

Late Quaternary Stratigraphy of the East Bay Plain

by

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ABSTRACT

To better understand the observed variations in strong motion site response during the 1989 Loma Prieta earthquake, we undertook a study to collect and evaluate available subsurface information on the East Bay margins from San Leandro to Richmond. The subsurface data were correlated and compiled into a series of contoured regional depth and thickness (isopach) maps. Several key points emerged from the study. Instead of just one, there are a series of older bay muds extending down to 100m below the East Bay Area. The effect of these units on the seismic response of the area is unknown. The study also documented significant lithologic variations over short distances. This finding brings into question the current practice of estimating site specific seismic properties based upon regional stratigraphic descriptions. In addition, it is found that *Young Bay Mud*, deposited upon the late Pleistocene topography of the Bay, can cause large complications of strong ground motion during Bay area earthquakes, although two and three-dimensional basinal effects may locally exert anomalous site response.

INTRODUCTION

A unique aspect of the October 17, 1989 Loma Prieta earthquake of magnitude 7.1 was the extensive structural damage and highly variable ground response observed in the Oakland-East Bay plain, approximately 100 kilometers (km) north of the quake's epicenter. Strong motion recorders on Yerba Buena and Treasure Islands registered motions with 250% variance over a separation of 914 meters. A container wharf at the Port of Oakland recorded peak round accelerations (PGA) of between 0.27g and 0.29g (horizontal). These ground amplification effects appeared to be ascribable to site geology. To test this idea, the National Earthquake Hazard Reduction Program (NEHRP) funded a study to analyze the subsurface geology of the greater Oakland area. The study included collection of published and unpublished subsurface information. Information was collected on more than 200 deep wells, ranging in depth from 30 to 300 meters, extending from Hayward, north to Richmond (Figure 1). The well information was entered into a computerized well data base. The data base was configured to be compatible with the existing U.S. Geological Survey well data base at Menlo Park, CA. The data were then used to characterize the subsurface stratigraphy of the Oak-

land-Alameda area. The resulting 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

The Loma Prieta earthquake occurred at 5:05 p.m. local time on Tuesday October 17, 1989. Maximum recorded site response was approximately 15 seconds 95 to 105 km to the north, in San Francisco and Oakland. 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. *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 recorder on hydraulic sand fill, only 914 meters away, registered 0.16g before its record was obliterated by massive ground disturbance. The dramatic variance in amplification between adjacent rock and mud sites can be readily appreciated.

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STRATIGRAPHIC UNITS

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 study area, the dominant overlying 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.

Franciscan Basement Topography

In the *San Francisco Bay depression*, a veneer of unconsolidated late-Pleistocene sediments lies upon dense "bedrock" of the *Franciscan assemblage*. Figure 2 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 (1957). Extending from the north side of this depression is a north-west-trending trough that cuts beneath west Oakland and the I-880 Cypress Structure. Established gravity surveys confirm the overall shape of the bedrock depression. 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 a *pull-apart model* (Figure 3) was found to be more plausible. Page and Tabor (1967) formerly proposed such a model for the areas surrounding San Francisco Bay. The data developed during our study provides at least partial validation of their model.

