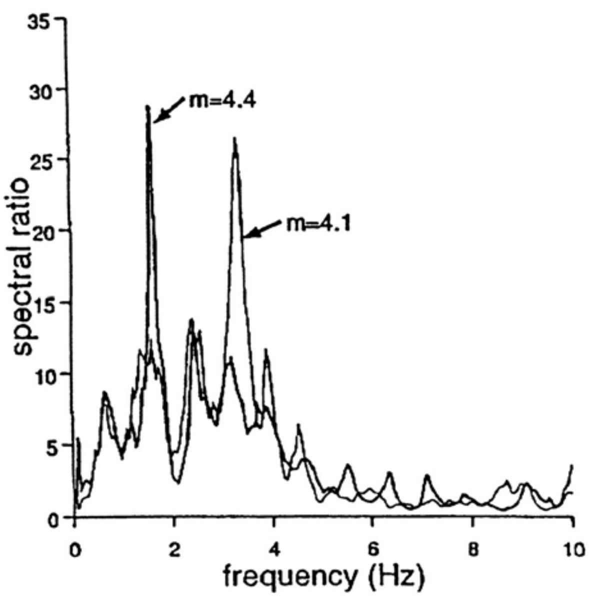


FIGURE 8 – *Spectral ration versus frequency for adjacent bay mud and Franciscan greywacke sites during M4 and M 4.4 Loma Prieta aftershocks. Note the downward shift in resonant amplification with increasing quake magnitude. It would appear that the fundamental site period varies with input frequency of the seismic energy (taken from Hough, et al., 1990). Large earthquakes (above M. 6.4) will usually generate wave frequencies closer to 1 Hz (Greensfelder, 1990).*

Research Institution of Seismology (IRIS), placed six portable seismographs in the vicinity of the collapsed Cypress Structure to measure ground response variances in after-shock events. The approximate locations of this array are portrayed in Figure 6, (taken from Hough, et al, 1990). The sites were chosen because it was felt, based upon the information at the time, that they represented a wide range of geologic site characteristics. These included a "bedrock" site less than 2 miles away from the Cypress Structure, an older alluvial site 800 feet east, and a site underlain by Young Bay Mud, approximately 2000 feet west of the collapsed section of the Cypress viaduct.

Figure 7 shows the respective real-time motions recorded on the north-south horizontal component of the three above-mentioned stations during a M 4.1 aftershock. Computed *spectral ratios* for mud versus rock from this particular aftershock and a larger, M 4.4 event, are presented in Figure 8. The dramatic variance in amplification between adjacent rock and mud sites can be readily appreciated. In analyzing this record the Lamont-Doherty scientists and Roger Borcherdt of the U.S.G.S. concluded that the complicated nature of the ratios was likely *"due to a complex resonance of both mud and underlying alluvium layers"* (Hough, et al, 1990). Borcherdt had previously demonstrated that such site response variances not only existed (Borcherdt, 1970), but were also responsible for the variances previously described by Wood (1908), who sought to explain localized effects of the 1906 San Francisco earthquake (Borcherdt and Gibbs, 1976).

FRANCISCAN BASEMENT TOPOGRAPHY

In order to fully appreciate the potential effects of soft *"soil cover"* on the amplification of seismic waves, it is first necessary to know the approximate depth, density and geophysical wave propagation properties of the geologic units mantling higher-density *"bedrock basement"*. In the *San Francisco Bay depression*, a veneer of unconsolidated late-*Pleistocene-age* sediments lies upon dense *Jurassic-Cretaceous-age* "bedrock" of the *Francis-can assemblage*. The depth of the geologic contact between the *two zones* varies from over 650 feet above sea level on the East Bay hills to over 2500 feet below sea level beneath Daly City, on the Pacific coastline (Bonilla, 1964).

One of the important ideas documented in this study is that the *velocity boundary* does not always mimic the geologic contact, but is controlled by the depth of weathering of the basement rock. In some areas, such as deeply incised valleys (now buried by the *Pleistocene-age* sediments), the depth of weathering may exceed 300 feet. As a consequence, seismic exploration alone may be incapable of precisely locating the geologic contact between the *Franciscan* and the overlying sediments. However, as discussed later, it appears that geologic models alone cannot be utilized to create wave propagation models, as is the currently accepted practice of geotechnical earthquake engineers.

Figure 9 presents *a structural contour map* showing the approximate depth below sea level of the Franciscan basement between San Lorenzo and Richmond. A conspicuous *bedrock depression* exists beneath Bay Farm Island and Oakland International Airport. This was first suggested by Radbruch in 1957. Extending from the north side of this depression is a

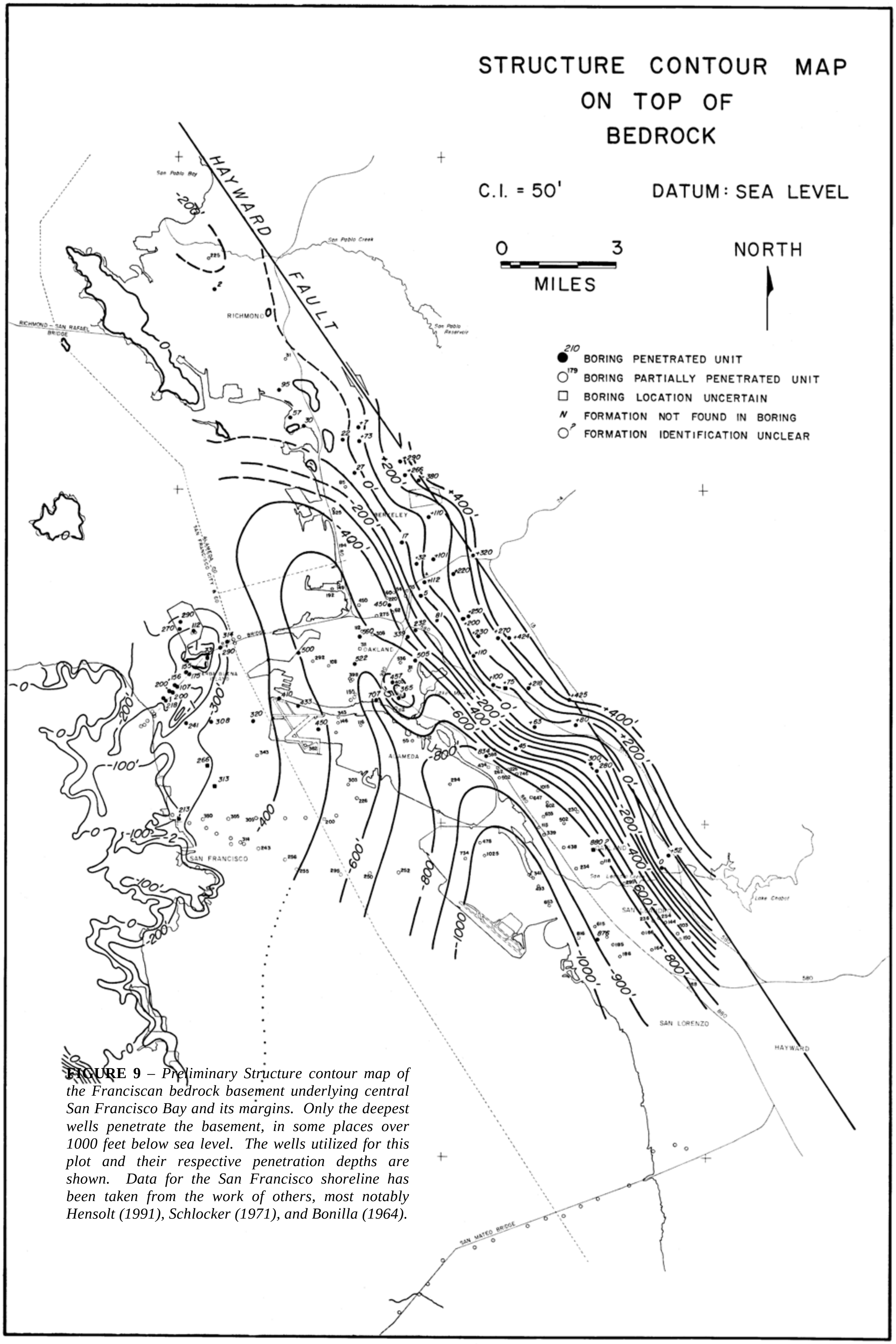


FIGURE 9 – *Preliminary Structure contour map of the Franciscan bedrock basement underlying central San Francisco Bay and its margins. Only the deepest wells penetrate the basement, in some places over 1000 feet below sea level. The wells utilized for this plot and their respective penetration depths are shown. Data for the San Francisco shoreline has been taken from the work of others, most notably Hensolt (1991), Schlocker (1971), and Bonilla (1964).*

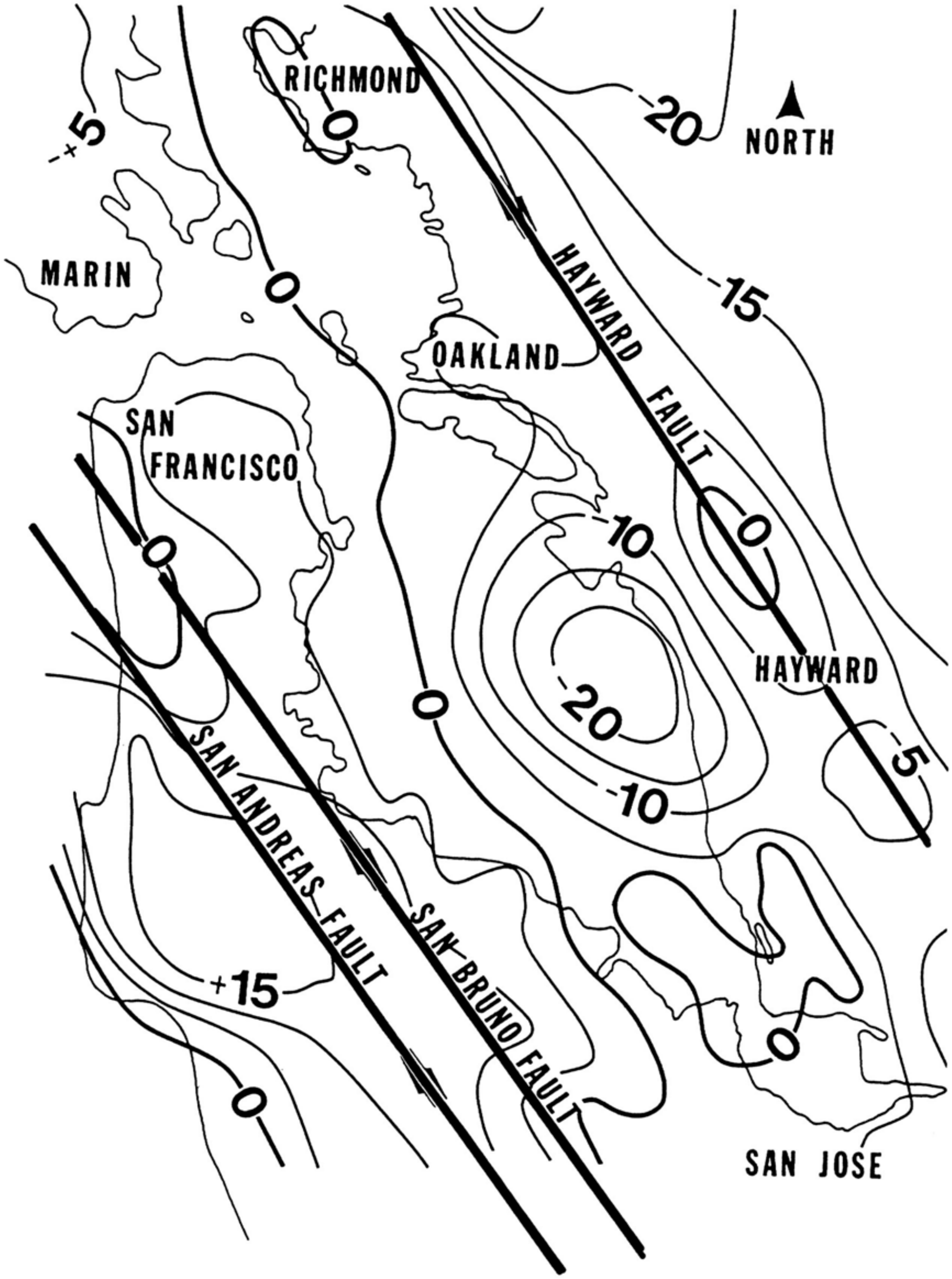


FIGURE 10 – *Reproduction of a portion of the Isostatic Bougier Residual Gravity map of the central San Francisco Bay, taken from the U. S. Geological Survey. Note the distinctive gravity low beneath the eastern half of the Bay off the Hayward shore.*

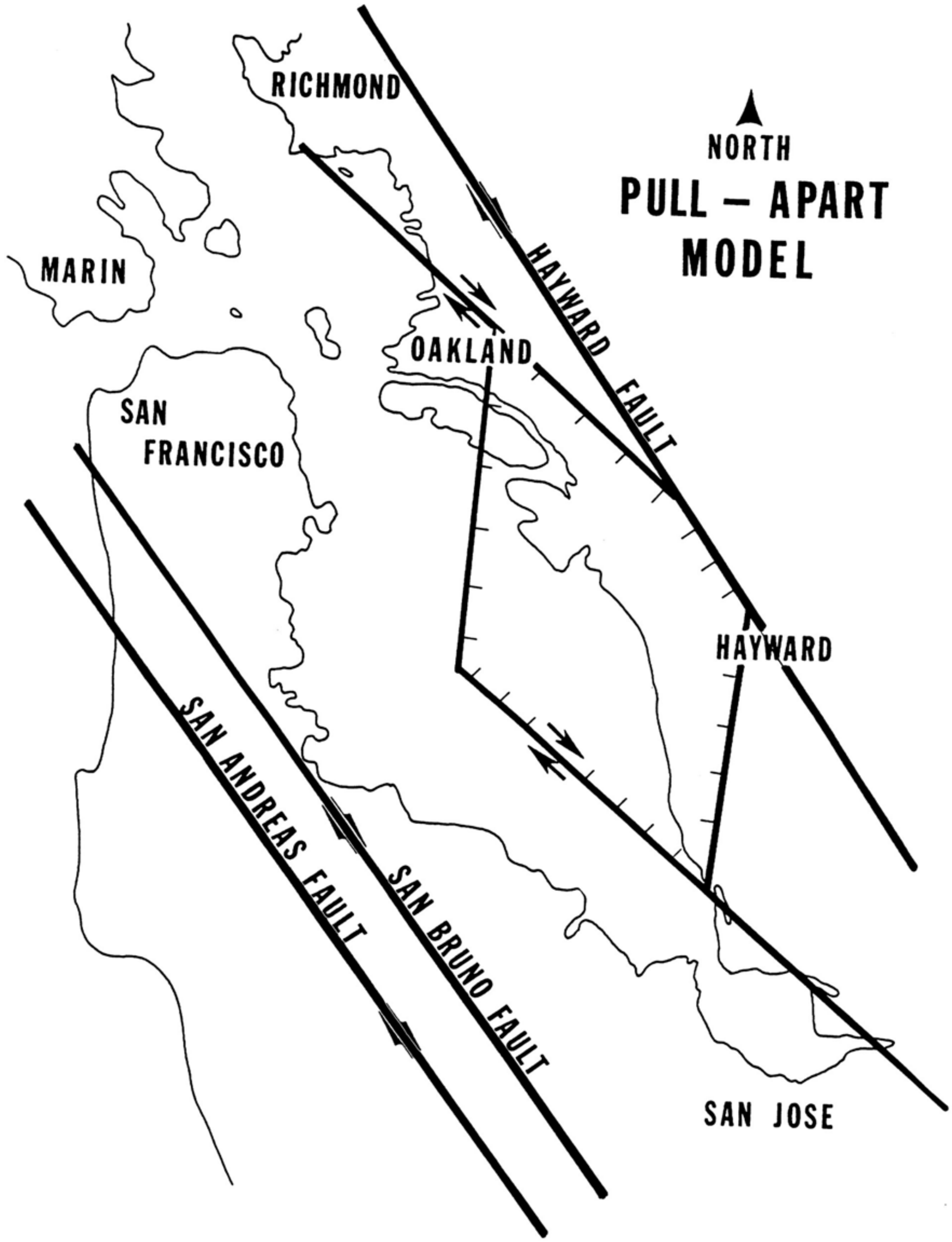


FIGURE 11 – *Postulated pull-apart model for the central San Francisco Bay. A modest pull-apart basin with around 5% extension could be expectable consequence between two right-lateral strike slip faults in close proximity to one another (Borchardt and Rogers, 1990).*

northwest-trending trough that cuts beneath west Oakland and the former position of the I-880 Cypress Structure.

Established gravity surveys confirm the overall shape of the bedrock depression. A portion of the *Residual Isostatic Gravity Map of the Greater San Francisco Bay is* reproduced in Figure 10. This map shows a well-defined *gravity low (10 - 15* milligals) beneath eastern San Francisco Bay, in the same area as the depression defined by the well data. The out-line of the depression is quite different than the current shape of San Francisco Bay. This suggests that the depression formed under a different tectonic regime than what currently exists.

Initially, it was thought that the depression formed under simple east-west extension, between the proto San Andreas and Hayward fault systems. However, such a model presents significant boundary problems, and was discarded. *A pull-apart model* was then tried, and found to be a plausible match. This is not the first time that *a pull-apart* model has been proposed. Page and Tabor (1967) proposed such a model for the areas surrounding San Francisco Bay. They were unable to identify *any pull-apart* features within San Francisco Bay because no reliable subsurface data were available at the time.

Figure 11 shows the overall geometry of the proposed *pull-apart basin* model. In this model a depression (pull-apart basin) will form between two parallel, right-stepping, en-echelon faults. The depression will have an overall parallelogram form.

