San Francisco Bay area aerial view east, taken November 22, 1967. The Golden Gate channel is at bottom center; San Francisco at bottom right. San Pablo Bay at left center.

Geology of the San Francisco North Quadrangle, California

By JULIUS SCHLOCKER

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The distribution and character of the bedrock and surficial deposits in the northern part of the City of San Francisco and southern Marin County, Calif., including a description of the Franciscan Formation in its type area and notes on engineering geology in an urban area

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GEOLOGY OF THE SAN FRANCISCO NORTH QUADRANGLE, CALIFORNIA

By JULIUS SCHLOCKER

ABSTRACT

The San Francisco North quadrangle, about 58 square miles in area, includes the north half of the city of San Francisco, the south tip of Marin and Tiburon Peninsulas, Belvedere, Angel, and Alcatraz Islands, and part of Treasure Island. The topography of San Francisco proper is characterized by rolling hills, rounded slopes, and broad valleys, whereas other parts of the quadrangle are characterized by steeper and more rugged slopes, rounded ridges and spurs, and steep-sided V-shaped canyons. San Francisco Bay covers nearly half the quadrangle. It is connected to the Pacific Ocean by the Golden Gate channel. Water depths in the tidal channels generally range from 100 to more than 360 feet below mean sea level; elsewhere water depths are generally less than 30 feet.

Two distinct groups of rocks, bedrock and surficial deposits, differ greatly in age, lithology, and topographic expressions. The bedrock consists of the Franciscan Formation and associated intrusive serpentine and gabbro-diabase of Jurassic(?) and Cretaceous age. The Franciscan Formation is at least 16,000 feet thick and consists mostly of graywacke sandstone, shale and siltstone, and mafic volcanic rocks, and lesser amounts of radiolarian chert, conglomerate, limestone, and glaucophane schist. Exposures of the Franciscan constitute 15–20 percent of the land area of the quadrangle, generally on hills. The surficial deposits, of Quaternary age, consist largely of unconsolidated dune sand and water-laid sand, mud, and clay. However, slopewash deposits, alluvium, landslide debris, and artificial fill are fairly extensive. Above sea level, surficial deposits mantle slopes and fill valleys to depths of a few feet to more than 100 feet. In San Francisco Bay, surficial deposits range in thickness from 100 to about 300 feet.

The major rock types of the Franciscan Formation in this quadrangle which are mappable at a scale of 1:24,000 are clastic sedimentary rocks, greenstone, radiolarian chert, metamorphic rocks, and sheared rocks.

The clastic sedimentary rocks of the Franciscan Formation consist predominantly of massive graywacke sandstone beds separated by sequences of shale and thin-bedded sandstone. Conglomerate lenses and zones, as much as 10 feet thick, are common on Angel and Belvedere Islands and on Tiburon Peninsula. Pillow lava and radiolarian chert are interbedded with the clastic rocks. Metamorphic equivalents of these rock types are present on Tiburon Peninsula and Angel Island. Although the clastic rocks of the Franciscan Formation consist mostly of alternating massive and thin beds, two exceptionally thick sections of predominantly thin-bedded shale and sandstone, each totalling more than 1,000 feet, crop out in the northeastern part of San Francisco.

The clastic rocks of the Franciscan Formation probably were deposited by turbidity currents in deep water in an orogenically active eugeosyncline lying west of a continental mass. A source area including metamorphic rocks is indicated by the clasts in the sandstones and conglomerates. Rocks whose composition is similar to the sand-size detritus in Franciscan sandstone are exposed in the Coast Ranges, Klamath Mountains, and Sierra Nevada. The pebbles in some conglomerates are very similar to sandstones and shales of the Franciscan, indicating that the conglomerates may have been derived from topographically high areas created by orogeny during Franciscan time.

The term "greenstone" is used to include all volcanic and related intrusive rocks in the Franciscan Formation. These consist mostly of fine- to medium-grained metabasalts, in large part altered to pumpellyite-albite-chlorite rock. Most basalts show pillow structure; a few are pyroclastic. Pillow structure, the presence of marine chert and limestone between pillows, and the interbedding of flows and marine sediments throughout the formation suggest a long history of submarine volcanism.

Thin chert and shale beds and less common massive chert bodies are closely associated with the greenstones. Radiolaria are common in the chert, less common in the shale. The larger deposits of radiolarian chert are closely associated with greenstone, which is believed to be the ultimate source of the silica from which the chert was formed.

Metamorphic rocks include slate, phyllonite, phyllite, fine- to coarse-grained schist, and granofels, commonly having relict textures. Many masses of metamorphic rocks occur along the borders of serpentine bodies or as tectonic inclusions from diapiric movement in the serpentine. They are believed to be metamorphic equivalents of Franciscan rocks and may have been formed under high shearing stresses or by hydrothermal alteration.

The map unit termed "sheared rocks" consists of a soft intensely sheared matrix of shale or serpentine that has moved plastically. It encloses hard blocks, as much as hundreds of feet in diameter, of various rock types found elsewhere in the Franciscan Formation. The blocks are rounded and slickensided externally, but most are relatively unsheared internally. Blocks greater than 20 feet in diameter are generally shattered internally.

The map unit designated serpentine also includes a few small bodies of calc-silicates (rodingites), pyroxenite, and gabbro. Serpentine intrudes the Franciscan Formation and is widely associated with it. The serpentine was derived from peridotite, and its present position is probably due to tectonic movement at relatively high pressures and low temperatures. Shearing is widespread within the serpentine bodies.

Unconsolidated late Pleistocene and Holocene surficial deposits cover about 80–85 percent of the land area of the quadrangle. These deposits are mostly sand, but they include rubbly slope debris and ravine fill, bay mud and clay, landslide deposits, and artificial fill.

The Colma Formation is the oldest of the surficial deposits. It includes a group of marine and dune sands that have grossly

similar physical properties and that occupy approximately the same stratigraphic position; however, the formation probably includes several marine deposits related to different sea levels. It also contains alluvial and colluvial deposits. The Colma Formation generally is horizontally bedded. The formation lies stratigraphically below latest Pleistocene and Holocene deposits.

A raised beach sand, probably deposited during a warm interglacial epoch when sea level was higher than it is now, has been exposed on the Presidio Military Reservation. This deposit was mapped separately from the Colma Formation because it is less cemented than the Colma Formation and its grains appear to be less weathered.

Surficial deposits mapped as alluvium are very restricted in extent and distribution, largely because of low surface runoff due to low rainfall and a cover of highly permeable material over large areas. Most of the alluvium in the quadrangle is related to old drainage systems and is now moderately dissected. The alluvium is composed of medium sand mixed with silt and clay.

Beach sand and coarser beach deposits occur along all shores except along the east edge of San Francisco and at Sausalito. Beach deposits vary seasonally—even hourly—in thickness and extent, depending on the nature of the waves and the supply of sediments. Along the Pacific shore of San Francisco, the probable sources of the beach sand and the related onshore dunes are the poorly consolidated Pliocene and Pleistocene Merced Formation, the younger formations along the shore to the south, and the sands of the continental shelf. The sands of the continental shelf probably were deposited by the ancestral Sacramento–San Joaquin River, during the Wisconsin Glaciation, when sea level was lower.

Dune sand, swept by prevailing westerly winds, underlies more than half the city of San Francisco and extends as far east as the area between Telegraph and Rincon Hills. It has been deposited more than 600 feet above sea level and attains a thickness of about 150 feet. The chief source of dune sand was the Ocean Beach area.

Slope debris derived largely from weathered rock mantles most slopes and fills the adjoining ravines. The slope debris as mapped locally includes soils developed on bedrock and minor amounts of alluvial, eolian, and landslide materials. The debris thickens downhill and locally is as much as 60 feet thick. The ravine-fill deposits, locally, are interbedded with and grade into alluvium.

Bay mud, the youngest deposit in San Francisco Bay, consists of soft unconsolidated sediment generally containing more than 90 percent of clay- and silt-size detritus. A similar deposit, bay clay, is nearly the same in texture but is more consolidated and contains less water. Bay mud and clay are found on the eastern shores of San Francisco and Sausalito, under surficial deposits and artificial fill adjoining the Bay, and under San Francisco Bay.

Landslides are among the chief agents of erosion in the quadrangle. Sheared rocks and serpentine are the most susceptible materials. The numerous landslides have resulted from combinations of hilly terrain, unconsolidated surficial deposits or sheared bedrock, abundant highly plastic and swelling clay, occasional periods of prolonged rainfall, frequent earthquakes, and disturbance and alteration of the terrain by man.

Artificial fill is extensive along the margins of San Francisco Bay, more than 3 square miles of land having been created by dumping artificial fill on the gently shelving tidal flats. The average thickness of the fill in San Francisco, north of China Basin, is about 10 feet; south of China Basin it is about 60 feet. The fill consists of dune sand, alluvium, debris from the bay, and manmade debris. Serious engineering problems in areas of artificial fill have been caused by differential subsidence.

The San Francisco North quadrangle lies in the western part of the Coast Ranges near the west edge of the North American crustal plate. The oldest exposed rocks in this part of the plate are those of the Franciscan Formation and its age correlative, rocks of the Great Valley sequence. The plate is bounded on the west by the San Andreas fault zone and farther south on San Francisco Peninsula by the Pilarcitos fault (both faults outside the map area), which separate the Franciscan Formation from granitic and associated metamorphic rocks. The Hayward fault zone is nearly parallel to and about 20 miles east of the San Andreas fault zone in this area. East of the Hayward fault, the Coast Ranges consist mostly of Cenozoic marine and nonmarine sedimentary rocks and marine sedimentary rocks of the Mesozoic Great Valley sequence. Movement along the San Andreas and Hayward faults is right lateral and has been responsible for the great earthquakes in this area.

The major faults and shear zones within the quadrangle are the northwest-trending Fort Point–Hunters Point and the City College shear zones. The major folds are a syncline that plunges northwest between Russian and Telegraph Hills, an anticline on Marin Peninsula whose axis lies in Richardson Bay, and a broad northwest-plunging syncline on Angel Island and Tiburon Peninsula.

