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Comments on Potential Geologic and Seismic Hazards Affecting Mare Island, Solano County, California

by
T.L. Holzer, C.M. Wentworth, W.H. Bakun, J. Boatwright, T.E. Brocher, M. Çelebi, W.L. Ellsworth, J.P.B. Fletcher, E.L. Geist, R. W. Graymer, R.E. Kayen, D. K. Keefer, D. H. Oppenheimer, W.U. Savage, D.P. Schwartz, and R. W. Simpson

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Executive Summary

This report was prepared in response to a written request from the City of Vallejo, California, to the U.S. Geological Survey (USGS). By letter of October 4, 2002, the City requested that the USGS "provide advice to the City's LNG Health and Safety Committee on its review of a potential liquid natural gas project" on the southern portion of Mare Island. The City specifically requested that the USGS advise the committee on potential hazards including fault rupture, earthquake ground motion, soil failure during earthquakes, tsunami and seiche, and landslides. The City requested that the USGS: (1) comment on these hazards, (2) describe its degree of confidence in its opinions, and (3) describe the scope of additional studies that will be needed if the City enters into an agreement with project sponsors. Advice was also requested on the selection of the safe shutdown and operating basis earthquakes as specified in the NFPA 59A standard (NFPA, 2001).

This review of published reports and other publicly available information indicates that all of the hazards on which the USGS was asked to comment should be considered for the proposed project on the southern portion of Mare Island. Available information differs greatly for each of these potential hazards, and adequate understanding for design will require detailed site-specific investigations.

- *Surface fault rupture:* Available data are inconclusive regarding the precise location and recency of faulting on the Franklin Fault, although there is considerable evidence that it does not pass directly through the site on southern Mare Island proposed for the liquefied natural gas (LNG) project. Clarification of the recency of faulting on the Franklin Fault and the possibility of minor surface faulting at the site is necessary to resolve the potential for faulting at the land surface.
- *Near-source ground motion:* The proposed LNG project site may be as close as about 7 km (4 miles) from the Hayward/Rodgers Creek Fault system, one of the major active fault systems in the San Francisco Bay region. This fault system has a 32 percent probability of producing a magnitude 6.7 or greater earthquake in the next 30 years and may be capable of producing an earthquake with a magnitude as large as 7.4. Shaking typically is greater closer to the earthquake source. In addition, the proposed site is close enough to this fault system to experience large near-source ground-motion phenomena. The phenomena include elevated levels of ground motion produced by propagation of the earthquake fault rupture toward the site (rupture directivity) and potentially large tectonic displacements of the land (static offset). Estimates of design ground motions at the proposed LNG project should consider near-source ground-motion effects, particularly for evaluating the ground displacement levels in the design of base-isolated systems.
- *Foundation conditions:* Portions of the proposed site appear to be underlain by artificial fill and by soft bay mud deposited in San Pablo Bay. Both of these materials historically have performed poorly in earthquakes and should receive special investigation at the site. Artificial fill, if not properly engineered, may fail and cause large displacements at the land surface. Bay mud typically modifies the amplitude and frequency of seismic waves as they propagate upwards from bedrock. These modifications should be included in estimates of ground motion.
- *Tsunami and seiche:* Fluctuations of water level in the San Francisco Bay system associated with both distant and local earthquakes have been observed. While the

fluctuations have been small, their effect could be compounded by adverse tidal conditions. The potential effects of tsunamis and seiche should be included in design and operational considerations of the proposed project.

- *Landslides:* The steep bedrock slope adjacent to the proposed site may be susceptible to both earthquake and rainfall-induced landslides. Possible effect of such slope failures on proposed project structures should be considered.

Selection of the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) should consider the potential effects of rupture directivity, static offset, and site-specific soil conditions.

Introduction

This report was prepared at the written request of the City of Vallejo to the U.S. Geological Survey (USGS). By letter of October 4, 2002, the USGS was requested to "provide advice to the City's LNG Health and Safety Committee on its review of a potential liquid natural gas project" on the southern portion of Mare Island. The City specifically requested that the USGS advise the committee on potential hazards including fault rupture, earthquake ground motion, soil failure during earthquakes, tsunami and seiche, and landslides. Advice was also requested on the selection of the safe shutdown and operating basis earthquakes as described in NFPA 59A standard (NFPA, 2001).

This report reviews the geologic and seismic hazards that may affect the southern portion of Mare Island. It includes a summary of findings, followed by more extensive and technical discussion of issues and evidence. This report is neither a study of the proposed LNG project nor an evaluation of any aspect of the project.

This report is based on regional studies of the San Francisco Bay region conducted by the USGS and on other published sources. In addition, the City of Vallejo provided the USGS with a report prepared for Bechtel Enterprises/Shell by William Lettis & Associates, "Interim Report on Surface Investigations of the Potential for Earthquake-related Surface Deformation at Proposed LNG and Power Plant Facilities, Southern Mare Island, Vallejo, California", dated October 14, 2002 (WLA, 2002). Discussions were also held with representatives of William Lettis & Associates and the California Geological Survey. No new field investigations or surveys were conducted by the USGS in the preparation of this report. For the purposes of this report, it is assumed that the proposed LNG project site is as shown in Figure 1 of WLA (2002).

Feasibility studies and the design of engineering projects begin with assessments of the conditions at and near the project site that may influence design and operation. The purpose of this report is to comment on potential hazards and geologic conditions pertaining to Mare Island. Design of the proposed facility should consider these hazards and conditions.

Setting

The proposed LNG project lies within a 70-km-wide (44 miles) set of major faults of the San Andreas Fault system that forms the boundary between the Pacific and North American tectonic plates (Figure 1). The persistent northwestward movement of the Pacific plate relative to North America primarily causes right-lateral slip across the major faults, but also causes deformation between the major faults. The ongoing complex deformation field is revealed by modern geodetic surveys and earthquake patterns as well as the regional geologic structure. The proposed site is located at the eastern shore of San Pablo Bay between two major active fault systems: the Hayward-Rodgers Creek Fault system on the west and the Concord-Green Valley Fault system on the east. The site lies near the middle of the 65-km-long (40 miles) Carneros-Franklin Faults, which juxtapose different suites of rocks, and for which the earthquake potential is unknown.

Shaking sufficient to seriously damage structures at Mare Island occurred during the M6.8[1] 1868 Hayward Fault earthquake, the M7.8 1906 San Andreas Fault earthquake, and particularly during the M6.3 1898 Mare Island earthquake (Appendix 1). The 1898 earthquake may have occurred about 20 km (12 miles) to the northwest on the southern Rodgers Creek Fault. Even larger nearby events than the 1898 earthquake can be expected in the future. In addition, the site is depicted on the USGS National Seismic Hazard Maps to have a high probability of strong shaking in the future (http://geohazards.cr.usgs.gov/eq/; Frankel and others, 1997).

The regional geology of the proposed site is shown in Figure 2. The proposed site lies near sea level at the southern end of Mare Island adjacent to a steep slope underlain by relatively hard fractured rock. The island is surrounded by soft mud deposited in San Pablo Bay. Portions of the proposed site are underlain by artificial fill (Figure 2). In general, areas in the San Francisco Bay region that are underlain by fill and bay mud have experienced disproportionately greater damage during historic earthquakes. Such damage is caused by soil failure in the fills and amplification of ground shaking by the soft bay mud.

Earthquake Sources

This section of the report describes potential earthquake sources that may cause shaking at the proposed site. Earthquake sources occur throughout the San Francisco Bay region on faults with a broad range of slip rates, lengths, and styles of movement. The proposed site is at a location where earthquakes on some of these faults have the potential to produce ground motions that may be important for engineering design. These faults can be grouped into three categories:

- *Well-documented strike-slip faults that produce large earthquakes in the region:* The site is located between two major, largely strike-slip fault systems (Figure 1). The Hayward-Rodgers Creek Fault system, which is approximately 7 km (4 miles) west of the site, generated damaging earthquakes in 1868 and probably in 1898. The Concord-Green Valley Fault system, which is12 km (7 miles) east of the site, produced a M5.5 earthquake in 1954; while it has not generated a large historical event, there is strong evidence for recent pre-historic activity. The 1999 Working Group on California Earthquake Probabilities (WG99, 1999) concluded that the Hayward-Rodgers Creek Fault system has a 32 percent probability of generating a large earthquake (M6.7 to 7.4) by the year 2030, and the Concord-Green Valley Fault system has a 6 percent chance of generating a large earthquake ($M \geq 6.7$) in the same time period (Figure 1).
- *Insufficiently characterized faults closer to the site that may produce moderate to large earthquakes*: The crustal block between the two major faults is broken by several other faults that could be active (Figure 3), including the Pinole, West Napa, Franklin, Southhampton, Lake Herman, and Sky Valley Faults. Although only the West Napa Fault is known to have displaced Holocene-age sediment — which is positive evidence of surface fault rupture in the last 11,000 years (Hart and Bryant, 1999; CDMG, 1983) — no evidence demonstrates that any of these other faults are not active. Small earthquakes recorded in the area over the past 34 years indicate that the crustal block is being actively deformed by small slippage on faults at depth (Figure 4). Notable among these small

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[1] M refers to earthquake magnitude

earthquakes is a tabular subvertical grouping at depths of 5-12 km just east of the surface trace of the Franklin Fault (**a** in Figure 4, map and cross section).