In Figure 13 the pull-apart model is overlain on the isostatic residual gravity map in. There is a good correlation between the two. This model serves to explain most of the known *Franciscan* bedrock features surrounding and shaping the eastern shore of central San Francisco Bay. These features include the Bay's widest and deepest position between Hayward and San Mateo; the uplift of the Coyote Hills, just east of Dumbarton; the elevation of the bedrock basement at Albany Hill and Point Richmond; and the bedrock trough feeding into the depression beneath Oakland (shown in Figure 9).

ALAMEDA FORMATION

The *Alameda formation* was the initial unit deposited upon dissected *Franciscan* bedrock when the area began down-dropping between 1,000,000 and 500,000 years ago. Little is known about the formation. Previous studies (Lawson, 1914; Trask and Rolston, 1951; At-water, Hedel and Helley, 1977) described only the upper 100 feet or so, of the unit. The *Alameda formation* spans a number of older interglacial periods of sea level rise, as well as the intervening glacial ages, when sea level was 275 to 350 feet lower than present, and is the most extensive of all the late *Pleistocene-age* deposits, reaching thicknesses in excess of 1000 feet. Selective infilling of the *Alameda* units upon the dissected bedrock surface and within the down-dropped *pull-apart basin is* depicted schematically in Figure 14. Figure 15 presents an *isopach*, or formational thickness, map of the *Alameda formation.* This includes both the lower continental as well as upper marine facies of the *formation.* It can be seen in Figure 16 that the *Alameda* reaches thicknesses of over 900 feet beneath the area around Oakland International Airport, thinning to less than 400 feet beneath the southern end of the ill-fated Cypress Structure.

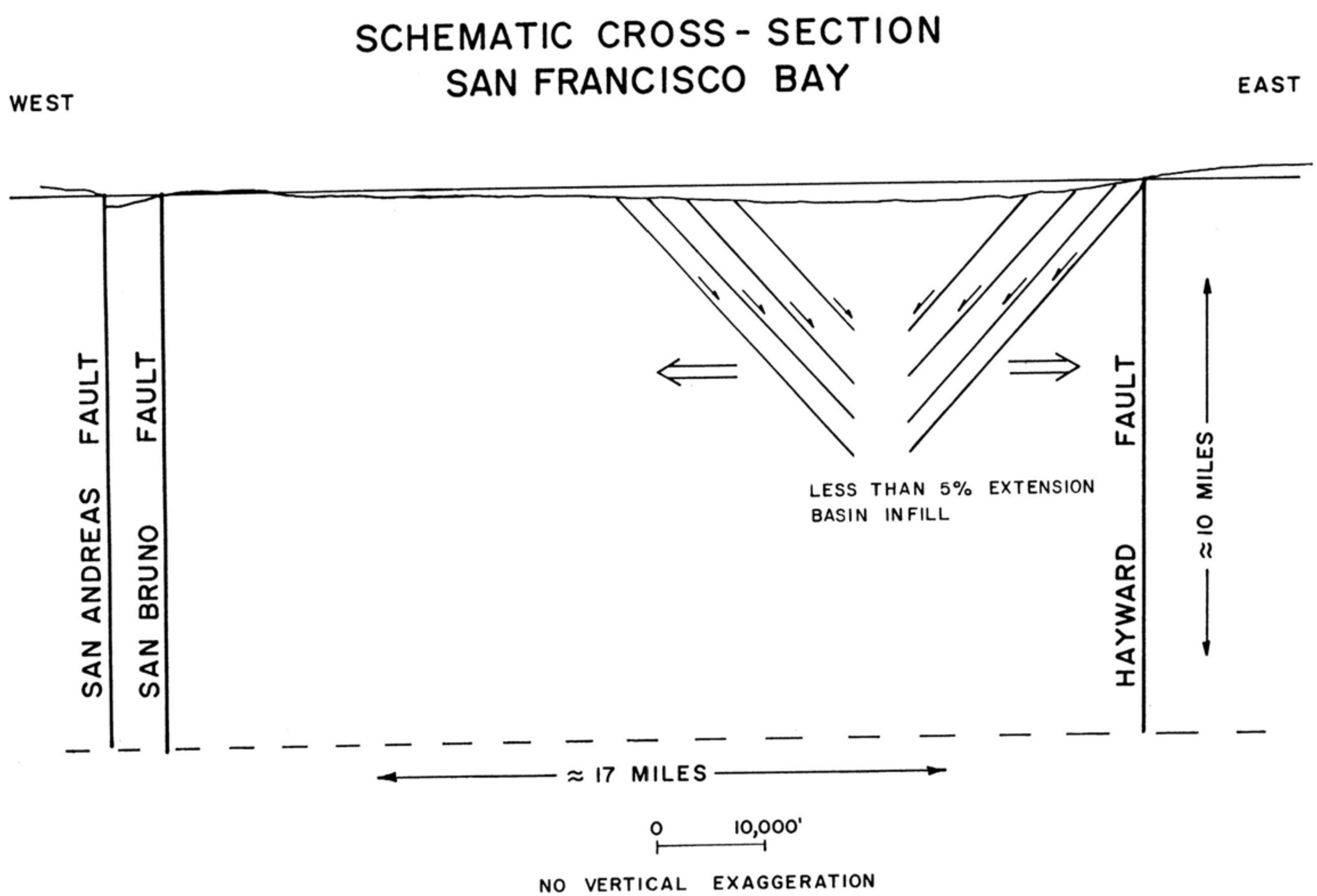
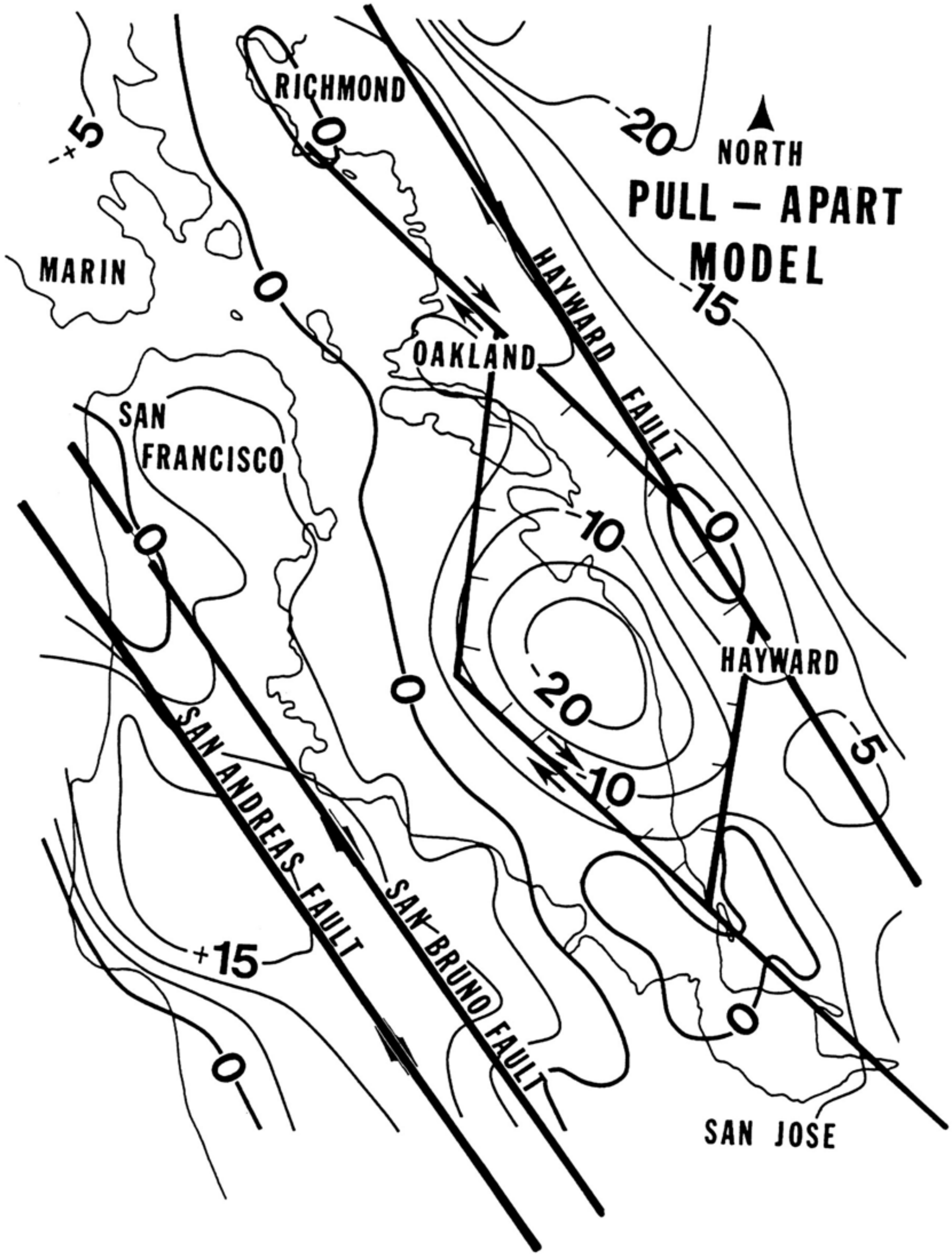


FIGURE 12 – *Schematic cross section of the postulated pull-apart basin portrayed in the previous figure. This section, made without any vertical exaggeration, shows just how slight the San Francisco Bay bedrock depression really is. The San Andreas and Hayward faults are just 17 miles apart. A 5% extension is all that would be necessary to create the section shown.*



ISOSTATIC RESIDUAL GRAVITY MAP

FIGURE 13 - *Overlay of Figures 10 and 11 showing the apparent correlation between the postulated pull-apart structure and the anomalous gravity low. It would appear that such a basin may be responsible for the relative maximum width and depth of the San Francisco Bay between Hayward and San Mateo.*

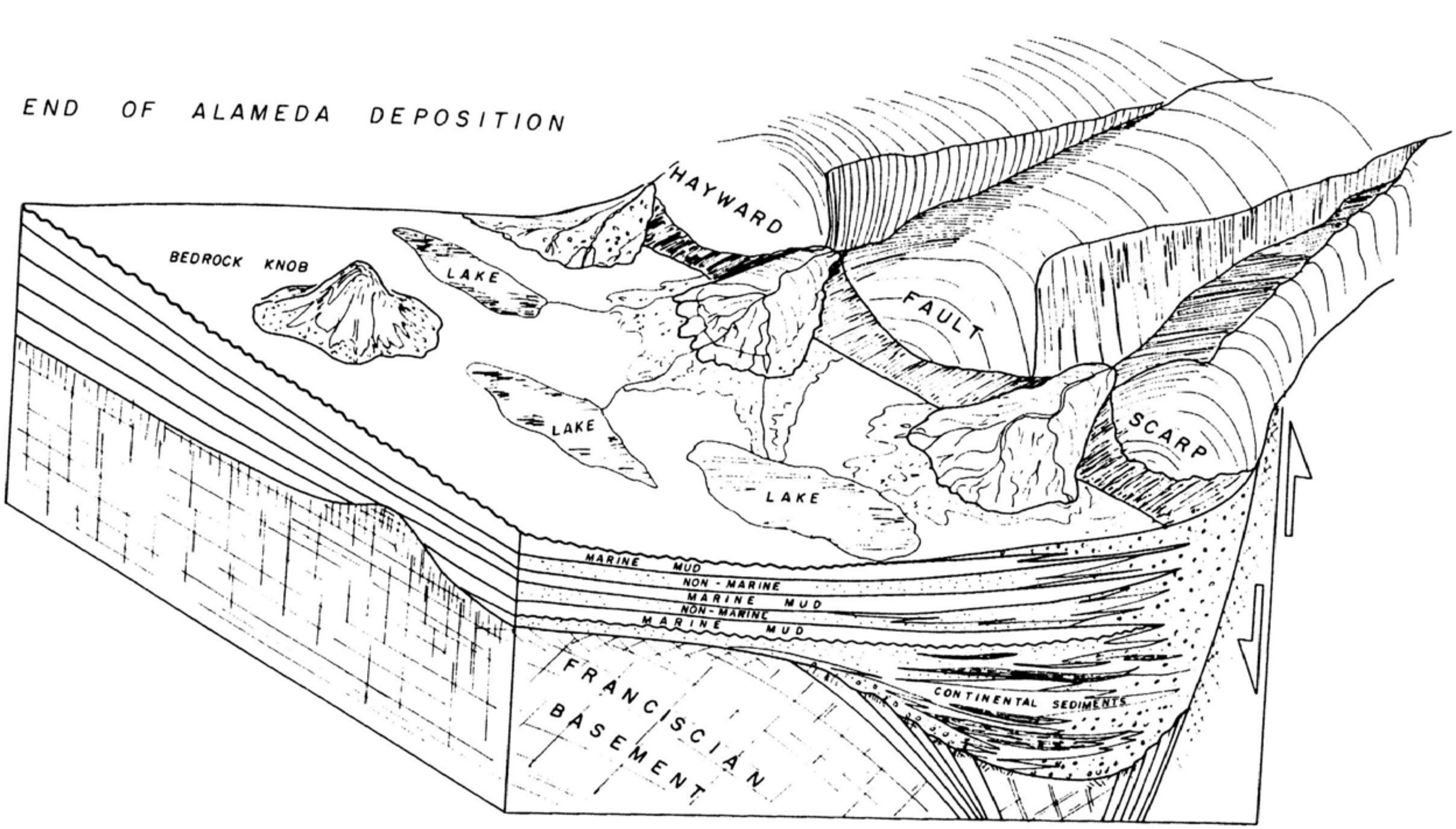


FIGURE 14 - *Schematic block diagram looking north at the end of Alameda deposition. By this time, the proto San Francisco Bay which appeared much as it does today. Continental sediments have infilled the pull-apart basin, which lies much lower than any seaward outlet now existing across the San Francisco peninsula.. Landward oceanic transgressions have deposited several series of marine muds, interspersed with continentally-derived alluvium. The Hayward escarpment is being dissected while, locally, portions of the Bay contain short-lived lakes and infilled basis influenced by bedrock inselbergs.*

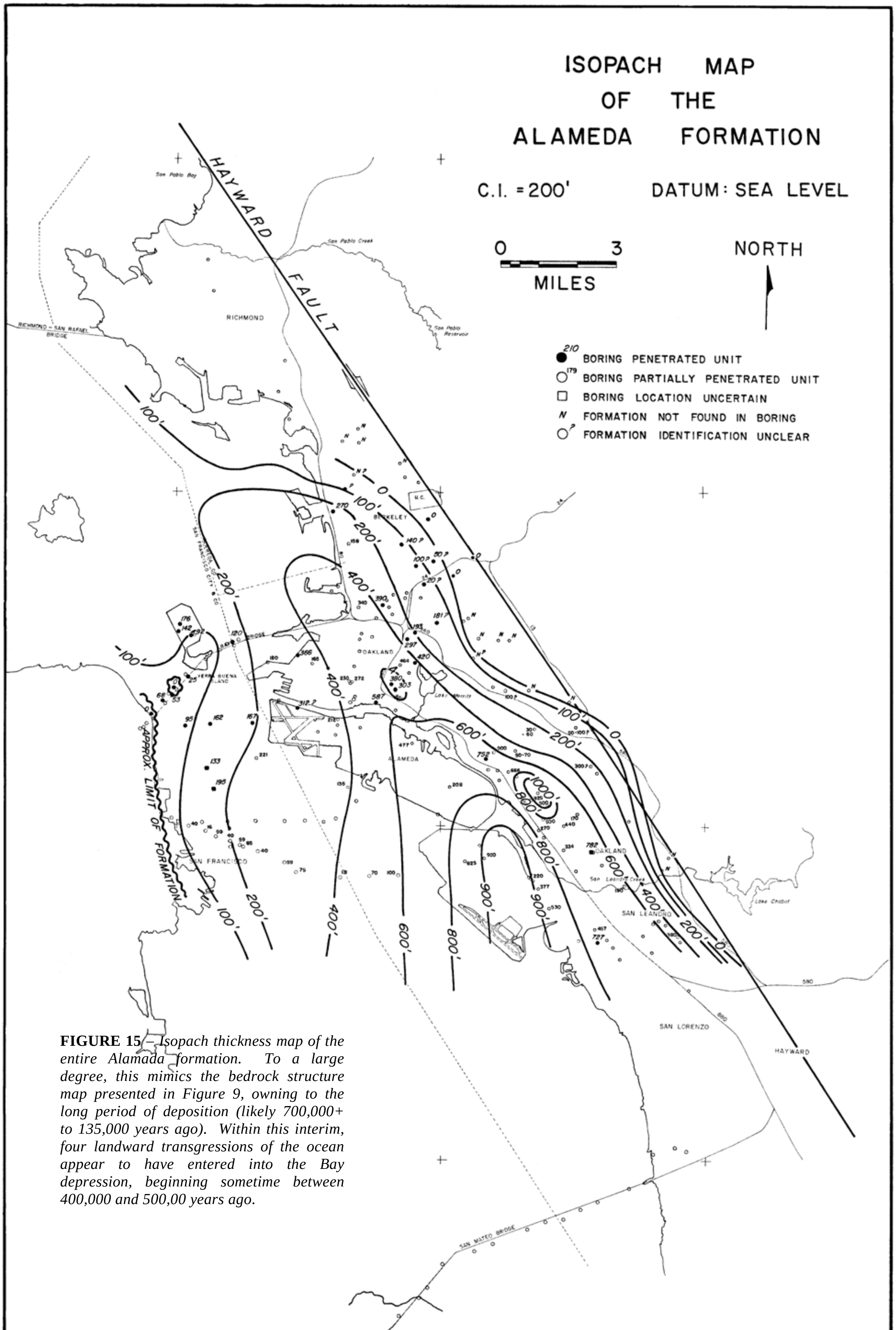


FIGURE 15 – *Isopach thickness map of the entire Alamada formation. To a large degree, this mimics the bedrock structure map presented in Figure 9, owning to the long period of deposition (likely 700,000+ to 135,000 years ago). Within this interim, four landward transgressions of the ocean appear to have entered into the Bay depression, beginning sometime between 400,000 and 500,00 years ago.*

