Earthquakes, Faults, and Tectonics

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Summary and Introduction

On April 18, 1906, the San Francisco Bay region was rocked by one of the most significant earthquakes in history. This magnitude 7.8 earthquake began on a segment of the San Andreas Fault that lies underwater in the Gulf of the Farallones, just a few miles offshore of San Francisco. The quake ruptured nearly 430 km (270 mi) of the fault from San Juan Bautista to Cape Mendocino. Damage from the intense shaking during the earthquake, along with the devastation from the ensuing fire, wreaked havoc in San Francisco, a city of 400,000 inhabitants at the time (fig.1). Although the official death toll from the earthquake was reported to be about 700, it is now widely believed that the actual loss of life was three to four times greater. In addition, more than 50 percent of the population of the city was homeless following the earthquake.

Today, a large metropolitan area of more than 6 million people covers more than 18,000 km^2 (7,000 mi^2) around San Francisco Bay. Many small earthquakes occur in the bay region every year, although only those greater than about magnitude 3 are usually felt. The 1989 magnitude 6.9 Loma Prieta earthquake was a strong reminder of the potential for large, destructive earthquakes in the region. The Loma Prieta earthquake killed 63 people, injured more than 3,700 others, and caused property damage in excess of $6 billion. It should be kept in mind, however, that devastation occurred only in limited areas because the epicenter of this earthquake was on a somewhat remote segment of the San Andreas Fault, 115 km (70 mi) south of San Francisco in the Santa Cruz Mountains. An earthquake of similar magnitude located closer to the center of a densely populated urban area is capable of causing much greater damage and loss of life. This was shown by the 1995 Kobe, Japan, earthquake (magnitude 6.9), which caused more than 6,000 deaths, injured 35,000 people, resulted in $100 billion in property damage, and destroyed the homes of more than 300,000 people.

The rigid outer shell of the Earth is made up of large "tectonic plates" that move horizontally relative to one another. The Gulf of the Farallones includes part of the boundary between two of the Earth's largest tectonic plates (fig. 2). Tectonic motion along this boundary is what makes the San Francisco Bay region so susceptible to earthquakes and is a significant factor in creating the geology and geomorphology of the region. The Pacific and North American Plates are sliding relentlessly past each other at an average rate of about 5 cm/yr (2 in/yr). Most of this motion occurs in catastrophic bursts of movement—earthquakes—along the San Andreas Fault system. Near San Francisco, the San Andreas Fault system is a complex zone of faults about 80 km (50 mi) wide. It stretches from offshore to as far east as the cities of Vallejo and Livermore. In addition to the San Andreas Fault, the numerous faults that are part of the San Andreas Fault system include the San Gregorio, Hayward, Rogers Creek, and Calaveras Faults.

Much of the geomorphology (surface features) of the San Francisco Bay region is a consequence of the location and motion of past and presently active faults within the San Andreas Fault system, and of the juxtaposition of blocks of different rock types by movements along these faults. For example, the Farallon Islands offshore and Montara Mountain located onshore north of Half Moon Bay are parts of large fault blocks that contain granitic rocks believed to be originally derived from the southern Sierra Nevada. At least 17 such fault-bounded structural blocks (terranes) of different sizes and rock types have been identified in the bay region.

To help reduce injuries and property damage from future earthquakes in the San Francisco Bay region, it is necessary to have a good understanding of the geology of this region. This must encompass both the onshore and offshore geology, including that of the Gulf of the Farallones.

Seismicity

Every year hundreds of earthquakes greater than a magnitude (M) 1.5 are detected in northern California by a network of seismometers established in the mid-1970's. The magnitude of an earthquake is related to the amount of energy released during the quake. As a point of reference, the energy released from a mine blast is equivalent to that released by about 1 ton of TNT. A tornado releases the energy of about 32 tons of TNT, and the Great 1906 San Francisco earthquake (magnitude 7.8) released the energy of more than 6 million tons of TNT, which is about the energy generated by Niagara Falls in 10 years. Only earthquakes greater than about M 3 are commonly felt. Large earthquakes greater than M 7 occur infrequently, but when they do they are capable of causing severe damage, particularly in large urban areas. There is a 70 percent chance of at least one M 6.7 or greater earthquake occurring in the San Francisco Bay area over the next 30 years.