The engineering properties of the natural foundation materials in the quadrangle vary greatly over short distances; so, some building sites are in part on soft bay mud and in part on hard bedrock. Almost every site on the Franciscan Formation encompasses shear zones less than 1 inch to several feet wide. Unconsolidated surficial deposits, which generally contrast greatly in engineering properties from bedrock, cover more than half the land area of the quadrangle. The location of the bedrock surface is therefore important in engineering work. As each construction site presents a unique combinaton of natural conditions, such as slope, hydrology, and foundation materials, detailed geologic investigations and slope stability analyses are needed in the design of specific structures.

The San Francisco North quadrangle is in a region of high seismic activity. Structures have been seriously demaged by three major earthquakes since 1865.

INTRODUCTION

PURPOSE

San Francisco is a heavily built up city in a region of active faults and is subject to earthquakes and landslides. In such an area careful selection of building sites and foundations is imperative. This geologic investigation of the San Francisco North quadrangle was carried out to obtain basic geologic data to aid in construction and other civil engineering problems. The study also contributes to a better understanding of the geology of this part of the Coast Ranges in general and of the Franciscan Formation and surficial deposits in particular.

On the geologic map (pl. 1), consolidated rocks are delineated by their composition, age, and origin. Such a classification also gives an approximate indication of the engineering properties of each formation. To make the map more useful to the civil engineer, unconsolidated deposits are shown where thick enough to be depicted. This report and the accompanying map should be a useful guide for planning foundation studies necessary in engineering design.

LOCATION AND TOPOGRAPHY

The San Francisco North quadrangle includes the north half of the city of San Francisco, part of San Francisco Bay, the south tip of Marin and Tiburon Peninsulas, Angel Island, Belvedere Island, Alcatraz Island, and part of Treasure Island (fig. 1).

San Francisco Bay covers approximately half of the quadrangle. The bay is connected to the Pacific Ocean by the Golden Gate channel, a deep narrow waterway between the San Francisco Peninsula on the south and Marin Peninsula on the north. The Golden Gate channel and much of the bay are drowned parts of the valleys of the Pleistocene Sacramento–San Joaquin River and its tributaries, and the Santa Clara Valley. Water depths in the quadrangle vary from shallows of less than 60 feet located south of Rincon Point, north of Treasure Island, southwest of Angel Island, in Richardson Bay, and along a narrow shoal between Alcatraz Island and Fort Point to deeps of more than 300 feet in the Golden Gate channel. The deepest point, approximately 360 feet below sea level, is in the bottom of a hole near the middle of the Golden Gate Bridge (Carlson and others, 1970).

The present topography of the San Francisco North quadrangle has resulted principally from erosion of a lithologically complex terrain and from deposition of sand dunes. Marine and estuarine processes and late Quaternary tectonism also have affected the topographic evolution of the quadrangle. In general, the city area consists of bedrock hills surrounded by broad valleys underlain by dune sand and other unconsolidated deposits. Hills along the north (Golden Gate) border of the city reach heights of approximately 375 feet above sea level above Point Lobos, in the Presidio, and at Lafayette Square park; heights of approximately 325 feet are attained on Russian Hill, and heights of 275 feet on Telegraph Hill at the northeast edge of the city. Hills on the north border vary in relief from about 150 feet in the Richmond District on the west to 200–225 feet in Russian and Telegraph Hills on the east. Potrero Hill, in the southeast, has a relief of about 225 feet. The central and western parts of the city rise to the south border of the quadrangle to a small group of hills including Sunset Heights, more than 750 feet in altitude, Mount Sutro, 908 feet in altitude, and South Twin Peak, 922 feet in altitude. The central hills of Mt. Sutro and Twin Peaks have a relief of about 850 feet on the east and about 500 feet on the west. Approximately one-third of the city area, the central and western parts, is more than 200 feet above sea level.

The topography varies from gently rounded hills with broad basins between to the sheer sea cliffs that border the Golden Gate. The rolling terrain of Golden Gate Park and the moderate slopes in the central part of the city in part are modifications by the deposition of tremendous quantities of dune sand.

The strong northwesterly trend of ridges and valleys that characterizes most of the Coast Ranges is obscured in the city itself, although it is suggested by such minor features as Russian and Telegraph Hills and the valley between them, by Hayes Valley between the hills at Lafayette and Alamo Square parks, and by Potrero Hill.

The gradient of abandoned channels filled with old alluvium in the Twin Peaks area appears to be much more gentle than that of present-day surface runoff channels. Evidently, Twin Peaks formed by dissection of a gently rolling surface.

The shoreline of San Francisco Peninsula has a varied topographic form. The west shore along the open sea is alternately low and high, marked by sandy beaches, such as Ocean and Bakers Beaches, and irregular bedrock cliffs such as those of the Point Lobos–Lands End area and the Fort Point area. Except for Black Point, the north and east shores are low and mostly made land. Prior to filling, high cliffs were present along the shore at Telegraph Hill and at Rincon Hill.

The topography of Marin Peninsula, Belvedere Island, Tiburon Peninsula, and Angel Island is generally steeper and more rugged than that of San Francisco, and the shorelines are generally high bedrock cliffs (fig. 2). Rounded ridges and spurs and steep-sided V-shaped canyons characterize these areas, although a few of the larger canyons widen near their mouths into flat-floored debris-filled valleys. Marin Peninsula has an average relief of 800–900 feet. The highest point in the quadrangle — 1,125 feet above mean sea level — is on a ridge half a mile west of Sausalito (fig. 3).

The typical northwesterly structural and topographic trend of the northern California Coast Ranges is well shown by Belvedere Island and Tiburon Peninsula (fig. 4) and by Alcatraz Island, Richardson Bay, and Corinthian Island. This trend can also be found in

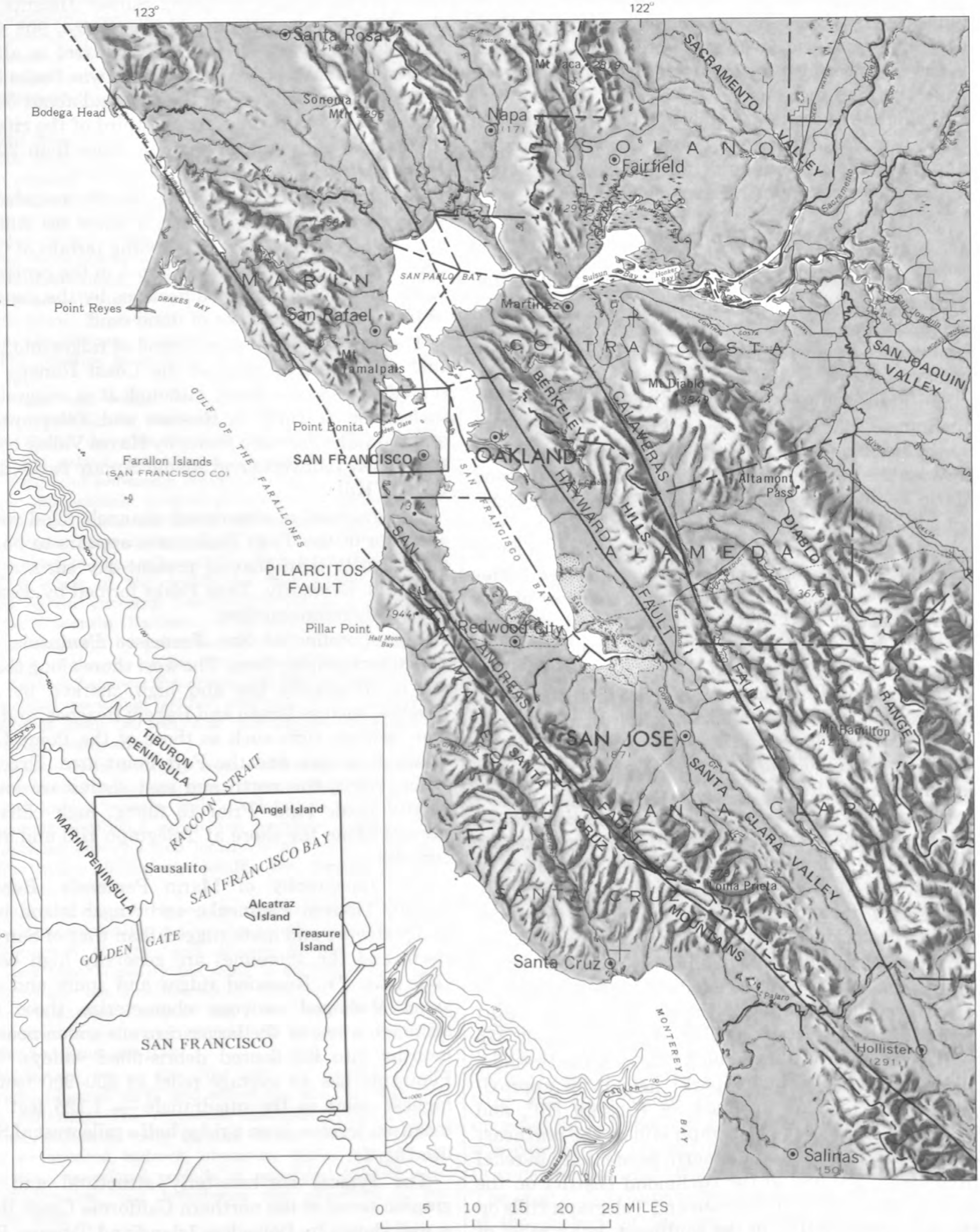

FIGURE 1.—Part of central California and the San Francisco Bay area showing the San Francisco North quadrangle and major structural and physiographic features.

FIGURE 2.—Angel Island, Raccoon Strait, and Tiburon Peninsula, viewed northwest. Prominent point in middle distance is Stuart Point, Angel Island. White building at right bottom is the lighthouse at Knox Point. Both points are greenstone of the Franciscan Formation.

FIGURE 3.—Marin Peninsula and part of Sausalito. Highest point in the quadrangle, with an altitude of 1,125 feet, is the broad peak right of center. View northwest.