Among these faults, the Franklin Fault is particularly relevant because of its proximity to Mare Island. The fault does not appear to have surface geomorphic features that are typical of very active faults and is not classified as an active fault by the California Geological Survey (CDMG, 1983). While the long-term rate of fault slip is thus low, the seismicity and geologic data suggest that it might be capable of generating earthquakes.

Further site studies should include analysis of these faults with regard to their activity, orientation, and type of deformation in order to estimate the size, type, and probability of earthquakes they can produce.

- *Unknown blind faults that may be earthquake sources:* Some recent damaging earthquakes in California, including the M6.5 Coalinga (1983), M6.9 Loma Prieta (1989), and M6.7 Northridge (1994) events, have occurred on blind faults — that is, on faults that have no primary surface rupture. Most of these faults are thrusts, but the Loma Prieta earthquake indicated that other types of active faults may not extend to the ground surface. Although no blind faults are recognized in the Mare Island area, they are known beneath Grizzly Island north of Suisun Bay (Unruh and Hector, 1999), and deformation evident in the geologic record of the past 5 million years makes their presence in the subsurface near Mare Island possible. The grouping of small earthquakes (**a** in Figure 4) described above could be related to an unknown blind fault. Further studies should include evaluation of the presence and activity of blind faults near the proposed site. Such studies would evaluate the presence of blind faults and their slip rates and ages by constructing structural models from surface geology, subsurface data from wells, seismic-reflection profiles, seismicity, and gravity and magnetics.

Surface Faulting

This section addresses the potential for surface faulting near and at the proposed site. Surface faulting at the site would pose a serious hazard, and therefore has been the subject of a preliminary study by William Lettis & Associates (WLA, 2002). There are two issues: (1) the location of faults near or at the site, and (2) whether they are active. The WLA work addressed the potential for surface faulting on Mare Island and along the western and inferred eastern traces of the Franklin Fault using the record of deformation in the bedrock core of Mare Island, the elevation of marine terraces, and the continuity of subsurface horizons in seismic-reflection profiles.

Fault location:

- The WLA study presents considerable evidence that no major fault passes through the exposed bedrock next to the site. The regional distribution of geologic units requires that the main (western) trace of the Franklin Fault lies west of the bedrock exposed on Mare Island, as shown on geologic maps (for example, see Figure 3). The WLA (2002) mapping of the bedrock places the inferred eastern trace of the Franklin Fault east of the island. The bedrock next to the site, however, contains faults with small displacements and is locally concealed by landslides (WLA, 2002). Thus, the possibility of minor surface faulting at the site in association with a large event on the Franklin Fault cannot be precluded with present information.

Activity of faults:

- *Terrace deformation:* The shoreline angle of an uplifted marine terrace — the intersection of a former sea cliff with its wave-cut platform (Figure 6 of WLA, 2002) — defines an originally horizontal line from which to evaluate subsequent tectonic deformation. WLA (2002) mapped remnants of the Qt2 terrace, with an estimated age of 120,000 years, and graphed the elevations of its shoreline angle (Figure 9 of WLA, 2002). These elevations are given as ranges of values that reflect the uncertainties in the techniques of field measurement and reconstruction. The reported elevations of the shoreline angle are similar throughout Mare Island and thus show no evidence of deformation within the 8-9 m (25-30 ft) ranges of values. The reported range in elevations of the shoreline angle of the Qt2 terrace east of Mare Island, however, averages about 4.6 m (15 ft) lower. This observation would be consistent with relative vertical uplift of about 4.6 m (15 ft) across the inferred east trace of the Franklin Fault.
- *Seismic-reflection profiles:* Seismic-reflection profiles can provide the highest resolution for subsurface structure and deformation, short of drilling or trenching. Profiles acquired as part of the WLA (2002) study across the south end of Mare Island and east of the island across Mare Island Strait to examine the Franklin Fault typically image shallow reflecting horizons to depths of several meters (WLA, 2002, Figures 12-16). Most of the profiles show disruption of shallow reflections where they cross the inferred eastern trace of the Franklin Fault. Although WLA (2002) interprets these disruptions as fluvial cut-and-fill structures, a reasonable alternative with present information would be to consider them to represent faulting. In reflection profile G-3 across Mare Island Strait (WLA, 2002, Figure 16), a shallow horizon above the first multiple at the eastern trace of the Franklin Fault is vertically displaced about 3 to 4 m (10 to 13 ft). This occurs where there is also a change in the slope of the seafloor. The possibility that the displacement is real, and not an artifact of data processing, warrants further investigation. The vertical resolution of the data is about 2 m (7 ft), which implies that faulting associated with a sizeable prehistoric earthquake could remain undetected.
- *Seismicity:* The tabular grouping of small earthquakes shown at **a** in Figure 4 may occur on the Franklin Fault. This may indicate that the fault is active, although this alone would not indicate whether it could produce larger earthquakes and surface faulting.

The principal traces of the Franklin Fault do not pass through the exposed bedrock next to the site. Refinement of the marine terrace data around the northern margin of Mare Island and exploration of the continuity of young sedimentary layers at the southern margin of Mare Island will help constrain the possibility of any minor surface faulting through the bedrock. At present the evidence is insufficient to conclude that the Franklin Fault is inactive, and three lines of evidence — possible vertical displacement of the Qt2 terrace, disruption of a shallow reflection horizon near the east Franklin Fault, and possible spatial association with small earthquakes — suggest the contrary may be true. Further studies will be needed to resolve whether or not the Franklin Fault is active. These should include more intensive investigation of the marine terraces to refine the estimates of shoreline angle elevations, imaging of the deeper subsurface with seismic-reflection profiling to examine any persistence with depth of the disruption of shallow reflections and their relation to bedrock structure, and refinement of the analysis of the instrumental seismicity.

Earthquake Ground Motions

This section addresses the potential for and level of earthquake shaking at the southern end of Mare Island. The proposed site lies about 7 km (4 miles) east of the southernmost Rodgers Creek Fault where it overlaps with the Hayward Fault. The proximity of the proposed site to this active fault system implies the possibility of high levels of ground motion or earthquake shaking as well as special ground-motion phenomena that are only observed close to rupturing faults. These special phenomena include two effects, both of which could further increase levels of ground motion at the site. One effect, known as directivity, is associated with the direction in which a fault ruptures during an earthquake. The other effect, known as static offset, is a large sudden permanent ground displacement close to an earthquake.

Although the Hayward-Rodgers Creek Fault system will probably be the most important seismic source for the proposed LNG project, the earthquake potential of the Franklin Fault and possible blind faults near the site is unknown.

Soil conditions beneath a structure can significantly influence shaking by modifying the amplitude of the seismic waves as they propagate upward from depth. Soils with low shear-wave velocity, like the soft mud deposited in San Pablo Bay, have the greatest influence. The effect varies with both the level and the frequency of shaking. For example, ground motion may be increased at lower levels of shaking and decreased at higher levels of shaking. Many earthquakes in the San Francisco Bay region have demonstrated that shaking and damage are greater in areas underlain by soft soils than in nearby rock areas.