Plate Tectonics

The unifying theory of plate tectonics, first proposed in the 1960's, guides efforts to predict and minimize the consequences of natural disasters such as earthquakes and tsunamis. According to the theory, the earth's outer shell is composed of a mosaic of irregularly shaped, rigid slabs or plates that spread away from (divergent boundary), push against (convergent boundary) or slide horizontally past (transform boundary) each other. These slabs form the lithosphere, which is composed of the crust and upper mantle, and rides atop hotter, more mobile material termed the asthenosphere. The motion of the plates with respect to each other averages a few centimeters per year (about the speed that fingernails grow). An obvious effect of the grinding of plates against each other is the generation of earthquakes within the lithosphere along plate margins. Only the upper part of lithosphere has the strength and properties to fracture in a brittle manner and cause earthquakes.

Most of the west coast of California lies along the plate boundary between the Pacific Plate, one of the largest plates, and the North American Plate. The Pacific-North American Plate boundary is classified as a transform boundary where the two plates slide horizontally past each other at an average rate of 5 cm/yr (2 in/yr). The major surface break caused by the plate boundary is the 1,300-km-long (800 mi) San Andreas Fault system that connects the East Pacific Rise east of Baja California to the Gorda Ridge at the south end of the Juan de Fuca Plate. West of the San Andreas Fault, the Pacific plate is moving to the northwest with respect to the North American plate. South of the San Andreas Fault, the East Pacific Rise forms a divergent plate boundary where new crust is generated; north of the fault, the North American and Juan de Fuca plate boundary form a convergent boundary where the Juan de Fuca Plate dives beneath North American and is consumed.

San Andreas Fault Zone

In central California, the San Andreas Fault is not a discrete fault strand, but rather a broad zone of faults as much as 120 km (75 mi) wide. Along this zone earthquakes occur to depths of about 15 km (9 mi). Most of the fault zone is now on land, although originally the fault may have been at the base of the continental slope. Presently, the major active segments of the San Andreas Fault Zone in central California include, from west to east, the San Gregorio, San Andreas, Hayward, Rogers Creek, and Calaveras Faults (figs. 3 and 4).

The San Gregorio Fault Zone is a 400-km-long (250 mi) set of coastal faults that lie southwest of the San Andreas Fault proper. It is almost entirely offshore, except for a 5-km-long (3 mi) segment at Seal Cove north of Half Moon Bay and a 32-km-long (20 mi) segment that stretches from Point Año Nuevo to near the town of San Gregorio (about 10 km (6 mi) south of Half Moon Bay). At its northern end, the San Gregorio Fault joins the San Andreas Fault near Bolinas Bay, north of San Francisco. The San Gregorio Fault extends at least as far as Big Sur to the south. The sea floor is offset along the trace of the San Gregorio Fault in Monterey Bay and west of the Golden Gate Bridge, indicating that the fault is active. It is estimated that the San Gregorio accommodates about 7 mm/yr (0.25 in/yr) of the motion between the Pacific and North American Plates. A midden (an archeological debris pile) located on the fault near Moss Beach, Calif., was offset about 5 m (16 ft). This suggests that a large earthquake (about M 7) occurred there. Charcoal dating and the arrival of the Spanish missionaries suggest it happened between 200 and 700 years ago. While the motion of the San Gregorio fault averages 7 mm/yr (0.25 in/yr), it isn't continuous; it appears to take place in sudden jumps of about 5 m (16 ft) during infrequent earthquakes.