FIGURE 4.—Belvedere Island and Tiburon Peninsula, view north. The island is elongated northwestward along the regional structural trend. Cliffs above the shore of Belvedere Island expose Franciscan sandstone to right of trees at the shore, Franciscan greenstone to left.

the ridges of Marin Peninsula, although somewhat modified by the erosional features associated with a large transverse stream valley whose mouth is drowned by Rodeo Lagoon.

Angel Island is the upper part of a drowned mountain cut off from Tiburon Peninsula by Raccoon Strait, a former channel of the Sacramento River. The rounded summit, 781-foot Mount Caroline Livermore, and the broad radial spurs are modified by sharp ridge crests and by steep shorelines (fig. 5).

FIGURE 5.—Mount Caroline Livermore and southwestern slope of Angel Island. Viewed toward the northeast. Serpentine and metamorphic rocks are exposed in cliffs above the shore.

CLIMATE

The influence of the Pacific Ocean keeps the temperature moderate and the air breezy, especially in the vicinity of the Golden Gate channel and in those parts of the quadrangle not separated from the ocean by high hills. The following climatic data were obtained from the U.S. Weather Bureau in July 1968: The average annual rainfall (1931–60) in San Francisco (Civic Center) is 20.78 inches, falling mostly from November through March. About 10 days per month in this period are rainy. Maximum precipitation measured at the Civic Center in 1 hour is 1.07 inches (for the period 1889–1950); maximum for 24 hours is 3.65 inches. Drought conditions exist during the summer. Snow is exceedingly rare. The mean annual number of days of frost in the quadrangle is zero. Mean relative humidity for 4 a.m., noon, and 4 p.m. is 85, 67, and 71 percent respectively. Annual mean temperature (1931–60) is 56.8°F. Highest temperature recorded is 101°F; lowest is 27°F. Highest monthly mean temperatures are 59.4°F, 62°F, and 61.4°F for August, September, and October, respectively. Highest wind velocity recorded at the San Francisco Civic Center is 51 miles per hour, for Mount Tamalpais, 120 m.p.h., and for the San Francisco International Airport, 62 m.p.h. (from the southwest). During the rainy season, highest winds are southeast through southwest at 53–62 m.p.h. with gusts to 74 m.p.h. The average storm lasts 3 days.

The summer climate is greatly influenced by the constant presence of an anticyclonic high-pressure air-mass west of the quadrangle, associated with the cold California Current and a zone of even colder upwelling water in the Pacific Ocean. Summer air temperatures along the ocean shore are among the coldest within the United States (excluding Alaska), though maximum temperatures 60 miles inland are among the hottest in the United States outside the Sonora–Mojave Desert (Patton, 1956, p. 113). In the summer high relative humidity, precipitation, and thunderstorms are exceedingly rare. Summer fog, from late afternoon through the night to late forenoon, is common in many parts of the quadrangle, especially in western San Francisco, Sausalito, and places reached by marine air in the vicinity of the Golden Gate channel. Winter fog of an inland origin is common also; at times it covers much of San Francisco Bay and connected bays and rivers into the Sacramento–San Joaquin Valley.

EARLY SETTLEMENT

When first discovered by Europeans in 1769, the area was inhabited by two Indian tribes, the Costanoan on San Francisco Peninsula and the Coast Miwok on Marin and Tiburon Peninsulas (Heizer, 1951, p. 40). The Indians used a variety of natural materials, such as seashells, rocks, and plants, for making tools and ornaments. They subsisted on plants and especially on marine life, as is shown by the contents of their refuse mounds ("kitchen middens") which are numerous on the shores of the bay and somewhat less common on the ocean shore (Nelson, 1909, map 1; Kroeber, 1911, p. 27–28). Some of the mounds are thought to have been started 3,500 years ago.

The first Europeans to visit the site of San Francisco were a small party of men led by Sergeant José Ortega. They were trying to reach Point Reyes from a base camp of the Portolá expedition (1769) in San Pedro Valley, near the ocean 11 miles south of the quadrangle. The main expedition, led by Gaspar de Portolá, started in Baja California and was the first attempt by Spain to colonize Alta California. Portolá planned to settle at Monterey Bay but failed to recognize it and continued northward. On November 1, 1769, the Ortega scouting party left the sand dunes of Ocean Beach behind and climbed Point Lobos only to find their way to Point Reyes, which they had sighted earlier, blocked by the Golden Gate. They then turned eastward across the ridge and from a high hill saw San Francisco Bay. Point Lobos was visited again in 1773 or 1774 by Commandante Rivera with the Father Palou party.

In August 1775 a small boat from the ship *San Carlos*, under the command of Juan Manuel de Ayala, was the first vessel to enter the Golden Gate. The *San Carlos* sailed into the Golden Gate at night, searching for the boat, and dropped anchor off Sausalito. Using Hospital Cove on Angel Island as its main anchorage, the expedition made the first survey of San Francisco Bay and gave names to many of the landmarks in the quadrangle, such as Angel Island and Alcatraz Island.

In 1776, Captain Juan Bautista de Anza brought a group of colonists to the area. Captain Anza first left the settlers to rest in Monterey while he and a small party went on to San Francisco. On March 27, 1776, they camped at Mountain Lake and the next day erected a cross at Fort Point to mark Anza's choice for the site of the military post, or presidio. Fort Point at that time was bounded by high unstable cliffs of serpentine. In 1853 these cliffs were cut back in connection with the construction of Fort Scott by the United States, and the surface on which the cross had been erected was lowered.

Anza selected a mission site about 3 miles southeast of Fort Point, near a small creek flowing from the slopes of Twin Peaks into a lake. The position of this lake is indicated on the geologic map (pl. 1) by the area of artificial fill that extends westward from about 17th and Mission Streets.

The Presidio was established on September 17, 1776, about half a mile southeast of Fort Point. Neglected by Spain and later by Mexico, it never became an important military post. The mission, however, became a prosperous agricultural and industrial community. Mexico won its independence in 1821 and acquired California as a province in September 1822. In 1834 the mission in San Francisco was secularized.

Captain William A. Richardson selected the Yerba Buena Cove area, now artificial fill between Telegraph Hill and Rincon Hill, as a port site in 1835. The port settlement growth soon outstripped that of the Presidio and mission.

In 1846 the United States flag was raised in Yerba Buena. In 1847, when the name San Francisco was formally adopted, the population was approximately 400. In May 1848 the town was abandoned by most of its inhabitants, who became gold seekers, but worldwide immigration brought its population to 20,000 by 1849; the dune sand west of the cove started to acquire its cover of manmade structures. In 1850 more than 500 ships were in the bay, many of them abandoned by their crews. Some of them in the cove became stores and hotels and eventually became part of the artificial filling of the cove, which by 1851 was largely reclaimed.

Scott (1959) gave additional information on the city's expansion. The population of San Francisco in 1960 was 750,000; its land area is 46.5 square miles.

Sausalito was long a port for whalers and other mariners where fresh water was obtained. In 1960 its population was 5,500.

PREVIOUS WORK

The first known geologic observations in the quadrangle were made in the early 1800's by voyagers on foreign exploring vessels visiting this remote Spanish port. In 1816 the Russian ship, *Rurik*, under the command of Otto von Kotzebue, brought Adelbert von Chammisso, a botanist who collected and described serpentine, sandstone, flinty slate (chert?), and quicksand (dune sand?) in San Francisco (VanderHoof, 1951, p. 110). The first geologic map of any part of California was one of this quadrangle and vicinity on a scale of 1:217,000 made in 1827 by Edward Belcher and Alex Collie of *H.M.S. Blossom*, sailing under the command of Captain F. W. Beechey. The map, reproduced in the popular "Geologic Guidebook of the San Francisco Bay Counties" (VanderHoof, 1951, p. 110), also shows a sketch of the Needles islets, located near Lime Point, and the general distribution of "serpentine, jasper, clayslate, sandstone, and alluvial." It was accompanied by a two-page text (Buckland, 1839, p. 174–176), which states that Angel Island is "of very confused formation" and identifies the hill west of Mission Dolores as serpentine.

The base for the geologic map was a hydrographic and topographic map prepared by the Beechey expedition and published in 1833 by the Hydrographic Office of The British Admiralty. It was used with minor revisions until the 1850's, when the U.S. Coast and Geodetic Survey maps were issued (Lincoln, 1969, p. 6–8).

In connection with a survey for railroad routes to the west Blake (1857, p. 145–162) in 1853 prepared a geologic map on a scale of 1:211,000 of the area from San Francisco to Richmond, including most of the San Francisco North quadrangle. He recognized and gave fair descriptions of the principal rock types of the Franciscan Formation (except greenstone) in chapter 12. His geologic cross section from Point Lobos to Yerba Buena Island can be used today with only minor changes. He interpreted the serpentine in the Fort Point–Hunters Point shear zone as an eastward-dipping sill in the sandstone. He also described numerous artesian wells in the surficial deposits on the flanks of the hills in the northeastern part of present-day San Francisco and in the vicinity of Mission Dolores. Unfortunately, he gave no information on rate of flow or on declining water levels, except for the following vague statement (p. 162): "and when the borings first commenced, an overflow was generally obtained."

The report of the 1860–64 Geological Survey of California, led by J. D. Whitney (1865, p. 76–79), includes observations probably made by Brewer (1930, p. 365–373), Whitney's principal assistant, on the geologic features in the San Francisco area. Unfortunately, this survey did not carry out its stated intention to begin "a map of the city and its vicinity, on a large scale, *** on which all the varieties of strata and of the superficial covering of soil and sands will be laid down." (Whitney, 1865, p. 78).

In 1891 Professor A. C. Lawson of the University of California and his students began geologic mapping that led to the publication of the monumental San Francisco Folio (Lawson, 1914) with a geologic map scale of 1:62,500. Other papers that resulted from their work include those of Ransome on Angel Island (1894) and Point Bonita (1893) and Palache (1894) on the serpentine of Potrero Hill. An earlier, more detailed report, "Sketch of the geology of the San Francisco Peninsula" (Lawson, 1895), included a geologic map of the peninsula from San Francisco almost to Half Moon Bay on a 1:113,000-scale shaded-relief base made by photographing a relief model. The field notebooks and field maps for the San Francisco Folio were not available to me for examination as a part of my study.