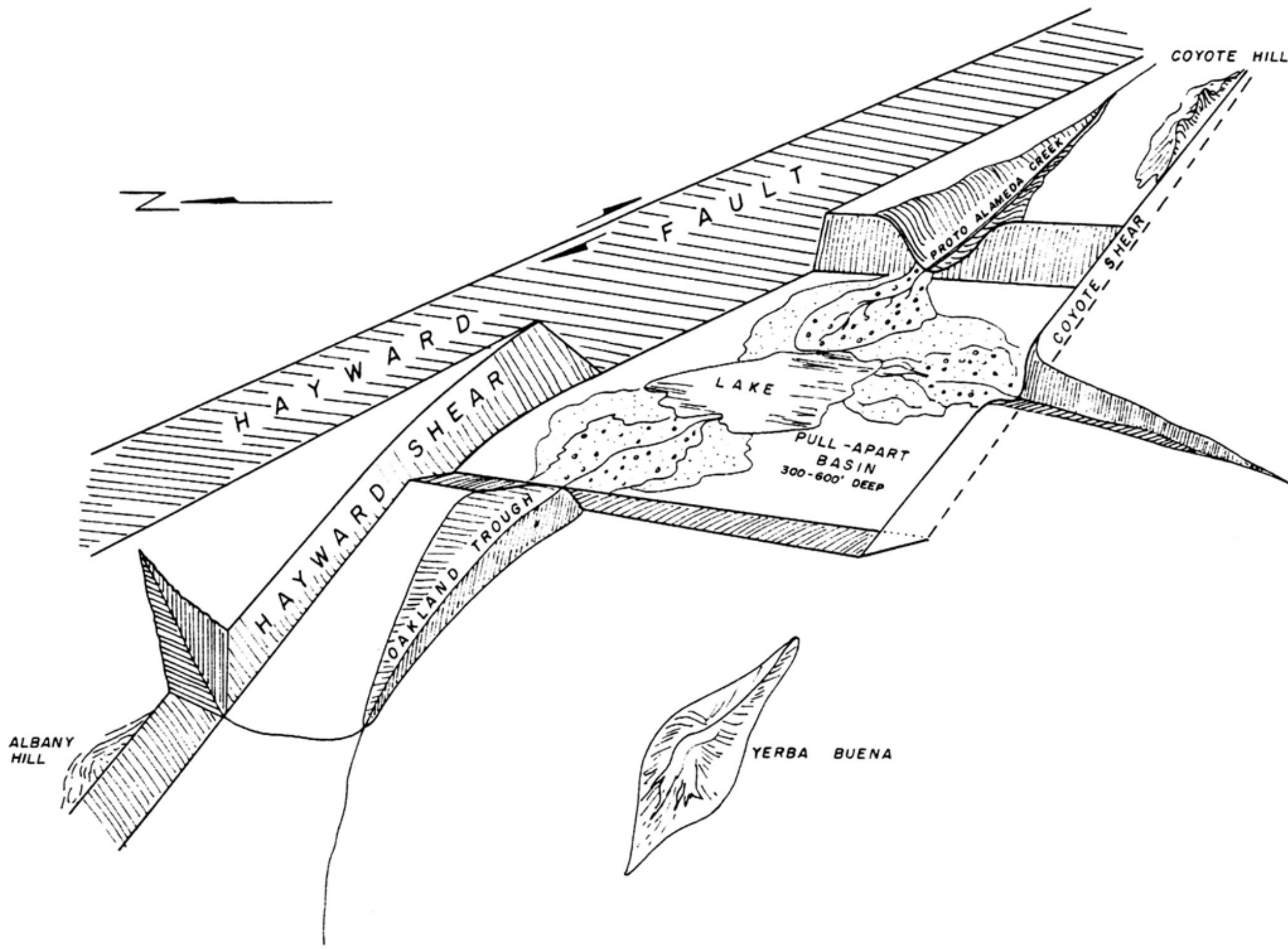


FIGURE 16 - *Schematic block diagram looking east at the beginning of Alameda deposition across the dissected Franciscan basement, the pull-apart basin hear Hayward, and the abrupt bedrock escarpment created by the Hayward fault.*

Correlations developed in this study suggest that the *Alameda formation* can be divided into a lower continental unit (300 - 600 feet thick) and an upper marine unit (200 - 400 feet thick). The lower continental unit records the filling of the initial *Franciscan* trough. The depositional environments suggested by the units include: alluvial fans, lakes, flood plains, streams, and swamps. These are portrayed schematically in Figure 16. Individual units within the *lower Alameda* are typically thin and discontinuous, and difficult to correlate from one well to another. Very little is known about this older, basal unit.

As the basin subsided, the original bedrock trough was replaced by a broad shallow bay, centered closer to what is now San Francisco. This suggests that the *pull-apart* tectonic regime ceased and the current tectonic regime began about the time of this depositional transition. At this time (somewhere between 400,000 and 500,000 years ago) the sea first entered the Bay depression and the deposits change from purely alluvial (continental) to a mixture of alluvial, brackish water (estuarine), and marine (Hall, 1965; Sarna-Wojcicki, 1985; Clifton and Hunter, 1991). These units appear similar to the blue-grey clay and silt that exist in the Bay today. These units are collectively known as the *upper Alameda formation*, a subdivision originally proposed by Margason in 1975. Atwater (1979) subsequently distinguished some of the same units (his units N, 0, Q and R), dating them at 200,000 to 700,000 years before present, but not utilizing the formational names presented herein (which we are using because Bay Area geotechnical practitioners utilize such nomenclature).

The end of the *Alameda formation* deposition approximately 200,000 years ago appears to have been marked by a major period of erosion. During this erosional period, a series of large east-west trending valleys developed along the *East Bay plain*. These valleys have exerted a major influence on the depositional patterns of all subsequent units. By the end of *Alameda* time the present overall shape of San Francisco Bay as it appears today had essentially formed. Depth below sea level to the top of the *Alameda formation* in the central San Francisco Bay area is presented in Figure 17.

Of particular interest is the apparent existence of a continuous deep channel incised into the upper part of the *Alameda formation*. This channel is up to 200 feet deep, and appears to have two branches. The northern branch extends from beneath the San Francisco-Oakland Bay Bridge, east of Yerba Buena Island, south, towards the San Bruno area. The geometry of the channel suggests that, at the end of *Alameda time*, the San Francisco Bay area drained through the San Bruno Channel (Rogers and Figuers, 1991) that formed between the San Andreas and East San Andreas faults (or San Bruno fault of Bonilla, 1964). This interpretation is different than that proposed by Trask and Rolston (1951), who felt that the area drained northward, towards Angel Island, as shown in Figure 17.

We do agree with Trask and Rolston (1951) that, by the close of *Alameda deposition time*, the trunk channel draining central San Francisco Bay existed just east of Yerba Buena Is-land. Since then the trunk channel has moved west, to the space between San Francisco and Yerba Buena Island.

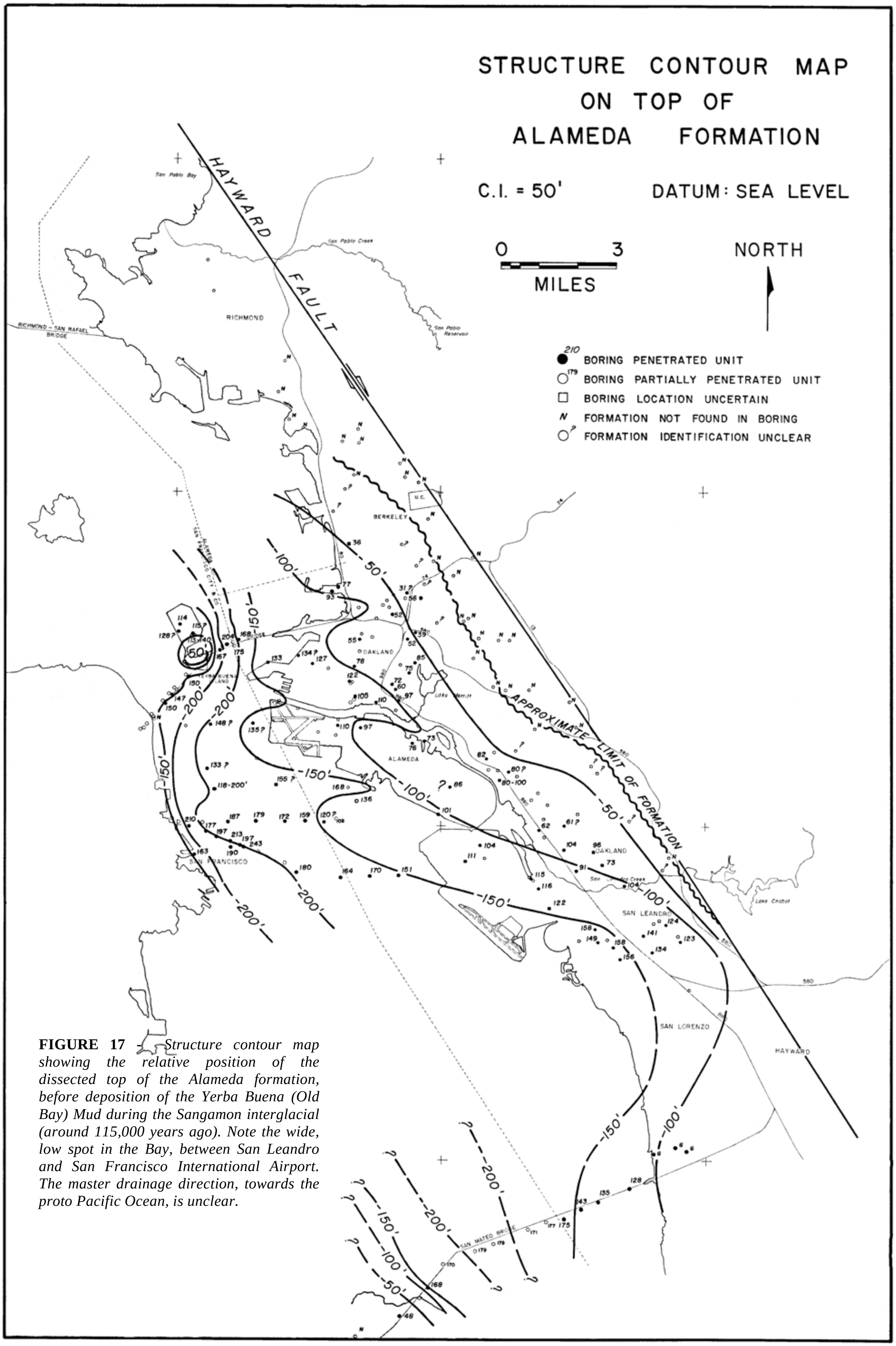


FIGURE 17 – *Structure contour map showing the relative position of the dissected top of the Alameda formation, before deposition of the Yerba Buena (Old Bay) Mud during the Sangamon interglacial (around 115,000 years ago). Note the wide, low spot in the Bay, between San Leandro and San Francisco International Airport. The master drainage direction, towards the proto Pacific Ocean, is unclear.*

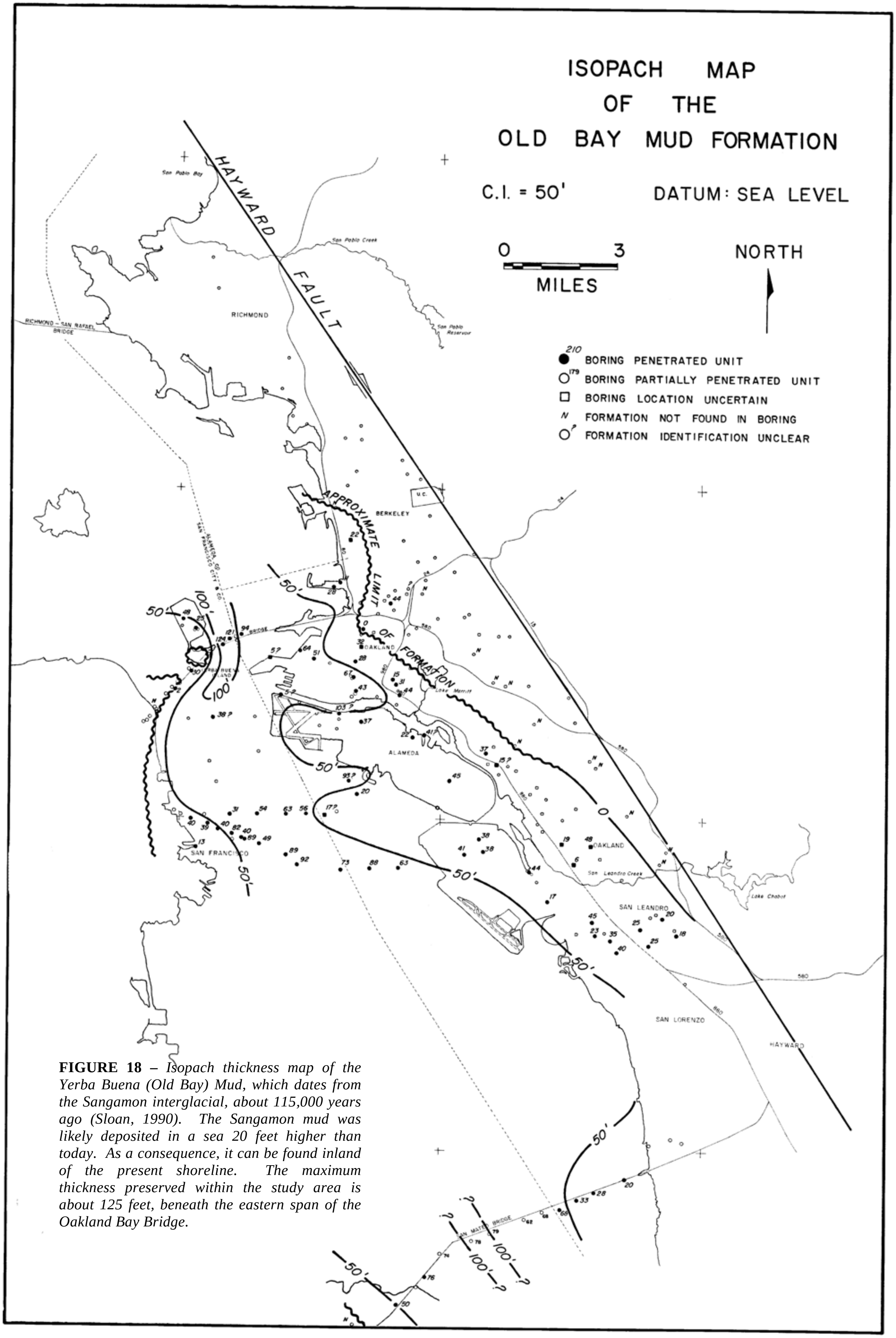


FIGURE 18 – *Isopach thickness map of the Yerba Buena (Old Bay) Mud, which dates from the Sangamon interglacial, about 115,000 years ago (Sloan, 1990). The Sangamon mud was likely deposited in a sea 20 feet higher than today. As a consequence, it can be found inland of the present shoreline. The maximum thickness preserved within the study area is about 125 feet, beneath the eastern span of the Oakland Bay Bridge.*

YERBA BUENA (OLD BAY) MUD

The ancestral *Pacific Ocean* re-entered San Francisco Bay approximately 115,000 years ago depositing the *Old Bay Mud* on top of the *Alameda formation* erosional surface. Trask and Rolston (1951) included the *Old Bay Mud* as the basal unit of their *San Antonio formation.* However, subsequent detailed stratigraphic analyses of this unit by Atwater, Hedel and Helley (1977) and Atwater (1979) showed that the *Old Bay Mud* (their unit "Qpe") was a distinct unit, unconformably overlain by the continental *San Antonio formation.* Atwater (1979) later dated this unit at 100,000 years old. About this same period, Sloan (1981) studied cores taken for the "Southern Crossing" alignments in the 1950's and was able to date the *Old Bay Mud* at *Isotope Stage 5e* (on the basis of entrained micro-organisms), or around 115,000 to 125,000 years ago, which would correspond to the *Sangamon interglacial stage.* Sloan (1990) subsequently made more detailed studies of the *unit,* delineating three distinct members, deposited in progressively cooler, deeper and more saline water within the Bay. Such a sequence would be expectable in a sustained landward transgression of rising seas during the *Sangamon Interglacial.* Sloan (1990) has proposed the term *"Yerba Buena Mud"* to supplant *"Old Bay Mud",* a colloquial term long employed by Bay Area geotechnical practitioners. We will honor this new terminology from here forward in the synopsis of our studies.

The *Yerba Buena Mud* is a good stratigraphic marker unit because it is wide-spread, homogenous, and easily identified. It is similar to the marine muds deposited in the San Francisco Bay today. Depositional patterns suggest that the Bay of 110,000 years ago was approximately the same shape, but slightly larger than today due to the *Sangamon* seas rising about 20 feet higher than those at present. As a consequence, the *Yerba Buena Mud* is found *inland of* the present limits *of* the Bay. For example, *Yerba Buena Mud is* found beneath virtually all *of* downtown Oakland and as far inland as the Hayward BART Station (Sloan and Aubry, 1991), more than two miles inland of the historic East Bay shoreline (as shown in Figure 18).

The *Yerba Buena Mud is* comprised primarily of a grey marine mud, but a thin (10 to 15 feet thick) sandy, shell-rich zone is commonly found in the middle of the unit. This zone would appear to represent a temporary, slight lowering of sea level with subaerial exposure of the unit.