The San Andreas Fault was originally named for a short segment of the fault along the San Francisco Peninsula that lies within San Andreas and Crystal Springs Valleys. During the Great 1906 San Francisco Earthquake (M 7.8), 460 km (280 mi) of the San Andreas fault ruptured, from Cape Mendocino to San Juan Bautista. Large horizontal displacements occurred along the fault, including as much as 6 m (20 ft) of offset near Tomales Bay. The first major rupture of the San Andreas Fault in northern California following the 1906 event was the 1989 Loma Prieta earthquake (M 6.9). The Loma Prieta earthquake was centered on a remote segment of the San Andreas Fault about 80 km (50 mi) from San Francisco. Since 1906, the San Andreas Fault in northern California has remained locked from Point Arena through the San Francisco Peninsula; locked segments of faults have the capacity of storing considerable amounts of energy that can be later released as large earthquakes.

It is estimated that about half of the relative plate motion between the Pacific and North American Plates occurs along faults east of the San Andreas Fault. In particular, the Hayward Fault is a zone of active fault creep (continual slow movement along the fault) at a rate of about 5 mm/yr (0.2 in/yr). The southern section of the Hayward Fault was the site of a large (M 6.9) historical earthquake in 1868. Heavy damage occurred along both the fault zone itself and in the cities of San Francisco and San Jose as a result of this quake.

Geology

The faults slicing through the San Francisco Bay area have a profound impact on the regional landscape. Differences in topography, geology, and sometimes vegetation can occur from one side of a fault to the other. Most of the topography of the area is geologically young, having formed only since about 3.5 million years ago. Straight, narrow valleys such as that now filled by the Crystal Spring Reservoir have formed along the San Andreas Fault from the erosion of soft rock that had been crushed within the fault zone. Other geomorphic features are related to uplift and subsidence resulting from vertical movements that can accompany faulting. These features include San Francisco Bay, Napa Valley, and Livermore Valley (subsidence) and the Santa Cruz

Mountains and Diablo Range (uplift). The coastal area between San Francisco and Monterey is presently uplifting at a rate of about 0.02 cm/yr (0.008 in/yr).

The present trace of the San Andreas fault is about 10 million years old, although the history of the fault begins about 30 million years ago at the time of the first contact between the Pacific Plate and the western edge of the North American Plate. Throughout the history of the San Andreas Fault, as the two plates have moved past each other, fragments of different crustal rock types have been sheared off and carried for various distances along the fault zone, and major blocks of crustal rocks have been offset at least 360 km (220 mi) by differential movement along the fault.

As a consequence of this and older plate interaction along the western edge of North America, the San Francisco Bay region is composed of a mosaic of about 17 different "exotic" terranes (fig. 4). Exotic terranes are fault-bounded blocks of crust that are termed exotic because it is apparent from geologic studies that each block did not form where it is found today but traveled a great distance from its place of origin. Blocks of similar ages that formed in significantly different geologic environments require significant tectonic mobility to explain their present juxtaposition.

Most of the terranes in the Bay area are either Salinian terranes or the Franciscan terranes. The San Andreas Fault separates Salinian terranes on the west from Franciscan terranes on the east; the Franciscan forms the eastern wall of the San Andreas Fault throughout central California. The Salinian terranes are a 500-km-long (310 mi) slice of rock that forms most of the basement in the central coastal part of the State. The Salinian rocks formed deep in the crust as part of a batholithic intrusion probably related to island arc volcanism during Mesozoic time. These granitic-type rocks, found prominently at the Farallon Islands and Montara Mountain, are similar in composition to granitic rocks found in the Mojave Desert today.

Franciscan terranes are a collage of folded, sliced, and metamorphosed rock of many different types including limestone, graywacke, radiolarian chert, basalt, blueschist, eclogite, and serpentinite (the California state rock). These rocks are thought to have formed as a consequence of scraping off material from the oceanic plate as it subducted or underthrust beneath the North American Plate prior to the formation of the San Andreas Fault system during Mesozoic time. Franciscan rocks contain minerals that form in a high-pressure and low-temperature environment, such as is created by the scraping at the leading edge of a subduction zone.