A report by Crandall (1907), "The Geology of the San Francisco Peninsula," which is accompanied by a map on a scale of 1:126,000, is of interest because it includes a few geologic details not mentioned by Lawson.

The 1906 earthquake was a great stimulus for geologic study within the quadrangle because of the great havoc it wrought. Many geologists contributed to the voluminous report of the California State Earthquake Investigations Commission, edited by Lawson (1908). Map 17 of the atlas is a fine geologic map of the City of San Francisco and Yerba Buena Island on a scale of 1:40,000. It differs from the geologic map in the San Francisco Folio in having a more legible base, in showing more detail in bedrock areas, and in showing areas of land reclaimed from San Francisco Bay.

The "Report on the Underground Water Supply of San Francisco County" (Bartell, 1913), popularly known as the "O'Shaughnessy Report," is a valuable source of borehole logs and well data. It contains a geologic map of the City of San Francisco by Lawson at a scale of 1:37,500, the base for which, apparently made by the City Engineer's office, shows streets and topography by contours. The geology depicted differs slightly from that on other geologic maps of the city.

"Hydraulic-Mining Debris in the Sierra Nevada" (Gilbert, 1917) contains much information on sedimentation in San Francisco Bay. A report on "Subsidence and the Foundation Problem in San Francisco" (American Society Civil Engineers, 1932) is a rich source of data on engineering, geology, and the historical development of the city.

G. D. Louderback was greatly interested in the geology of San Francisco Bay as well as in the Quaternary geology of the bay area. Early in his career, Louderback participated in a survey of the bay sediments (Sumner and others, 1914). Later he published a short paper on bay sediments (Louderback, 1939) and a geologic history of the bay (Louderback, 1951).

Studies in connection with constructing bridges across the bay have given valuable data on the geology of the east edge of the quadrangle. An early effort was reported by the Hoover-Young San Francisco Bay Bridge Commission (1930). Trask and Rolston (1951) presented data based on logs of holes bored to investigate the route of a bridge parallel to, but 300 feet north of, the present San Francisco–Oakland Bay Bridge and on holes bored to investigate a site for another bridge between the island of Alameda and the south edge of the quadrangle.

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Several Federal agencies assisted by furnishing boat transportation: U.S. Public Health Service; Corps of Engineers, U.S. Army; U.S. Coast Guard; Federal Bureau of Prisons.

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FIELDWORK

Fieldwork was started in August 1947 by C. A. Kaye, who mapped approximately 2 square miles of the southern Marin Peninsula. In November, Kaye was joined by M. G. Bonilla, who began systematically combing streets and alleys in San Francisco for rock exposures. The project was recessed from May 1948 to November 1948, when the author and Bonilla resumed geologic mapping and started a program of collecting, from private and public agencies, logs of boreholes and engineering and geologic reports of specific construction sites in the San Francisco Bay area. D. H. Radbruch started work on the project in June 1949. W. I. Konkoff assisted in geologic mapping during part of 1950 and 1951. Fieldwork was largely completed by the close of 1952. The geologic map (pl. 1), however, contains data obtained at a few excavation sites as recently as 1964.

Results of this study are published reports on the geology of the quadrangle (Schlocker and others, 1958), on a Cretaceous ammonite found in the Franciscan Formation in San Francisco (Schlocker and others, 1954), on the engineering geology of Islais Creek Basin, located at the southeast corner of the San Francisco North quadrangle (Radbruch and Schlocker, 1958), and on rodingite on Angel Island (Schlocker, 1960).

METHODS OF MAPPING

Because the land surface of much of the quadrangle is hidden by streets, buildings, and other manmade structures, geologic observations were confined largely to undeveloped lots and to excavations opened for utility lines and building foundations. These observations were supplemented by data from boreholes and earlier foundation construction. Several thousand logs of boreholes drilled by private firms and Federal, State, county, and municipal agencies provided data that were invaluable in preparing the geologic map.

Aerial photos taken in 1946 were used extensively in relatively open areas such as the Presidio, the Mount Sutro–Twin Peaks area, Marin Peninsula, Angel Island, Belvedere Island, and Tiburon Peninsula. The most commonly used scales were 1:12,000 and 1:6,000. Excellent aerial photographs, at a scale of 1:2,400 — made available by the San Francisco City Engineer's office — were used for part of the Twin Peaks–Mount Olympus–Corona Heights area. The topographic quadrangle map enlarged to 1:6,000 scale was used for parts of San Francisco covered with a dense street network.

STRATIGRAPHY

The geologic formations of the San Francisco North quadrangle fall into two distinct groups, bedrock and surficial deposits, that differ greatly in age, lithology, and topographic expression (pl. 1). The older group, the bedrock, comprises the sedimentary, igneous, and metamorphic rocks of the Franciscan Formation of Jurassic(?) and Cretaceous age, and the serpentine and gabbro associated with them. Areas of exposed Franciscan Formation are generally hilly.

The younger group, unconsolidated surficial deposits of Pleistocene and Holocene age, are predominantly dune sand and water-laid sand, mud, and clay, but they include some fairly extensive deposits of slope wash, alluvium, landslide debris, and artificial fill. The surficial deposits above sea level mantle and extensively modify the lower slopes and fill the valleys between the bedrock hills; their thickness varies from a few feet to more than 100 feet. In the bay, borings show that the pre-Tertiary bedrock is overlain by deposits of sand, clay, and mud ranging in thickness from 100 to 300 feet. In some of the channels cut in the bay floor, unconsolidated material is locally absent.

BEDROCK

FRANCISCAN FORMATION

The Franciscan Formation is a complex assemblage of various rock types, predominantly sedimentary, but also volcanic and metamorphic, exposed in southwestern Oregon and along much of western California from the Oregon border at least to Santa Catalina Island (fig. 6). Its exposures in California are generally bounded on the east by the Klamath Mountains and the Coast Range thrust fault (Bailey, 1970), which lies near the west border of the Great Valley, and on the west by the Pacific Ocean. It is exposed over roughly 15,000 square miles of the Coast Ranges, and its total extent on land and offshore may be as much as 75,000 square miles. The Franciscan Formation and its possible correlatives in Baja California, California, Oregon, Washington, Canada, and Alaska are typical of rocks deposited in orogenically active borders between oceanic and continental crustal plates.

The Franciscan Formation ranges in age from Late Jurassic to Late Cretaceous; however, rocks deposited during the entire age span generally are not present in any one area. The rocks were folded, shattered, and sheared many times after they were deposited. Because of the lack of key marker beds, the scarcity of fossils, and structural complexities, a standard section has not been established, and the total thickness is not known. Thickness measurements of part of the Franciscan at several places show that it is probably more than 50,000 feet thick.

A comprehensive description of the Franciscan Formation throughout its entire distribution and a discussion of its significance to the geology of the Coast Ranges is contained in a report by Bailey, Irwin, and Jones (1964). A detailed discussion of the history of the study of the formation is also contained in this 1964 report and in a report by Taliaferro (1943, p. 112–122).

In the San Francisco North quadrangle, the Franciscan Formation may be as much as 10,000 feet thick, and it consists of about 80 percent graywacke sandstone, 10 percent shale and siltstone, 6 percent mafic volcanic rocks, 3 percent radiolarian chert, and less than 1 percent conglomerate, limestone, and glaucophane schist. All these rocks have been intruded by ultramafic rocks, mostly serpentine. Fossils found in the Franciscan Formation in the San Francisco North quadrangle are Cretaceous in age.

The Franciscan Formation is exposed in the northeastern part of San Francisco where it is 3,650 feet thick and in the sea cliffs from the Cliff House to Bakers Beach where it is about 2,350 feet thick. In these places, the formation consists mostly of graywacke sandstone and shale. The formation also occurs as tectonic inclusions in a shear zone that extends from Hunters Point to Fort Point. An unknown thickness of graywacke sandstone, greenstone, and radiolarian chert forms the central highlands area of the city, which includes Sunset Heights, Mount Sutro, Twin Peaks, and the adjacent hills to the east.

The Franciscan Formation is estimated to be about 17,000 feet thick in a southwest-dipping section between Richardson Bay and Point Bonita (southeast tip of Marin Peninsula; not in quadrangle). Here the formation includes 8,000 feet of greenstone, more than 6,000 feet of sandstone and shale, and about 3,000 feet of radiolarian chert, which is more abundant here than in most Franciscan terranes (fig. 7).

On Angel Island and Tiburon Peninsula, the Franciscan Formation consists of sandstone and shale, with a minimum thickness of 1,850 feet, interbedded green-