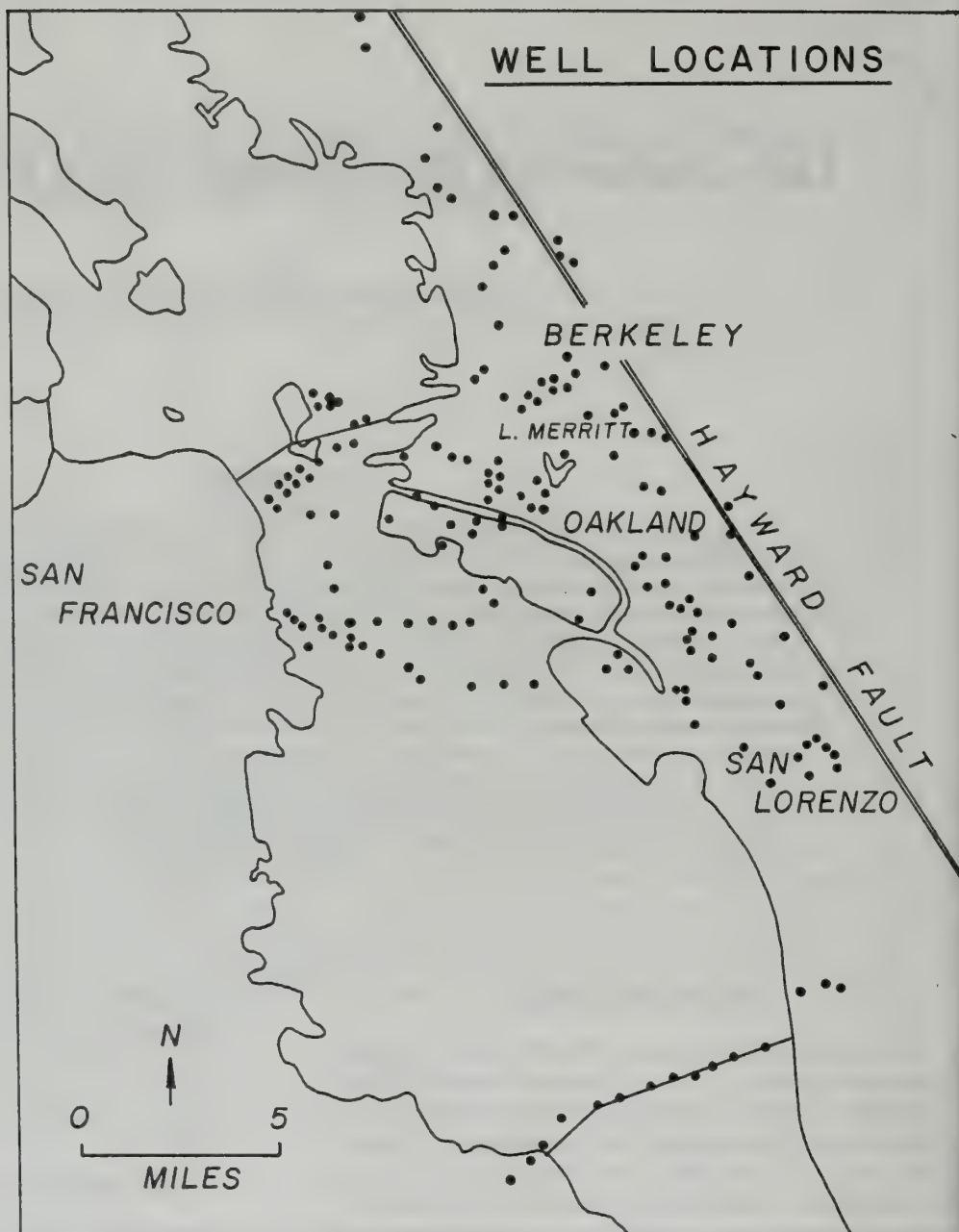


Figure 1. Map showing the locations of over 200 deep borings and wells utilized in this study. These borings ranged in depth from 36 to 315 meters below sea level, and extended along the East Bay margin from Hayward, north to Richmond.

Alameda Formation

The *Alameda formation* was the initial unit deposited upon dissected *Franciscan* bedrock when the area began down-dropping between 1 and .5 Ma. Little is known about the formation. Previous studies (Lawson, 1914; Trask and Rolston, 1951; Atwater and others, 1977) described only the upper 30 meters or so, of the unit. Selective infilling of the *Alameda* units has occurred upon the dissected bedrock surface and within the down-dropped *pull-apart* basin. The *Alameda* reaches thicknesses of over 274 meters beneath the Oakland