Hazards

Damage resulting from earthquakes is strongly related to rock type. Most susceptible are areas comprised of soft sand, soils, and clays, which can locally amplify shaking. Shaking on soft ground can be several times as intense as on nearby rock. For example, the devastation of the Marina District of San Francisco during the 1989 Loma Prieta earthquake was related to the fact that the Marina District sits on water-saturated uncompacted sediment fill. Areas of soft ground are particularly susceptible to liquefaction (the reduction of soil strength and stiffness due to shaking), landslides, lateral spreading, and other forms of ground failure. In general, the main cause of earthquake-induced damage is ground shaking and not ground failures. However, ground failures can also lead to fracturing, sliding, and slumping in hilly areas.

In coastal areas, an additional concern related to seismic hazards is the generation of tsunamis (also known as impulsively generated wave trains). Many people call tsunamis tidal waves, although they are not related to the tides, but are rather caused by earthquakes. During historic times, damage related to tsunamis has been relatively slight in coastal California in comparison to other Pacific coastal areas. However, the last 100 years have seen the rapid development of coastal areas in California, increasing the risk of damage to structures or loss of life from a tsunami. Tsunamis can be triggered locally by earthquake-induced subaerial (on land) and submarine landslides. Tsunamis can also be generated at great distances when there is large-scale displacement of the sea floor, such as that which occurred during the great Alaskan earthquake in 1964, which caused several fatalities and extensive damage in northern California around Crescent City.

Geologists generally believe that offshore strike-slip faults, such as the San Andreas Fault, do not usually produce large tsunamis because motions along these faults are primarily horizontal and would not cause the large vertical displacements of the sea floor needed to produce a tsunami. Therefore, it was not surprising that there was no significant tsunami observed during the 1906 San Francisco earthquake. However, a temporary 0.1-m (4-in) drop in sea level recorded near the Golden Gate Bridge at the time of the earthquake may have been caused by to displacement of the sea floor in the Gulf of the Farallones. There is other evidence of tsunamis in the San Francisco Bay area. For example, in 1859, a maximum run-up height (the highest altitude above the tide level that water reaches as it runs up on land) of 4.6 m (15 ft) was recorded south of San Francisco at Half Moon Bay, although the location of the earthquake that generated this particular tsunami is unknown. The tsunami generated by the great 1964 Alaskan earthquake also caused millions of dollars in damage in the San Francisco Bay area, mainly from damage to ports and marine facilities caused by high-velocity current surges.

Conclusions

The Gulf of Farallones National Marine Sanctuary is located astride the boundary between the Pacific and North American Plates. Tectonic motion at this boundary has been and is a significant factor in the formation of the geology and geomorphology of the San Francisco Bay region. The Pacific and North American Plates meet along the San Andreas Fault Zone, and seismic hazards related to large earthquakes along the San Andreas Fault system are major concerns for land-use planning in the bay area. Accurate knowledge of the geology of the area is a first step in understanding these seismic hazards. However, earthquakes are inherently difficult to study as they occur below the surface of the Earth, and therefore there is still much to be learned before we fully understand seismic hazards in the San Francisco Bay region.

Further Reading

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Web sites of interest:
http://quake.usgs.gov/
http://www.abag.ca.gov/bayarea/eqmaps/
http://quake.geo.berkeley.edu/

A

B

Figure 1. *A*, The photograph above, taken from a “captive airship” 5 weeks after the great earthquake of April 18, 1906, shows the devastation wrought on the city of San Francisco by the quake and subsequent fire. In the city and surrounding region, the official death toll was about 700, but it is now believed that the actual loss of life was three to four times greater. At the time, property losses were estimated to be more than $400 million. If a similar earthquake occurred in northern California today, after many decades of rapid urban growth, many thousands of people might be killed, and economic losses could be in the hundreds of billions of dollars. *B*, Photograph showing a fence near Bolinas, about 20 miles southeast of Point Reyes, that was offset by ground movement along the San Andreas Fault in the 1906 quake.