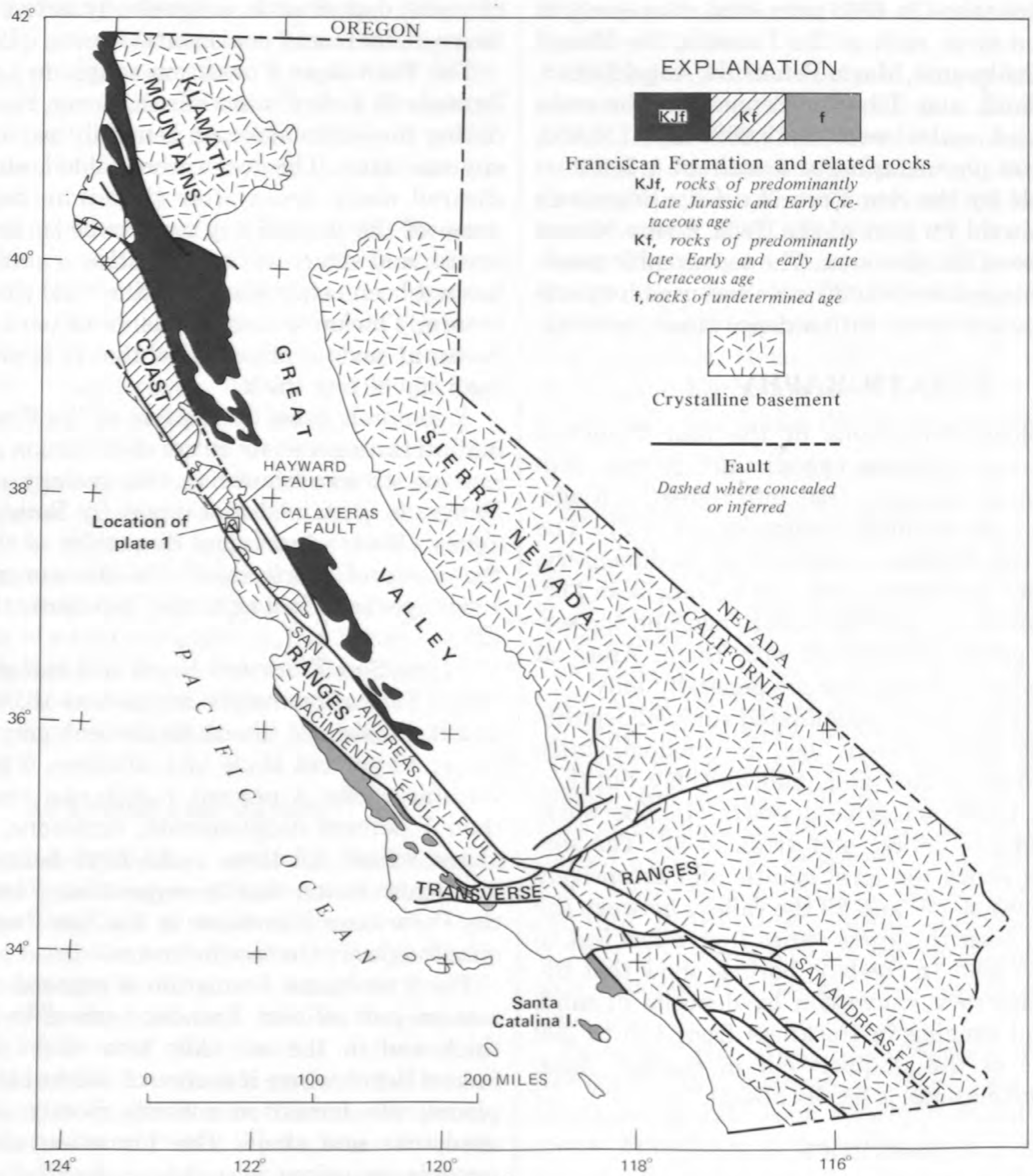

FIGURE 6.—Distribution of Franciscan Formation, related rocks, and principal structural features of western California (modified from Bailey and others, 1964, fig. 29).

stone 350 feet thick, and minor radiolarian chert. Most of the Franciscan here has been metamorphosed.

Lawson (1895, p. 415) named the Franciscan Series and later (1914, p. 4) employed the name Franciscan Group. He designated San Francisco as the type area, stating that "the Franciscan group was named from San Francisco, where it occurs in extensive exposures ***." He believed that two radiolarian cherts interbedded with the sandstone constituted "well-defined and easily recognizable stratigraphic horizons," and he used these cherts to divide the Franciscan into five formations. He named these formations, in ascending stratigraphic order, the Cahil Sandstone, the Sausalito Chert, Marin Sandstone, Ingleside Chert, and Bonita Sandstone. These were later reduced to members within the Franciscan Formation. All but the Bonita were recognized by Lawson in this quadrangle. The present writer found numerous sections of lithologically indistinguishable radiolarian chert interbedded with sandstone and for the most part was unable to use them as stratigraphic marker beds as suggested by Lawson. These five names are therefore considered obsolete and are abandoned.

Because the Franciscan Formation in this quadrangle consists of a very complex assemblage of rocks, with no marker beds, the formation has been divided

FIGURE 7.—Horseshoe Bay and vicinity, southern Marin Peninsula. Franciscan Formation dips about 50° westward (to left). In the photograph, greenstone terranes appear nearly white; radiolarian chert, sandstone, and shale appear medium to dark gray. The large cut along U.S. Highway 101 exposes sandstone and shale on left (west) and radiolarian chert on right. Parking area at level of freeway was (1949) site of 75-foot-high hill of radiolarian chert and shale. (See figs. 10, 18).

into its major rock types for purposes of discussion: clastic sedimentary rocks, greenstone, radiolarian chert, metamorphic rocks, and sheared rocks.

CLASTIC SEDIMENTARY ROCKS

Clastic sedimentary rocks of the Franciscan Formation consist of massive sandstone beds, commonly more than 10 feet thick and as much as 35 feet thick, sections of alternating thin-bedded shale and sandstone, and rare thin conglomerate beds.

Sandstone of the Franciscan Formation generally fits the description of graywacke (in Williams and others, 1954, p. 297) as "aggregates of sharply angular fragments of every size between sand or fine gravel and impalpable particles." The grains are mostly angular and range in size from coarse sand to clay. The most common sandstone consists predominantly of fine to medium grains. The sandstone has other attributes characteristic of graywacke, such as poor sorting, 10 percent or more clayey matrix, low porosity, and dark color.

On the geologic map (pl. 1), units consisting of massive sandstone and minor amounts of interbedded shale are shown as sandstone. In the northeastern part of San Francisco, two exceptionally thick sequences of shale and thin-bedded sandstone are separated from the massive sandstone. The shale and thin-bedded sandstone sequences vary considerably. In some places they are predominantly shale with a few 1–3-inch-thick beds of sandstone. In other places they are predominantly 2–3-foot-thick beds of sandstone separated by 3–4-inch-thick beds of shale. Where exposures in the city are too poor to determine which combination of lithology and bedding predominates, the clastic rocks are shown as sandstone and shale, undifferentiated.

Structural and stratigraphic relations between discontinuous exposures of clastic rocks are generally obscure, owing to poor exposures, scarcity of fossils, lack of bedding in sandstone, and absence of key marker beds. Some separated exposures evidently are stratigraphically continuous, but only in a few places could sandstones be recognized in distinguishable stratigraphic positions.

Soils developed on the clastic rocks vary from slightly sandy clay to clayey sand, but most are sandy silty clay of low permeability. The soils swell greatly and are highly plastic when wet and shrink greatly when dried. Distinct soil horizons are poorly developed. Thickness of the soil (A and B horizons) above weathered rock (C horizon) varies from 3 to 20 feet. Total thickness of soil and moderately weathered rock is between 5 and 30 feet in most places but as much as 70 feet in some places.

Most slopes underlain by clastic rocks of the Franciscan Formation are rounded or only moderately steep because of the thick cover of clayey soil. Landslides of surface debris are common on these slopes. Where erosion is rapid, such as along shorelines, the sandstone maintains natural cliffs by landsliding.

SANDSTONE

Bedding within the massive sandstone beds generally is absent or obscure even in good exposures. In some sandstone, bedding is indicated by the orientation of detrital mica, shale flakes, or carbonaceous matter. Some of the sandstone beds, as much as 25 feet thick, appear to be lenses that fill channels in the shale and thin-bedded sandstone sequences. Beds ½–4 inches thick show grading from fine- to medium-grained sandstone at the base to shale at the top (fig. 8). The top few inches of massive sandstone beds also grade upward to shale and show channeling, ripple-type cross-bedding, and, in places, distortion of beds that suggests preconsolidation slumping. In some localities striations, grooves, and spatulate depressions are preserved as casts on the underside of bedding planes.

Most of the structural attitudes shown on the geologic map (pl. 1) were observed on shale and thin-bedded sandstone sequences that separate the massive beds.

The color of fresh sandstone, according to the rock color chart (Goddard and others, 1948) is dark gray (*N*3) to medium gray (*N*5), with rare tinges of blue (5*B* 5/1). Weathered sandstone ranges from dark greenish gray (5*GY* 4/1) and olive gray (5*Y* 6/2) when slightly altered to grayish orange (10*YR* 7/6) when greatly altered. Hydrothermally altered sandstone is white (*N*9) with streaks of yellowish orange

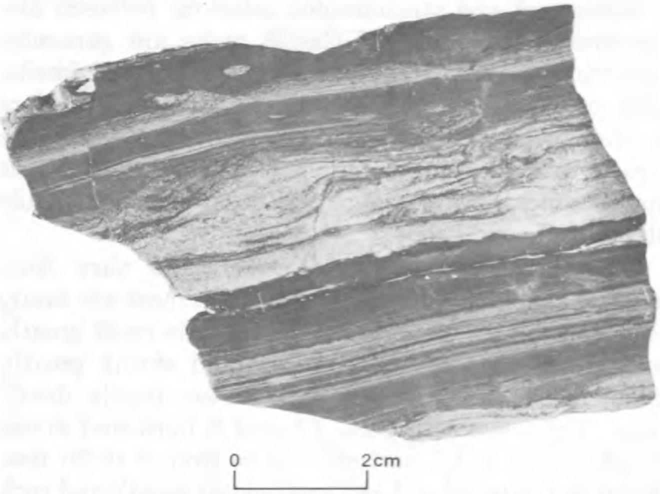

FIGURE 8.—Shale and thin-bedded sandstone of the Franciscan Formation showing graded and distorted bedding and laminae. Broadway Tunnel excavation, Russian Hill, San Francisco.

FIGURE 9.—Jointed thick-bedded sandstone and interbedded 3-foot-thick section of shale and thin-bedded sandstone, Franciscan Formation. Northeast side of Telegraph Hill, San Francisco.

(10*YR* 7/7). Chloritized sandstone is light olive (10*Y* 5/2) to dark greenish gray (5*GY* 4/1).

Closely spaced joints are common in the sandstone beds (fig. 9). Most joints are randomly oriented and have plane or curved surfaces, but many joints are in poorly to moderately well defined parallel sets. Some joint systems consist of one set parallel to the bedding and two or more perpendicular to the bedding.

Closely spaced joints are especially prominent in irregular shear and mylonite zones, which consist of thoroughly mashed shale and crushed sandstone (fig. 10). Such zones are commonly found in exposures that also contain less fractured sandstone in which the joints are from 4 to 48 inches apart. Joints in unsheared sandstone are most commonly 2–3 inches apart.

