FINAL TECHNICAL REPORT

CHARACTERIZATION OF SUBSURFACE SEDIMENTS, SOUTHERN SAN FRANCISCO BAY AREA

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National Earthquake Hazards Reduction Program
U.S. Geological Survey Award Number 99-HQ-GR-0097

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 99-HQ-GR-0097. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

August 2003

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ABSTRACT

Our study delineates the subsurface distribution of potentially liquefiable sediments in the southern San Francisco Bay area, including the densely populated Santa Clara Valley. The purpose of our mapping is to provide the geologic and geotechnical framework required to prepare three-dimensional liquefaction hazard maps in the southern San Francisco Bay area. Based on interpretation of compiled subsurface data, we have produced a series of 1:24,000-scale interpretive, digital maps for the southern San Francisco Bay that show the following:

- Elevation of the buried top of Pleistocene deposits,
- Thickness of overlying Holocene deposits, and,
- Distribution, thickness, and age of artificial fills along the Bay margins.

Our derivative maps showing the thickness of Holocene deposits contribute toward the ultimate goal of isopach maps depicting the cumulative thickness of sandy sediments (i.e. potentially liquefiable sediments), within the Holocene deposits. Our research addresses Element I, Products for Earthquake Loss Reduction, and Element II, Research on Earthquake Occurrence and Effects, of the National Earthquake Hazard Reduction Program.

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1.0 PURPOSE

The focus of liquefaction hazard mapping is shifting from an assessment of the surficial distribution of liquefiable deposits to an understanding of the three-dimensional distribution of liquefiable deposits. A complete assessment of liquefaction hazard requires not only an understanding of the areal distribution of susceptible deposits, but also a characterization of the thickness, depth, and geometry of these potentially liquefiable units. In this study, we provide the three-dimensional geologic framework required for quantitative assessment of liquefaction hazard for the densely populated margins of the southern San Francisco Bay and Santa Clara Valley, California (Figure 1). Our research addresses Element I, Products for Earthquake Loss Reduction, and Element II, Research on Earthquake Occurrence and Effects, of the National Earthquake Hazard Reduction Program.

Much of the urban development within the broad flatlands bordering the San Francisco Bay is underlain by Holocene sediments deposited during the last interglacial rise in sea level. These largely unconsolidated to semi-consolidated sediments are vulnerable to liquefaction and amplification of strong ground motions. However, the subsurface distribution, thickness, seismic response, and geotechnical properties of these young sediments and overlying artificial fill within the Bay basin are poorly characterized.

Historically, localized liquefaction-induced ground failure and ground motion site amplification have been a major cause of damage to property and lifeline facilities during large-magnitude earthquakes in the San Francisco Bay area. For example, liquefaction produced by the October 17, 1989 Loma Prieta earthquake resulted in significant damage to bayshore areas on the borders of the bay. The distribution and thicknesses of soft sediment exerted a strong influence on both the occurrence of liquefaction and the severity of ground shaking throughout the affected region (EERC, 1990). As a result, major structural damage and corresponding loss of life was concentrated at a few sites along the Bay margin underlain by young sediments and artificial fill which failed during liquefaction and/or amplification of strong ground motions at the ground surface.

Figure 1. Map showing the San Francisco Bay study area within the Holocene Bay Plains contained within the green boundary. Gray rectangles show the 7.5' USGS quadrangles which cover the area mapped as part of this research.

Our research builds on the approach employed by Helley (1990) to delineate the top of Pleistocene deposits in the Santa Clara Valley, within the southern part of the San Francisco Bay area (Figure 1). Helley (1990) initially contoured the top of Pleistocene deposits within Santa Clara Valley using CALTRANS geotechnical borings. Helley's map contributed to the understanding of the subsurface structure of the Santa Clara Valley and has been used to estimate the thickness of liquefiable sediments for liquefaction hazard evaluation in San Jose (e.g. Power et al, 1992).

The top of the Pleistocene deposits typically is accompanied by a notable increase in borehole penetration resistance (i.e. blow counts) that coincides with a marked reduction in liquefaction susceptibility with depth (Power et al, 1992; Hitchcock and Helley, 2000). In general, the 'top of Pleistocene' represents the probable base of potentially liquefiable deposits within the Bay area. Based on this observation, first applied by Power et al (1992), we have produced derivative maps showing the thickness of the overlying Holocene and artificial fill deposits. These maps were constructed by contouring thicknesses of these deposits, as identified in boring logs, and by subtracting the elevation of top of the Pleistocene from the elevation of Holocene and/or artificial fill deposits mapped at the surface. Our maps contribute toward the ultimate goal of isopach maps showing the cumulative thickness of sandy sediments (i.e. potentially liquefiable sediments), within the Holocene deposits.

Although not the primary objective of this study, our results also contribute directly to the characterization of the subsurface structure and stratigraphy of basins in the San Francisco Bay region. The 'top of Pleistocene' represents a former land surface that existed prior to the rise of seawater through the Golden Gate at the beginning of the Holocene (Helley and Lajoie, 1979; Atwater and others, 1977). Reconstructing the buried Pleistocene landscape, therefore, provides a unique and important strain gauge for evaluating the location and style of Holocene deformation along the Bay margins with the potential to add new knowledge about faults and folds previously inferred beneath the Santa Clara Valley solely on the basis of groundwater data (e.g. DWR, 1953), geophysics, and geomorphic mapping (e.g., Hitchcock and Kelson, 1999). Contouring and reconstruction of this laterally extensive surface provides information on the location of possible deformation and, therefore, contributes to our understanding of the structural origin of San Francisco Bay and potentially active seismic sources in the southern Bay area.

The digital maps presented in this report represent interpretive products based on currently available subsurface data. We have compiled this subsurface data in cooperation with the California Geological Survey (CGS) and contributed our mapping for CGS's ongoing liquefaction hazard mapping program.

2.0 BACKGROUND

San Francisco Bay is a northwest-trending basin bounded on the west by the San Andreas fault and on the east by the Hayward and Calaveras fault systems. The Bay basin is filled with up to 1000 m of sedimentary strata. Poorly consolidated Holocene sediments deposited during the most recent sea level rise and intrusion into the Bay locally are up to 50 m thick (Atwater and others, 1977). Of these young sediments, typically only the upper 15 m (50 feet) are potentially susceptible to liquefaction where saturated. During the last glacial period, when sea level was significantly lower than today (up to 130 m elevation below the current sea level), fluvial and eolian sediments covered valleys that occupied the San Francisco Bay basin. These non-marine Pleistocene deposits experienced a sustained period of sub-aerial exposure and weathering and consolidation during this period of lower sea level (Helley and Lajoie, 1979). Melting and retreat of glacial ice at the end of the Pleistocene caused sea level to rise and invade the valleys now occupied by the Bay (Helley and Lajoie, 1979). Holocene sea levels in San Francisco Bay documented by Atwater and others (1977) suggest that water re-entered the Golden Gate about 10,000 years ago and that water levels in the Bay rose to their present level about 5,000 years ago.

The primary basis for identifying the top of Pleistocene unconformity, now buried beneath Holocene sediments, is based on the consolidation of Pleistocene deposits during subaerial exposure following lowering of water levels in the Bay during the last sea level low stand. This period of subaerial exposure is distinguished by the development of a distinct pedogenic soil horizon identified in excavations (e.g. Figures 2 and 3). The presence of this horizon typically is accompanied by a notable increase in density, and changes in color and texture that are identifiable in standard geotechnical boring logs (e.g. Figure 4). The horizon coincides with a marked increase in density, and, thus, reduction in liquefaction susceptibility with depth. Therefore the top of Pleistocene deposits represents the probable base of potentially liquefiable deposits within the Bay area. Where Pleistocene deposits are not preserved, the unconformity is often distinguished by the presence of Holocene Bay Mud atop older bedrock. This depositional contrast (i.e., Holocene deposits on bedrock) represents the most significant subsurface seismic impedance known in the southern San Francisco Bay area (Figure 5; Lajoie and Helley, 1975).