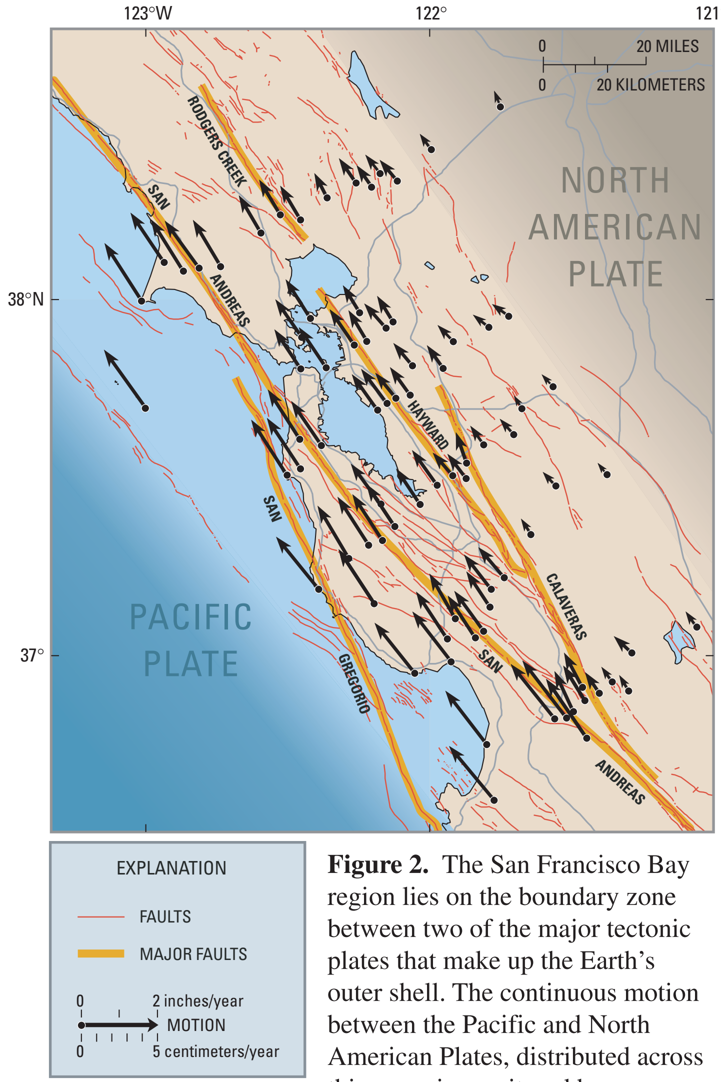

Figure 2. The San Francisco Bay region lies on the boundary zone between two of the major tectonic plates that make up the Earth's outer shell. The continuous motion between the Pacific and North American Plates, distributed across this zone, is monitored by geophysicists using the satellite-based Global Positioning System (GPS). Arrows on this map depict recent (mid to late 1990's) rates of movement, relative to the interior of the North American Plate, of reference markers anchored in rock or deep in solid ground. This relentless motion of the plates strains the crustal rocks of the bay region, storing energy that eventually will be released in earthquakes. During the time represented in this diagram, most of the faults in the bay region have been "locked," not producing earthquakes. (From Page and others, 1999.)