Some massive sandstone beds are adjacent to large bodies of dark-gray soft thoroughly sheared shale, in which rounded sandstone fragments, 1 inch to 25 feet in diameter, are embedded (fig. 11). The contact between the sheared shale bodies and the enclosing sandstone is usually sharp. Tabular shale bodies in the sandstone (1–6 in. thick) also have intruded fractures at all angles to the bedding; these condition indicate that shale apparently becomes very plastic under shear stresses. The mineralogy of some of these shale segregations is given in a later section.

Grain size of sandstone in the Franciscan Formation in this area ranges from coarse sand to clay; however, fine to medium sand sizes predominate. The predominant grain-size range in any one bed is fairly narrow and is a parameter that can readily be assigned in the field.

Nearly all the sand-size grains are angular. In a few sandstone beds, as much as 3 percent of the grains are subangular to round; in some tuffaceous sandstone, as much as 25 percent of the volcanic rock grains and about 3 percent of the quartz and feldspar grains are subround to round. In one unusual sandstone found in the excavation for the foundation of the Masonic Temple at California and Taylor Streets, about 25 percent of the grains were subround to round. The *Douvilleiceras*-bearing sandstone west of James D. Phelan Beach contains 1–2 percent well-rounded grains and about 5 percent of grains that are well rounded on one side and angular on the other side. Evidently, these grains were once well rounded and subsequently were broken.

In 50 percent of the sandstone specimens that were examined for grain sphericity, about 90 percent of the grains were equidimensional and 10 percent were elongate. In the other specimens, 50–65 percent of the grains were equidimensional and the remaining grains were elongate. The long axes of elongate grains generally lie in the plane of the bedding.

Dark-gray to black angular gravel-size fragments of shale, commonly oriented in the plane of the bedding, occur in some sandstone, especially coarse-grained sandstone (fig. 12). The largest fragments, as much as 4 by 4½ inches in size, were found in the *Douvilleiceras*-bearing sandstone. In a few places, large abundant paper-thin flakes of coaly material, 1 or 2 square inches in area, parallel the bedding.

MATRIX

The amount of matrix (detritus smaller than 0.02 mm) in sandstone beds of the Franciscan Formation

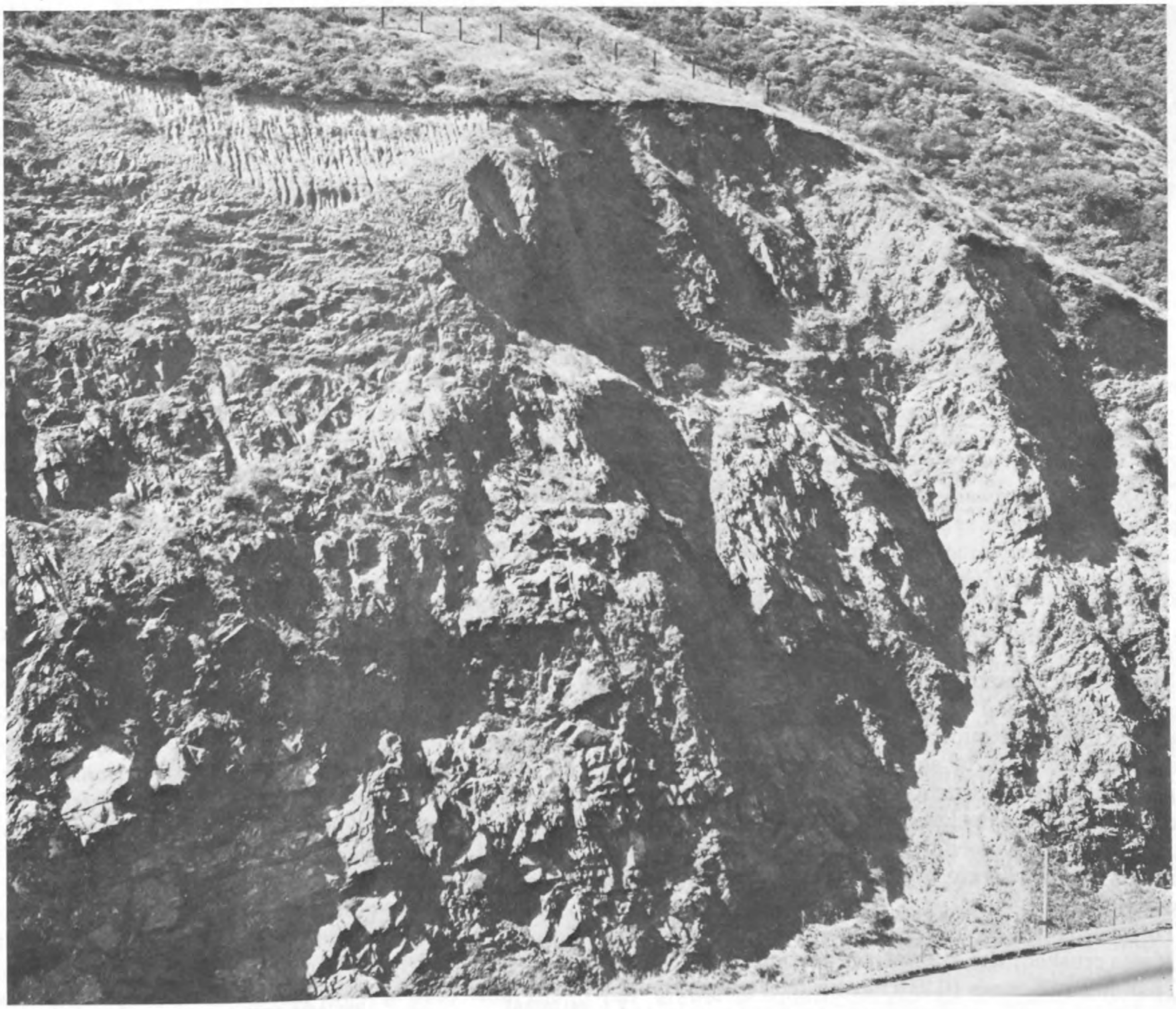

FIGURE 10.—Sheared and shattered sandstone and shale of the Franciscan Formation. Continuity of beds, seen near bottom of cut, is uncommon in the Franciscan Formation. Sandstone and shale at right edge of cut are especially strongly sheared. Old deposit of slope debris and ravine fill at top of cut. West side of U.S. Highway 101, three-quarters of a mile north of Golden Gate Bridge.

FIGURE 11.—Sheared shale of the Franciscan Formation containing large hard sandstone masses. Exposure is near top of blanket (melange) of sheared Franciscan rocks, approximately 1,000 feet thick, that covers many squares miles northwest of the San Francisco North quadrangle. Note berms and pipes draining water from nearly horizontal holes in slope used to prevent and control landslides along California highways. West side of U.S. Highway 101, 1 mile west of Sausalito Point, Marin Peninsula.

varies irregularly over short distances but generally constitutes 15–20 percent of the rock. Dikelike segregations of matrix-rich sandstone, generally less than 1 inch thick, are common. The amount of matrix in such

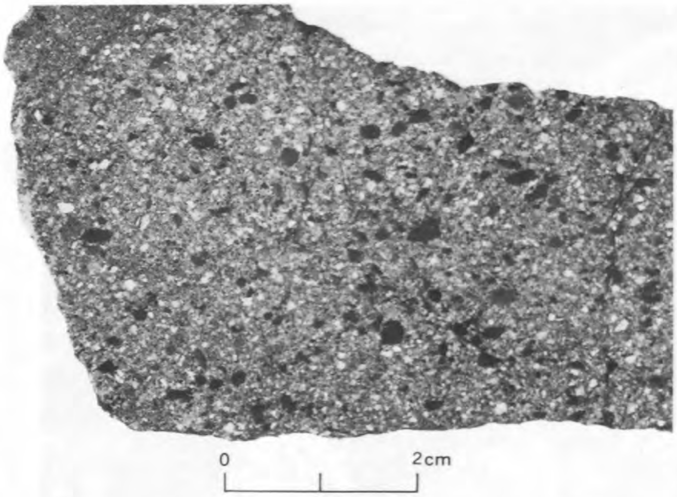

FIGURE 12.—Shale fragments (black) in coarse-grained graywacke sandstone of the Franciscan Formation. Section parallel to bedding. Laguna Honda Reservoir area, San Francisco.

segregations in sandstone beds on Marin Peninsula is so great that the rock is more properly called sandy mudstone.

Microscopic examination shows the matrix to be aggregates of silt- and clay-size crystals with equigranular, acicular, and micaceous habits. In some places, the matrix consists of shale clasts squeezed around harder grains. Constituents that can be easily identified are quartz, plagioclase, muscovite, biotite, and lignitic material. Exceedingly fine-grained micaceous minerals with moderate to high birefringence are very abundant.

To investigate the clay minerals in the matrix, the rock was crushed; the <2-micron fraction of the material passing a 65-mesh (0.210 mm) screen was assumed to be largely matrix and was used to prepare oriented aggregates for X-ray diffractometer analyses. This material from unweathered sandstone collected from widely separated localities consists mostly of mica and chlorite which are fairly well ordered, though some contain a low percentage of expandable layers. Mica is both the dioctahedral (muscovite) and trioctahedral (biotite, phlogopite) type; kaolinite is absent.

The matrix of the sandstone from Alcatraz and Yerba Buena Islands, Quarry Point on Angel Island, Telegraph and Russian Hills in San Francisco, and from north of Lime Point contains fibrous aggregates of acicular pumpellyite crystals. Some of the adjoining volcanic, feldspar, and quartz clasts also contain pumpellyite. The pumpellyite in the matrix and adjoining clasts appears to be metamorphic. Some isolated clasts of pumpellyite in radial fibrous sheaves with or without quartz may be detrital.

DETRITAL GRAINS

The lithologic composition of the sandstone beds varies from arkose to volcanic graywacke, but most beds are arkosic and lithic graywacke (fig. 13). The plotted positions of sandstone samples shown in figure 13 are estimates based on examination of thin sections and cut surfaces. Results of point-count analyses of thin sections of some of the sandstone samples are given in table 1.