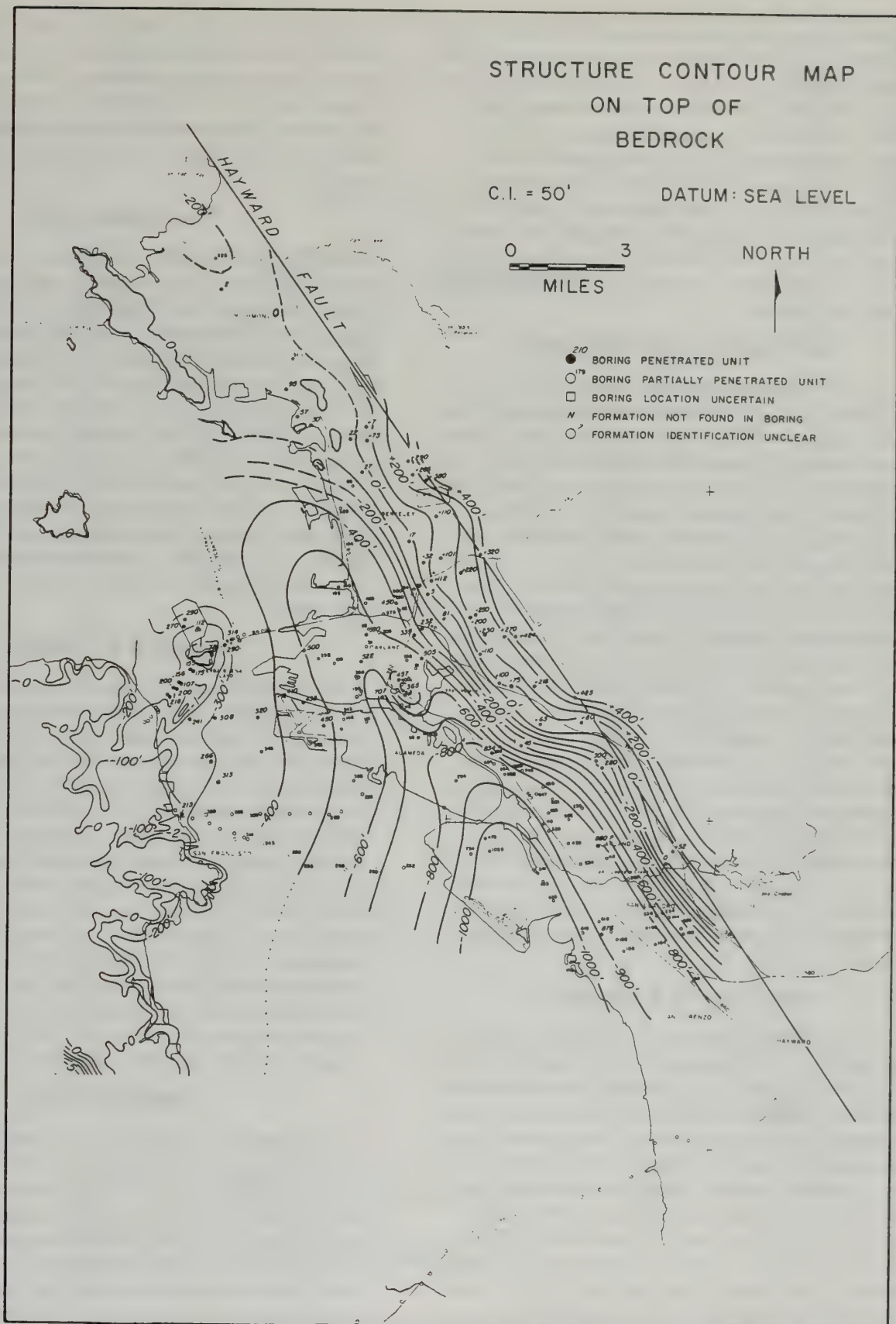


Figure 2. Preliminary structure contour map of the Franciscan bedrock basement underlying central San Francisco Bay and its margins. Only the deepest wells penetrate the basement, in some places over 305 meters below sea level. The wells utilized for this plot and their respective penetration depths are shown. Data for the San Francisco shoreline has been taken from the work of others, most notably Hensolt (1990), Schlocker (1971) and Bonilla (1964).

International Airport, thinning to less than 122 meters beneath the southern end of what was the I-880 Cypress Structure. Of interest is the apparent existence of a continuous deep channel incised into the upper part of the *Alameda formation*. This channel is up to 61 meters deep, and appears to have two branches. 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). By the end of *Alameda time* the present overall shape of San Francisco Bay had essentially formed.