Estimating ground motion at the proposed LNG project should include the following considerations:

- *Directivity:* Large earthquakes result from a rupture propagating a considerable distance along a fault. In front of the rupture, seismic waves effectively pile up, causing large amplitudes in the direction in which the rupture is propagating (directivity). Consequently, if a rupture initiated at some distance from a site and propagated toward it, large amplitude seismic waves could affect the site (Somerville et al., 1997). For example, large-amplitude velocity pulses greater than 100 cm/s (39 inches/s) were recorded at two stations in Turkey during the M7.4 Kocaeli earthquake on August 17, 1999 (Figures 5 and 6). Both stations were less than 5 km (3 miles) from the fault on which the earthquake occurred. This effect could be significant at the proposed site if a rupture on the Hayward/Rodgers Creek Faults were to propagate toward it.
- *Static offset:* When faults rupture, the ground experiences large sudden permanent movements near the fault, called static offsets. If the Hayward and Rodgers Creek Faults ruptured in a single M7.4 earthquake, the static offset at the proposed site could be as large as 1 m (3 ft) and would be reached in several seconds (see examples in Figures 5 and 6). Such static offset is relevant to the selection of the maximum lateral displacement limit of base-isolated structures.
- *Site amplification:* The docking area for the proposed LNG project presumably is underlain by bay mud that overlies stiff soil or hard fractured rock of the Great Valley Complex (see Fumal, 1991, p. 140). This could result in a marked shear-wave velocity

contrast. Site amplification or resonance of the bay mud above such a contrast would be significant and the frequency response would depend explicitly on the shape of the contact or interface between these geologic units. Such strong amplification and the potential spatial variability of the ground motion would need to be considered in the design of long structures.

- *Deviation from standard ground-motion attenuation relations:* Estimates of ground motion for engineered structures near active faults are commonly based on curves (known as attenuation relations) that are fitted to recorded observations of ground motion from large earthquakes (for example, Boore and others, 1997, Campbell, 1997). Because relatively few recordings of ground motions close to faults during large earthquakes are available, the standard curves for predicting ground motion should be used with caution.

Tsunami and Seiche

This section addresses the potential for temporary changes of water level in water bodies, such as oceans and bays, that are observed during many earthquakes. This phenomenon is known as either tsunami or seiche, depending on its characteristics. A tsunami is a series of waves of long wavelength generated by earthquakes, landslides, and volcanic eruptions beneath the ocean. Hazards from tsunamis include: (1) runup where tsunami waves wash ashore at heights above normal wave action, and (2) strong currents. A tsunami-induced seiche is generated where the tsunami reflects off shorelines and oscillates in an enclosed body of water.

Tsunamis generated from distant sources arrive at the Golden Gate many hours after the causal event. Although the narrow Golden Gate admits only a portion of such tsunami energy into San Francisco Bay, measurable wave heights have been reported along the shore of San Pablo Bay from past events (Lander and others, 1993). The Great 1964 Alaska earthquake generated a tsunami with reported wave heights of 0.67 m (2.2 ft) at Point San Pablo and 0.98 m (3.2 ft) at the San Pablo yacht harbor (see Figure 7 for tide gauge records in San Francisco and Alameda).

Few records of local tsunami generated by earthquakes are available because most of the active faults in the San Francisco Bay region are onshore and display primarily horizontal slip. In offshore areas where there are lateral steps in fault trends, earthquakes may produce local tsunamis. For example, the M7.8 1906 San Francisco earthquake generated a small 0.08-m-high (0.25 ft) tsunami at Fort Point (Figure 8) that may have been generated by a lateral step on the San Andreas Fault near the Golden Gate. Such a lateral step also occurs between the Hayward and Rodgers Creek Faults beneath San Pablo Bay.

Tsunami and seiche issues that could potentially affect the proposed site include:

- Earthquakes that are on faults that rupture beneath San Pablo Bay as well as fast-moving coastal landslides or bluff failures near the proposed site (for example, bluffs bordering Carquinez Strait) may generate local tsunamis. Warnings of local tsunamis will not be available because the time interval between the earthquake or slope failure and arrival of tsunamis at Mare Island will be only a few minutes.
- Design earthquakes for tsunami hazards at the proposed site may be different than those for ground motion and foundation stability.
- Maximum runup and currents from a tsunami will be affected by tidal stage (ebb, flood, or slack; spring or neap tide).

Standard hydrodynamic models exist to evaluate potential hazards from tsunamis.

Foundation Stability

This section addresses the stability of the ground at the proposed site. Foundation stability refers to the ability of underlying geologic materials and fills — referred to as soils in geotechnical engineering — to support both buried and surface engineering works. Both static loading and earthquake shaking may cause vertical and horizontal ground displacements. Portions of the proposed project may be developed on artificial fill (Figure 2), which generally performs poorly during earthquakes if not properly engineered. The potential for earthquake-induced liquefaction of wet and loose sandy material and several other potential causes of instability should be addressed for the proposed LNG project, including base-isolated structures. Stability considerations should include:

- *Liquefaction—horizontal displacements:* Horizontal ground displacement is an important potential hazard when soils liquefy. Displacements as large as tens of feet may occur.
- *Liquefaction—vertical displacements:* Venting of ground water as it is expelled from the liquefied sands during the liquefaction process causes the land surface to settle vertically. Although differential displacements and tilting, which can affect both buried and surface structures are the primary concern, large areas that already are only slightly above sea level could lose elevation and be submerged.
- *Liquefaction—venting of toxic subsurface material:* Discharge (or venting) of subsurface material to the land surface is a common manifestation of liquefaction. Although such venting usually is just an inconvenience, it could be hazardous where toxic material present in the subsurface either in or above the liquefiable material is vented to the surface.
- *Displacements in clayey soils:* Earthquake shaking may cause large displacements in clayey soil, such as bay mud.
- *Displacements at soil boundaries:* Earthquake shaking can result in ground cracking and permanent displacements even if general landsliding does not occur. In past earthquakes cracking has been observed at soil-unit boundaries and soil-rock contacts.
- *Soil consolidation:* Geologically young clay soils, like bay mud, may consolidate slowly when subjected to new surface loads, causing structures to settle. This process involves the slow expulsion of pore water and can occur over decades.
- *Tsunami and seiche:* A secondary effect of earthquake-induced tsunamis and seiches is the rapid temporary lowering of water level, which can cause soil instability along shorelines. Such failures can occur when a submerged slope rapidly emerges from water without adequate time for pore water to drain and equilibrate to the temporarily lower sea level.

For all of these aspects of foundation stability, routine and well-developed site-investigation techniques are available to characterize the physical properties of soils, and widely accepted geotechnical engineering models exist to evaluate potential deformation hazards.

Landslides

This section addresses the potential hazard of slope failure on Mare Island. The steep flanks of the bedrock core of Mare Island may be subject to landslides that could affect foundations or impact facilities with falling or sliding rock debris from above. Numerous small to moderate-sized landslides and debris-flow chutes have been recognized on the steep bedrock slopes adjacent to the site (WLA, 2002, Figure 17). The fractured and jointed rock of the bedrock core may also be subject to large failures as rockfalls or large landslides triggered by earthquake shaking. Considerations relevant to the proposed LNG project include:

- *Rainfall-related landslides:* Existing and new landslides as well as debris flows can be activated or caused by a single large storm or during a particularly rainy winter.
- *Earthquake-induced landslides:* Both rock falls, rock slides, and debris slides — which are highly disrupted and can travel far beyond the slopes on which they originate — and deeper-seated slumps and block slides, can be caused by strong earthquake shaking of steep slopes in fractured rock (Keefer, 1984).

Routine and widely accepted geotechnical techniques are available by which to characterize the rock and soil and to evaluate the potential for such landslides. Detailed geotechnical and analytical site investigations that include dynamic engineering-based slope-stability analyses may be necessary to ensure adequate understanding of the potential hazard from earthquake-induced failures.

Selection of SSE and OBE

The Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) as described in NFPA 59A (NFPA, 2001) are estimated from probabilistic estimates of ground motion. Near-source effects on ground motion are not specifically described in the NFPA 59A standard. The large near-source effects discussed in this report could produce much larger ground motions than those yielded by conventional probabilistic seismic hazard analysis. It is therefore important that estimates of ground motions for the OBE and SSE explicitly consider near-source effects. Both OBE and SSE earthquake considerations should also include site-specific aspects when defining design response spectra.

Conclusions

Extensive geologic and seismologic data are available for the region surrounding the proposed Mare Island LNG project. These data and modern understanding of earthquake processes indicate that several geologic and seismic hazards may be present at the proposed site and need improved characterization and clarification. Ground motions from large earthquakes on the nearby Hayward/Rodgers Creek Fault system present a hazard for project structures and should be addressed in the design of project facilities. The potential for a significant earthquake on the Franklin Fault and possible blind faults near the site is not known, and additional data and analysis are needed. Additional potential hazards deserving attention are foundation stability, landslides, and tsunamis and seiche. The selection of the Safe Shutdown and Operational Basis

Earthquakes as described in the NFPA 59A standard (NFPA, 2001) should include consideration of near-source ground motions and site conditions in defining site-specific design response spectra.