We have produced derivative maps showing the thickness of Holocene deposits. These isopach maps have been derived by subtracting the elevation of top of the Pleistocene from the elevation of Holocene deposits mapped at the surface. Our maps contribute toward the ultimate goal of isopach

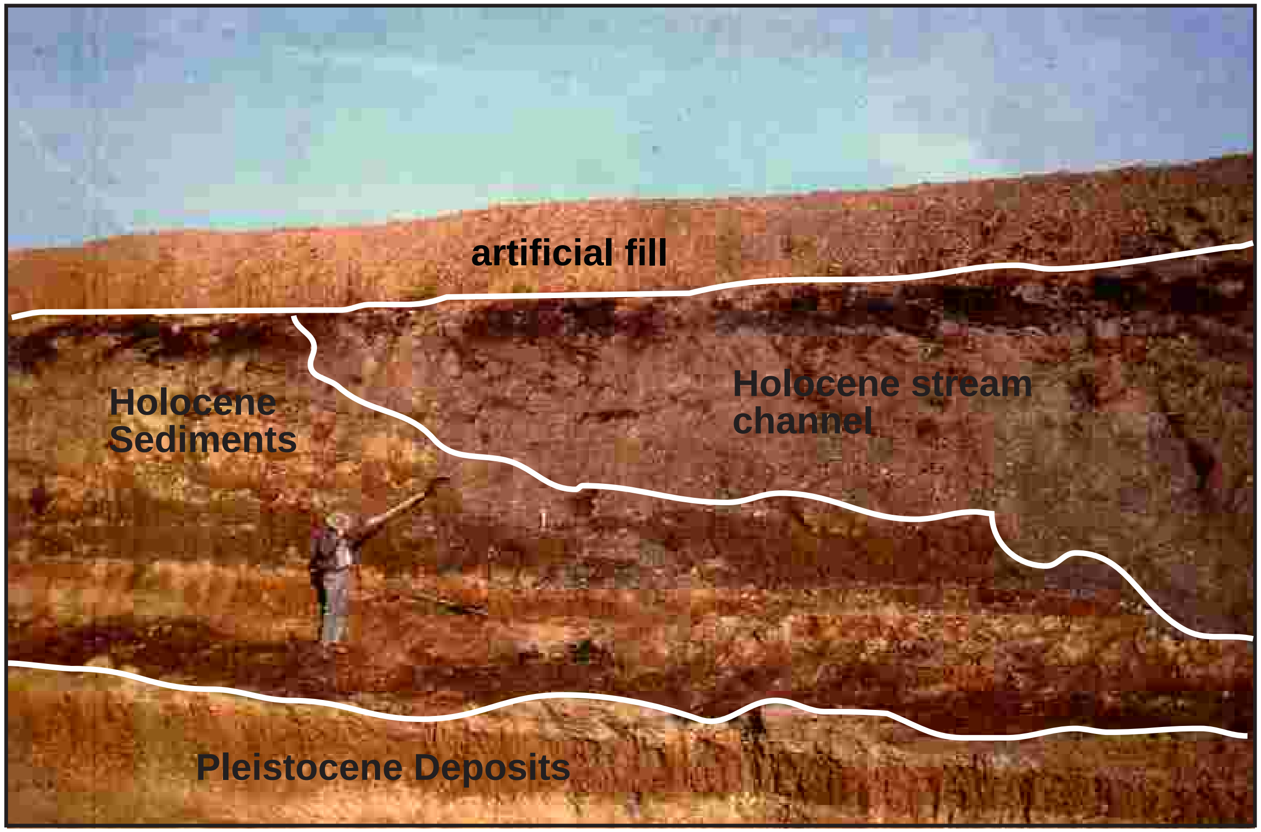


Figure 2: Photo of exposure in the Mountain View dump, now covered, that shows the contact between artificial fill (at the top), Holocene sediments, and Pleistocene deposits (at the base).

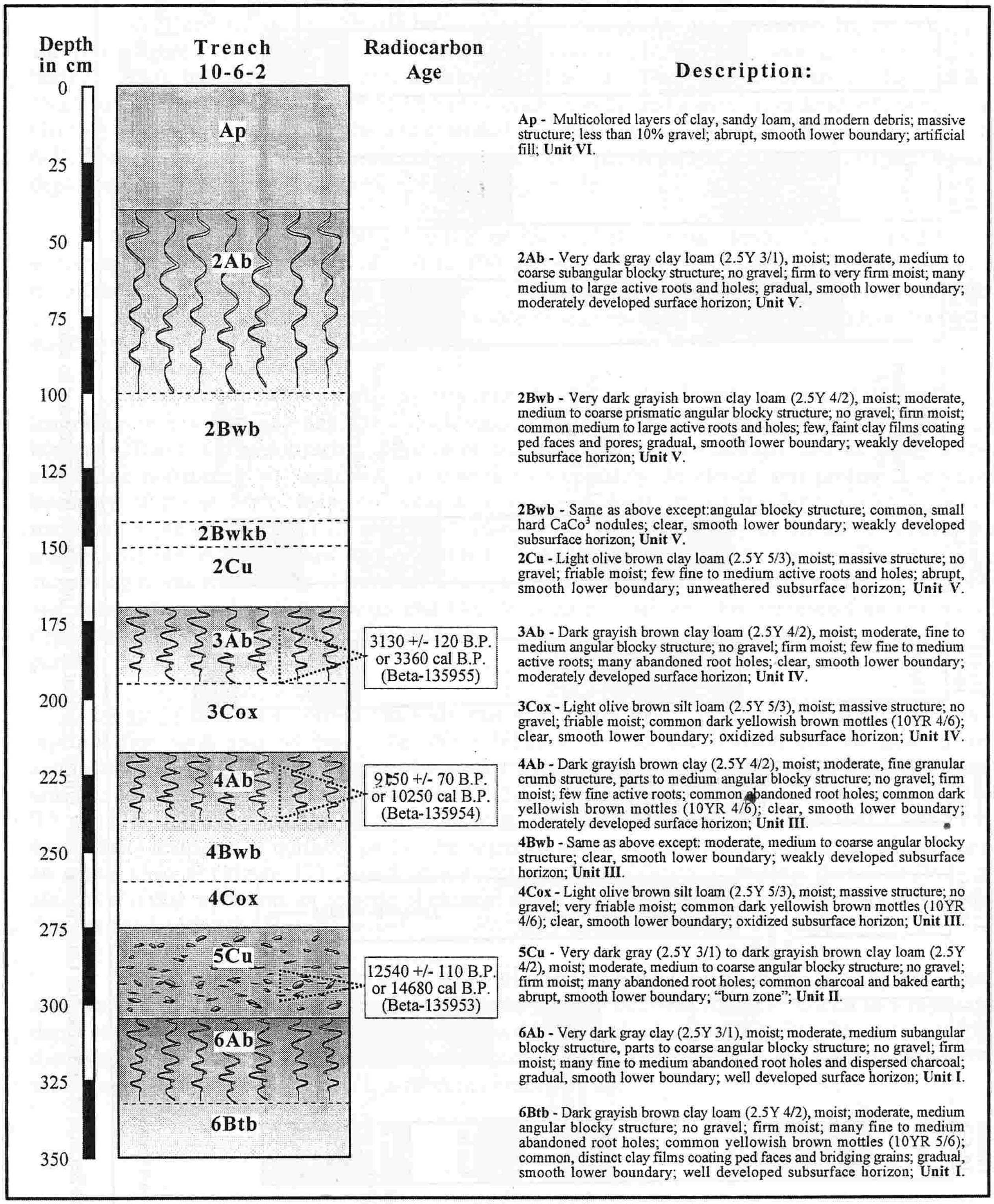


Figure 3. Soil profile of trench in San Jose (from Meyer, 2000).