Yerba Buena (Old Bay) Mud

The *Yerba Buena Mud* is wide-spread, homogenous, and easily identified. It is similar to the marine muds deposited in the San Francisco Bay today. The *Yerba Buena Mud* is found beneath virtually all of downtown Oakland and as far inland as the Hayward BART Station (Sloan and Aubry, 1991). The *Yerba Buena Mud* is comprised primarily of a grey marine mud, but a thin (3 to 4 meters thick) sandy, shell-rich zone is commonly found in the middle of the unit. The *Yerba Buena Mud* infills valleys and depressions cut into the underlying *Alameda formation* landscape. Our studies suggest that maximum thicknesses in excess of 30 meters 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. However, there is no apparent main trunk channel developed upon the *Yerba Buena Mud* along the Hayward-San Mateo Bridge alignment. Instead, the *Yerba Buena Mud* surface appears planar and un-dissected. In assessing the stratigraphy beneath the Southern Crossing, Hayward-San Mateo and Dumbarton bridge alignments, Atwater and others, 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*, or its stratigraphic equivalents.

San Antonio Formation

The 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*. 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. 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*. The *Merritt sands* overlay alluvial deposits of the *San Antonio*, draping over old channel banks along the San Antonio estuary. Individual units are discontinuous and difficult to correlate over distance. 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 15 meter north-to-south drop of the *San Antonio/Yerba Buena* contact (between the Oakland Coliseum and central San Leandro). An alternative explanation would be the hydro-compaction of the thick sequence of sediments filling this basin.

Young Bay Mud

Following rises in sea level 11,000 and 8,000 years ago, the stream valleys incised into the *Merritt, Posey and San Antonio formation* were soon filled with estuarine mud, known as *Young Bay Mud* (Whitworth, 1932; Trask and Rolston, 1951; Treasher, 1963). Infilling of the Bay is depicted schematically in Figure 3 and structure contours of the base of this *Young Bay Mud* is shown on Figure 4. These recent, unconsolidated muds were initially deposited in quiet water with high initial void ratios and low unit densities. Along the San Francisco Embarcadero *Young Bay Mud* is divisible into three distinct members; lower, middle and upper; each more saline than its predecessor. *Young Bay Mud* reaches a maximum thicknesses of about 36 meters (100', Figure 4) in the main South Bay trunk channel, east of China Basin and Hunter's Point (Goldman, 1969).

Temescal Formation

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. The *Temescal formation* is readily identifiable by its mottled, variegated color; intertwined yellowish-ochre color (oxidized) with its original olive grey (likely unoxidized) color. 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 610 meters north of the late Wisconsin-age channel, which formerly ran directly beneath what is now Alameda Naval Air Station.

Artificial Fill

Development of the Oakland area has resulted in a progressive in-filling of the natural Bay margins. The waterfront was progressively encroached upon from downtown Oakland in order to create commercial properties along the San Antonio estuary. Following the 1906 San Francisco earthquake, infilling of the tidal flats began. Most of the fill came from hydraulic dredging of *Merritt Sand*. In 1941, the Army Corps of Engineers and the Port combined to place approximately 5 million cubic meters of fill in the Bay to create the Army's Oakland Terminal (Hamilton and Boyce, 1946). Fill material came