Appendix 1. Historical Earthquakes and Mare Island

The following historical earthquakes with estimated magnitudes (Bakun, 1999) are known to have shaken Mare Island severely:

M6.3 near Mare Island — March 31, 1898

No surface rupture was observed, making the causative fault uncertain. The probable epicenter is on the southern part of the Rodgers Creek Fault because of the distribution of MMI ≥ VIII damage and reports of aftershocks at sites near there (Toppozada et al., 1992). Toppozada et al. (1992) do not suggest a specific epicenter location. They note that the strongest and most numerous reports of aftershocks were from Sonoma and Lakeville; the adjacent section of the Rodgers Creek Fault is about 20 km (12 miles) from Mare Island. Other aftershock reports (in order of decreasing severity) noted by Toppozada et al. (1992): Tubbs Island, Vallejo, Napa, Petaluma, Martinez, and Santa Rosa. The reports of a tsunami associated with the 1898 earthquake listed in Toppozada et al (1992), which might suggest a blind causative fault beneath San Pablo Bay, are not convincing.

MMI IX effects were reported at Mare Island (Toppozada et al., 1981). Two-story sawmill and other buildings collapsed; Partial collapse of other brick buildings. Nearly every brick building was more or less damaged. The ground all around the navy yard was seamed and creviced.

M6.8 on southern Hayward Fault — October 21, 1868

At Mare Island, "Chimneys were thrown, and some buildings were considerably shaken. Shock accompanied by a rumbling sound." (Lawson, 1908, p.439)

M7.8 on San Andreas Fault — April 18, 1906

At Mare Island, "The earthquake was much less severe than that of 1898, which wrecked many of the Government buildings in the navy-yard. None of the government buildings was wrecked this time, nor was the damage at all serious except in the case of two or three new buildings recently erected on the "made" land near the water-front." (Lawson, 1908, p.212-213)

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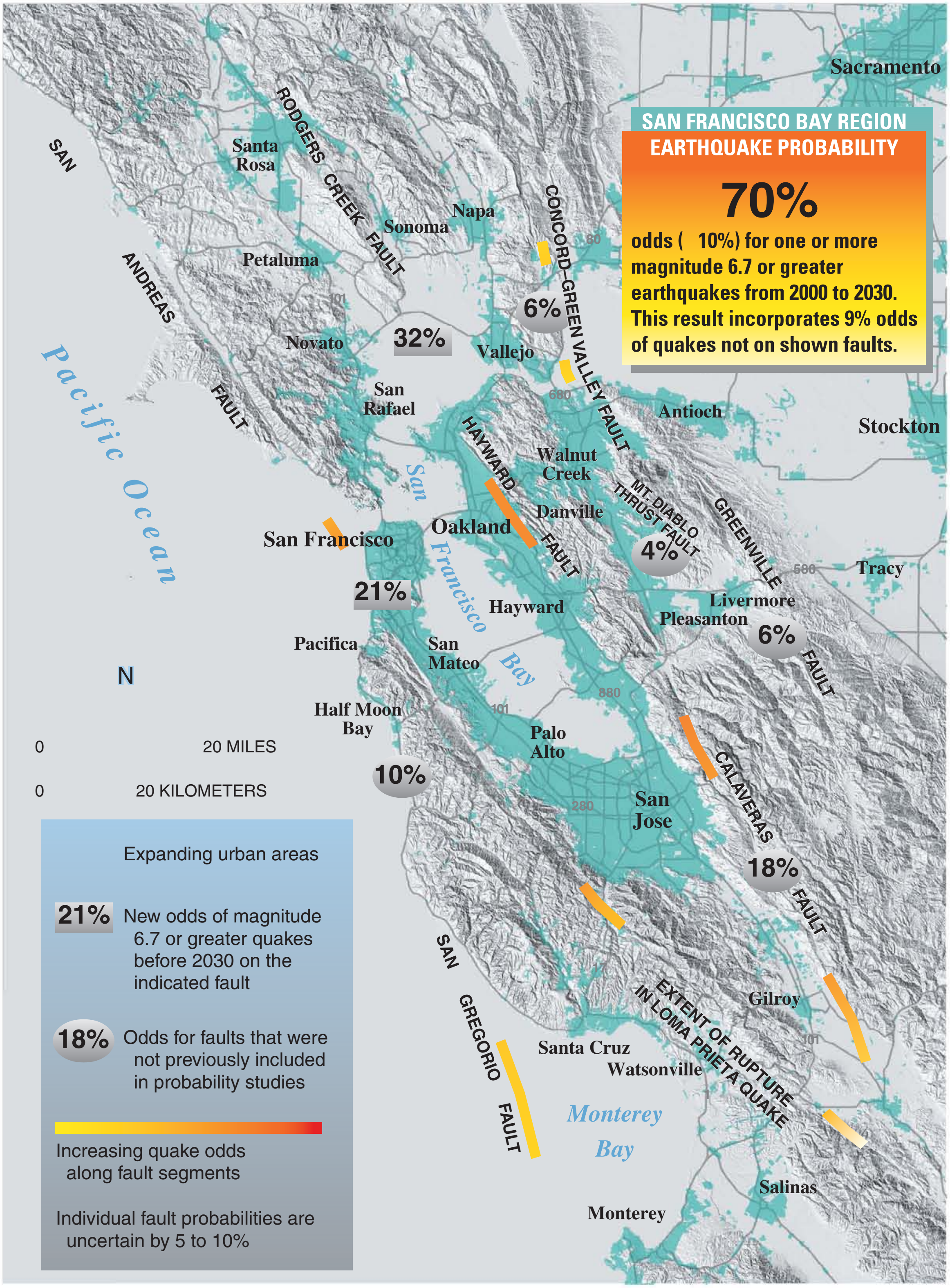


Figure 1. Major faults in the San Francisco Bay region and their probabilities of earthquakes with M > 6.7 from 2000 to 2030. From Michael and others (1999).