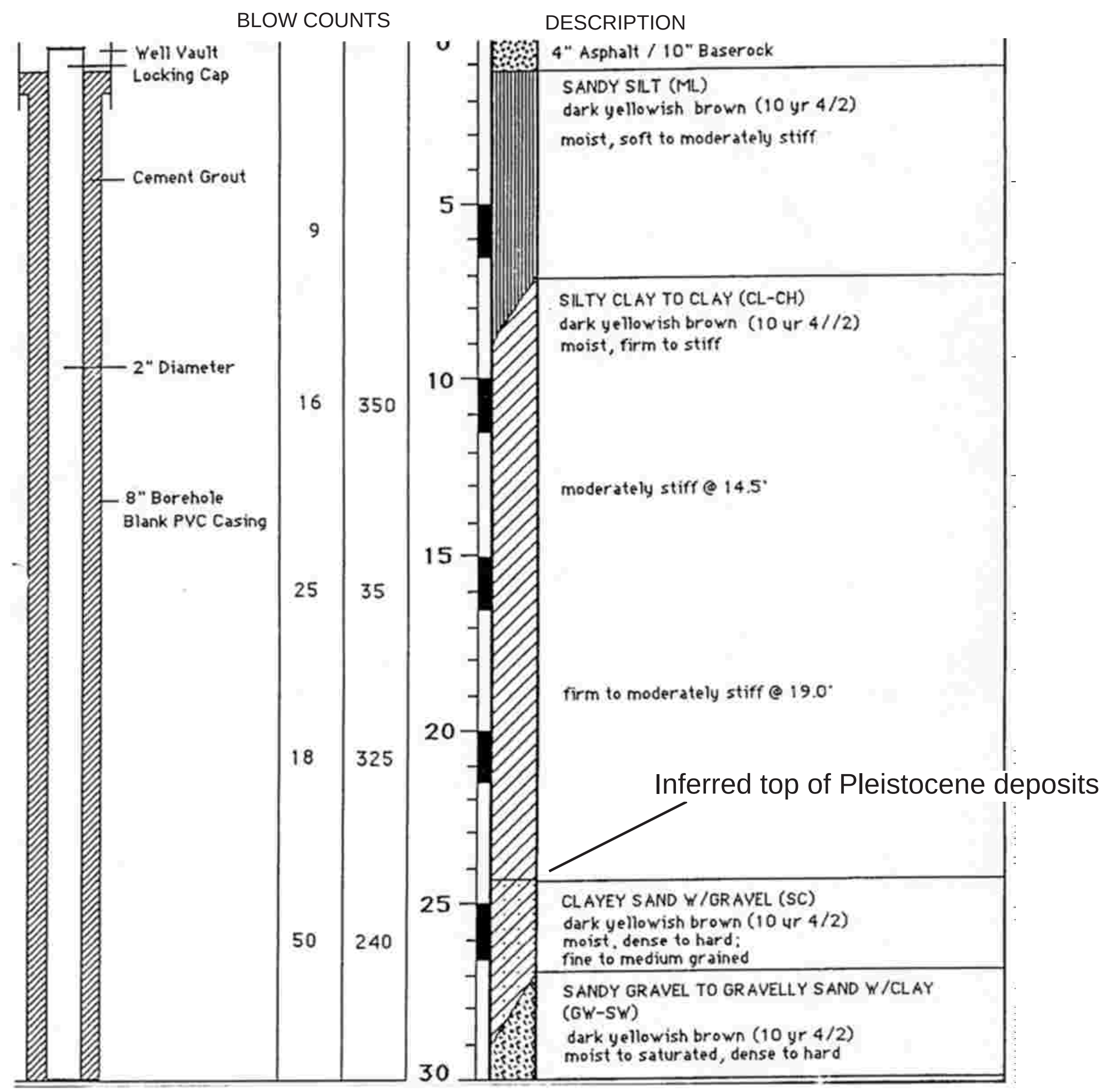
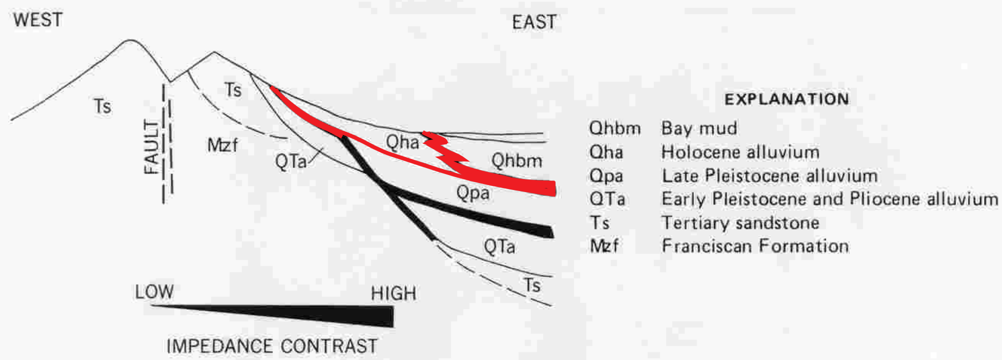


Figure 4. Representative soil boring log from Caltrans site in Fremont showing inferred top of Pleistocene. Note increased blow counts below contact, color change, and lithologic change at inferred contact.



Unit	Thickness (m)	Relative bulk density, ρ (g/cm³)	Penetration resistance[1] (blows/ft)	P-wave velocity, V_p (m/sec)	S-wave velocity, V_s (m/sec)	Impedance, $V_s \rho$
Qhbm	0–36	1.3–1.7	0	*1400* [2]	90–130 [3]	117–153
Qha	0–15	1.9	20–80	300–600 [4]	*200–300*	380–*570*
Qpa	10–45	2.1	100	1500–2100	200–400 [5]	420–*630*
QTa	0–250?	2.0	100-refusal	2500	*1200*	*2400*
Ts	0–*300*	2.4	Refusal	1500–3300	500–*1400*	*1200–3360*
Mzf	......	2.7	Refusal	2800–4000	*1400–2000*	*3780–5400*

[1] Test used 140-lb hammer dropped 30 in.
[2] Figures in italics are estimated values
[3] From Warrick (1974)
[4] Above water table. Below water table $V_p = 1500-1700$
[5] R. E. Warrick (oral commun., 1974)

Figure 5: Representative cross section of the southern San Francisco Bay area with description of physcial properties, including seismic impedance, for subsurface geologic deposits (Lajoie and Helley, 1975). Holocene/Pleistocene seismic impedence constrast to be deliniated in this study is shown in red.

maps showing the cumulative thickness of sandy sediments (i.e. potentially liquefiable sediments), within the Holocene deposits. Because the lithologic and engineering properties of sediments along the Bay margins typically vary both laterally and with depth, it is necessary to interpret surface and subsurface data within a geologic context that accounts for the depositional environment of sediments. Our maps provide information for input into detailed, quantitatively-derived liquefaction hazard maps that illustrate the likely distribution and magnitude of liquefaction-related effects during future large earthquakes in the San Francisco Bay Area.

The behavior of artificial fill along the Bay margin is a source of concern for potential liquefaction. Knudsen (2000) documented that artificial fill over Bay Mud (regional map unit “afbm”) has hosted about 50 percent of all historical liquefaction occurrences in the San Francisco Bay area. The fact that about 83 percent of liquefaction occurrences from the 1989 Loma Prieta earthquake occurred in artificial fill whereas only about 30 per cent of liquefaction failures were documented in fill emplaced on Bay margins in historic earthquakes prior to the Loma Prieta earthquake reflects the extensive reclamation of the Bay shoreline following the 1906 earthquake.

Based on the observed performance of such fills and uncharacterized underlying Holocene sediments in historic earthquakes, knowledge of the thickness, age, and method of placement of artificial fill generally is critical for predicting the location and magnitude of permanent ground deformation from liquefaction and settlement during future large earthquakes (Seed, 1969, O'Rourke, 1990). Pease and O’Rourke (1998) documented that the most significant factor influencing ground subsidence and permanent lateral spreading in the south San Francisco area during the 1906 earthquake is thickness of saturated fill. The maximum lateral displacements documented at the ground surface correlate well to the mapped thickness of underlying saturated fill (Pease and O’Rourke, 1998).

In addition to thickness of fill, Seed (1969) recognized that failures within engineered and non-engineered fills during future large earthquakes can be predicted, in part, by determining: (1) the age, composition, and method of fill emplacement; and (2) the nature of the material that underlies the fills. A variety of techniques have been used to emplace and compact fills, with material derived from diverse sources, along the San Francisco Bay margins. Much of the artificial fill was placed prior to 1965 when the effects of strong ground motions on non-engineered fill was poorly understood and Bay fills often were not reviewed or documented. In 1965 the San Francisco Bay Conservation and Development Commission (BCDC) was created, in part, in response to this concern about the artificial filling of the San Francisco Bay. Seed (1969) classified fills in three main categories: (1) dumped fill of all types of soil, (2) hydraulic sand fills, and (3) well-compacted fills of select material.