The *Yerba Buena Mud (Old Bay Mud)* infills valleys and depressions cut into the underlying *Alameda formation* landscape up through the *Sangamon interglacial.* It thereby offers an accurate depiction of the *Alameda* erosional surface, showing the approximate trend and depths of continental drainages developed during the glacial epochs. *Unit* thicknesses are presented in Figure 18. As in the case for the underlying *Alameda formation*, some mystery still shrouds where various paleo-drainages existed and in which direction they trended. The isopach (unit formational thickness) map presented in Figure 18 suggests that maxi-mum thicknesses in excess of 100 feet were preserved in a broad channel beneath the Hayward-San Mateo Bridge alignment and in a similar sized channel beneath the San Francisco-Oakland Bay Bridge, just east of Yerba Buena Island. Tributary infilling along San Leandro Creek, San Antonio slough and Temescal Creek is also suggested in the isopachs presented in Figure 18.

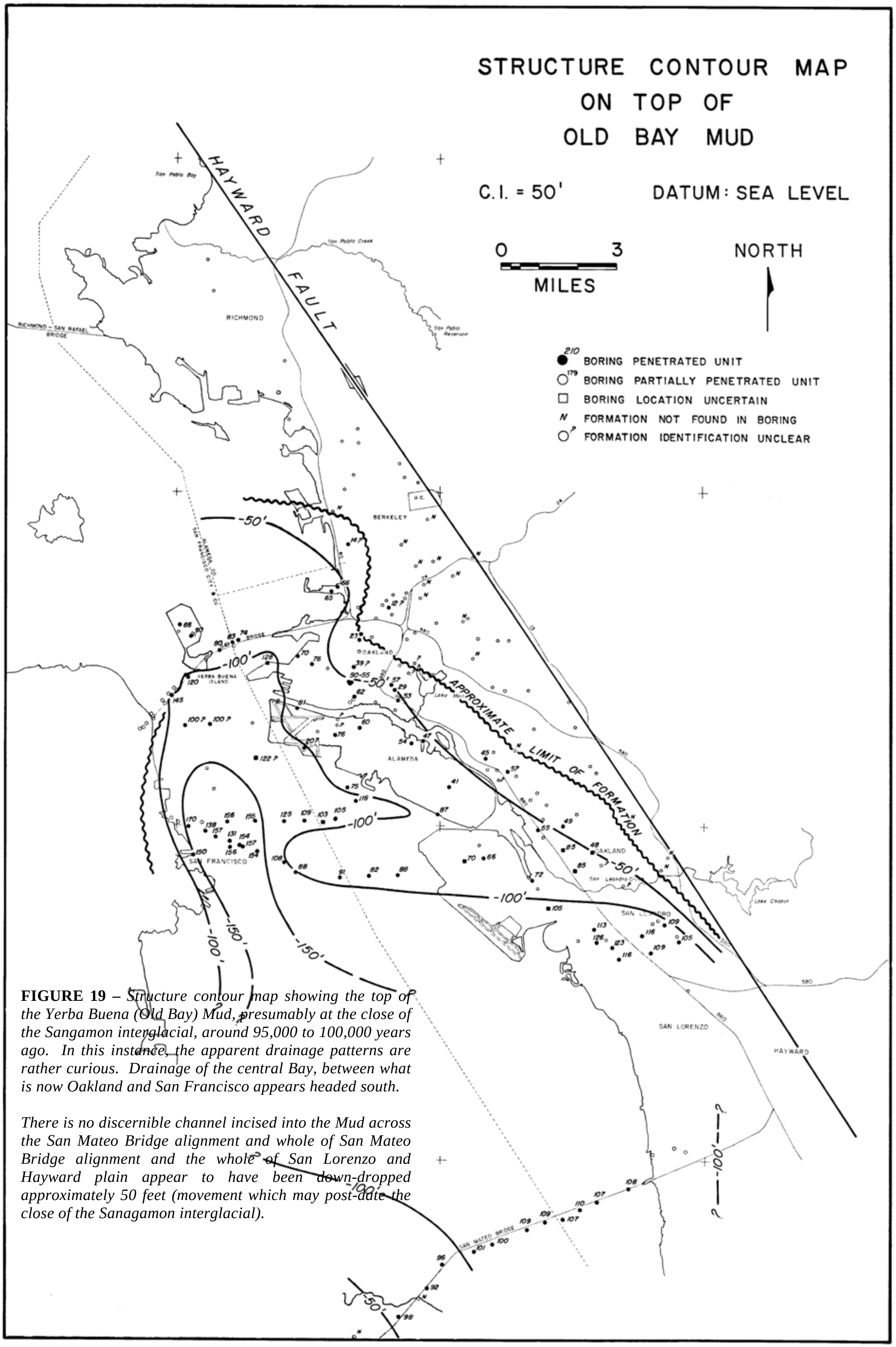


FIGURE 19 – *Structure contour map showing the top of the Yerba Buena (Old Bay) Mud, presumably at the close of the Sangamon interglacial, around 95,000 to 100,000 years ago. In this instance, the apparent drainage patterns are rather curious. Drainage of the central Bay, between what is now Oakland and San Francisco appears headed south.*

There is no discernible channel incised into the Mud across the San Mateo Bridge alignment and whole of San Mateo Bridge alignment and the whole of San Lorenzo and Hayward plain appear to have been down-dropped approximately 50 feet (movement which may post-date the close of the Sanagamon interglacial).

Figure 19 presents *a structural contour map* on the top of the *Yerba Buena Mud.* This compilation serves to depict the subaerial erosion of the *Yerba Buena Mud* which presumably occurred during the low sea stand of the *Wisconsin glacial stage,* 90,000 to 11,000 years ago. Here again, preliminary results are rather surprising when compared with what was assumed a few years ago. By *post-Yerba Buena time,* the major trunk channel accepting drainage from the East Bay plain shifted westward (see figure 19), and appeared to be trending southerly, towards the open portion of the Bay east of what is now San Francisco International Airport.

Of particular curiosity, however, is the *apparent absence* of a main trunk channel developed upon the *Yerba Buena Mud* along the Hayward-San Mateo Bridge alignment, where detailed stratigraphic analysis was undertaken (this is in stark contrast to the channel revealed upon the older, underlying *Alameda* sediments, mentioned earlier). Instead of a collective channel depression, the *Yerba Buena Mud* surface appears planar and undissected.

According to the stratigraphic compilation presented in Figure 19, the top of the *Yerba Buena Mud* lies over 100 feet below current sea level between Yerba Buena Island and somewhere between the Hayward-San Mateo and Dumbarton Bridge crossings, suggesting a closed depression of sorts. This finding is in contrast with the previously-held findings of U.S.G.S. scientists Atwater, Hedel and Helley (1977) who had convincingly demonstrated that, by the *end of the Wisconsin glacial stage* (11,000 years ago), the southern and central San Francisco Bay drained northward, between Yerba Buena island and San Francisco, around Angel Island, through Raccoon Straits, through the Golden Gate to the Pacific Ocean. The only alternative hypothesis we can offer is the very preliminary assertion that the *San Bruno,* and possibly *Colma Channels* (Rogers and Figuers, 1991) may have been periodically open to the sea along with the Golden gate Channel at the close of the *Sangamon interglacial,* shortly before deposition of the continental *Colma formation* (Bonilla, 1964; Clifton and Hunter, 1991) within such low lying coastal margins between *90,000* and 100,000 years ago (Clifton (1991) maintains that the *Colma formation* was deposited along bay margins under subaerial conditions, contrary to the thoughts of some previous workers who had assumed the *Colma* to have been deposited in a shallow, off-shore environment, like the underlying *Merced formation).*

In assessing the stratigraphy beneath the Southern Crossing, Hayward-San Mateo and Dumbarton bridge alignments, Atwater, Hedel and Helley (1977) also found the *Yerba Buena* surface (their unit "Qpe") to be little incised, apparently having been rapidly covered by alluvial sediments of the *San Antonio formation* (their unit "Qpha"), or its stratigraphic equivalents.

SAN ANTONIO FORMATION

The stratigraphic term *San Antonio formation* was originally coined by Trask and Rolston (1951) to describe a thick expanse of estuarine and alluvial sediments lying between the older *Alameda formation* and *Young Bay Muds* along the San Francisco Oakland - Bay Bridge and Southern Crossing alignments. In this study the term is used to describe the *non-marine*

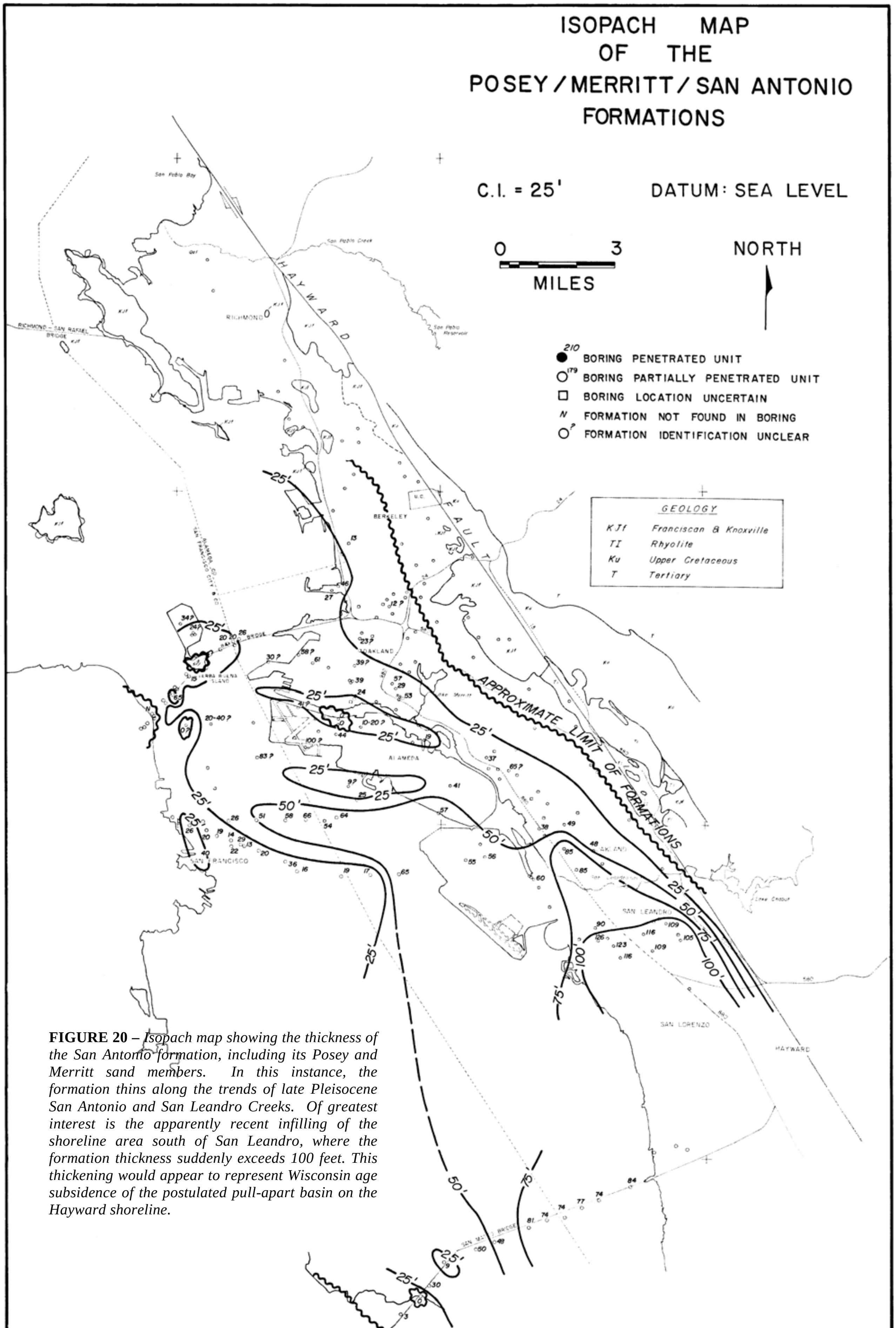


FIGURE 20 – *Isopach map showing the thickness of the San Antonio formation, including its Posey and Merritt sand members. In this instance, the formation thins along the trends of late Pleisocene San Antonio and San Leandro Creeks. Of greatest interest is the apparently recent infilling of the shoreline area south of San Leandro, where the formation thickness suddenly exceeds 100 feet. This thickening would appear to represent Wisconsin age subsidence of the postulated pull-apart basin on the Hayward shoreline.*

sediments (predominantly sands and silts) that were deposited adjacent to and on top of the *Yerba Buena Mud (Old Bay Mud).* This usage would, therefore, include the "traditional" *San Antonio formation of* Trask and Rolston as well as the *Merritt Sands* and the *Posey formation* (terms originally coined by Lee and Derleth, among others; see Whitworth, 1932; and Lee, 1935). This same nomenclature was continued by Radbruch (1957, 1969) as well as Lee and Praszker (1969). Atwater, Hedel and Helley (1977) utilized the terms "Qpha" and "Qpht" to describe what is stratigraphically equivalent to what we are terming the *San Antonio formation.*

The *San Antonio* sediments were deposited in a complex and ever-changing depositional environment that ranged from alluvial fans to flood plains to lakes to swamps to beaches. It is crucial to appreciate that individual units are discontinuous and difficult to correlate over distance.

Within the uppermost portion *of* the *San Antonio* are old broad channels infilled with firm sandy clay underlain by a sandy channel fill called the *Posey sand, Posey formation, or Posey member of the San Antonio.* It was originally identified in the vicinity of the Webster Street Crossing, or Posey Tube, between downtown Oakland and Alameda in the early 1930's (Louderback, 1939).

Sometime late in the *Wisconsin glacial stage* (90,000 to 11,000 years ago) the weather became somewhat drier, and aeolian sands accumulated along offshore wind corridors adjacent to the Golden Gate, Richmond-Carquinez gap, the East Bay plain and Oakley (in the San Joaquin Delta). Trask and Rolston (1951) called these the *Merritt Sands.* The *Merritt sands* overlay alluvial deposits of the *San Antonio,* draping over old channel banks along the San Antonio estuary. Petrographic analyses show the *Merritt* to be immature blow sands, virtually indistinguishable from their underlying alluvial source material, like the *Posey sands.* This means that the *Merritt sands* could not have been reworked by the prevailing on-shore winds for a very long period.

The *Posey/Merritt/San Antonio formation* units lie in lenticular bands across the *East Bay plain,* as depicted in the unit isopach map presented herein as Figure 20. These "bands" are thinnest in old channels which experienced subsequent rejuvenation in extreme *late Wisconsin time.* Of particular interest is the apparent reactivation of the old *pull-apart basin* margin, along the East Bay shore, south *of* San Leandro. The well logs record a consistent 50 foot north-to-south drop of the *San Antonio/Yerba Buena* contact.

Figure 21 presents several hypotheses to explain the consistent down-dropping of *post-Sangamon age* units south of San Leandro. The upper part of Figure 21 presents a fault model. This model implies that consistent vertical offset of the *Yerba Buena Mud is* ascribable to a boundary fault. In such a case, the *Mud* would be missing from the stratigraphic section along the fault trace. An alternative, fold hypothesis, is presented in the middle portion of Figure 21. In a fold model we could expect the *Yerba Buena Mud* to be thinned as it was extended across the fold axis. The lower portion of Figure 21 presents the remaining hypothesis, that of miss-correlation of the *Yerba Buena Mud across* the East Bay plain. In such a scenario, the *Yerba Buena Mud* would consistently pinch out, while an older, deeper mud unit extending across the

East Bay plain, would be miss-identified as the *Yerba Buena* beneath San Lorenzo and Hayward. Further study is necessary to determine which scenario is closest to the truth.

In very late *Wisconsin time,* the *Merritt sands* were themselves eroded by an apparently rejuvenated stream system (see Figure 21), which cut down some 150 feet into parts of the underlying *San Antonio formation.* As the Wisconsin glaciers began to retreat approximately 11,000 years ago, the East Bay's stream system discharged into a main trunk stream located between Yerba Buena Island and what is now downtown San Francisco (Atwater, Hedel and Helley, 1977). The *Wisconsin-age* Temescal Creek made a sharp turn, south and around Yerba Buena, crossing over the southern flank of the Yerba Buena rise and connecting with the north-flowing trunk channel (see figure 20). Other east Bay tributaries, principally San Antonio, San Leandro and San Lorenzo Creeks, cut similar paths, albeit more direct than that of Temescal. The main trunk channel likely conveyed the drainage from the entire South bay area as well as Alameda Creek (draining the Pleasanton-Livermore-Sunol Valleys. The Coyote Creek drainage near Morgan Hill is thought to have periodically flowed north through this same gap (as it does presently) and south, through the Pajaro Gap towards Watsonville.

YOUNG BAY MUD

According to Atwater, Hedel and Helley (1977), between 11,000 and 8,000 years ago sea level rose sharply, at an *average rate* of 24 mm (about 1 inch) per year. Since 8,000 years ago there has been a somewhat slower rate of sea level rise, averaging about 1 mm per year to its present level. The stream valleys incised into the *Merritt, Posey and San Antonio formation* were soon filled with estuarine mud, known as the *Young Bay Mud* (Whitworth, 1932; Trask and Rolston, 1951; Treasher, 1963) or "Qpha" by Atwater, Hedel and Helley (1977).

These recent, unconsolidated muds were initially deposited in quiet water with high initial void ratios and low unit densities. Along the San Francisco Embarcadero the *Young Bay Mud is* divisible into three distinct members; lower, middle and upper; each more saline than its predecessor. The *Young Bay Mud* reaches a maximum thicknesses of about 120 feet in the main South Bay trunk channel east of China Basin and Hunter's Point, near the San Francisco shoreline (Goldman, 1969). The *Young Bay Mud* infills the drowned valleys of the late *Wisconsin glacial stage,* as depicted vividly in Figure 22.

TEMESCAL FORMATION

On the East Bay plain in the present study area, a distinctive younger alluvial unit, known as the *Temescal formation* (Radbruch, 1957, 1969) overlies *San Antonio* alluvium, and occurs as inset terraces in incised East Bay alluvial channels. More fine-grained than the underlying *San Antonio,* the *Temescal* is almost wholly comprised of silt and clay, which contains noticeable amounts of the swelling clay mineral montmorillonite. This smectite clay mineral is likely derived from the weathering of the *Pleistocene-age Leona Rhyolite,* which outcrops along the *Hayward fault* in the upper part of the stream's watersheds.