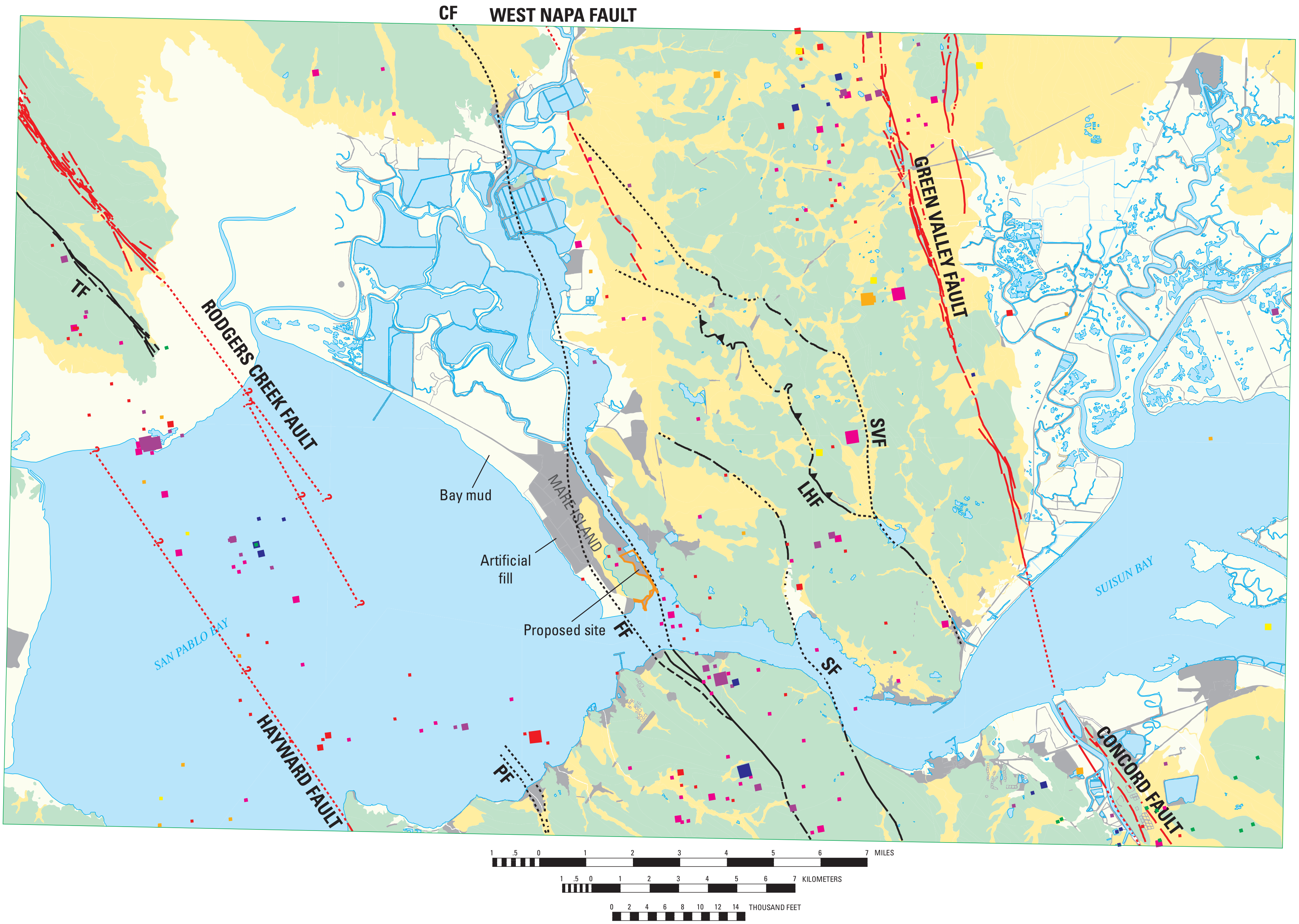


Figure 2. Simplified geologic map of Mare Island and the surrounding region with superimposed earthquake epicenters for the period 1971-2002. Known Holocene-active faults are shown in red. Other named faults are labelled (CF = Carneros Fault, FF = Franklin Fault, LHF = Lake Herman Fault, PF = Pinole Fault, SF = Southhampton Fault, SVF = Sky Valley Fault, TF = Tolay Fault). Epicenters are marked with squares sized in proportion to earthquake magnitude (1.1-4.1), and are color coded according to the depth (0-2.5 km = yellow, 2.5-5 km = orange, 5-7.5 km = red, 7.5-10 km = magenta, 10-12.5 km = purple, 12.5-15 km = blue, >15 km = green). Bedrock older than one million years is shown as light green, surficial deposits less than one million years old are shown as yellow, bay mud less than ten thousand years old is shown as light cream, artificial fill is shown as gray. (Modified from Graymer and others, 2002; Wright and Smith, 1992; California Division of Mines and Geology, 1983; epicenters from Northern California Seismic Network catalog, maintained jointly by the USGS-Menlo Park and the Berkeley Seismological Laboratory, University of California, Berkeley. Events in this catalog can be obtained from the Northern California Earthquake Data Center, a joint project of the University of California Berkeley Seismological Laboratory and the USGS).

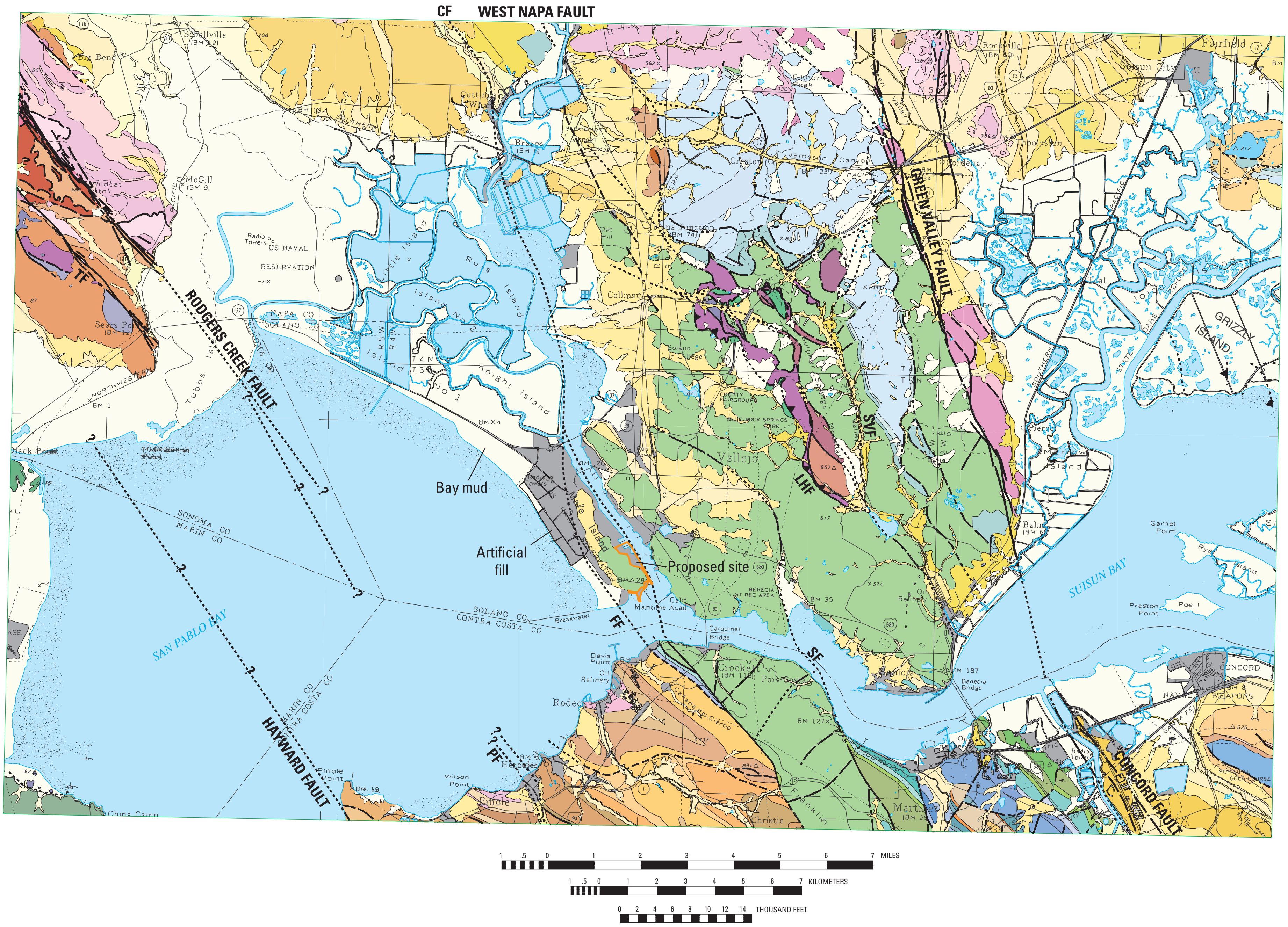


Figure 3. Geologic map of Mare Island and the surrounding region with superimposed earthquake epicenters. Other named faults are labelled (CF = Carneros Fault, FF = Franklin Fault, LHF = Lake Herman Fault, PF = Pinole Fault, SF = Southhampton Fault, SVF = Sky Valley Fault, TF = Tolay Fault). (Modified from Graymer and others, 2002; Wright and Smith, 1992; California Division of Mines and Geology, 1983)

LIST OF MAP UNITS

SURFICIAL DEPOSITS

- ■ Artificial channel deposits (Historic)
- ■ Artificial fill (Historic)
- ■ Artificial fill over Bay Mud (Historic)
- ■ Artificial levee fill (Historic)
- ■ Alluvium (Holocene)
- ■ Alluvial fan deposits (Holocene)
- ■ Fine-grained alluvial fan deposits (Holocene)
- ■ Stream channel deposits (Holocene)
- ■ Natural levee deposits (Holocene)
- ■ Floodplain deposits (Holocene)
- ■ Basin deposits (Holocene)
- ■ Bay mud deposits (Holocene)
- ■ Alluvium (Holocene and late Pleistocene)
- ■ Alluvial fan deposits (Holocene and late Pleistocene)
- ■ Landslide deposits (Holocene and Pleistocene)
- ■ Alluvial fan deposits (late Pleistocene)
- ■ Pediment deposits (late and early Pleistocene)
- ■ Alluvium (late and early Pleistocene)

BLACK POINT ASSEMBLAGE

Great Valley Complex

- ■ Novato Conglomerate (Early Cretaceous)

PINOLE POINT ASSEMBLAGE

- ■ Orinda Formation (late Miocene)

HERCULES ASSEMBLAGE

- ■ Conglomerate (late Miocene)
- ■ Tuffaceous sandstone (late Miocene)
- ■ Diatomite (middle to early Miocene)
- ■ Sandstone (middle to early Miocene)

RODEO ASSEMBLAGE

- ■ Pinole Tuff (late Miocene)
- ■ Neroly Sandstone (late Miocene)
- ■ Cierbo Sandstone (late Miocene)
- Briones Sandstone (late and middle Miocene)
  - ■ Upper member
  - ■ Hercules shale member
  - ■ Lower member
- ■ Rodeo Shale (middle Miocene)
- ■ Hambre Sandstone (middle Miocene)
- ■ Tice Shale (middle Miocene)