Based on the areal distribution of liquefaction during the 1989 Loma Prieta earthquake, there appears to be a similar strong correlation between the prevalence of localized sand boils and ground settlement and the type of fill (hydraulic versus dumped) and type of underlying deposit (sand shoals versus Bay Mud). However, geologic maps of the San Francisco Bay Area currently do not differentiate the ages, composition, or method of emplacement of artificial fills. These often highly heterogeneous materials, with few exceptions, can not be characterized sufficiently by analyses of existing borehole data. In this study, we provide a series of maps showing the distribution, thickness, and age of artificial fills along the Bay margin.

3.0 METHODS

Our methodology emphasizes delineating the thickness and lateral continuity of liquefiable sediments. In cooperation with the CGS, we have collected subsurface boring logs representative of surface and subsurface deposits within the southern San Francisco Bay Area (Figure 6). We interpreted these subsurface data to produce a series of 1:24,000-scale maps for the central and southern San Francisco Bay that delineate; (1) elevation of the top of Pleistocene deposits; (2) thickness of Holocene sediments; and (3) thickness and age of artificial fills.

Our research builds on the approach employed by Helley (1990) to delineate the top of Pleistocene deposits in the Santa Clara Valley, within the southern part of our proposed San Francisco Bay study area (Figure 1). Helley (1990) contoured the top of Pleistocene deposits within Santa Clara Valley using geotechnical borings from the California Department of Transportation (CALTRANS). We have refined Helley's existing map (Helley, 1990), by incorporating recent CALTRANS geotechnical data and other geotechnical data collected for construction (e.g. airport expansions, earthquake retrofits, new construction) and remediation sites (e.g. EPA Superfund sites). We have compiled the new borehole data and extending Helley’s (1990) map of the top of Pleistocene deposits across the southern San Francisco Bay area.

The top of Pleistocene deposits typically is accompanied by a notable increase in penetrometer resistance, and changes in color and texture that are identifiable in standard geotechnical boring logs (e.g. Figure 5). Identifying the buried top of Pleistocene deposits provides a basis for delineating the thicknesses of overlying Holocene deposits and artificial fills. Below we provide more information on our approach and the mapping techniques we used.

3.1 Data Compilation

Geological, geotechnical, and hydrological data compiled during the course of the study has been entered into our in-house ArcView GIS system and formatted to meet requirements of CGS’s Seismic Hazards Mapping Program (Real, 1993). Each borehole location was digitized into the computer via on-screen digitization. Selected data have been entered for each boring log, including depth to groundwater, elevation, total borehole depth, depth to Pleistocene deposits, thickness of Holocene deposits, thickness of artificial fill, thickness of Holocene Bay Mud, and depth to bedrock (where appropriate). These data were entered in Microsoft Excel format and converted into GIS format by linking the table data with ARCVIEW tables that contain the borehole location.

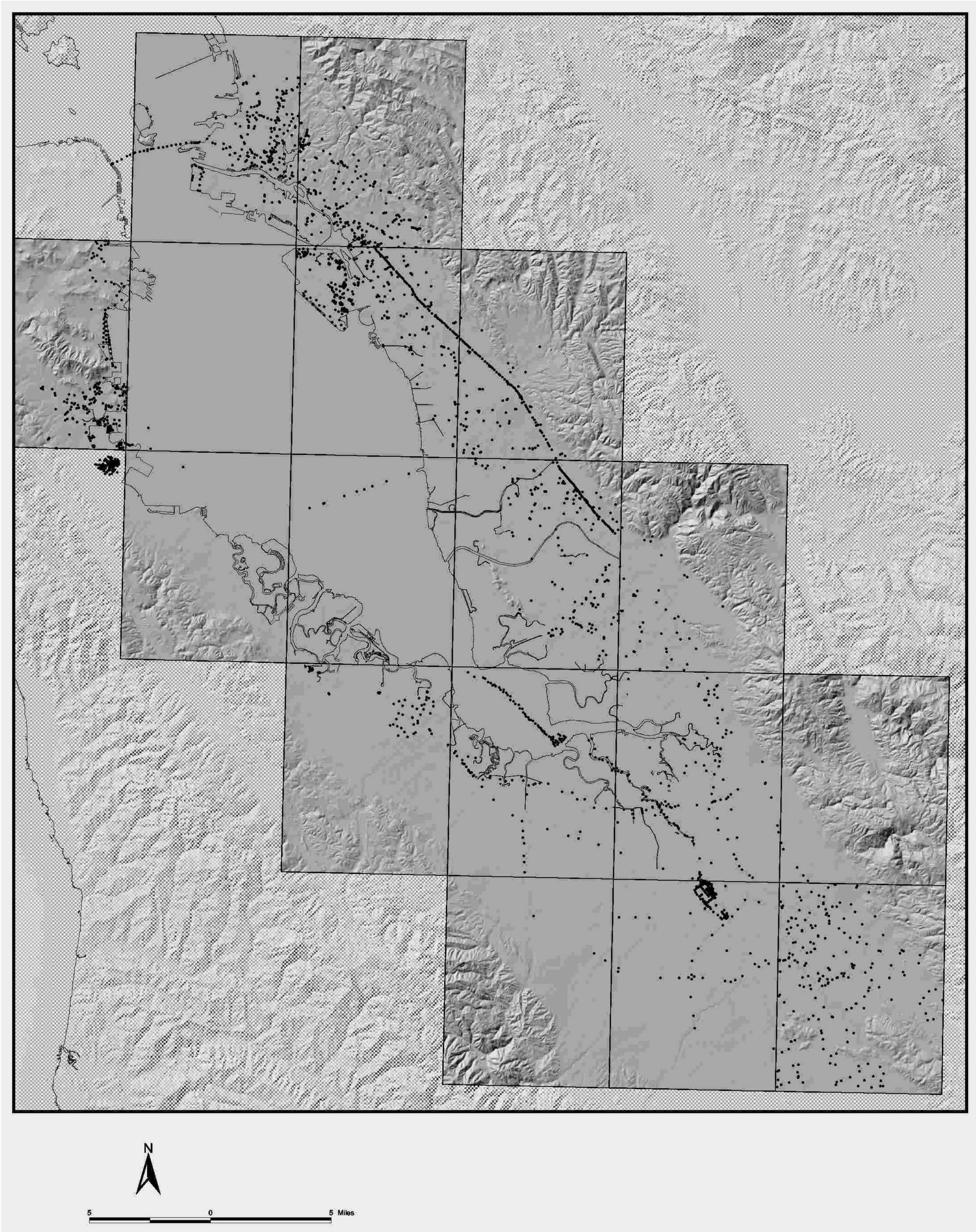


Figure 6. Map showing borehole locations used within the San Francisco Bay study area.

We collected borehole data from the Alameda County Public Works Agency, Alameda County Water District, City of South San Francisco, the Bay Area Rapid Transit District (BART), and the California Department of Transportation (CALTRANS). CALTRANS data for right-of-ways, earthquake retrofits, and bridge crossings are especially valuable because CALTRANS collects the data using standardized procedures and equipment. CALTRANS borehole data typically include blow count information, lithologic soil descriptions, and depth to groundwater. We spent a week at CALTRANS in Sacramento copying Logs of Test Borings (LOTB) for the major highway intersections along the Bay margins. These LOTBs include borings completed for highway undercrossings, overcrossings, bridges, and soundwall investigations for Highways 37, 680, 880, and 101. We also collected LOTBs for the San Mateo, Dumbarton, and Bay bridges.

3.2 Map Preparation

This phase of our investigation included the analysis of data derived during our study, and preparation of digital maps. The final products of this study are digital maps (1:24,000-scale) including:

(1) 10-foot contour maps showing the top of the Pleistocene;
(2) isopach maps showing the thickness of Holocene deposits; and,
(3) thicknesses and ages of artificial fills emplaced along the Bay margins.