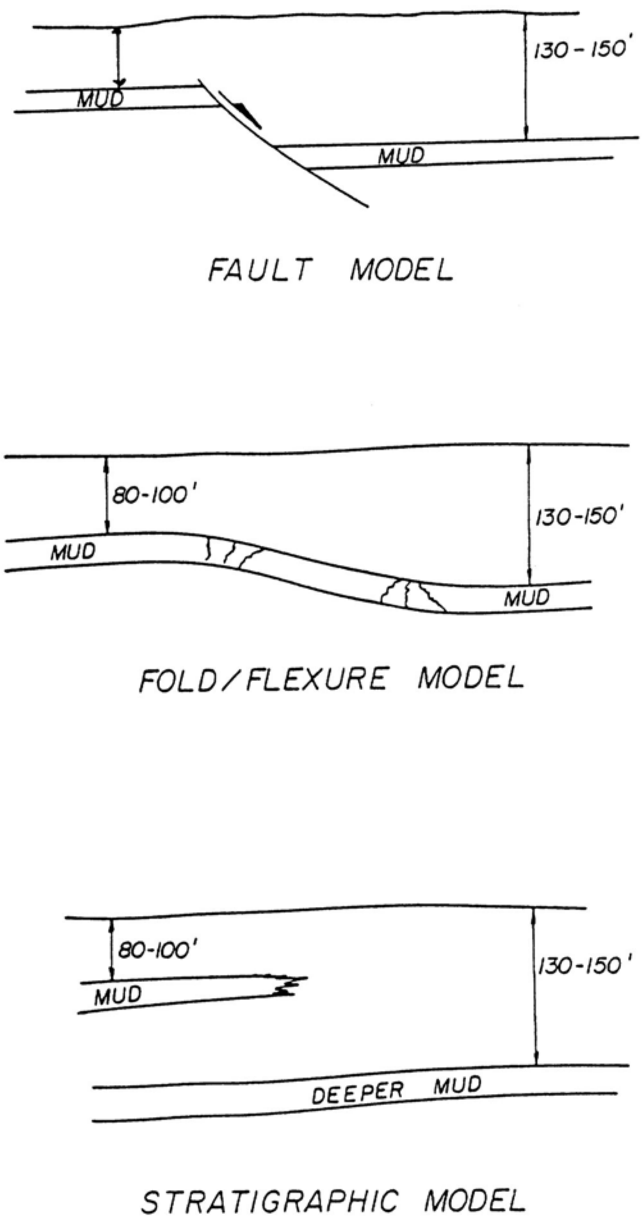


FIGURE 21 – *Geologic model postulates to explain apparent down-drop of the Yerba Buena (Old Bay) Mud beneath the east Bay plain south of San Leandro. The entire post-Sagamon section appears to lie 50 feet deeper beneath Hayward and San Lenadro than in all other adjacent parts of the Bay to the south.*

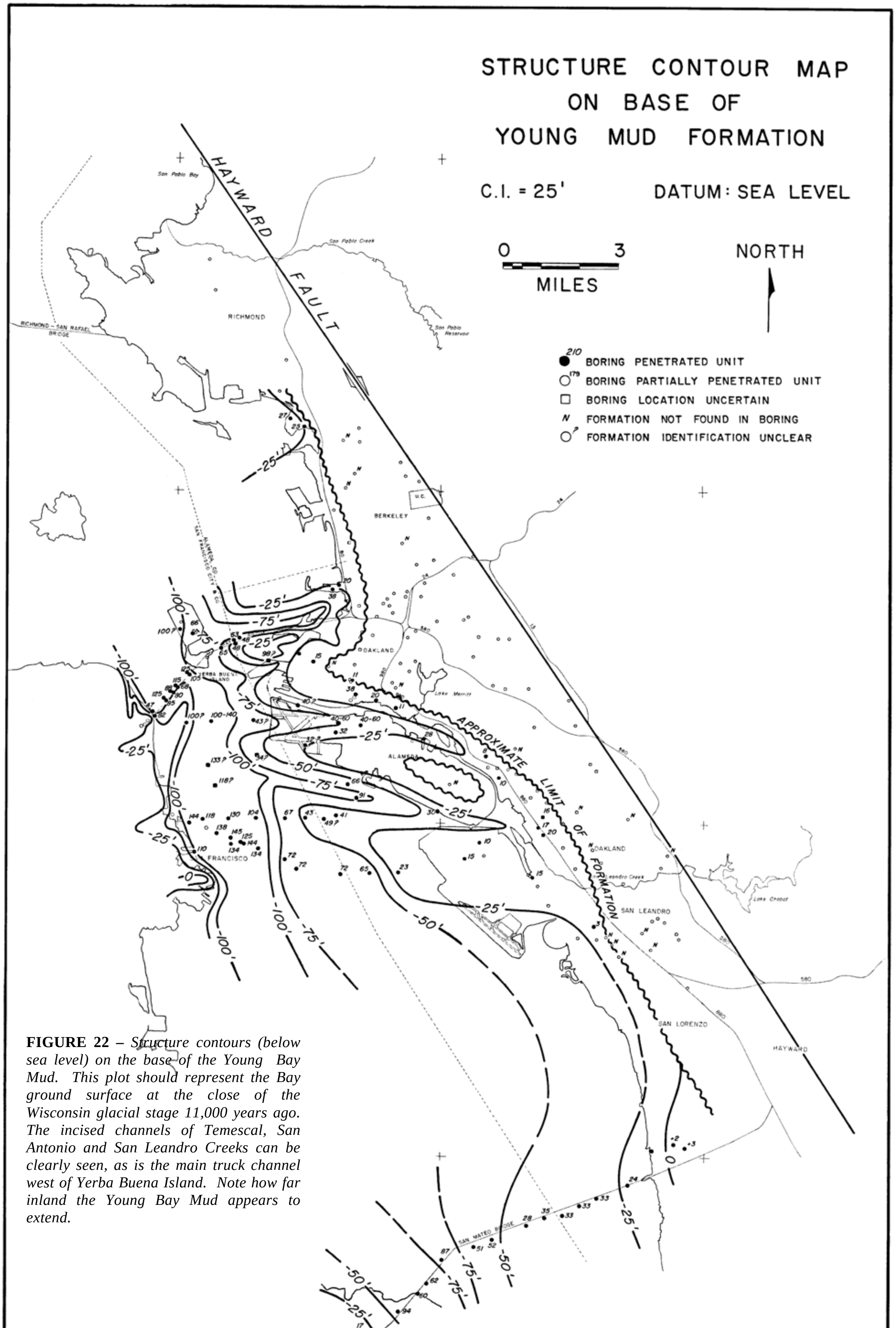


FIGURE 22 – *Structure contours (below sea level) on the base of the Young Bay Mud. This plot should represent the Bay ground surface at the close of the Wisconsin glacial stage 11,000 years ago. The incised channels of Temescal, San Antonio and San Leandro Creeks can be clearly seen, as is the main truck channel west of Yerba Buena Island. Note how far inland the Young Bay Mud appears to extend.*

The *Temescal formation is* readily identifiable by its mottled, variegated color; intertwined yellowish-ochre color (oxidized) with its original olive grey (likely unoxidized) color. The *Temescal* materials likely represent cooler, wetter periods of *early Holocene* time (11,000 to 6,800 years ago), when abundant colluvial production (higher sediment budgets due to in-creased levels of erosion and landsliding in the highlands) and stream carrying capacity was sufficient to choke the local channels with these fine-grained materials.

Over the past 6,800 years there has been a progressive drying of weather in coastal California, thereby promoting a period of renewed stream entrenchment. *Temescal* inset terraces are being excavated, leaving remnants pasted to the walls of incised East Bay channels.

In the latest stream system adjustments within the study area, the San Antonio-Glen Echo-Trestle Glen Creek system join at Lake Merritt and have collectively cut a new channel through the Merritt Sands called San Antonio Slough. This present-day channel lies approximately 2,000 feet north of the *late Wisconsin-age* channel (prior to 11,000 years ago), which formerly ran directly beneath what is now Alameda Naval Air Station (which can be discerned in Figure 22). Part of this shift appears to be due to piracy of nearby Sausal Creek to a new San Leandro channel, between Alameda and Bay Farm Island.

ARTIFICIAL FILL

Beginning in the mid-19th Century development of the greater Oakland area has resulted in a progressive in-filling of the natural Bay margins. Due to the westward migration of the South Bay trunk channel during the *Wisconsin glacial age* (11,000 to 95,000 years ago) the slope of the East Bay alluvial plain has become very gradual. The eastern half of San Francisco Bay is very shallow, no more than 6 feet deep. The creeks discharging into the Bay from the East Bay plain were choked with sediment, creating noticeable bars near their mouths following large storms. These offshore conditions necessitated the construction of the 1.3 mile long wharf, originally constructed by Southern Pacific in 1879 to enable deep draft ships to serve the Oakland shore.

The natural network of brackish sloughs along the Oakland waterfront in 1876 is reproduced herein as Figure 23. The original waterfront was progressively encroached upon from the downtown Oakland area in order to create commercial properties along the San Antonio estuary. Around the turn of the Century more and more of the undeveloped brackish slough areas were infilled to create commercial zones along the Southern Pacific and Western Pacific railroad yards, west of the downtown area. At about this same time (1879-1893) a local group of merchants sponsored the creation of a continuous channel between Fruitvale (then known as "The Annex") and Alameda, thereby making Alameda an island. The idea behind such a long-lived project was to create a continuous channel which would hopefully utilize the natural tidal draw to pull natural silt out of San Antonio slough. Once this channel was completed the City of Oakland began to take an active role in planning and promoting its Port facilities. By 1899 the Oakland shoreline appeared as shown in Figure 24, taken from the U.S.G.S. San Francisco quadrangle. By 1905 Oakland sported the Key System electrified interurban railway, the first of its kind in the East Bay. A great mole, some 2 miles long, was constructed out into the Bay parallel to what is today the Oak-land Bay Bridge.

FIGURE 23 - *Tract map of the Oakland and Alameda areas, as they appeared in 1878. Note how land parcels have been drawn extending out into the Bay just north of the foot the Southern Pacific Long wharf. A comparison with Figure 25 shows how much bayward encroachment has occurred over the past century (taken from Thompson and West, 1878).*

In the great San Francisco earthquake of April 18, 1906, Oakland suffered a moderate amount of structural damage, all to tall unreinforced masonry structures. In Oakland only one person was killed and there was no disastrous fire as there had been in San Francisco and Santa Rosa. Following the disaster that overtook San Francisco, the Oakland area be-came a haven for quake-shocked inhabitants of the San Francisco area. Oakland's population quadrupled over the next 10 years, necessitating a series of infrastructure crises. Within this same interim came the western terminus of both the Western Pacific and Santa Fe railroads, making Oakland the western terminus for the three largest transcontinental railroads. During World War I (1917-18) the Port of Oakland became the west coast's largest shipbuilding facility almost overnight, developing the Inner Harbor area along the Oakland Estuary. The railroads and the Port authority combined to begin infilling the tidal flats adjacent to the rail yards and north of the Great Long wharf. Most of the filled ground came from hydraulic dredging of *Merritt Sand* lying just under the waters of the Bay a short distance away (see Figure 25).

In the year before the United States' entry into World War II, the Army Corps of Engineers and the Port combined to infill over 6.5 million cubic yards of fill into the Bay to create the Army's Oakland Terminal of the San Francisco Port of Embarkation (Hamilton and Boyce, 1946). Fill material came from several sources: sand infill was hydraulically placed from the source areas presented in Figure 25; rock fill for the seawalls was imported by barge from quarries at Point Richmond and Point San Pedro (in San Rafael); and the surface course (top few feet) was taken from quarries in the *Leona Rhyolite* near Lake Temescal and the Leona Quarry, near Oak Knoll Naval Hospital. Trucks ran 24 hours per day from these two quarries to serve the enormous fill requirements (Oakland, 1952).

With the construction of the Eastshore Freeways in the mid-1950's, the present shorelines of the Oakland area were basically set as they appear today. The bayward progression of these infilling activities in the vicinity of Oakland are presented graphically in Figure 26.

PRESENT DAY SITE CONDITIONS ALONG THE EAST BAY MARGIN

The East Bay shoreline appears to be underlain by a heterogeneous assemblage of *late Pleistocene-age* alluvial sediments interspersed with shallow marine muds. At depth (in the *Alameda formation),* some very soft lacustrine clays may also locally be present (as discussed later). The dominant geologic units with respect to seismic site response are those deposited in the past 125,000 years: *the Yerba Buena (Old Bay) Mud, the San Antonio/Posey/ Merritt formation, the Young Bay Mud, the Temescal formation and the recent bay fills.*

The alluvial sediments (the lower *Alameda***,** the *San Antonio***,** and the *Posey/Merritt sands***)** tend to be extremely sorted, both with respect to longitudinal as well as lateral position (see sketch in Figure 27). This means that as the alluvium is transported down-gradient, across the old East Bay plain, sediment grain size drops as the hydraulic slope diminishes. As a consequence, succeeding finer particles are deposited with increasing distance from the Hayward fault escarpment (as shown in Figures 14 and 15). Concurrently, the high energy transport afforded by these same stream channels tends to deposit more granular materials along narrow, confined

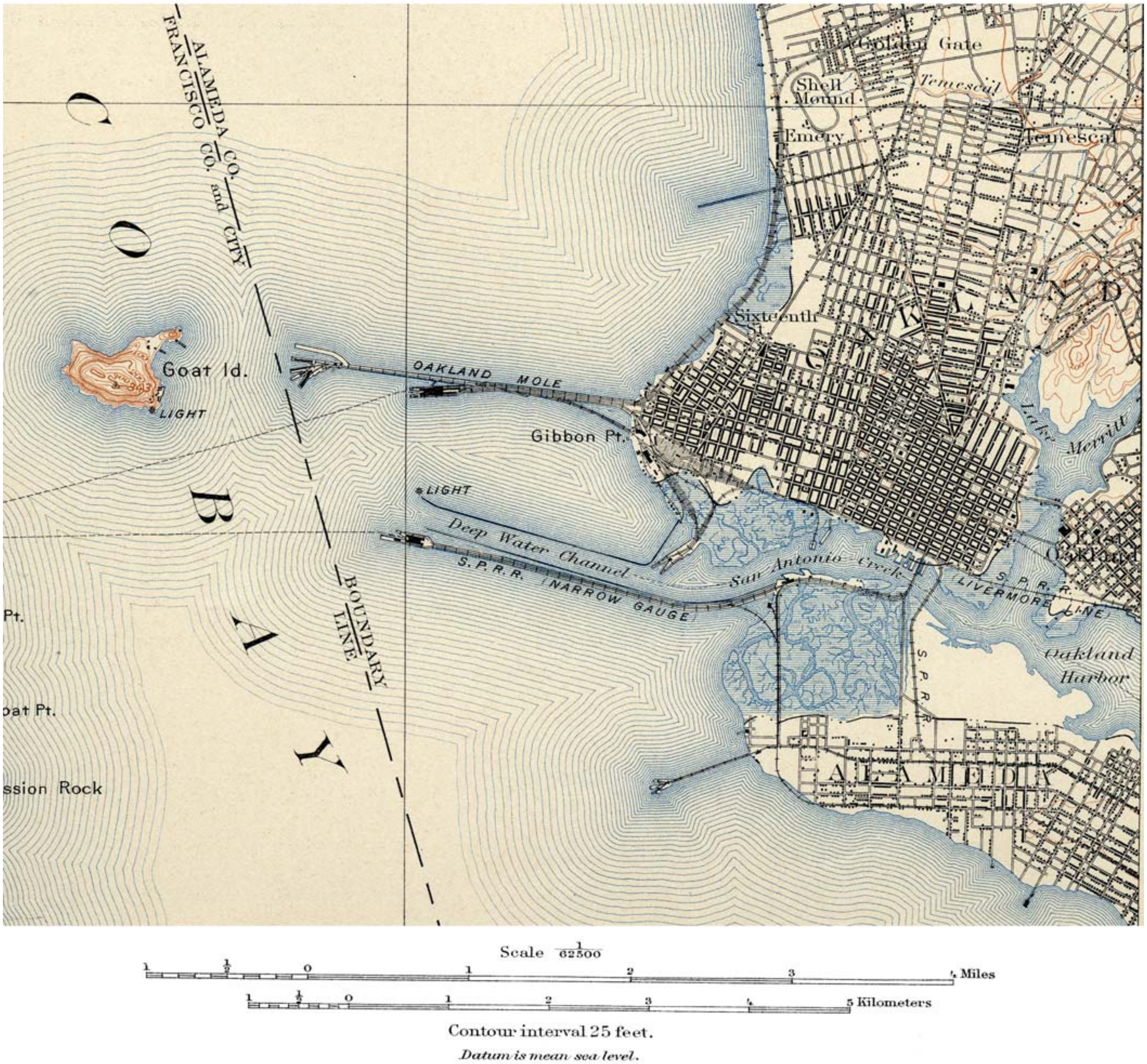


Figure 24 – *Portion of the 1899 U.S.G.S San Francisco Quadrangle (1:62,500) showing the Oakland and Alameda shoreline as it the appeared. In 1905, the Key System mole was extended along the pier shown just south of Emery. In 1911 Western Pacific constructed their terminal yard upon the brackish slough, just above the words "San Antonio" Creek. In 1940 the Navy constructed Alameda Naval Air Station south of the old S.P.R.R narrow gag mole, utilizing that structure as their northern breakwater.*