With one exception, data are insufficient to suggest a correlation between sandstone composition and stratigraphic position or geographic location. The mineral and chemical composition of sandstone beds west of Corona Heights and east of Twin Peaks and their megascopic appearance suggest that this belt of sandstone is largely volcanic graywacke. In several other places throughout the quadrangle, greenstone grades into volcanic graywacke.

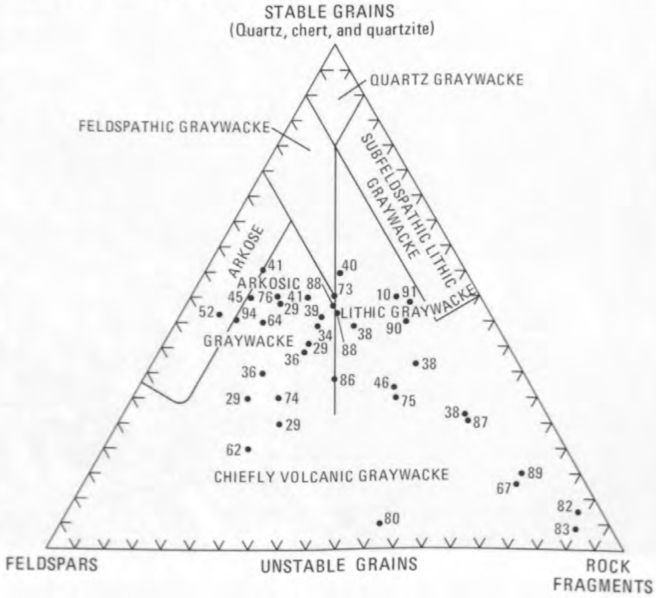

FIGURE 13.—Classification of sandstone samples of the Franciscan Formation. Location of samples is shown in figure 14.

TABLE 1.—*Modal composition of sandstone samples of the Franciscan Formation*

		Approximate volume percent determined by point-count analyses of thin sections								
Map No. (fig. 14)	Sample No.	Matrix[1]	Quartz	Feldspar	Volcanic rocks	Shale	Chert	Quartzite and metachert	Granitic rocks	Minerals other than mica, quartz, and feldspar
91	1649	32.5	14.9	12.5	14.9	3.6	10.5	7.6	0.2	3.3
45	1228	55.7	18.4	17.6	1.6	1.5	1.6	2.0	—	1.5
40	1899	24.4	35.0	16.2	10.4	4.1	4.3	4.4	—	1.2
46	1934	17.7	13.7	19.2	19.5	16.4	2.7	9.4	.8	.6
39	1979	50.8	20.2	15.1	3.0	6.8	3.6	—	—	.5

[1]Grains smaller than about 0.03 mm, but matrix also includes all sizes of mica crystals and carbonaceous material.

Mineral grains are mostly quartz and feldspar. About one-half to three-fourths of the quartz grains found in the sandstone of the Franciscan Formation show slight strain effects at extinction under crossed nicols. A small number of quartz grains show strong strain effects and brecciation. Most of these grains were classed as quartzites in the grain composition studies. The slight strain effects shown by most of the quartz grains are much less intense than those shown by quartz in semischistose sandstone of Angel Island but are of slightly greater intensity than those shown by quartz crystals in veinlets cutting the sandstone.

Most of the feldspar grains are plagioclase. They range in composition from albite (An_4) to sodic labradorite (An_{51}). Andesine, An_{33}–An_{39}, is the plagioclase in two-thirds of the sandstone. In some sandstone, andesine is accompanied by oligoclase, An_{12}–An_{20}. Even in sandstone containing large amounts of basic volcanic rock fragments, the predominating feldspar detritus is andesine. Less than 1 percent of the plagioclase shows zoning.

A remarkable aspect of the sandstone is the scarcity of potassium feldspar grains (fig. 14; table 2). An exception is the sandstone of Point Lobos, which contains 5–10 percent potassium feldspar. Sandstone from a few other localities also contains small but persistent amounts of potassium feldspar; these are unsheared, unmetamorphosed sandstone beds of Quarry Point on Angel Island, the *Douvilleiceras*-bearing sandstone and adjoining sandstone in the cliffs of South Bay and Bakers Beach, and the sandstone of Alcatraz Island.

Heavy mineral determinations of nine sandstone samples were made, using procedures outlined by Hutton (1950, p. 639). The approximate proportions of heavy minerals in the sandstone (table 3) are weighted-average frequencies (Hutton, 1950, p. 650) from estimates made by counting grains in the 20–74- and 74–149-micron-size ranges identified under the petrographic microscope. The weighted-average frequencies also include less accurate estimates for coarser sizes, for which only representative grains were subjected to petrographic and X-ray diffraction analysis.

Biotite, chlorite, vermiculite, and, to a lesser extent, nontronite predominate in the heavy fraction of almost all sandstone. X-ray diffraction analysis shows that these minerals are present together in composite grains. Individual flakes of chlorite and muscovite are fairly abundant. The epidote group minerals, epidote, clinozoisite, and zoisite, the related mineral pumpellyite, and sphene and garnet are present in conspicuous proportions.

The heavy-mineral analyses show some slight, inconsistent differences between sandstones containing potassium feldspars and those that do not. Because potassium feldspar in a sandstone suggests that granitic rocks were components of the source area, minerals characteristic of a granitic source, such as zircon and tourmaline, would also be expected to be more abundant in the potassium feldspar-bearing sandstone, but the results do not show this. Sandstone sample 1931 from the Golden Gate Bridge area in Marin County contained rare grains of the chromian spinel, picotite, as did a sample of semichistose sandstone near the west shore of Angel Island 1,000 feet south of Point Ione, suggesting that ultramafic rocks were in the source area.

All the sandstones contain sedimentary, volcanic, granitic, and metamorphic rock grains. Shale is conspicuous in many sandstone samples, and silty, clayey, and carbonaceous varieties can be seen in a single thin section. Chert grains, in which no Radiolaria have been found, are common in all sandstones. Graywacke sandstone grains are sparse; quartz sandstone or orthoquartzite grains are somewhat more common. Detrital carbonaceous matter, probably representing plant remains, is also common.

Altered volcanic rocks are found in almost all sandstone. Many sandstones contain grains of chlorite or vermiculite-chlorite-nontronite aggregates that appear to be altered glassy basalts. Some of these grains contain microlites of albite-oligoclase and rarely labradorite. Grains of greenstone with spherulitic, hyaloophitic, intersertal, and pilotaxitic textures are common, as are what appear to be grains of acidic felsites. Acidic to intermediate volcanic grains are abundant in coarse-grained sandstone at California and Taylor Streets.

Small amounts of lithic grains with fine-grained granitic textures are found in most sandstones. Most of these grains are quartz-plagioclase in composition, but grains of quartz-plagioclase-orthoclase, quartz-perthite, and quartz-microcline rocks are present in small amounts in a few sandstone beds. For example, the *Douvilleiceras*-bearing sandstone on the cliffs of the South Bay part of Golden Gate channel is distinguished by the presence of such lithic granitic grains as well as by a more-than-average amount of mica quartzite and graphite quartzite. Thin sections of sandstone from the Presidio, Nob Hill, and southern Marin Peninsula contain a small percentage of serpentine grains.

Grains of fine-textured metamorphic rocks, such as quartzite or what appears to be metachert, are common in almost all sandstones. These consist largely of quartz, generally with suture texture, with one or more of the following minerals: Epidote-group minerals, particularly epidote and clinozoisite, rarely zoisite; amphiboles, generally hornblende pleochroic in brown hues, pumpellyite in radial-fibrous sheaves; micas, commonly muscovite, rarely brown biotite; and graphite.

FIGURE 14.—Locations of sandstone samples of the Franciscan Formation and annotations as to potassium feldspar content.

TABLE 2.—*Potassium feldspar in sandstone of the Franciscan Formation*

[Grain size: VF=very fine, F=fine, M=medium, C=coarse, and VC=very coarse. Samples are fresh except as noted. Massive sandstone samples are from beds more than 3 ft thick, and thin-bedded samples are from beds less than 4 in. thick. Bedding indications not noted where exposures are poor. Tr.=trace]

Location No. on fig. 14	Sample No.	Approximate median grain size	Descriptive remarks	Percent
			Angel Island	
1	S5	F–M	Sheared by faulting	
2	S64	M–C	Semischistose	
3	S39	C	do	
4	S28	M	Semischistose, slightly to moderately weathered.	
5	S27	M–C	Semischistose	
6	S33	C	Semischistose, slightly to moderately weathered.	
7	S23	M	do	
8	B48	C	Semischistose	
9	S74	F–M		4
......	S75	F	Thin bedded, graded bedding, laminated	
10	B40	M	Massive	2
11	B34	M–C	Semischistose	
12	1879	F–M	do	
......	1879	VF	Laminated	
13	1667			
14	B55	VF	Semischistose	
15	S47	F	do	
16	B56	M–C	do	
17	S13	C	do	
18	S52	VF	do	
19	S71	C	do	
			Tiburon Peninsula and Belvedere Island	
20	704	VC	Much detrital shale, semischistose	
21	709	F		
22	710	M	Moderately weathered	
23	692	C	Moderately weathered, semischistose	
24	735	F–M	Semischistose	
25	739	C		
			Marin Peninsula	
26	594	F–M		
27	598	M	Moderately weathered	Tr.
28	602	M		
29	2026	M	Massive	
......	2027	M	do	Tr.
......	2028	M	do	Tr.
......	2029	M	do	Tr.
......	2031	F	Thin-bedded, laminated	
30	612	VC		
......	621	M		
31	619	F–M		
32	627	M–C		
33	2000	M	Massive	
34	2041	F–M	Graded bedding, thin bedded, small-scale channeling	
35	2039	M	Massive	
36	2035	M	Massive	Tr.
......	2036	F–M	Thin bedded, small-scale channeling	
......	2037	M–C	Massive	
......	2038	M	do	
37	1931	C	do	
......	2032	C–M	do	½
......	2033	M–C	Thin bedded, small-scale channeling	¼
......	2034	M	do	½
38	1980	M–C	Massive, moderately weathered	
39	1979	M–C	Massive	Tr.
			Alcatraz Island	
40	1899	M	Massive	1