Identification of 'Top of Pleistocene'

As part of our mapping, all compiled borehole logs were examined for information that might indicate the buried 'top of Pleistocene'. The primary basis for identifying the 'top of Pleistocene' is the consolidation of Pleistocene deposits during subaerial exposure following lowering of water levels in the Bay during the last sea level low stand. This period of exposure and consolidation typically is distinguished by the development of a distinct pedogenic soil horizon (e.g. Figures 2 and 3). The 'top of Pleistocene' is identified by a typically marked increase in density, changes in soil color, and changes in texture associated with: (1) development of this soil horizon and/or, (2) distinct stratigraphic changes associated with the unconformity between the top of Pleistocene deposits and Holocene deposits.

We have identified, and quantified in the selection and description within our borehole database, two main areas of uncertainty in interpretation of the "top of Pleistocene". Uncertainties in the subsurface location of the "top of Pleistocene" include those; (1) derived from the drilling method, logging procedure, and documentation for each borehole and, (2) derived from variations in subsurface stratigraphy and in the development of the buried soil horizon(s) associated with "Top of Pleistocene. We addressed the first source of uncertainty in our selection of representative boreholes for inclusion in our borehole database. The second source of uncertainty is directly dependent upon our interpretation of the buried "Top of Pleistocene" surface. We have addressed this source of uncertainty by listing the criteria upon which our interpretation is based and by assigning a numeric value for each interpreted boring that expresses our degree of confidence in the interpretation.

Uncertainties associated with the physical process of drilling boreholes include the varying accuracy of borehole locations (borehole coordinates and elevation), quality of data derived from drilling method used (e.g. mud rotary, hollow-stem auger, etc.), and type and quality of geologic data recorded for each boring (i.e. detail and relevance of borehole descriptions). Additional information that, if missing, might reduce the utility of a boring include the presence or absence of in-situ density data (e.g. SPT-compatible blowcounts, CPT penetration data, etc.), and presence or absence of laboratory data (e.g. dry density tests, grain-size distribution data, etc.).

We have reduced the initial uncertainty associated with the variable quality of the available borehole dataset by sorting through available boreholes and selecting only those representative boreholes in which we have a reasonable degree of confidence. Typically in the environmental and geotechnical borings we have examined, samples are taken and described every five feet. We therefore only use those boreholes that contain positive evidence for the presence of the "top of Pleistocene". We do not include in our subsurface mapping borings that are not well located, lack adequate descriptions, or may be too 'shallow' to penetrate "top of Pleistocene".

In our opinion, the non-linear nature of drilling means that absence of evidence for the "top of Pleistocene" within a boring can not be used to preclude the presence of "top of Pleistocene". This assumption is based on our repeated examination of multiple adjacent borings in the same locations around the Bay. Some borings of similar depth contain clear evidence for the location "top of Pleistocene" while others contain no evidence for the presence of the buried horizon.

Second, there is considerable uncertainty associated with the spatially and temporally variable nature of the "top of Pleistocene" beneath the southern San Francisco Bay. In our borehole database, we list the various criteria used to identify the "top of Pleistocene". Where preserved, soils developed within the 'top' of Pleistocene deposits may be associated with a weak- to well-developed argillic or, more rarely, calcic B horizon exhibiting ped development, clay coatings around grains and peds, minor color changes, presence of rootlets and/or root casts, and increased density relative to overlying deposits. Less well-developed soils coincident with the ‘top of Pleistocene’ include those with thin soil profiles that may have developed during shorter periods of subaerial exposure or those from which the A- and upper B- soil horizons were possibly eroded before deposition of overlying Holocene sediment. Thinner soils may have similar characteristics to well developed soils but typically these are more subtle, less identifiable in the subsurface, and more likely to be missing within most borings that sample every five feet. Horizons interpreted to be associated with soil development, whether well developed or not, typically are moderately denser than overlying sediment and coincide with an abrupt increase in bulk density decreasing gradually downward into less dense material.

We assign three levels of confidence in our interpretation of “top of Pleistocene”: (1) definite, (2) probable, and (3) possible. Our confidence is based on the accompanying identification criteria that we list but our degree of confidence is not necessarily dependent upon the number of criteria seen.

In summary, we rejected logs of borings that are not well located, not deep enough, or contain inadequate descriptions. We set aside for interpretation logs that contained density information (typically blow count data) with accompanying lithologic descriptions required for identification of changes in soil density, texture and stratigraphy associated with the buried “top of Pleistocene”. In locations with multiple boreholes, we typically selected a representative borehole with the best available data. For each borehole, we listed the criteria used to identify “top of Pleistocene”. As described below, during our review of our initial contouring, we have re-examined our borehole interpretations. In areas with anomalous results, we reviewed the available borehole logs and, in some cases, have selected more representative borehole logs for inclusion in our borehole database.

Preparation of Contour Maps of ‘Top of Pleistocene’

We contoured borehole data points by hand. Contouring by hand is slow and tedious but allows the relative weighting of individual data points based on geological knowledge. For example, our contouring was guided in some areas by surface contours on remnant outcrops of Pleistocene deposits. Because of the uneven distribution of available subsurface data, gaps exist in the data that test the limit of a computer-based interpolation scheme. In addition, data that should be re-examined or disregarded may be interpreted incorrectly by computer-aided contouring. Thus, extrapolation of widely-spaced data points and interpretation of ambiguous data requires the exercise of geologic judgment in the initial data evaluation and contouring process.

However, our approach does not preclude computer-aided contouring of our final borehole data set. Based on our review of various contouring approaches, the most successful applications of contouring have occurred when the data points have been hand picked. We have used an iterative process to sort through the available borehole data and select representative data points (boreholes) in which we have the most confidence. Recognizing potential errors in both manual and computer methods, and adjusting those methods where necessary and appropriate, is essential to produce a truly representative contour map.

The data points we to produce our final maps have been culled from thousands of borehole records as the most representative and reflect the initial results of hand contouring. The process of recognizing and eliminating potentially erroneous data points was accomplished by recognizing "bulls-eye" anomalies on the preliminary hand-contoured maps. Often these anomalous features were not identified until we had constructed the accompanying ‘thickness of Holocene’ maps. Interpreted borehole logs associated with apparently anomalous points were reexamined, and where appropriate, reinterpreted or removed. In several cases, we removed anomalous data points based on subsequent inspection that revealed our initial interpretation to be erroneous or the data to be ambiguous. As a result, the final contours better conform to adjacent data points and other known geologic and/or topographic features.

Preparation of Isopach Maps of Holocene Deposits

We have produced maps showing the thickness of Holocene deposits. These isopach maps were constructed by; (1) contouring Holocene thickness values from borehole logs and, (2) subtracting the elevation of top of the Pleistocene from the ground surface elevation (inferred top of Holocene deposits) (Figure 7). First, we contoured thickness of deposits identified within individual borehole logs. Then, we supplemented these data points by contouring deposit thickness values derived from subtraction of ‘top of Pleistocene’ elevation contours from topographic contours. Specifically, we have examined the intersection of contours from vintage, pre-development topographic maps to derive ten-foot interval isopach maps of Holocene deposits. We checked our hand contouring against computer-aided (GIS) mapping in which we have subtracted two grid files; the gridded ‘top of Pleistocene’ surface from the available 10-m USGS Digital Elevation Models (DEMs). In addition, we incorporated the actual measured thickness of Holocene values at each borehole location as a check against our preliminary isopach maps.