MARTINEZ ASSEMBLAGE

- ■ Briones Sandstone (late and middle Miocene)
- ■ Sobrante Sandstone (early Miocene)
- ■ San Ramon Sandstone (early Miocene and/or Oligocene)
- ■ Escobar Sandstone of Weaver (1953, Eocene)
  - ■ Basal shale member
- ■ Muir Sandstone of Weaver (1953, Eocene)
  - ■ Upper member
  - ■ Lower member
- ■ Las Juntas Shale of Weaver (1953, Eocene and Paleocene)
  - ■ Upper member
  - ■ Lower member
- ■ Vine Hill Sandstone of Weaver (1953, Paleocene)
  - ■ Upper member
  - ■ Lower member

Great Valley Complex

- ■ Undivided sandstone, siltstone, and shale (Late Cretaceous)
  - ■ Massive sandstone
  - ■ Sandstone, siltstone, and shale
  - ■ Massive sandstone
- ■ Sandstone and shale (Early Cretaceous and Late Jurassic)

SEARS POINT ASSEMBLAGE

- ■ Huichica and Glen Ellen Formations, undivided (early Pleistocene and Pliocene)
- ■ Sonoma Volcanics (Pliocene and late Miocene)
  - ■ Andesite to basalt flows
  - ■ Rhyolite flows
  - ■ Ash-flow tuff
  - ■ Volcanic sand and gravel
- Petaluma Formation (early Pliocene and late Miocene)
  - ■ Mudrock, sandstone, and conglomerate
  - ■ Claystone
- Donall Ranch volcanics of Youngman (1989, late Miocene)
  - ■ Mafic member
  - ■ Rhyolite member

SONOMA ASSEMBLAGE

- ■ Huichica Formation (early Pleistocene and Pliocene)
- Sonoma Volcanics (Pliocene and late Miocene)
  - ■ Ash-flow tuff

CORDELIA ASSEMBLAGE

- ■ Huichica Formation (early Pleistocene and Pliocene)
- ■ Sonoma Volcanics (Pliocene and late Miocene)
  - ■ Andesite to basalt flows
  - ■ Andesite to dacite plugs and dikes
  - ■ Rhyolite flows
  - ■ Rhyolite plugs and dikes
  - ■ Rhyolite and perlitic flows and plugs
  - ■ Ash-flow tuff
  - ■ Welded ash-flow tuff
  - ■ Lithic tuff
  - ■ Volcanic sandstone, siltstone, and conglomerate
  - ■ Diatomite
- ■ Cierbo Sandstone (late Miocene)
  - ■ Intercalated basalt
- ■ Claremont Shale (Miocene)
- ■ Markley Sandstone (Eocene)
  - ■ Jameson shale member
- ■ Nortonville Shale Member of Kreyenhagen Formation (Eocene)
- ■ Domingene Sandstone (Eocene)

Great Valley Complex

- ■ Sandstone and shale (Late Cretaceous)
- ■ Sandstone and shale (Early Cretaceous and Late Jurassic)
- ■ Keratophyre (Jurassic)
- ■ Massive and pillow basalt (Jurassic)
- ■ Gabbro (Jurassic)
- ■ Serpentinite (Jurassic)
- ■ Silica-carbonate rock
- ■ Limestone (age unknown)

PITTSBURG ASSEMBLAGE

- ■ Sandstone, siltstone, and gravel (early Pleistocene and late Pliocene)
- ■ Tehama Formation (Pliocene)
- ■ Lawlor Tuff (Pliocene)
- ■ Cierbo Sandstone (late Miocene)
- Markley Sandstone (Eocene)
  - ■ Upper member
  - ■ Lower member

Franciscan Complex

- ■ Sandstone (Late Cretaceous)
- ■ Metagraywacke (Early Cretaceous and Late Jurassic)
- ■ Melange

——— — — —······ **Contact**-- Depositional or intrusive contact, dashed where approximately located, dotted where concealed

━━━ ━ ━ ━ ·······?·· **Fault**-- Dashed where approximately located, small dashes where inferred, dotted where concealed, queried where location is uncertain.

—▼—▼— **Reverse or thrust fault**-- Dashed where approximately located, dotted where concealed

━━━ **Boundary of proposed LNG site**

Figure 3 (continued).

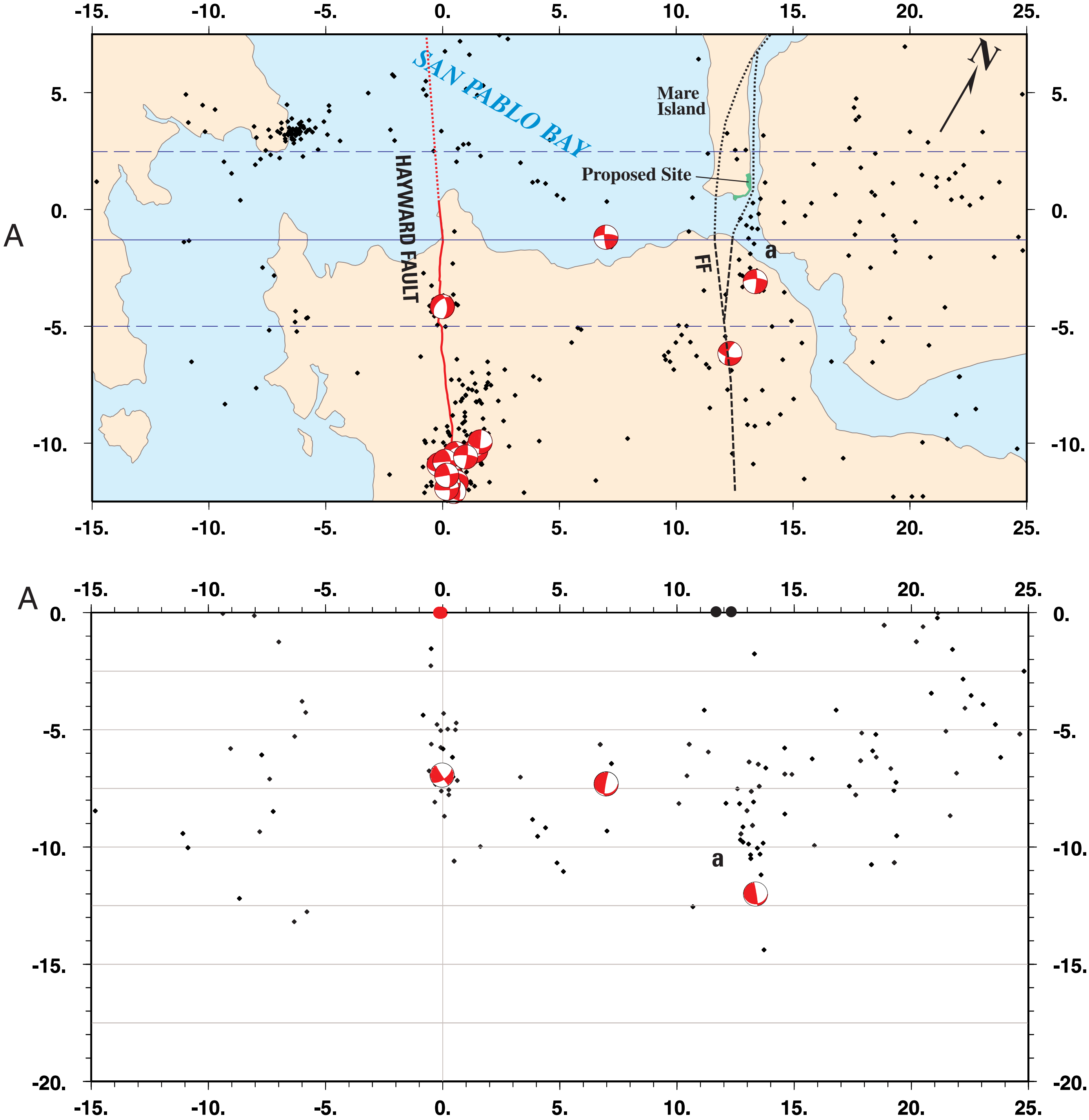


Figure 4. Map and cross section showing 1967-2001 seismicity (M 0.0 - 4.1) in the vicinity of Mare Island. The cross section line is oriented perpendicular to the trace of the Hayward Fault (shown as a red line in map view and a red dot at the surface in cross section). The cross section projects hypocenters within a 7.5-km-wide box into a single vertical plane at the center of the box. Focal mechanisms are shown as lower hemisphere (map view) or far hemisphere (cross-section view). A tabular group of hypocenters (labeled **a**) is present which is roughly aligned with, below and slightly east of the surface trace of the Franklin Fault (labeled **FF** and schematically shown as a pair of black lines on the map and pair of black dots on the cross section). A single focal mechanism indicating largely right-lateral strike-slip on a steeply east-dipping fault has been calculated from the tabular group and is shown.