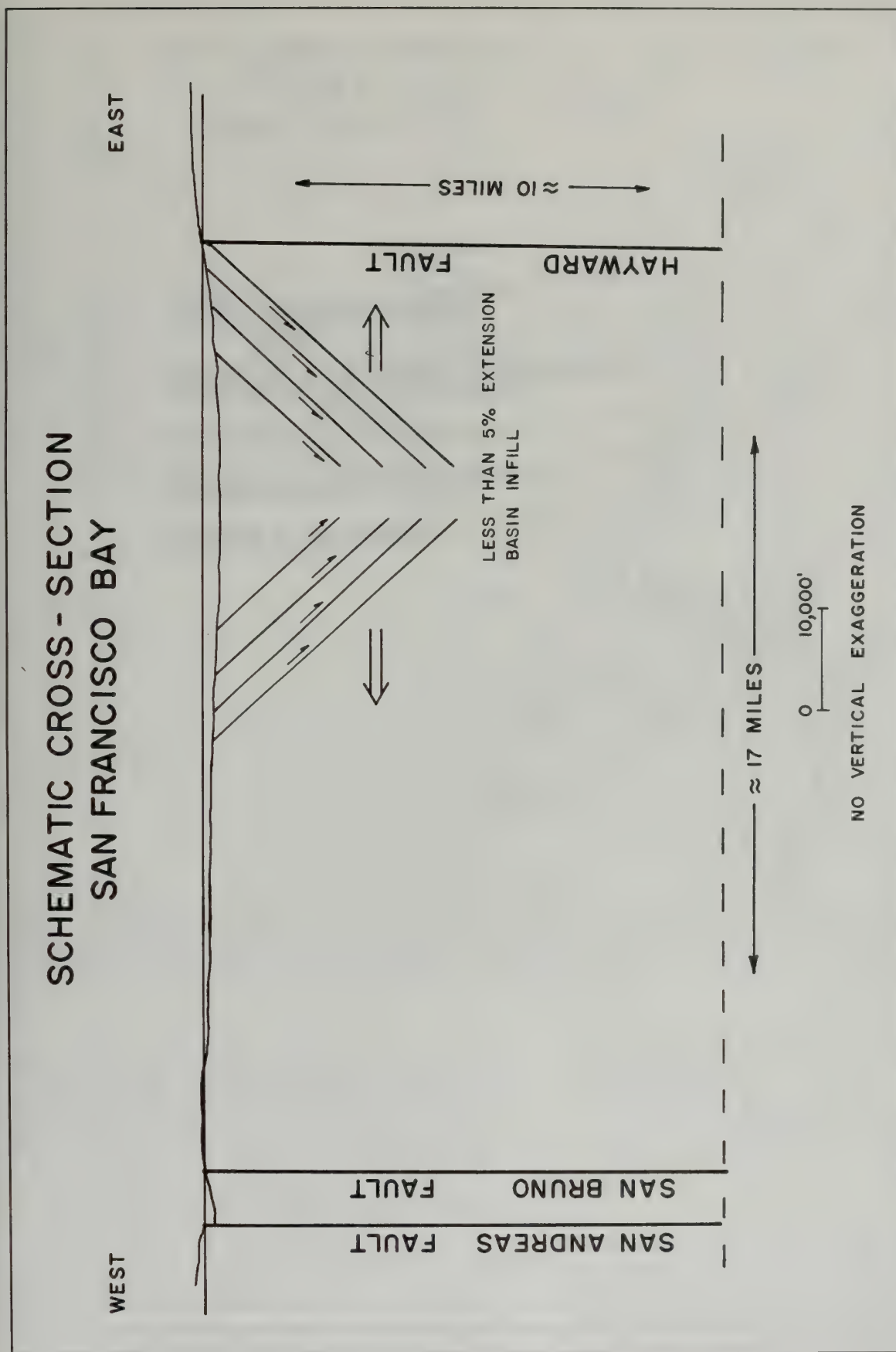


Figure 3. Schematic cross section of the postulated pull-apart basin portrayed in the previous figure. This section, made without any vertical exaggeration, shows just how slight the San Francisco Bay bedrock depression really is. The San Andreas and Hayward faults are just 27 kilometers apart. A 5% extension is all that would be necessary to create the section shown.