The uneven distribution of currently available subsurface data required substantial interpretation in some areas. We have documented our uncertainty and confidence in our contouring within the GIS

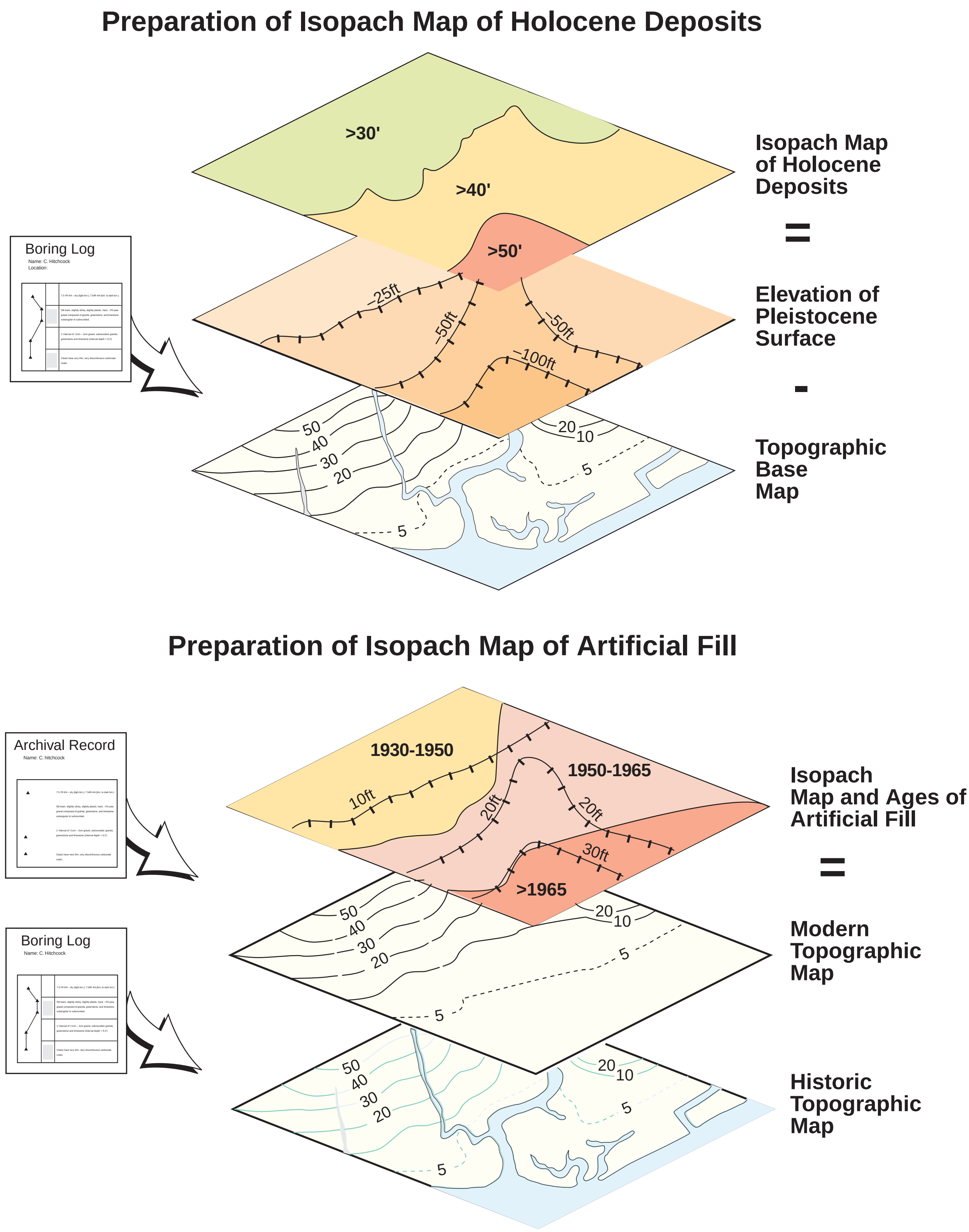


Figure 7. Data sources and integration used to develop interpretive contour and isopach maps.

database. However, the absence of data has led us to retain several key borehole data points that, as contoured, remain anomalous. We believe that these data are accurate and that collection of additional data is required to fully resolve the apparent contouring anomalies.

Preparation of Maps of Artificial Fill

We compiled available unpublished site-specific geotechnical studies and consultant reports, performed archival research and aerial photography analysis, and examined borehole data to produce a series of maps characterizing artificial fill. These maps show the distribution, inferred thicknesses and ages, and methods of emplacement of artificial fills.

Our approach is based on Ken LaJoie (unpublished) and previous unpublished mapping of the "historical development of reclaimed lands" along the Bay margins by the Corps of Engineers. We are determining and mapping the thickness of fill based on: (1) interpretation of compiled borehole data; and (2) subtraction of the top of Holocene from modern topographic maps. We have compared the current margin of the Bay to the Bay margin as shown on historic aerial photography, historic topographic maps, and the 1850 margin of marshlands mapped by Nichols and Wright (1971). Our mapping of fills along the Bay margins will be presented in our final report for the north Bay region that will include our south Bay mapping.

Where available, we provide additional information on the ages and types of material in uncompacted fill. We also identify source materials for some fills, i.e. silty clay vs. sand (e.g. Merritt Sand). We are classifying artificial fills within three main categories (based on Seed, 1969);

- Uncompacted dumped fill of all types of soil,
- Hydraulic sand fills, and
- Well-compacted fills of select material.

4.0 RESULTS

4.1 Borehole Database

We completed data collection for twelve 7.5-minute topographic quadrangles, including quadrangles containing Santa Clara Valley and the East Bay plains (Figure 1). Over 1,600 boring logs have been compiled, digitized, and interpreted (Figure 6). Our database includes records with the following information:

- unique integer identifier,
- boring or well number (from original source),
- longitude (decimal degrees),
- latitude, (decimal degrees),
- northing (UTM NAD27),
- easting (UTM NAD27),
- elevation of top of boring or well,
- depth to 'top of Pleistocene',
- elevation of the 'top of Pleistocene',
- criteria used in interpretation of 'top of Pleistocene',
- uncertainty rating (1=definite, 2=probable, and 3=possible),
- thickness of Holocene deposits,
- thickness of artificial fill, and
- whether borehole data was used for mapping.

4.2 Maps of the Top of Pleistocene and Isopach Maps of Holocene Deposits

Our mapping of the 'top of Pleistocene' and thickness of Holocene deposits covers the Santa Clara Valley including San Jose; the East Bay plains including Newark, Fremont, and Hayward; and the San Francisco Peninsula, including South San Francisco and Mountain View. Plate 1 shows contours of the interpreted 'top of Pleistocene' with borehole locations. Plate 2 shows the inferred thickness of Holocene deposits derived from the 'top of Pleistocene' mapping and topographic mapping.

5.0 DISCUSSION

5.1 Interpretation of "Top of Pleistocene" Mapping

Our maps show that the buried top of Pleistocene surface is relatively flat lying with the notable exception of local depressions and indentations. It is likely that the Pleistocene landscape consisted of broad alluvial plains incised by stream channels, similar to the modern landscape. However, the locations of buried stream channels inferred from our mapping of the 'top of Pleistocene' do not necessarily coincide with the locations of similar Holocene and recent landforms. We believe that differences between surficial landforms visible today and the Pleistocene landscape is the result of both climatic changes, including meandering of existing streams, and tectonic influences. Dr. Janet Sowers (1995, 1997) of WLA has shown that buried stream channels that contain sandy sediments can be correlated to the mapped pre-development (latest Holocene) courses of streams in the East

Bay using historic topographic and Bay survey maps. Sowers (1995, 1997) mapped pre-development (latest Holocene) courses of streams in the East Bay.

5.2 Thickness of Holocene Deposits

The uneven distribution of currently available subsurface data required substantial interpretation in contouring thicknesses of Holocene deposits. The absence of data has led us to retain several key borehole data points that, as contoured, remain anomalous. We believe that these data are accurate and that collection of additional data is required to fully resolve the apparent contouring anomalies. These data likely are representative of locally buried features (e.g. stream channels in buried 'top of Pleistocene) that currently can not be fully characterized (i.e. contoured) due to gaps in the available subsurface data (e.g. Figure 8).

5.3 Hazard from Artificial Fills along the Bay Margin

Past occurrences of liquefaction-related ground deformation within the Bay Area have not been randomly distributed but rather have increasingly reflected the urbanization of the Bay margins. Knudsen (2000) documented that about 83 percent of liquefaction occurrences from the 1989 Loma Prieta earthquake occurred in artificial fill whereas only about 30 per cent of liquefaction failures were documented in fill emplaced on Bay margins in historic earthquakes prior to the Loma Prieta earthquake. This increase in the percentage of documented earthquake-related damage in fills likely reflects the extensive reclamation of the Bay shoreline following the 1906 earthquake.