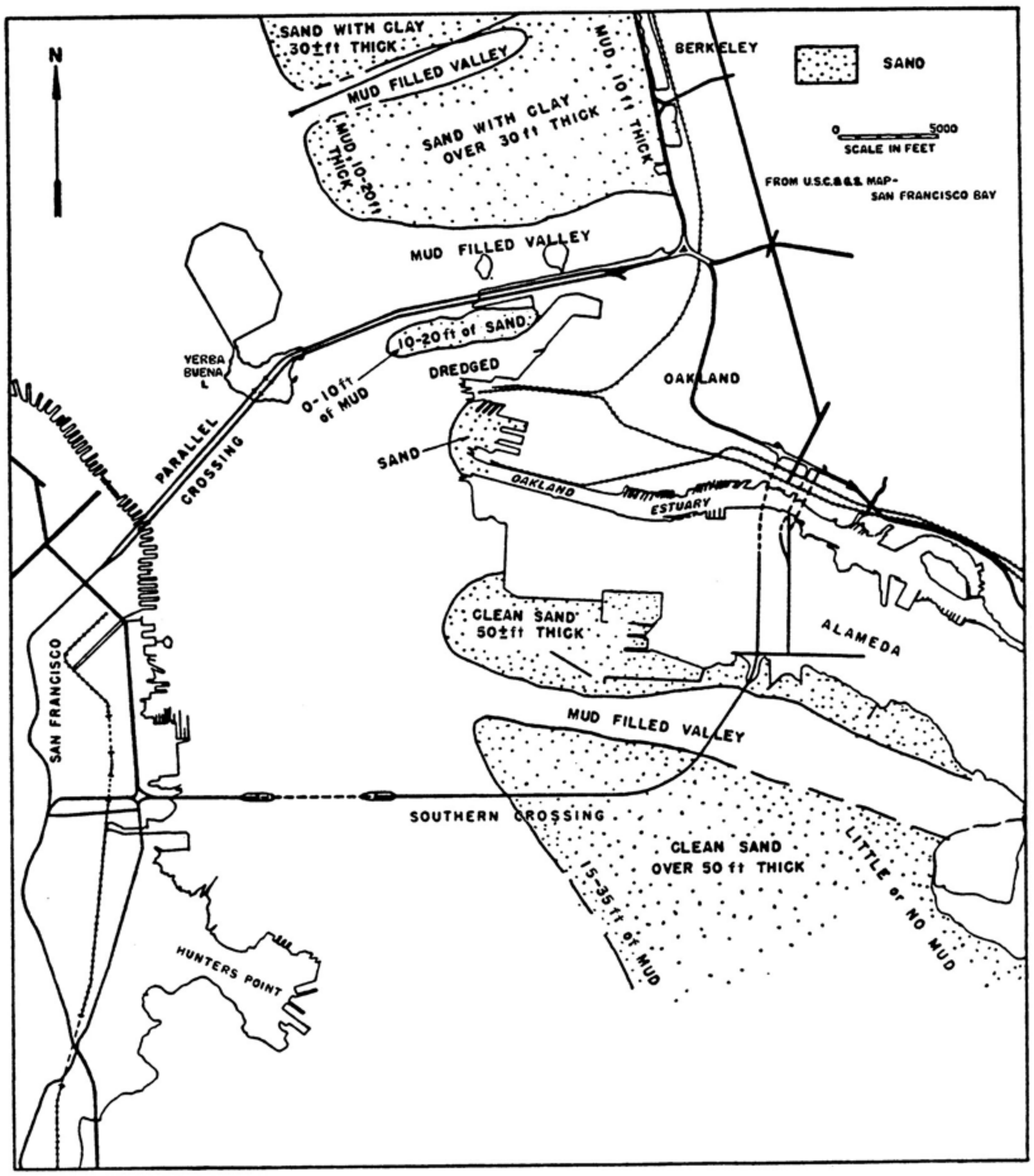


FIGURE 25 – *Distribution of Merritt Sand used as borrow material to infill the margins of central San Francisco Bay between 1905 and 1942. Thickness of mud refers to the overburden of Young Bay Mud lying atop the sand (taken from Trask and Rolston, 1951).*

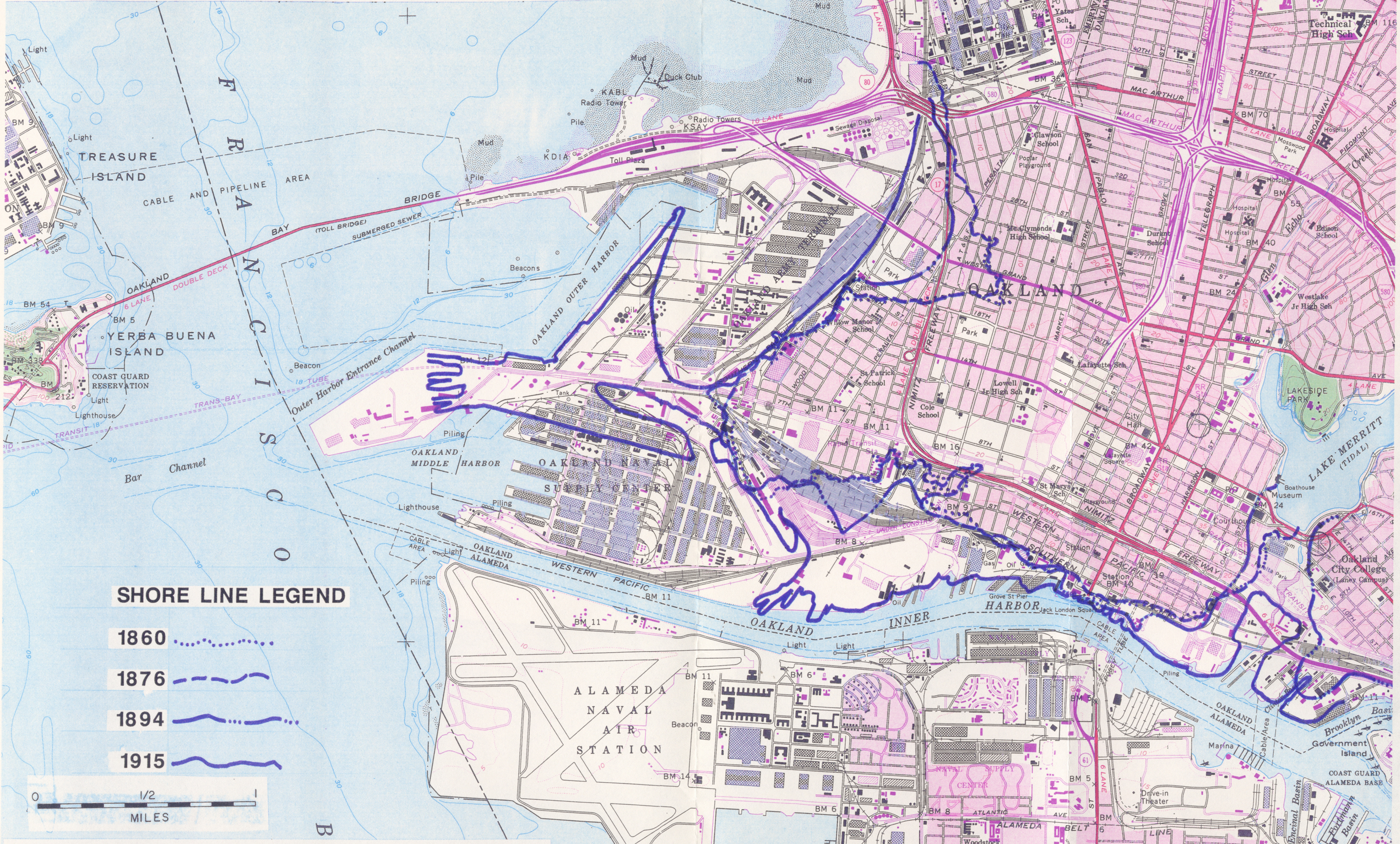


FIGURE 26 - *Overlay of historic shorelines along the Oakland waterfront from 1860 to the present (1991). Virtually the entire Port of Oakland and western half of Alameda has been constructed upon recent bay fill.*

channel corridors. Fine-grained flood overbank deposits were deposited on the alluvial plain separating major drainages. As a consequence, it can be very difficult to make discrete stratigraphic correlations between borings or wells over very modest distances across the fall-line of the East Bay alluvial plain. It would also be very dangerous to apply geophysical properties (such as shear wave velocities) to alluvial formational units, as the consistency of such units vary so dramatically over short distances.

On the other hand, the marine muds deposited in the quiet water of successive marine transgressions into the East Bay are deposited in a much more uniform manner. As a consequence, these units are much easier to correlate over long distances. However, the muds also tend to infill old channels, creating marked differences in thickness over a short distance normal to the stream's fall-line (see Figure 27). In addition, the muds from one inter-glacial stage may not be deposited atop channels of an older age. In most cases, the *Old Bay Mud (Yerba Buena) and Young Bay Mud* channels are slightly offset from one another, as depicted schematically in Figure 27.

Towards their continental margins the bay muds also appear to be mixed with age-equivalent alluvial sediments, which tends to make them much stiffer. For example, in the vicinity of the collapsed I-880 Cypress Structure, the *Young Bay Mud* was completely inter-tongued with its age-equivalent alluvial counterpart, the *Temescal formation.* Shear wave propagation properties within these two units are dramatically different, owing to the extremely high initial void ratio of the marine muds as compared to the alluvium.

REPRESENTATIVE CROSS SECTIONS OF THE EAST BAY MARGIN

A regional view of the geology within the San Francisco Bay bedrock depression provides a framework onto which we can better understand the highly variable site response experienced in the Oakland-Alameda area during earthquakes.

Through a progressive review of the stratigraphic column we have seen that deposition within the San Francisco Bay bedrock depression appears to have occurred within the past million years, with the bulk of deposition having taken place in the latter half of that interim. Regional cross sections, taken across the Bay have been prepared as a part of this study. Their locations are shown in Figure 28, and the sections are included as plates in the appendix[3]. Plate 1 cuts through the North Beach section of San Francisco, Treasure Island, and into Emeryville. Plate 2 bisects the China Basin area of San Francisco, across Alameda Naval Air Station, downtown Oakland, Piedmont and up to the Hayward fault. Plate 3 extends from the Hunter's Point area of San Francisco, across the Bay through central Alameda and under the Fruitvale portion of Oakland up to the Hayward fault. Plate 4 extends from Brisbane across the Bay and just misses the northern tip of Bay Farm

Island while catching the southern tip of Alameda and through south Oakland**.** The sections in Plates 1 and 4 are almost 8 miles apart, and, when combined with the intervening plates, offer

[3] The plates were originally 2 by 3 feet in size. Reduced versions of the plates have been included with this digital version of the report.

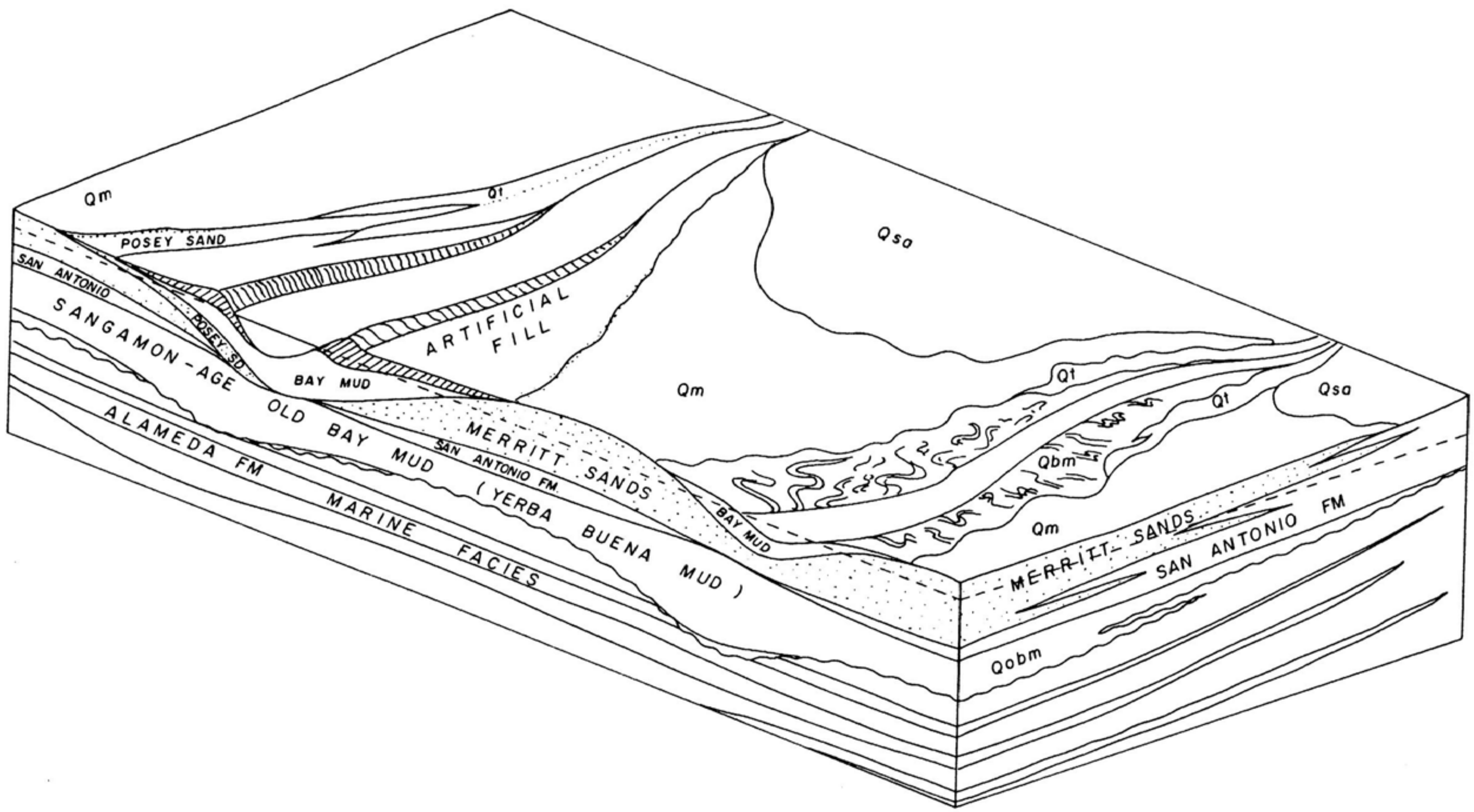


FIGURE 27 – *Schematic block diagram view looking north across the East Bay shoreline in the vicinity of Oakland and Alameda (with the dashed line representing mean sea level). Along the Bay margins, Young Bay Mud has been deposited in late Wisconsin-age channels, cut in the San Antonio formation when sea level was 350 feet lower than today. In places this incision cut down to the Old Bay Mud. In many of the sloughs, the present channel thalweg is offset from those of past interglacial stages. Much of the 20th Century infilling along the old shore has been upon Young Bay Mud. Note how the Merritt Sands vary in thickness, at times pinching out altogether.*

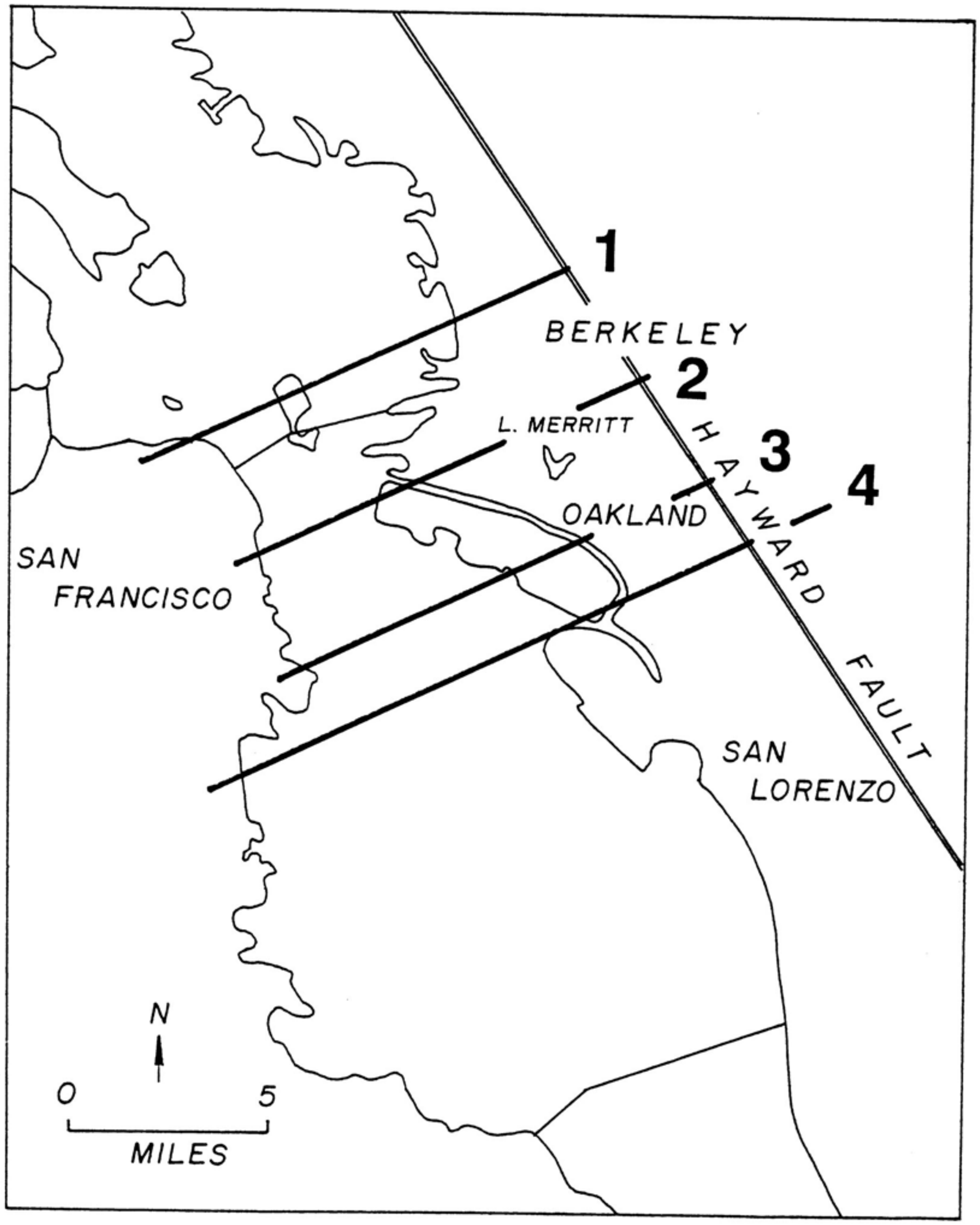


FIGURE 28 – *Locations of comparative geologic cross sections through Central San Francisco Bay, included as over size Plates 1 through 4 in the Appendix.*

the first detailed look at the geology underlying the Oakland-Alameda area.