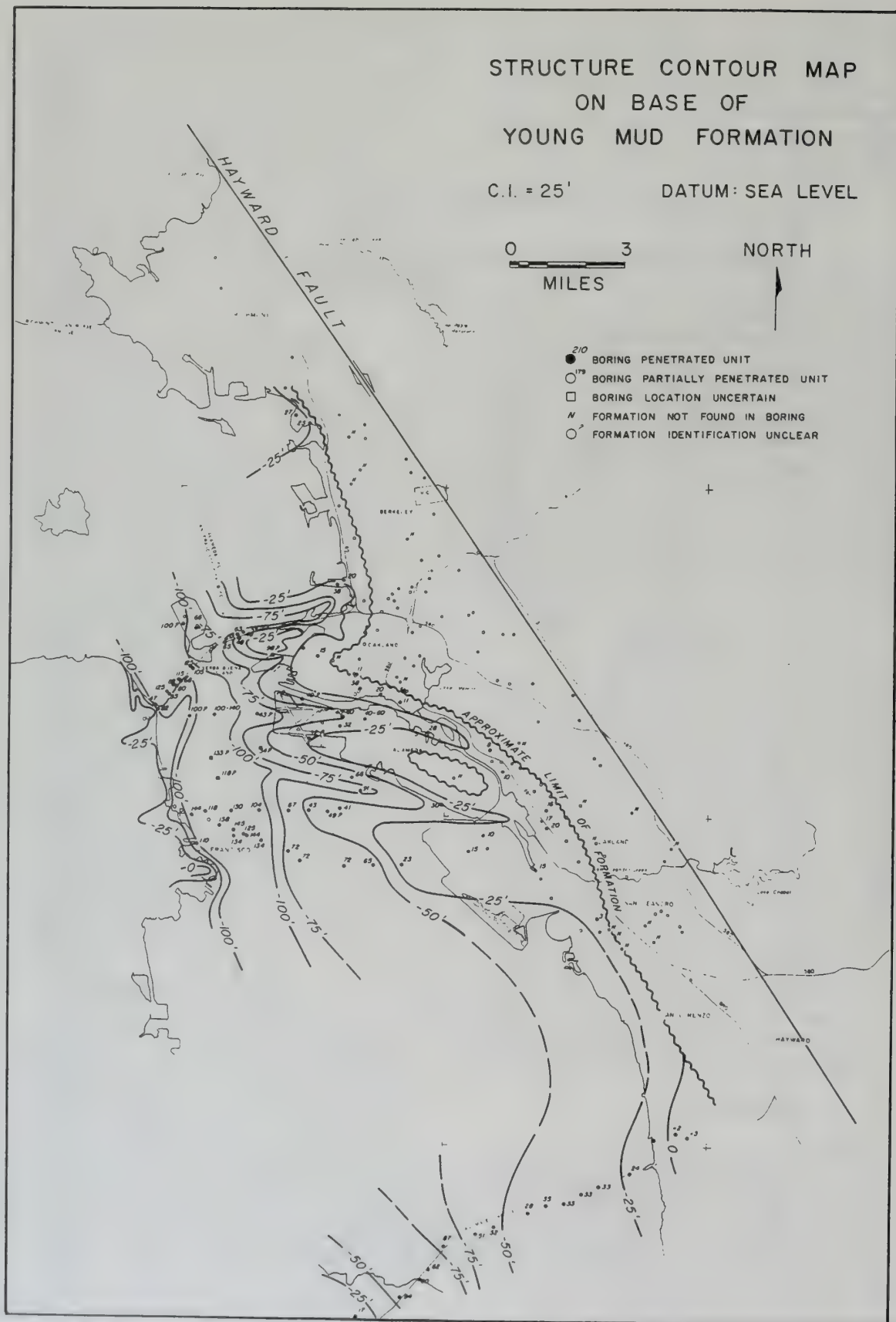


Figure 4. Structure contours (below sea level) on the base of the Young Bay Mud. This plot should represent the Bay ground surface at the close of the Wisconsin glacial stage, 11,000 years ago. The incised channels of Temescal, San Antonio and San Leandro Creeks can be clearly seen, as is the main trunk channel west of Yerba Buena Island. Note how far inland the Young Bay Mud appears to extend.