Similarly, most structures destroyed by the 1995 Kobe earthquake were concentrated in areas of "reclaimed land" developed since the turn of the century (Hamada et al., 1996). The worst devastation within the city of Kobe occurred in areas where fill (mostly decomposed granite from nearby hills) had been emplaced on tidal marshes along the margin of Kobe Bay (Hamada et al., 1996). After the turn of the 20th century, the marsh had been turned into paddy fields. Ultimately city expansion led to residential land via fill emplacement; by about 1920 about 23 km^2 had been reclaimed from the bay. Liquefaction-induced damage was especially damaging on the man-made Kobe Port and Rokko Islands, which cover approximately 10 km^2 and 6 km^2, respectively. Both islands were constructed with fill derived from decomposed granite emplaced on bay mud. Overall, artificial fills emplaced over estuarine sediment along bay margins performed very poorly during the Kobe earthquake, even resulting in damage to state-of-the-art engineered structures.

In the central San Francisco Bay Area, similar urbanization has built outwards into the Bay by incremental emplacement of artificial fills (Figure 9). During a large earthquake on the nearby

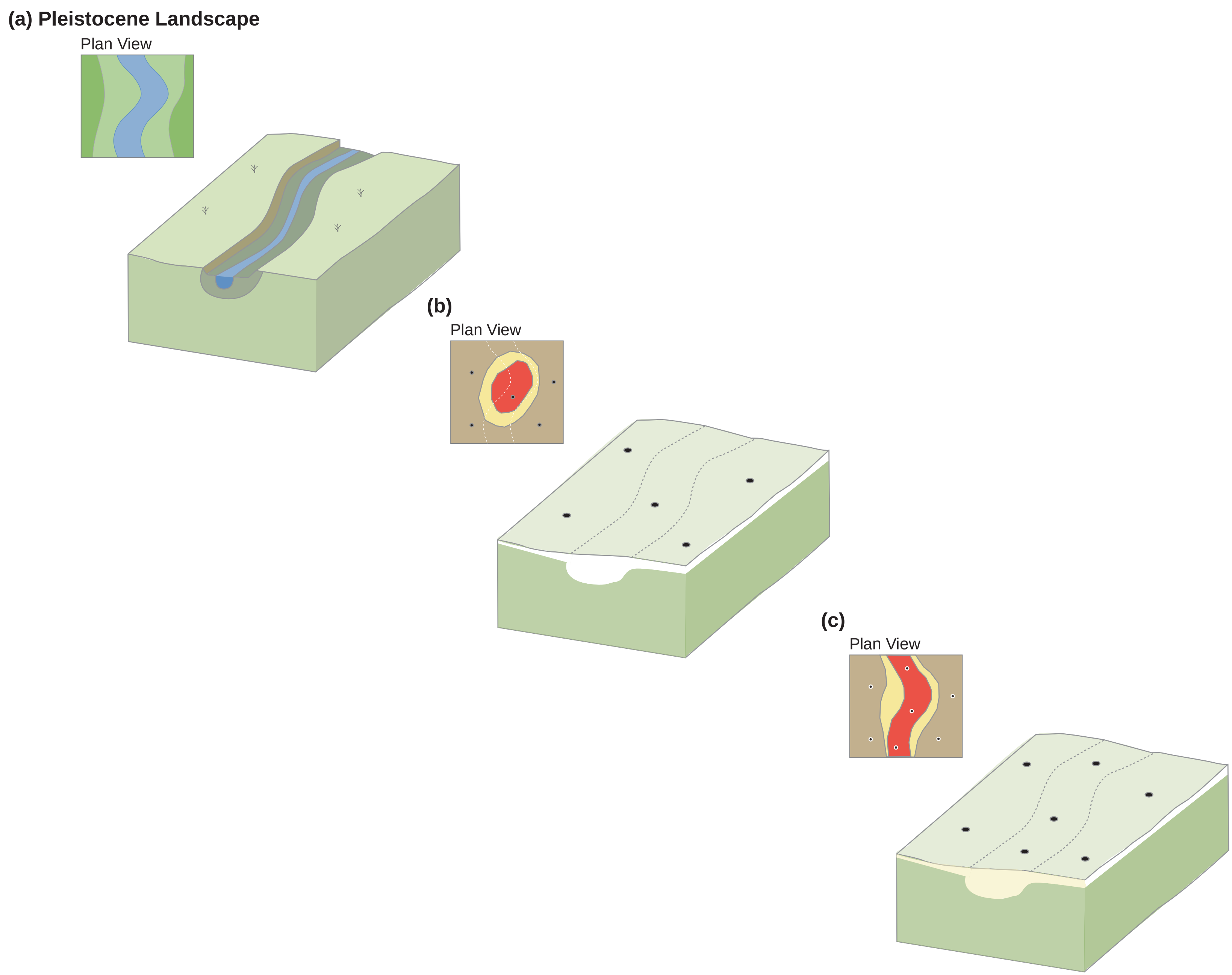


Figure 8. Block diagrams showing (a) stream channels as inferred origin of low areas in top of Pleistocene, (b) existing contouring based on available borehole data, and (c) preferred contouring with additional (not currently available) subsurface data.

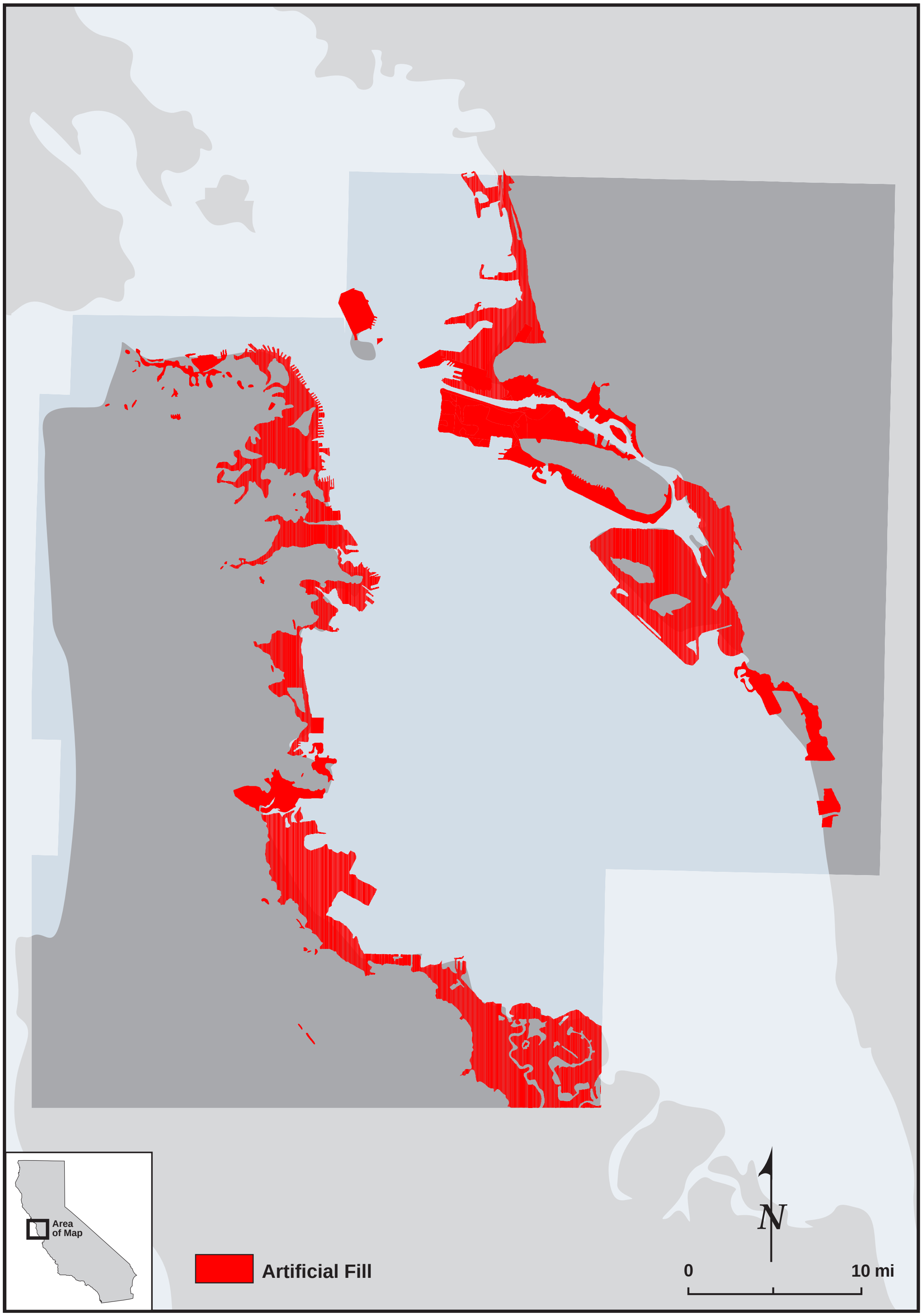


Figure 9. Map showing the central San Francisco Bay area. Distribution of artificial fill is derived from Knudsen et al. (2000).