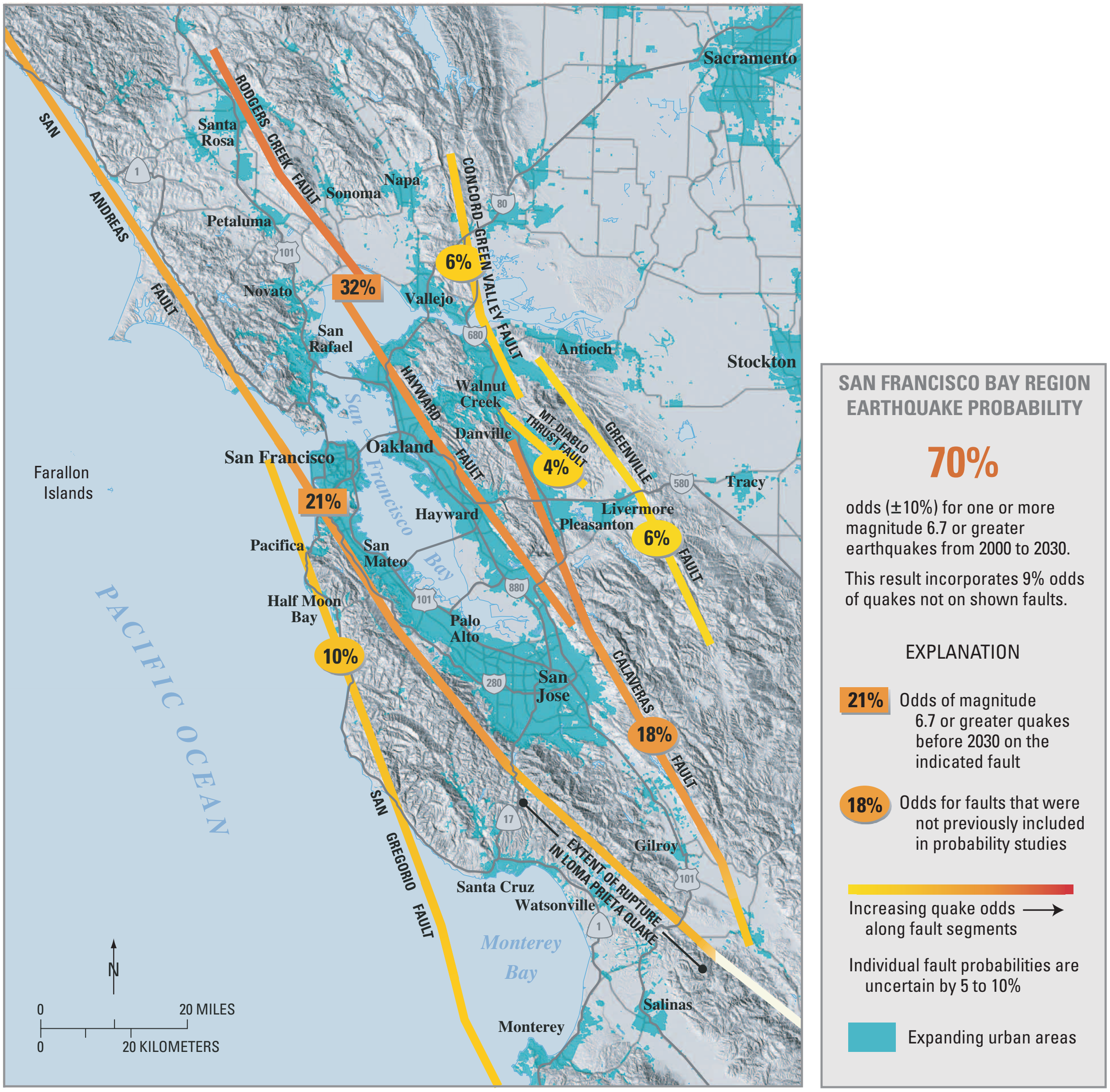

Figure 3. In 1999, the U.S. Geological Survey and cooperators released this earthquake probability map for the San Francisco Bay region. The threat of earthquakes extends across the entire region, and a major quake is likely before 2030. As continuing research reveals new information about earthquakes in the bay region, these probabilities are revised. (From Michael and others, 1999.)