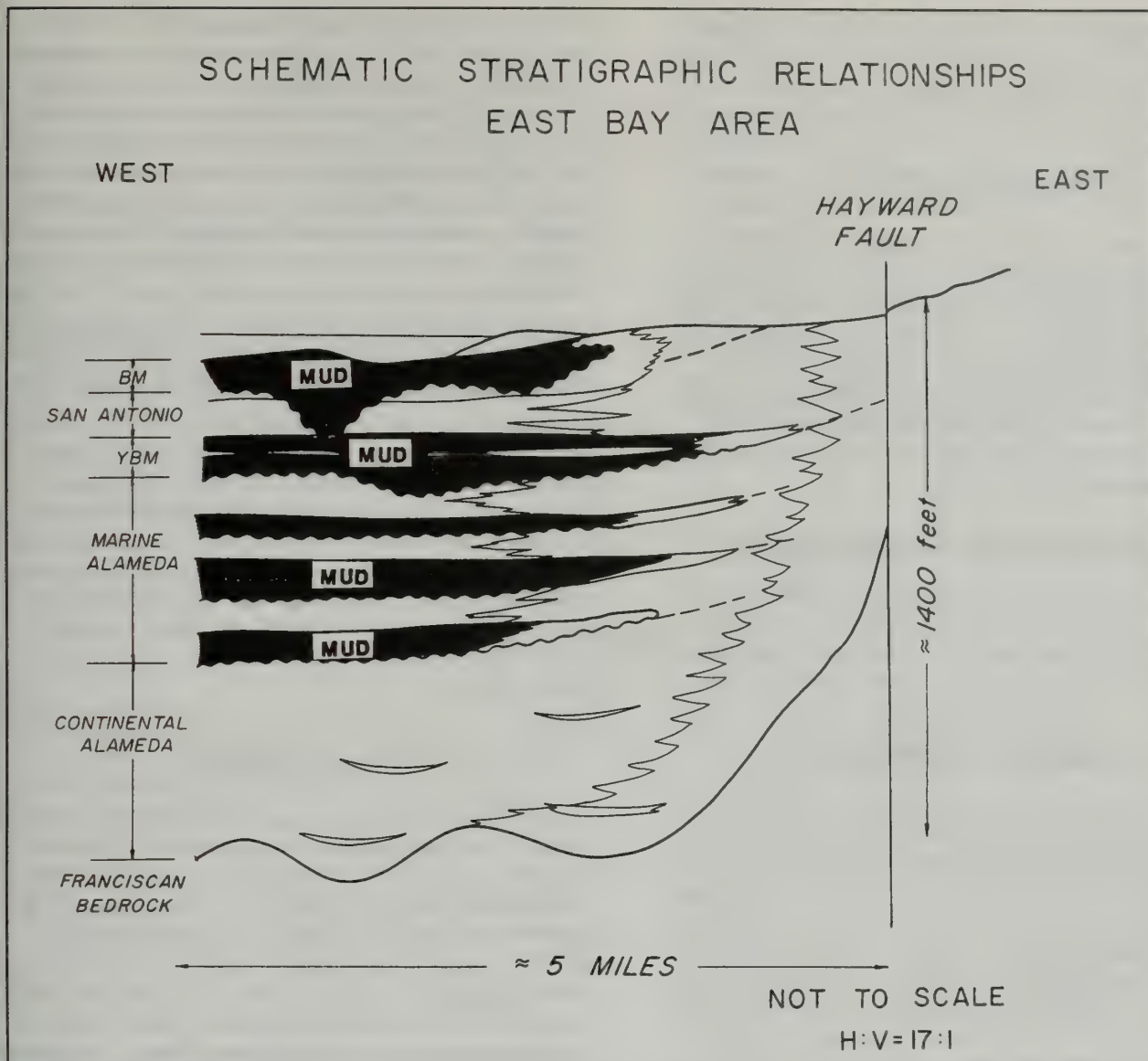


Figure 5. Schematic section view (with 17:1 vertical exaggeration) looking at typical stratigraphic relationships across the eastern shoreline of central San Francisco Bay. At least three, and possibly four, landward transgressions of late Pleistocene seas are recorded in the upper (marine) Alameda formation. 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.

from several sources: dredged sand was hydraulically placed; rock fill for seawalls was imported by barge; and from quarries near Lake Temescal and near Oak Knoll Naval Hospital. With construction of the Eastshore Freeway in the mid-1950's, the shorelines were basically set as they appear today.