Hayward, Rodgers Creek, or Calaveras faults, it is likely that liquefaction-related damage within artificial fill along the San Francisco Bay margins will be extensive and extremely costly to Bay Area infrastructure and lifelines. During the 1989 Loma Prieta earthquake, areas of greatest settlement and sand boils coincided with hydraulically emplaced sand fills (mostly emplaced in the 1930s and 1940s).

Another significant factor that may control the likely locations and amounts of liquefaction-related effects is the composition of deposits that underlie bay fills. Most of the fill along the Bay margins has been placed directly on top of late Holocene sediments, chiefly late Holocene estuarine deposits, including sand shoals and Bay Mud. These underlying deposits typically were uncharacterized at the time of fill placement, and although covered, likely still control, in part, the stability of the overlying fills. For example, the abundance of sand boils and magnitude of settlement on Treasure Island during the 1989 Loma Prieta earthquake appears to have been greatest in areas underlain by sand shoals whereas the greatest amounts of ground cracking and lateral spreading at the island margins occurred in the thickest part of fill underlain by Bay Mud (Figure 10).

6.0 SUMMARY

The results of our research include compilation in digital form of over 1,600 boring logs for twelve 7.5-minute quadrangles that cover the southern San Francisco Bay margins. Interpretation of data compiled has resulted in revision of, and extension of, preliminary mapping of the top of the Pleistocene in the San Jose area by Helley (1990). Our derivative maps showing the thickness of Holocene deposits contribute toward the ultimate goal of isopach maps showing the cumulative thickness of sandy sediments (i.e. potentially liquefiable sediments), within the Holocene deposits. Our mapping contributes to the geologic and geotechnical framework required to prepare three-dimensional liquefaction hazard maps in the southern San Francisco Bay area.

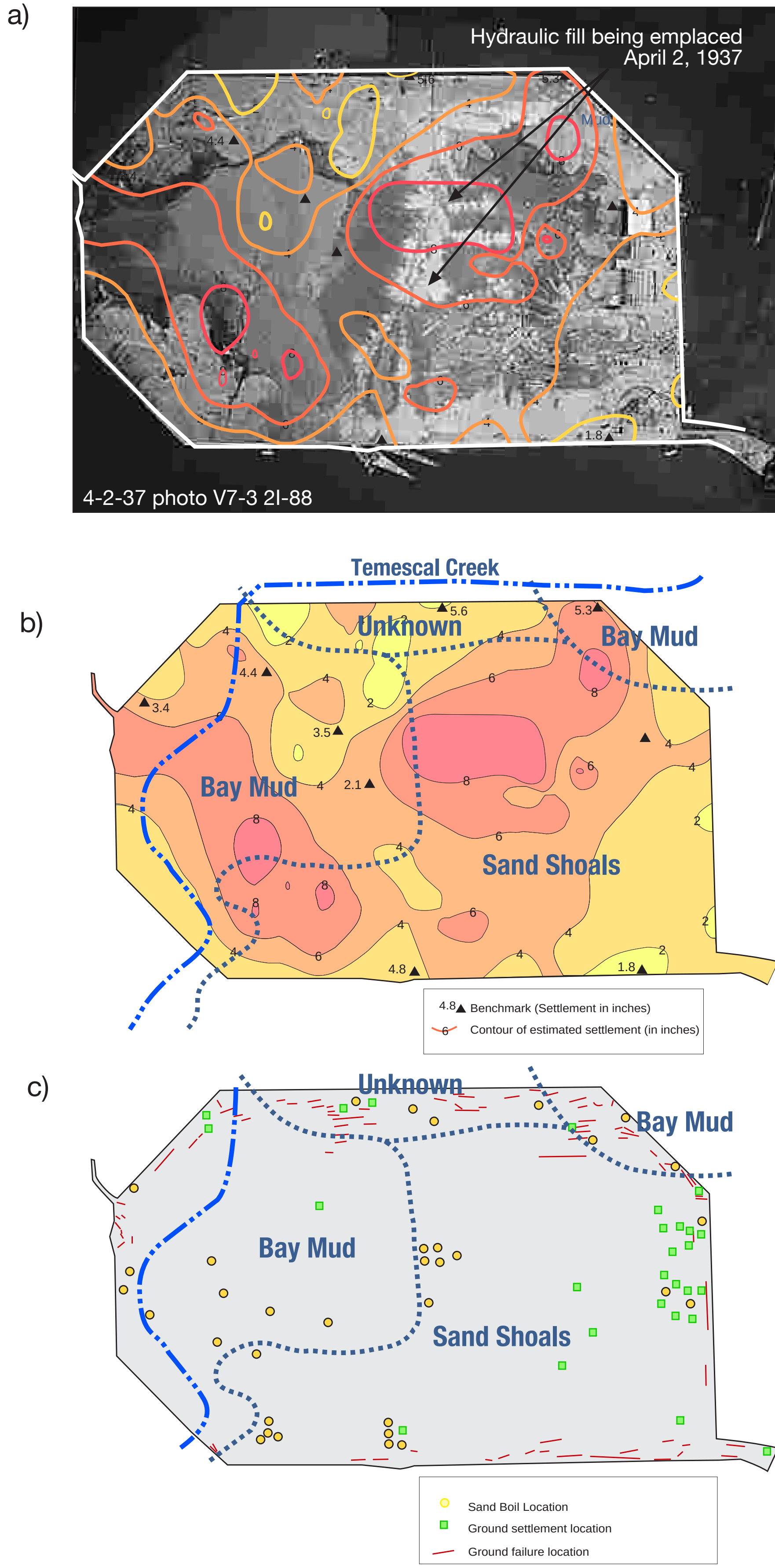


Figure 10. Maps showing (a) aerial photograph of Treasure Island filling (note large central area of hydraulic fill) with contours of settlement from 1989 Loma Prieta earthquake (from Powers et al., 1998), (b) ground settlement (in inches) during 1989 relative to underlying sediment type, and (c) three main types of liquefaction features (settlement, sand boils, and ground failures).

7.0 ACKNOWLEDGMENTS

We thank Kevin Clahan, Keith Knudsen, Charles Real, Ralph Loyd, and Mark DeLisle of the California Geological Survey (CGS) for their assistance and sharing of borehole data collected by CGS as part of the CGS Seismic Mapping Program. The borehole data used to produce our maps would be much less comprehensive without the generous assistance and data sharing by the CGS. We also thank Carl Wentworth and David Schwartz of the USGS for constructive conversations and advice. Andrew Barron and Rick Koehler of William Lettis & Associates, Inc provided assistance in compilation of borehole information. William R. Lettis provided technical review.

We thank the individuals and agencies that provided access to borehole logs and other information on local geology. These include the California Division of Mines and Geology, California Department of Transportation, Alameda County Public Works Agency, City of South San Francisco, and the Bay Area Rapid Transit District. Special thanks to Jack Meyer of Sonoma State University, Richard Harmon of the City of South San Francisco, Gart Kimball and Jim Ingle of the Alameda County Water District, Andreas Godfrey of the Alameda County Public Works Agency, and Stacey Paul of CALTRANS for their assistance.

This work was supported by the U.S. Geological Survey National Earthquake Hazards Reduction Program Grant #99-HQ-GR-0097. This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial Standards or with the North American Stratigraphic Code. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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