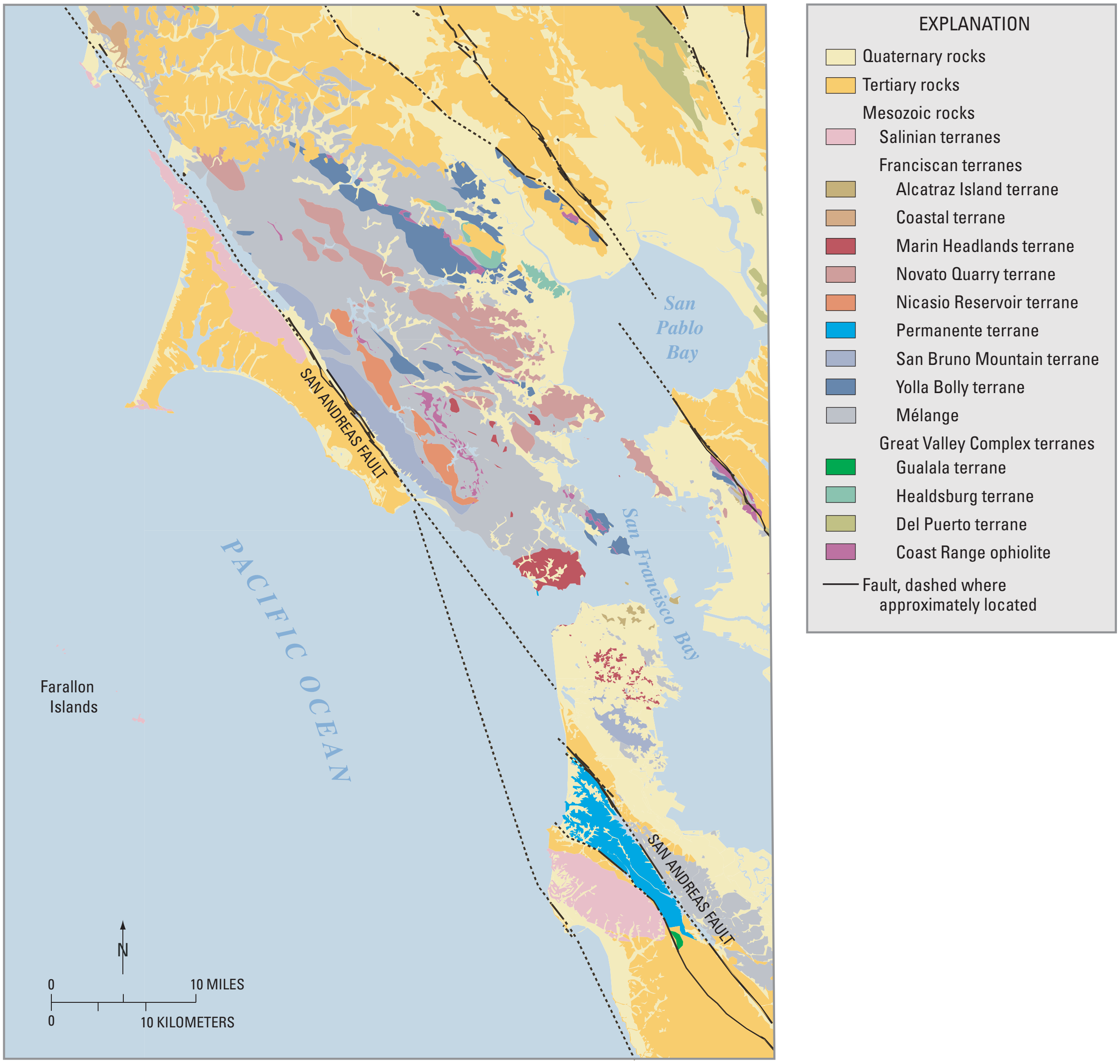

Figure 4. Terrane map of the San Francisco Bay region. Beneath the landscape of the bay region lie fragments of at least 17 different bedrock types that have been transported and juxtaposed by movement along faults. The major basement rock types can be ascribed to either the Franciscan terranes or the Salinian terranes. Rocks west of the San Andreas Fault are generally part of the Salinian terranes, whereas those east of the San Andreas Fault are generally part of the Franciscan terranes. These major terranes, separated by the San Andreas Fault, are composed of rock types that formed in very different geologic environments and some of which were transported long distances by tectonic motion to their present positions.