REPRESENTATIVE CROSS SECTIONS

Regional cross sections, across the San Francisco Bay were prepared as part of the study. From the cross-sections, it became clear that the Bay depression is very slight in comparison to the region's size (a factor long espoused by Page, 1991). In Figure 3, a real-scale section shows just how insignificant the *Franciscan* bedrock depression is with respect to

the Bay's width (it is 27 kilometers between the San Andreas and Hayward faults). Only 5% extension is necessary to create the depression as we currently understand it. 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.

As can be seen schematically from Figure 5, 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 and slight densification. 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 correlatable, meaning that down-hole logging 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 better definition of individual sand and clay units than could ever be identified by an experienced well-logging geologist. Such logs should be an integral part of any deep subsurface site evaluation.

DETAILED SITE ASSESSMENTS

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 1989 Loma Prieta earthquake.

I-880 Cypress Structure

Our studies indicate that the Cypress Structure area was located near a shoreline since *upper Alameda time*. As described earlier, a "proto San Francisco Bay" trough formed beneath the south Oakland-Alameda area during *early Alameda time*. The trough filled with local, continentally-derived sediments. 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* in the area of the Cypress Structure extends from the *Franciscan* bedrock contact (163 to 189 meters deep) up to a depth of about 85 to 91 meters. The entire zone has an average shear wave velocity of around 518 meters per second (Redpath 1990). However, 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 30 meters apart, yet only vague correlations between units can be made. The low velocity zone reported in Boring B-8 (near Cypress bent 78) at about 114 meters is likely a lake mud rather than an initial deposit of marine clay. This interpretation is supported by the detailed boring logs (of other holes drilled by Caltrans), as well as the regional interpretation.

Eastern Oakland Bay Bridge

The eastern Bay Bridge structure is in an entirely different geologic environment than the Cypress Structure. Our studies suggest that the Bay Bridge likely spans the thickest section of

Yerba Buena Mud in the Bay Area (around 30 to 38 meters). The *Young Bay Mud* is 12 to 18 meters thick across this same area (between Yerba Buena Island and the Bay Bridge Toll Plaza), which is about normal considering its position within the confines of San Francisco Bay. The *Alameda formation* is only half as thick (36 to 55 meters) as it is beneath the former position of the Cypress Structure. Near Yerba Buena Island 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.

Along the Bridge alignment east of Yerba Buena Island, the *Franciscan* basement drops steeply, to -100 meters beneath Pier E-3. From this point the fall is more gradual, but consistently towards the east. 4,572 meters east of Pier E-3, the basement reaches a depth of -158 meters where Grand Avenue joins Interstate 80 in the Bridge Toll Plaza. At the close of *Alameda time*, a large valley (46 to 61 meters deep) formed just east of Yerba Buena Island. This valley was subsequently infilled with the *Yerba Buena 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.

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 disparity appears to have been *site-induced amplification* of incoming seismic waves. The revised stratigraphic correlations made in the 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 Mud*, are actually more widespread, and in some areas, such as beneath the Bay Bridge, are sufficiently thick and low-lying to have survived subaerial erosion and desiccation.

By evaluating the data taken from over 200 deep borings in the Oakland area, we have demonstrated that a significant assemblage of unconsolidated continental and marine sediments mantle a weathered and dissected *Franciscan* bedrock basement. The *seismic velocity boundary* **does not always mimic the geologic contact**, but is controlled by the depth of weathering of the basement rock. In deeply incised valleys (now buried by *Pleistocene* sediments), the depth of weathering may exceed 91 meters. As a consequence, seismic exploration alone may be incapable of precisely locating the geologic contact between the *Franciscan* and the overlying sediments. It appears that geologic models alone cannot be used to create wave propagation models, as is the currently accepted practice of geotechnical earthquake engineers.

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. This finding points out the inherent problem of utilizing formation names to define mechanical properties. Geologic formations/units are described and defined where they are most distinct, but it must be remembered that the lithology of a formation/unit is rarely uniform from place-to-place. The changes can range from subtle to major, but variations are normal and should be expected. 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. 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

This manuscript was reviewed by C. L. Taylor. 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. Additional data and support was made forthcoming by the California Department of Transportation, Transportation Laboratory Engineering Geology Division.

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