By comparing the Bay cross sections, we can see that, during *Alameda time*, most of the deposition was along the down-dropped *eastern side* of the Bay. In more recent time, the majority of sediment appears to have been deposited on the western side of the Bay. This shift suggests that the regional cross slope of the Bay has likely been controlled by continued uplift of the East Bay Hills along the Hayward fault.

It is also clear that the San Francisco Bay depression is very slight in comparison to the region's size (a factor long espoused by Page, 1991). In Figure 12, a real-scale cross section shows just how insignificant the *Franciscan* bedrock depression is with respect to the Bay's width (it is 17 miles between the San Andreas and Hayward faults). Only 5% extension is necessary to create the depression as we currently understand it.

On a larger scale, today's East Bay shore virtually mimics the exact position of the same paleo-continental margin during past interglacial high sea stands. Over the past half-million years, these warm intervals have seen sea levels rise 300 to 370 feet, for periods of 10,000 to 20,000 years on an average cycle of about once every 100,000 years. As a consequence, global glacial fluctuations creating high sea stands only occur over about 10% of the total time interval. During the remaining 90% of *late Pleistocene* time the Bay area has existed as a coastal lowland, separated by about 30 miles from the continental shelf and the open sea. During this extensive interval of subaerial exposure, all manner and form of continental deposition appears to have occurred; from brackish tidal flats, like those today surrounding Suisun Bay, to the kinds of deep alluvial, fault-controlled valleys, as now exist between the Coyote Valley (just south of San Jose), to well south of Hollister.

There is little doubt that the East Bay plain, and the Bay block itself, are integrally tied to the San Andreas and Hayward-Calaveras fault systems. A detailed look at the stratigraphy beneath the East Bay shoreline (Figure 29) reveals that, over a more than half-million year interim, the interglacial Bay shoreline has shown very little change in its relative position. Succeeding series of sediments seem to have been deposited in the same relative locations. This is a surprising fact given that, as a shoreline margin area, the mix of geologic materials lain upon it are extremely variable, as depicted schematically in Figure 29. Over an extreme range of just 5 miles, the geology underlying the East Bay plain has recorded dramatic changes in the depositional environment, yet the relative range of deposition has remained surprisingly constant. In part this consistency is likely attributable to static position and continued motion of the Hayward fault, which serves to laterally restrict erosional decay of the East Bay Hills while continuously providing rejuvenated uplands in a semi-constant geographic position (the strike-slip component moves Bay-side materials northwestward, but the vertical component of motion retains the massif of hills in a relatively un-changed position).

DETAILED CORRELATIONS

The interpretations presented in the cross sections (Plates 1 - 4) are regional in nature, and thereby, unsuitable for detailed site-specific correlations. Downhole electric (e-logs), spontaneous potential (SP) and gamma logs were available for a few of the deeper wells in the study area. These were analyzed to determine if detailed correlations were possible.

Schematic Stratigraph Relationships, East Bay Area

West East

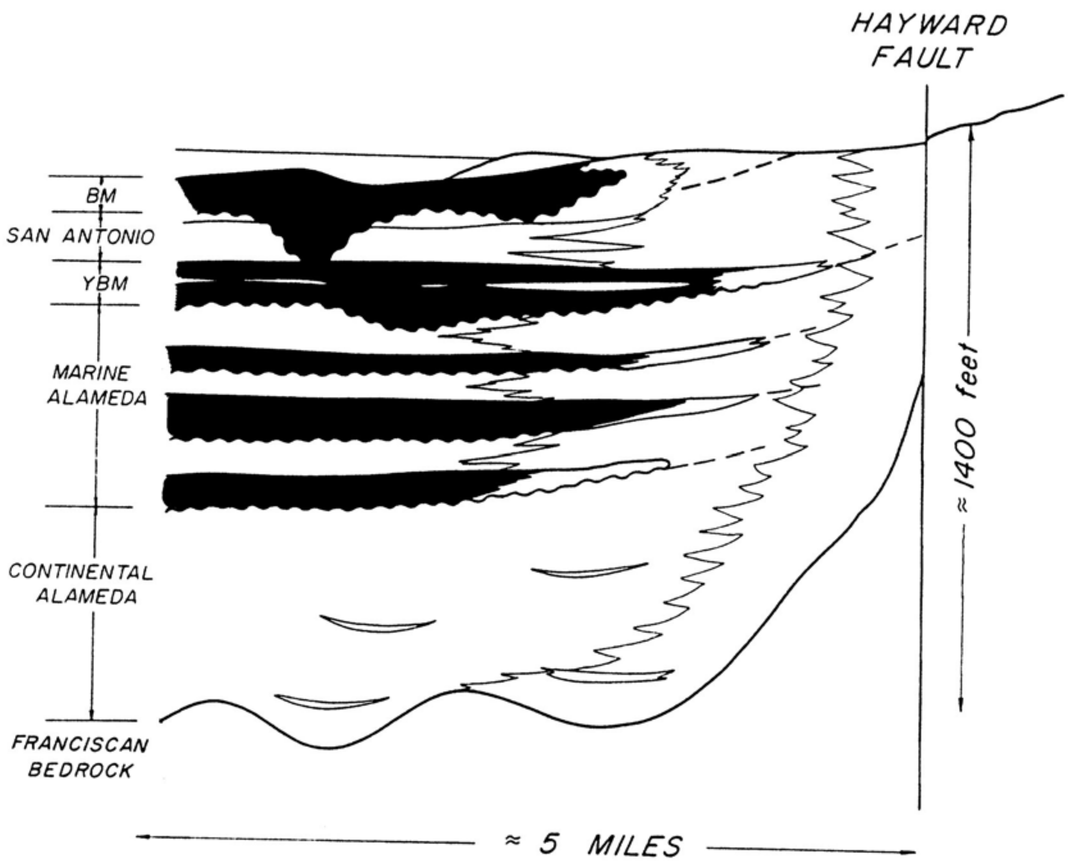


***Figure 29** – Schematic section view (with 17:1 vertical exaggeration) looking at typical stratigraphic relationships across the eastern shoreline of central San Francisco Bay. At least three, and possibly four, landward transgressions of late Pleistocene seas are recorded in the upper (marine) Alameda formation. During glacial sea stands, local channels appear to have deeply incised themselves, later filling with muds during the high sea stands of the short-lived interglacial periods, approximately every 100,000 years.*

Figure 30 presents another form of cross section showing e-log correlations for five wells. This projection extends from the north end of the I-880 Cypress Structure 7 miles south-west, to the Alameda Golf Course on Bay Farm Island (adjacent to Oakland International Airport). This section demonstrates two important ideas. First, detailed correlation of formations, and even sand and shale units within a formation is quite good across the sample interval. Secondly, formation names should be used with caution, recognizing that local environments of deposition and mechanical properties may be different than what is commonly implied by a formation assignment.

If formations were identified solely on down-hole log characteristics , only two formations would be defined: *a non-marine Alameda* and a younger, *marine Alameda*. The *Yerba Buena Mud* and *Young Bay Mud* are just the most recent in a series of bay muds. There is no physical difference between them and the *upper Alameda* muds except age. It follows that just because the *Young Bay Mud* is not present at a site, one should still assume that there is a potential for ground amplification at the site, due to the likely presence of older muds underlying the Bay margins.

The continuity of units also suggests that *unit seismic velocity* may be correctable, meaning that down-hole logs could provide a quick method to make reasonable estimates of unit seismic velocities over a wide area.

Downhole geophysical logs also provide a much more precise pick of formation boundaries, as well as much better definition of individual sand and clay units than could ever be identified by a well-logging geologist. Such logs should be an integral part of any significant subsurface site evaluation.

DETAILED ASSESSMENT OF THE I-880 CYPRESS STRUCTURE SITE

At this juncture in our report it may be illustrative to discuss what can be garnered about localized geology effects on seismic site response by summarizing two sites that were subjected to enormous scrutiny following partial collapses during the October 1989 Loma Prieta earthquake.

As described earlier, a "proto San Francisco Bay" trough formed beneath the south Oakland-Alameda area during *early Alameda time* (500,000 to 1,000,000 years ago). This trough appears to have been a bedrock channel heading southeasterly, towards the *pull-apart basin* discussed earlier. The trough filled with local, continentally-derived sediments (alluvial fans, closed depression lakes, streams, etc.). These units are seen today as red and brown colored sands and clays in the lower part of Caltrans Cypress Borings B-2 and B-8 drilled in late 1989 and early 1990. The lower facies of the *Alameda formation* extends from the *Franciscan* bedrock contact (535 to 620 feet deep) up to a depth of about 280 to 300 feet. According to Redpath (1990), the entire zone has an average shear wave velocity of around 1700 feet per second (see logs of Borings B-2 and B-8 in Figures 31 and 32).

The low velocity zone reported by Redpath (1990) in Boring B-8 (near Cypress bent 78) at about 375 feet is likely a lake mud rather than an initial deposit of marine clay. This interpretation is supported by the detailed boring logs (of other adjacent holes drilled by Caltrans) as well as the

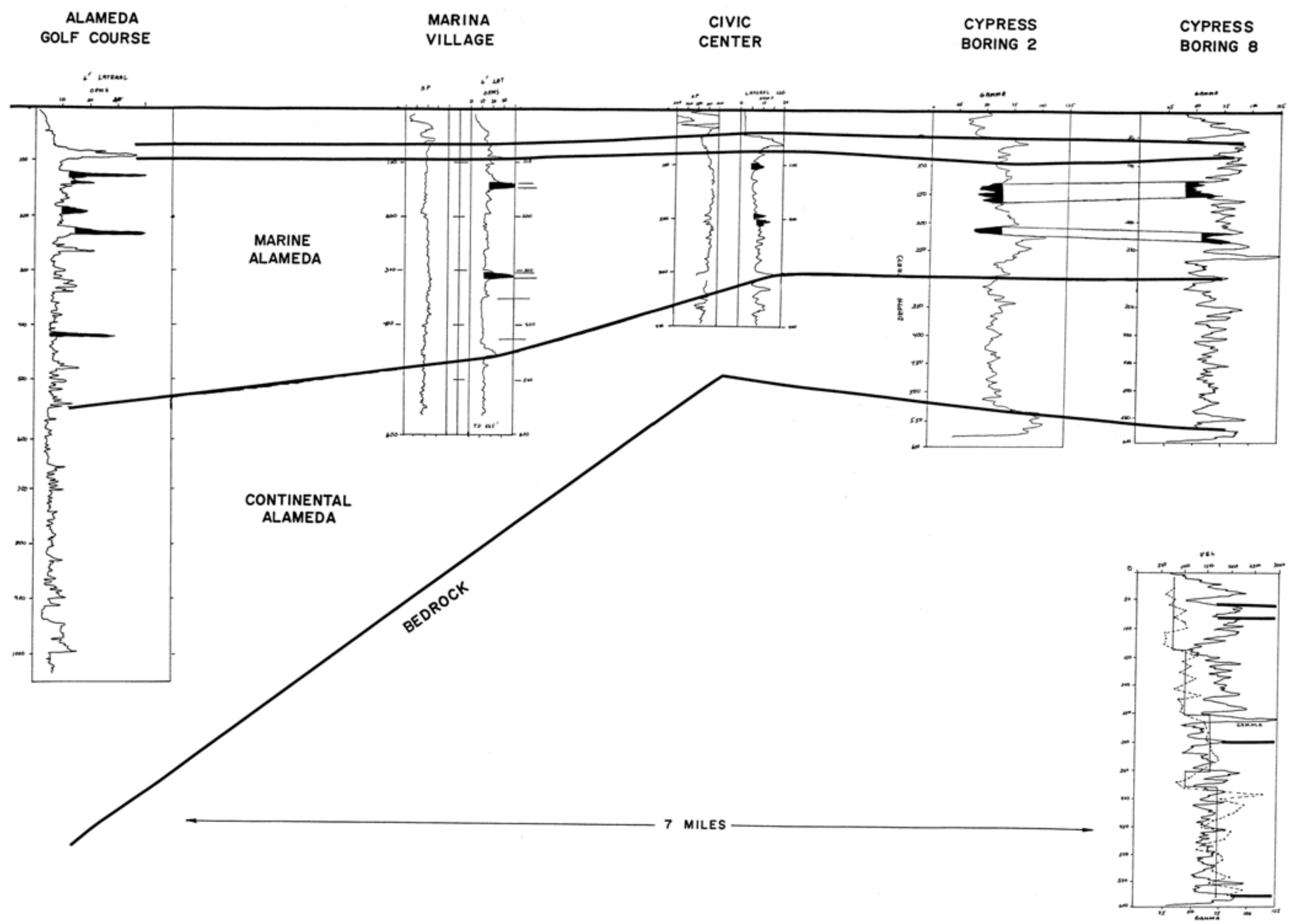


Figure 30 – *Downhole electric log stratigraphic correlations, taken over a 7 mile area, stretching from Alameda Golf course on Bay Farm Island, north to the former position of the I-880 Cypress Structure near Cypress and Grand Avenues, in west Oakland. Although highly variable on a detailed scale, the overall, formational contacts carry well over such distances.*

CYPRESS BOREHOLE B-2

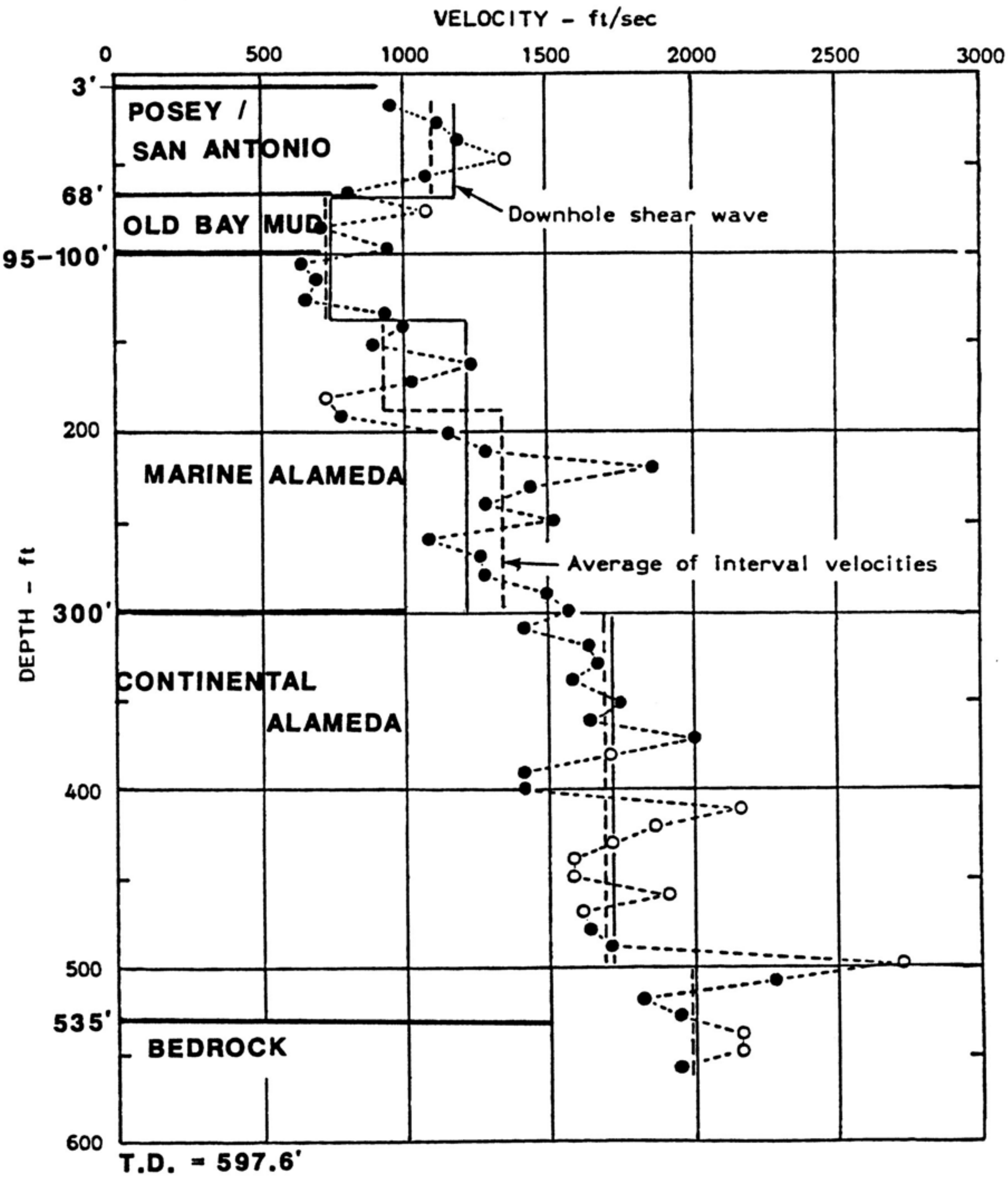


Figure 31 *– Comparison of Quaternary stratigraphy beneath the southern half of the ill-fated Cypress Structure, showing average shear wave propagation velocities of the respective units (velocity data taken from Redpath, 1990).*