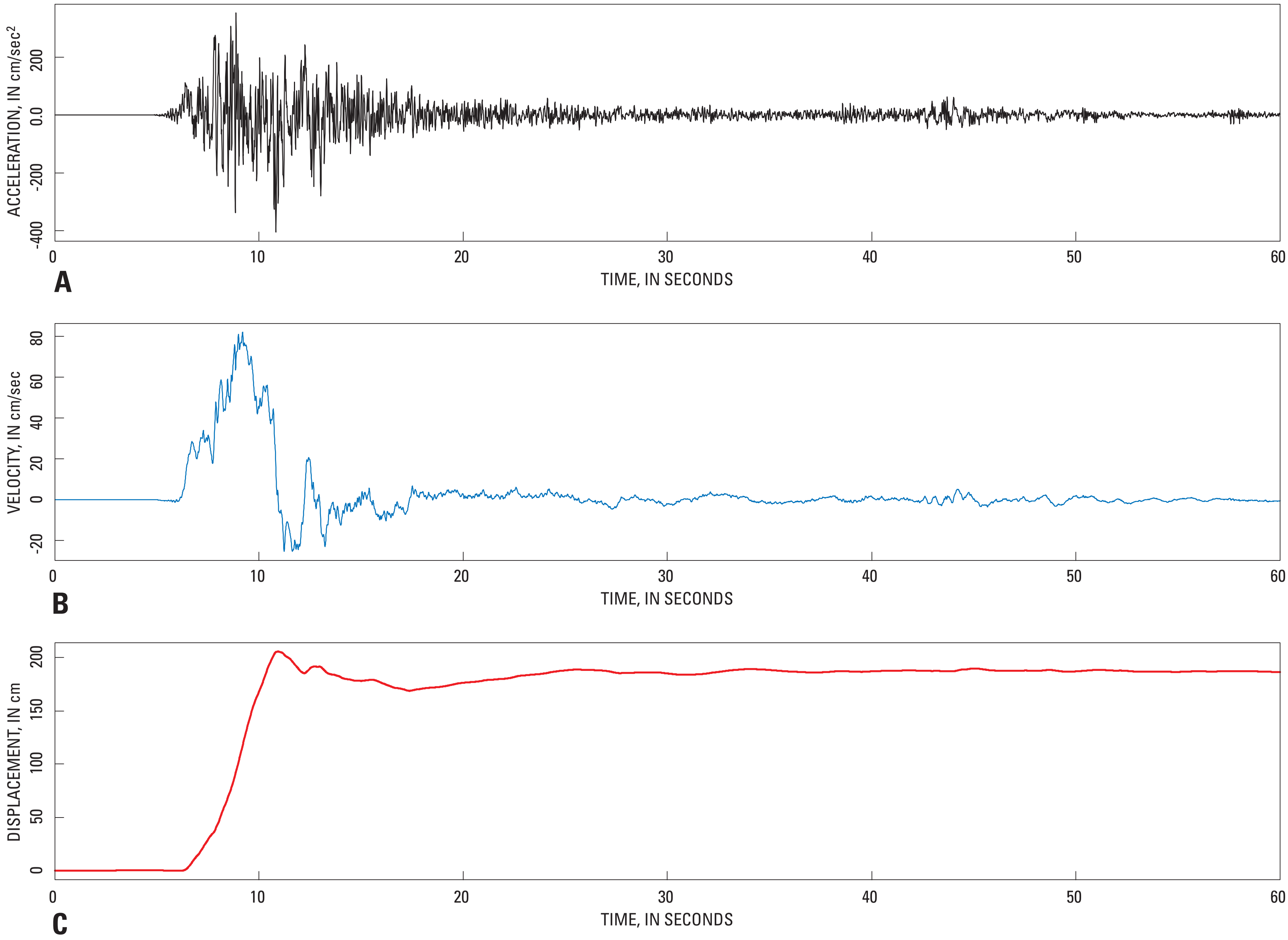


Figure 5. **A,** Recorded east-west accelerations at the Turkish National Strong Motion Network station, SKR, in Adapazari. Turkey, during the August 17, 1999, M7.4 main shock. Station is about 3.5 km from the surface rupture. **B,** Velocities computed from acceleration time history showing large velocity pulse. **C.** Displacements computed for acceleration time history showing large displacement pulse. (From Holzer and others (1999), Figure 3).

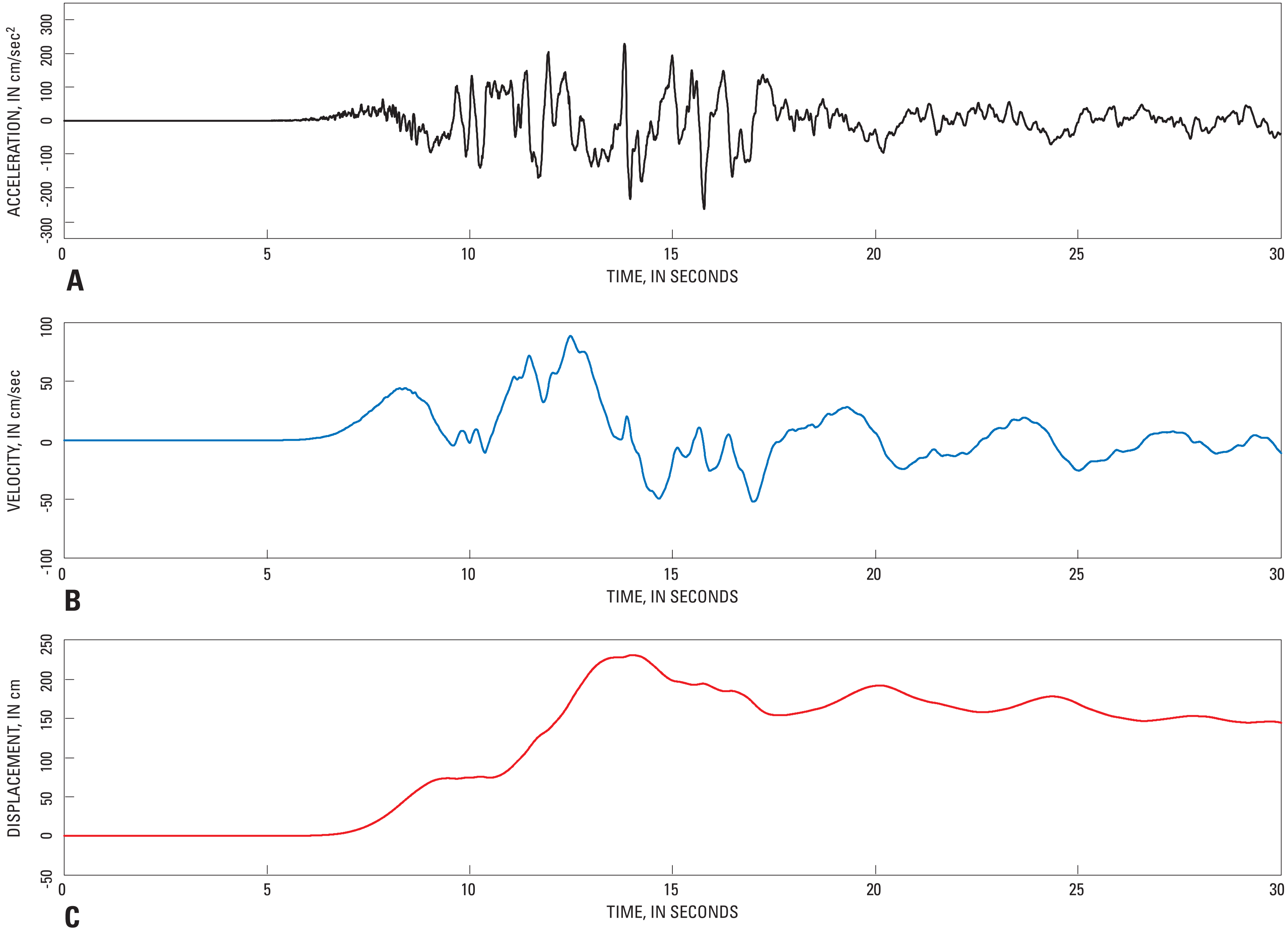


Figure 6. A, Recorded east-west accelerations at the Kandilli Observatory and Earthquake Research Institute strong motion station, YPT, at the Petro-Chemical Plant in Korfez, Turkey, during the August 17, 1999, M7.4 main shock. Station is about 4 km from the surface rupture. **B,** Velocities computed from acceleration time history showing large velocity pulse. **C,** Displacements computed for acceleration time history showing large displacement pulse. (From Holzer and others (1999), Figure 4).