CYPRESS BOREHOLE B-8

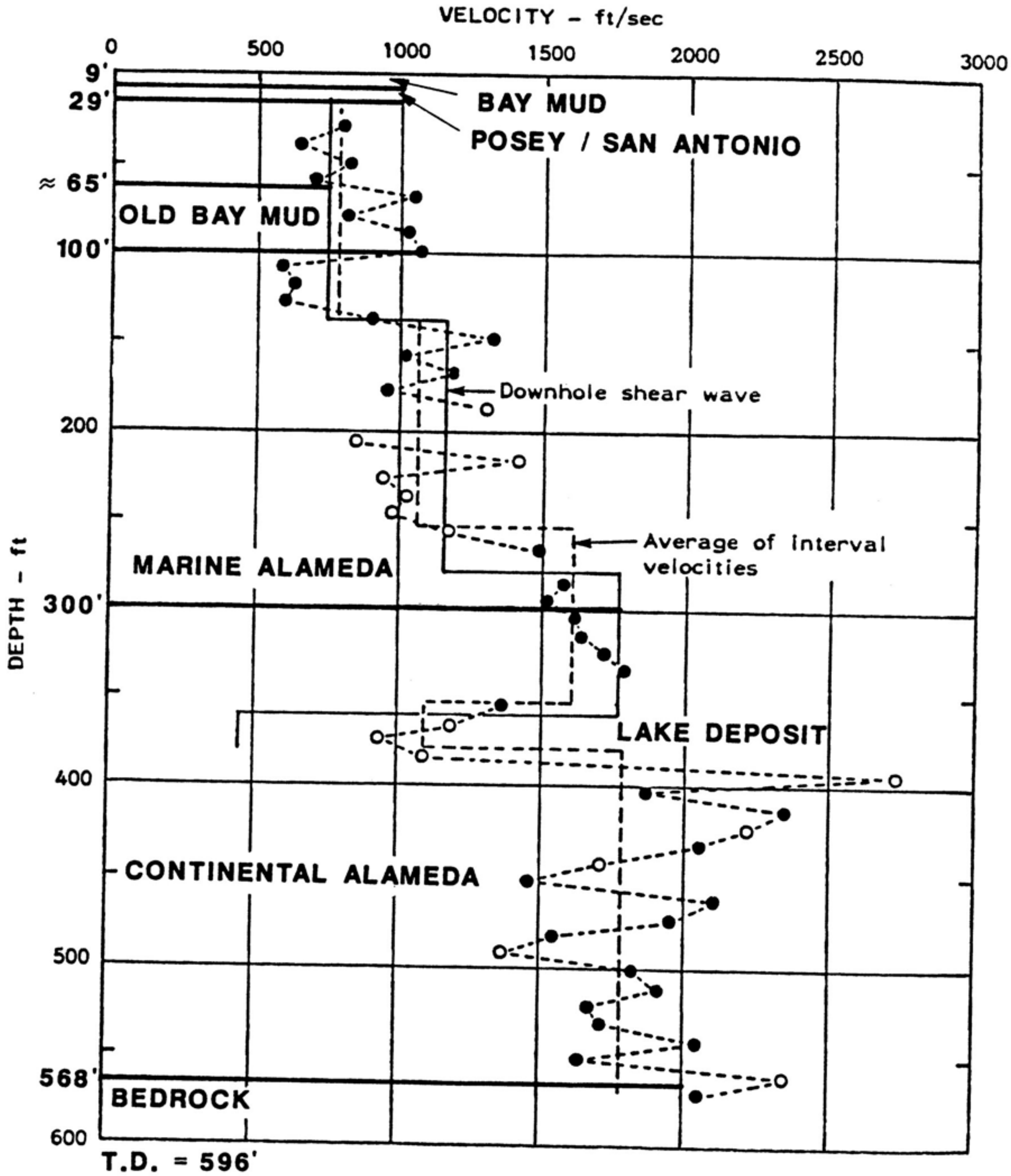


Figure 32 – Comparison of Quaternary stratigraphy with shear wave velocity beneath the northern, collapsed end of the Cypress Structure (near 24th and Cypress) in west Oakland. In this area the Young Bay Mud was impure and no velocity data could be gathered on it due to ambient surface noise. Along the San Francisco Embarcaderos shear wave velocities in Young Bay Mud are generally in the range of 300 to 500 fps (velocity data taken from Redpath, 1990).

regional interpretation. This implies that the low velocity layer should be thin and localized, and explains why it was not observed in Boring 2 (near Cypress Bent 41).

In San Francisco Bay *lower Alameda* units are overlain by a succession of marine units of the *upper Alameda formation***.** They consist of a thick sequence of dark grey muds similar to the present-day bay muds. However, the equivalent units in the Caltrans Cypress borings consist of brownish, reddish, and greyish sand and silts. These lithologies suggest a continental depositional origin rather than a marine environment. Our study indicates that the Cypress Structure area was located near a shoreline since *upper Alameda time*. This would serve to explain the observed lithologies; a shoreline brackish slough area is generally comprised of both marine and non-marine environment sediments. The well logs and electric logs also support this interpretation.

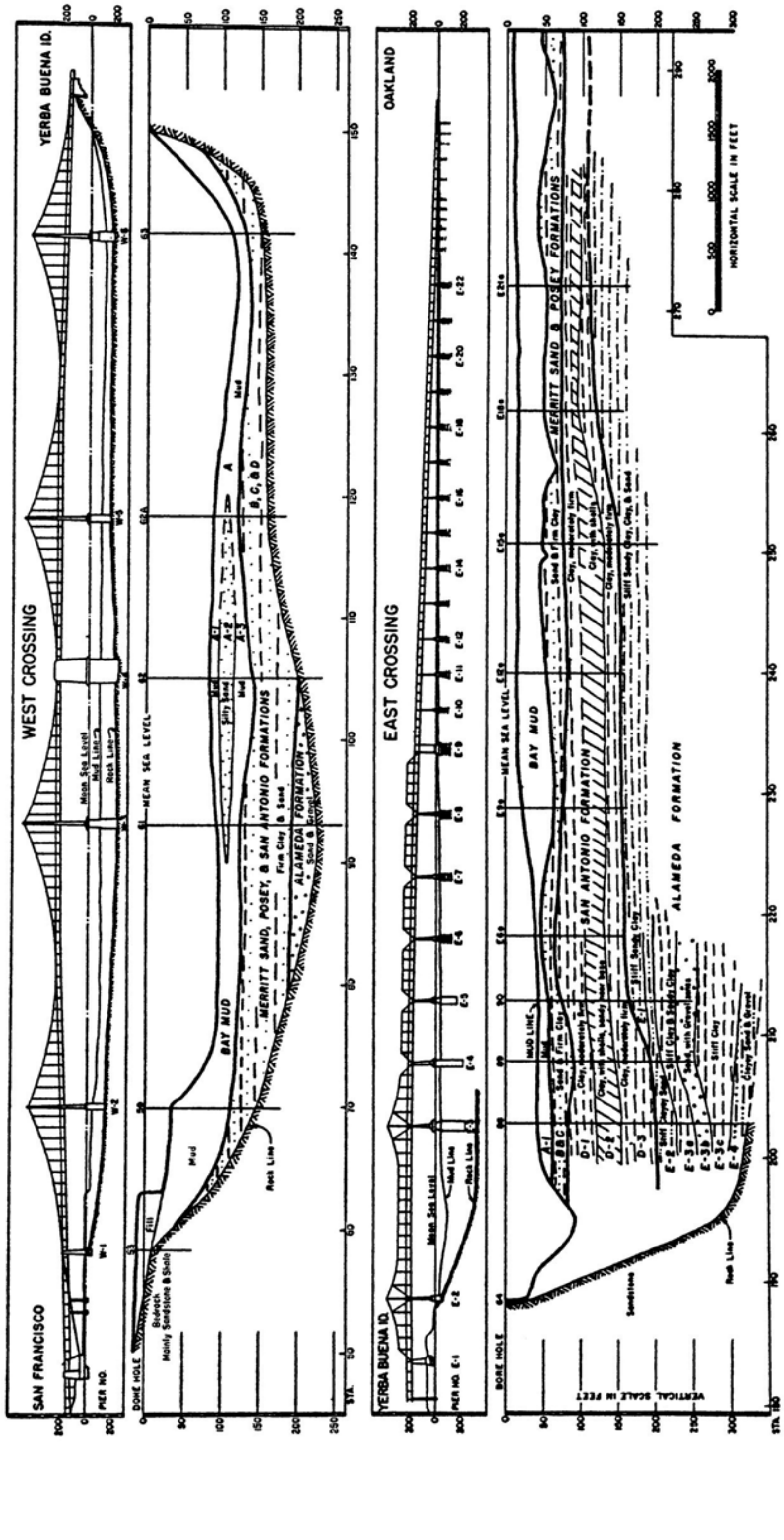
Because a shoreline environment contains complex and shifting depositional patterns, poor correlation between individual units is to be expected. Caltrans Borings B-7 and B-8 are less than 100 feet apart, yet only vague correlations between units can be made. However, the *overall patterns* correlate well. The electric logs (shown in Figure 30) show these over-all, formational correlations quite well. These patterns suggest that Boring B-8 was closer to the *Alameda-time* shore than Boring B-2.

The extreme variation in shoreline lithologies can cause *average shear wave velocities* to significantly vary from one location to another, as well as make it difficult to determine the thickness of the zone over which velocities are to be averaged. The average velocity is determined by the percentage of sand and mud. A dense sand layer with a much higher velocity than the surrounding muds and silts can unduly influence the average velocity of a particular stratigraphic zone. Great care should be taken in choosing the *intervals* over which velocities are to be averaged.

The alternating continental/marine depositional pattern has continued through the present. As a result, the *Yerba Buena (Old Bay) Mud* and *Young Bay Mud* can be very difficult to differentiate. Both units contain a higher percentage of silt and sand than they do in other, less-transitory locations (such as in deep channels or the interior of the Bay). On the downhole electric logs the two mud units cannot be separated from the *upper Alameda formation* muds.

DETAILED ASSESSMENT OF THE EASTERN OAKLAND BAY BRIDGE

The eastern Oakland Bay Bridge structure is situated in an entirely different geologic environment than the I-880 Cypress Structure (as shown in the 1951 profile, reproduced herein as Figure 33). In this area, the *Alameda formation is* only half as thick (120 to 180 feet) as it is beneath the former position of the Cypress Structure. Near Yerba Buena Is-land it appears to consist mainly of sands and gravels. There is no outward evidence for the marine units that exist closer to the eastern margins of the Bay. This could be due to erosion of the *upper Alameda*, or that the area has perennially been a shoreline.



*F**igure 33** – Subsurface geology beneath the San Francisco-Oakland Bay Bridge, as inferred by Trask and Rolston (1951). Subsequent borings by Caltrans at the Grand Avenue viaduct over the Toll Plaza (approximately 4000 feet to the right of the lower figure) revealed the bedrock contact to be at a depth of around –518 feet, an expectable result as the axis of the Oakland Trough (as shown in Figures 9 and 14) is approached.*

Along the Bridge alignment east of Yerba Buena Island, the *Franciscan* basement drops steeply, to -330 feet beneath Pier E-3. From this point the fall is more gradual, but consistently towards the east. 15,000 feet east of Pier E-3, the basement reaches a depth of –518 feet where Grand Avenue joins Interstate 80 in the Bridge Toll Plaza. This drop would appear to be *consistent* with that expected approaching the "Oakland trough", shown in Figures 9 and 14.

At the close of *Alameda time*, a large valley (150 to 200 feet deep) formed just east of Yerba Buena Island. This valley was subsequently infilled with the *Sangamon-age Yerba Buena (Old Bay) Mud*, the *Young Bay Mud*, and a small percentage of *Merritt Sand*. These muds appear to be classic shallow marine clays, not the near-shore units seen closer to the Bay margin beneath the former position of the Cypress Structure.

The geology of the San Francisco-Oakland Bay Bridge alignment has been understood since the publication of the original Hoover-Young Commission Report in 1930. Our regional study performed as part of this project has confirmed much of the previous work and also suggests that the Oakland Bay Bridge likely spans the thickest section of *Yerba Buena (Old Bay) Mud* in the entire Bay Area (around 100 to 125 feet). The average thickness of the *Sangamon-age Yerba Buena Mud is* about 50 feet. It is unlikely that this section has undergone subaerial exposure which would allow it to overconsolidate (and thereby, heighten its shear wave velocity propagation potential). The *Young Bay Mud is 40* to 60 feet thick across this same area (between Yerba Buena Island and the Bay Bridge Toll Plaza), which is about normal considering its relative position within the confines of San Francisco Bay.

CONCLUSIONS

Localized site response of the greater Oakland-Alameda area during the October 1989 Loma Prieta earthquake was more severe than other areas at similar epicentral distances (with the exception of San Francisco's Marina District). The reason for this performance disparity appears to have been *site-induced amplification* of incoming seismic waves. Such distortions serve to magnify wave amplitudes and lengthen the fundamental site periods of many areas. This modification of seismic energy is fostered by the transmission of seismic energy upward, through large sequences of unconsolidated *late-Pleistocene* and *Holocene-age* sediments mantling a deeply dissected *Franciscan* bedrock basement.

Of the seven strong motion-instrumented sites in the Oakland-Alameda area, five recorded peak ground accelerations between 0.26g and 0.29g. Only one of these, at Naval Air Station Alameda, was situated upon any meaningful amount of *Young Bay Mud* (the other, at the Treasure Island naval base, experienced liquefaction of the hydraulic sand fill). Back-analyses of anchor bolt failures at Pier E-9 on the Oakland Bay Bridge (Astaneh, 1990) indicate a force level of approximately 0.33g at the time of failure (although this is a structural response, not an input ground motion).

Detailed aftershock assessments by Lamont-Doherty and U.S.G.S. seismologists showed that *spectral ratios* of between 6 and 9 could be expected between *Young Bay Mud* sites and those on nearby alluvium, and up to 30 on adjacent bedrock sites in higher frequency M 4.0 to 4.4

aftershocks (Borcherdt and Glassmoyer, 1990).

The revised stratigraphic correlations made in this study suggest that the *Young Bay Mud is* only the youngest in a series of marine muds that may contribute to *localized ground amplification.* Older mud units, such as the *Yerba Buena (Old Bay) Mud*, are actually more widespread than their youthful counterpart, and in some areas, such as beneath the Oakland Bay Bridge, are sufficiently thick and low-lying so as to have survived subaerial erosion and its appurtenant desiccation, which usually leads to enhanced shear wave propagation characteristics.

By evaluating the data taken from over 200 deep borings in the greater Oakland area, we have demonstrated that a significant assemblage of unconsolidated continental and marine sediments mantle a weathered and dissected *Franciscan* bedrock basement.

Although the current study has done much to shed light on the hitherto unknown structure beneath the eastern side of San Francisco Bay, it also has served to point out the many incongruities of attempting any simplistic quantification of the subsurface geology. In large part this is due to the periodic recurrence of the East Bay as a continental margin during the interglacial periods of the past 500,000 years.

Our study must also conclude that, seismically, the *upper Alameda formation* and the *Yerba Buena Mud (Old Bay Mud)* can be considered the same unit. Velocities tend to increase with depth, but this is an expected result of natural compaction and lithification rather than a change in lithology.

Lastly, this study should point out the inherent problem of utilizing formation names. Geologic formations are described and defined where they are most distinct. In contrast to classical soil mechanics, the actual lithology of a geologic unit is rarely uniform. The changes can range from subtle to major, but variations are normal and should be expected. Unfortunately, over time, a formation name will tend to develop certain environmental and depositional connotations. Historically, the use of a formation name has tended to imply a specific set of parameters that may not have any relationship to the particular locality in question. As the entire East Bay margin has long been an interface area between continental and marine depositional environments. Formation names should, therefore, be used with CAUTION, recognizing that the environment of deposition and the mechanical properties may be different than what is commonly implied by a formation name.

ACKNOWLEDGMENTS

The authors are indebted to the National Science Foundation and the National Earthquake Hazard Reduction Program for funding the core of this research study under Grant number BCS-9003785.

Many others contributed greatly to this study, including: B. Edward Margason, long-time manager of Woodward-Clyde' s Oakland office and the first to attempt bedrock borings and cross sections of Oakland, and who provided the root ideas and concepts pursued in this study;

Walt Hensolt, consulting structural engineer and long-time passionate archivist of Bay Area subsurface data; Doris Sloan of U. C. Berkeley who spearheaded the stratigraphic nomenclature maze; Earl Brabb, who provided the catalyst, the data, the contacts, and useful suggestions throughout the course of the project; Ed Clifton, Manuel Bonilla, Roger Borcherdt, Tom Holzer, Clyde Wahrhaftig and Dorothy Radbruch-Hall of the U.S. Geological Survey; Robert Sydnor, Mike Manson, Chris Wills, Earl Hart and Glenn Borchardt of the California Division of Mines and Geology; Klaus Jacob of Lamont-Doherty; Gerald Geiffer of the U.C. Water Resources Archives; Bill Sturm of the Oakland Public Library; Dick Wilhelms, Adlai Goldschmidt, Lalliana Mualchin and Iry Schroeder of the California Department of Transportation; Bruce Redpath, consulting geophysicist; Roger Greensfelder, consulting seismologist; J.P. Singh of Geospectra; Tom O'Rourke of Cornell University; Bob Darrah of Dames and Moore; Kyle Rollins of Brigham Young University; Ben Page of Stanford University; Ray Seed, Steve Dickenson, John Lysmer and Nick Sitar of U.C. Berkeley; and I.M. Idriss of U.C. Davis.

Lastly, we would like to thank Rogers/Pacific, Inc. for funding the greater portion of this research when it became apparent that much more data was retrievable than ever speculated (we had originally intended to retrieve 15 borings to bedrock in the immediate Oakland area, but ended up retrieving over 200 within a much larger area!). Kevin Crane kindly drafted the figures while Melanie Ham provided technical support for bringing the GTGS database on-line and producing this report.

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