Distant Tsunami

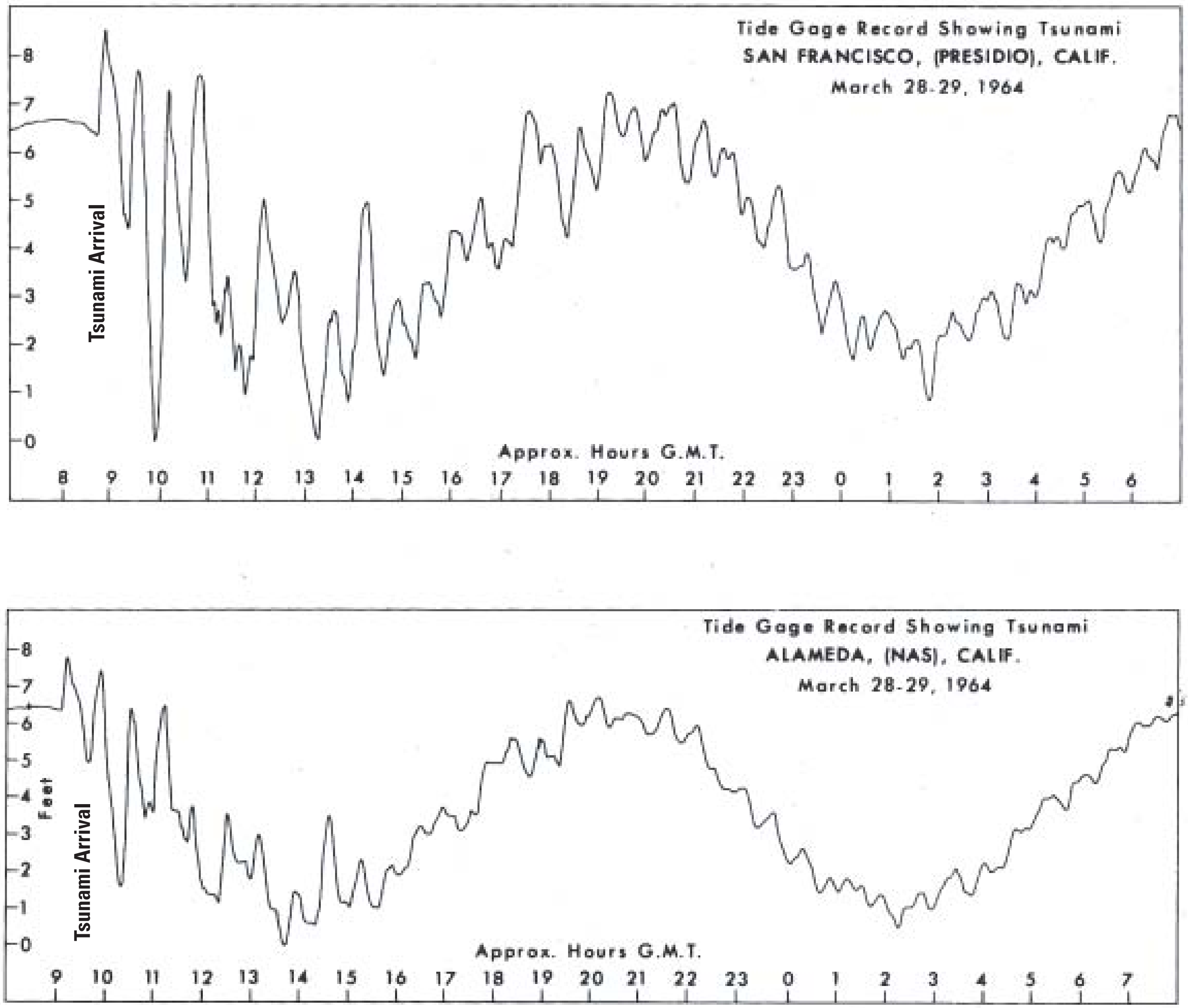
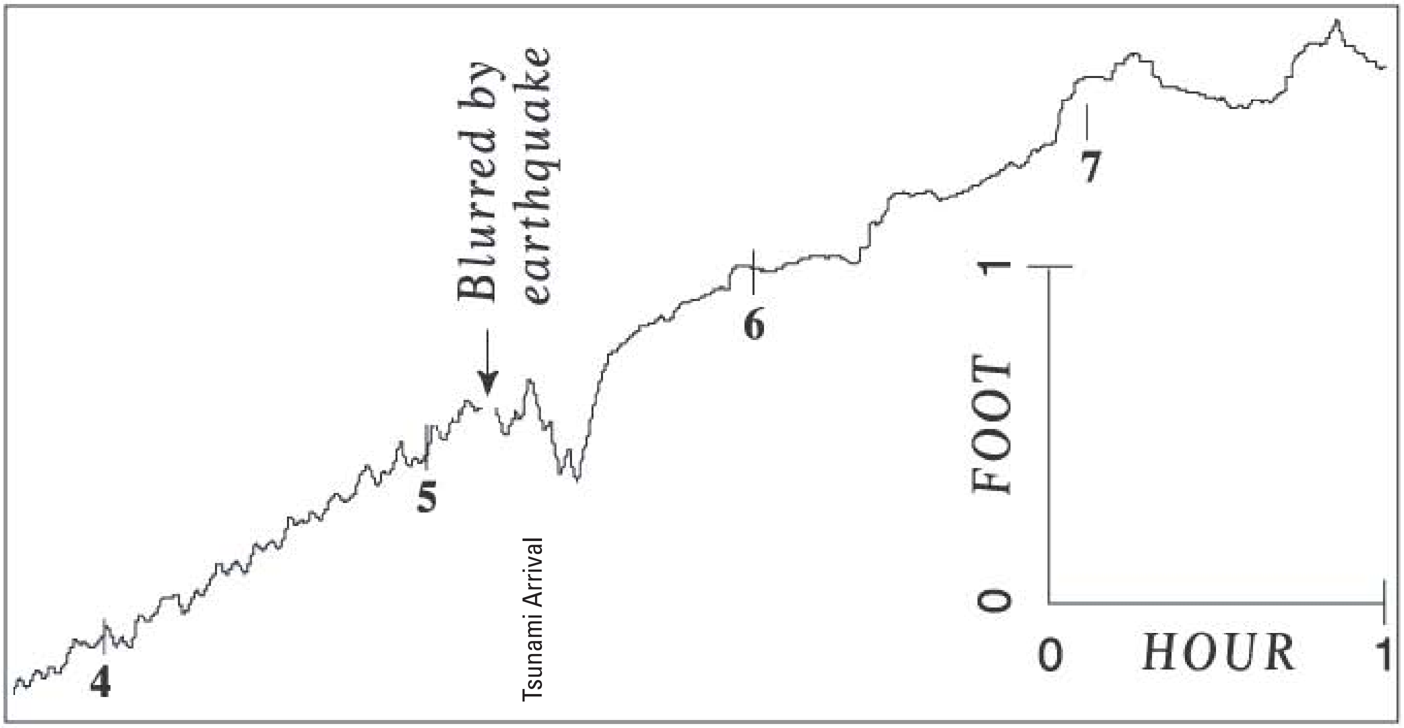


Figure 7. Example of tsunami observations in San Francisco Bay from a distant tsunami. Tsunami was generated by the M9.2 Great Alaska earthquake of 1964. Note that tsunami waves continue for many hours and occur at all stages of the tidal cycle. Tsunami amplitudes diminish as the tsunami travels through the Golden Gate and into San Francisco Bay toward Oakland. (From Lander and others, 1993).



Local Tsunami

Presidio Tide Gauge Record
April 18, 1906

Figure 8. Example of tsunami observations in San Francisco from a local tsunami. Tsunami was generated by the 1906 San Francisco earthquake where the San Andreas Fault trends offshore of San Francisco. Note that the tsunami amplitude in this case is much smaller than the amplitudes from a distant tsunami (Figure 7). Tsunami waves from the local source continue for several hours, but not as long as a distant tsunami. (From Lawson, 1908.)