TABLE 2.—*Potassium feldspar in sandstone of the Franciscan Formation*—Continued

Location No. on fig. 14	Sample No.	Approximate median grain size	Descriptive remarks	Percent
			San Francisco	
41	2042	M	Massive	
42	1250	M	do	
43	2083	F–M		
44	1135	F	Thin bedded, small-scale channeling	
......	1149	M	Massive	
......	1363	F	Thin bedded, small-scale channeling	
45	1195	M	Massive	
......	1228	M	do	
......	1230	M	do	
46	1934	VC		
......	1935	M		
47	149	M		
48	38	M	Laminated	
49	834	M	Massive	
50	2082	F	Laminated	
51	148	M	Moderately weathered	
52	358	M		
53	2005	F	Very coarse grained muscovite flakes	
54	8	VC	Semischistose, slightly to moderately weathered.	
55	1272	F–M		
56	1263	M		
57	1345	M	Massive	
58	117	VC	Semischistose	
......	118	C	do	
59	1276	F–M		
60	150	M	Massive	
61	341	C		
62	110	C	Massive	Tr.
63	131	M		
64	173	F		
65	923	F		Tr(?).
66	1275	M	Massive	
......	1275	F	Thin bedded	
67	112	M	Massive	½
68	147	M		
69	407	VF		
70	348	M	Moderately weathered	
71	36	M		
72	213	M	Moderately weathered	
73	109P	VF		
......	177S	C		
74	108P	F		
75	107P	F–M		
76	104P	VF		
77	185	M	Moderately weathered, thin bedded	
......	2018	F	do	
78	1556	C		
79	1624	F	Moderately weathered, laminated	
80	1442	F	Slightly altered	
......	1442	C	do	
81	1666	F–M		Tr(?).
82	1461	M–C	Slightly altered	
83	1466	M	do	Tr(?).
84	510	M		
85	340	F		
86	95	M	Moderately altered, laminated, tuffaceous	
87	96	M	do	Tr.
88	374	M		
89	1882	M	Carbonaceous partings	
90	373	M–C	Massive	2
91	1566	M–C		2
......	1566	F–M		2
......	1649	M–C	Massive, *Douvilleiceras sp.*–bearing	2
92	405	F		1
93	1906	M	Massive	
94	769	F–M	do	
95	2155–2	M	Massive, hydrothermally altered	15
96	2155–1	M	Massive, hydrothermally altered; much potassium feldspar veining	5
97	2155–7	M	Massive	7
98	2155–6	M–C	Massive, hydrothermally altered	5
99	2155–5	M–C	Massive	7
100	2155–8	M	do	7

Pyritic orthoquartzite, mica schist, amphibolite, and epidote-albite rocks are also present in some sandstones.

Chemical composition.—Franciscan sandstone contains less SiO_2 and more Al_2O_3, FeO, MgO, and Na_2O than Clarke's (1924, p. 30) average sandstone (table 4, column 6a). Taliaferro (1943, p. 136) showed the chemical composition of Franciscan sandstone is close to that of granodiorite, but microscopic observation shows that in this area sandstones contain substantial amounts of other rock types. The composition of a representative graywacke from the sandstone belt west of Corona Heights and east of Twin Peaks (table 4,

TABLE 3.—*Frequency of heavy minerals in sandstone of the Franciscan Formation*
[Modified from Evans and others (1934, p. 39 ff.)]

Frequency	*Approximate percent*	*Frequency*	*Approximate percent*
8+	90–100	6	18–22
8	75– 89	6–	14–17
8–	60– 74	5	7–13
7+	45– 59	4	4– 6
7	35– 44	3	2– 3
7–	28– 34	2	1– 2
6+	23– 27	1	½– 1
		1–	Less than ½

Map No. (fig. 14)	30	37	45	45	88	91	40	(1)	74
Sample No.	621	1931	1195	1363	374	1649	1899	1938A	180
Andalusite	1—	1—	.....	1—	.....	.....	.....	1—	.....
Apatite	1—	1—	1	1—	2	1	1	1—	2
Biotite-chlorite-nontronite-vermiculite composite	8	8	5	8	4	7	6—	6	7+
Brookite	.....	.....	1—	.....	.....	.....	.....	.....	.....
Cassiterite	.....	.....	.....	.....	.....	.....	1—	.....	.....
Chlorite	3	4	5	5	4	6+	1	.....	5
Clinopyroxene	.....	.....	2	.....	.....	.....	.....	.....	.....
Clinozoisite	.....	1	3	.....	4	3	5	2	.....
Calcite	.....	.....	.....	.....	.....	.....	.....	.....	5
Epidote	3	2	5	.....	1	3	5	5	2
Garnet	3	1	3	.....	1	5	1	2	2
Hornblende	.....	1—	.....	1—	1—	1—	1—	1—	.....
Hypersthene-enstatite	.....	1—	.....	1—	.....	.....	.....	.....	1
Kyanite	.....	.....	.....	.....	1—	.....	.....	.....	.....
Magnetite-ilmenite	1	2	1	.....	2	2	2	1	1
Monazite	4	.....	1	1—	2	1	3	1—	3
Muscovite	3	2	5	5	1	1	4	3	4
Picotite	.....	1—	.....	.....	.....	.....	.....	.....	.....
Pumpellyite	1—	1	2	.....	.....	1	5	5	.....
Pyrite	.....	3	.....	1—	.....	.....	.....	1—	.....
Rutile	.....	1—	1—	1—	.....	.....	.....	.....	.....
Saussuritic rock	.....	.....	7+	5	7+	.....	6—	7	6+
Sphene	4	3	4	1—	1	4	5	1—	3
Spinel (see picotite for chromian spinel)	.....	.....	.....	.....	.....	.....	.....	1—	.....
Tourmaline	1—	1—	1—	.....	1—	1	1—	1—	1—
Tremolite-actinolite	.....	3	2	.....	.....	1	1	1—	2
Zircon	1—	1	1	1—	2	2	3	1—	1—
Zoisite	.....	4	1—	.....	3	4	4	4	.....
Percent of heavy minerals (by weight)	4.6	1.5	1.2	1.5	1.2	1.6	10.3	1.5	3.1

[1]East shore Yerba Buena Island, 0.8 mile east of San Francisco North quadrangle.

column 5) substantiates its identity as a volcanic graywacke.

Specific gravity.—The specific gravity of fresh sandstone ranges from 2.62 to 2.69; most samples are 2.68. Fresh sandstone from the Laguna Honda area, with the lowest specific gravity, contains a more-than-usual amount of shale detritus. Specific gravity of semischistose sandstone on Angel Island, Belvedere Island, and Tiburon Peninsula ranges from 2.68 to 2.83. Sandstones containing jadeite generally have a specific gravity greater than 2.72. Specific gravity of fresh laminated siltstone and sandstone from the excavation for the Broadway Tunnel in Russian Hill is 2.69–2.70, though the value for fresh laminated siltstone and sandstone 1 mile north of the Golden Gate Bridge on Marin Peninsula is 2.64.

Weathering and alteration.—Weathering reduces the sandstone to a sandy silty clay containing detrital quartz and the clay minerals montmorillonite, vermiculite, and mixed layered minerals of expansive clay minerals with mica and chlorite. The high vermiculite and montmorillonite content causes the clayey soil to swell and become highly plastic when wet and shrink and crack when dry.

Hydrothermal alteration locally produces kaolinite-group clay minerals and iron oxides by replacement of quartz, feldspar, and other silica-bearing minerals. Joints in altered sandstone are commonly coated or filled with a brown waxy clay mineral that varies in thickness from a film to nearly one-fourth inch and composed randomly mixed layered mica, chlorite, vermiculite, and montmorillonite. Within or near the edge of serpentine bodies, some sandstone blocks retain the textural and structural appearance of sandstone, but their grains have been completely replaced, mostly by chlorite and randomly mixed layered mica-chlorite, and minor talc, calcite, and pyrite.

SHALE

Shale beds are massive, banded or laminated, silty and clayey layers. Fissility is poor even in the laminated variety, and the shale breaks along irregular slickensided shear surfaces that are commonly parallel to the bedding. The color of fresh shale is dark gray (*N2*), and the colors of altered shale are similar to those of altered sandstone described elsewhere. Jointing is generally more pronounced and more closely

TABLE 4.—*Analyses of sandstone, shale, and a phosphate nodule from the Franciscan Formation*

[Chemical analyses (rapid rock methods) by Paul Elmore, Samuel Botts, I. H. Barlow, and Gillison Chloe. Semiquantitative spectrochemical analyses by H. W. Worthing. Looked for but not found: As, Au, Bi, Cd, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, Lu, Nb, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

	Sandstone							Shale		Phosphate nodule
	1	2	3	4	5	6	6a	7	7a	8
Chemical analyses (weight percent)										
SiO_2	70.8	68.9	67.0	67.1	60.9	67.3	78.7	63.2	58.4	43.4
Al_2O_3	14.0	12.7	14.1	14.9	16.4	15.5	4.8	16.1	15.5	9.2
Fe_2O_3	.6	1.5	.9	1.0	1.4	.4	1.1	.7	4	.7
FeO	2.5	2.8	4.0	2.9	4.4	3.8	.3	4.9	2.5	11.2
MgO	1.7	2.5	2.8	1.6	3.1	1.9	1.2	3.1	2.5	2.6
CaO	1.5	1.9	1.3	2	3.9	.61	5.5	1.1	3.1	15.3
Na_2O	3.7	2.7	3.4	3.1	4.2	4.2	.45	2.4	1.3	.52
K_2O	2.2	2.1	1.6	2.3	.58	3.2	1.3	2.5	3.3	.54
H_2O^+	2.2	2.8	2.8	2.6	3.7	1.8	1.3	3.7	3.7	4.6
H_2O^-	.22	.68	.59	.78	.50	.18	.31	.49	1.3	.52
TiO_2	.42	.68	.60	.51	.65	.60	.25	.68	.65	.32
P_2O_5	.10	.13	.12	.12	.15	.15	.08	.20	.17	9.8
MnO	.05	.06	.08	.06	.10	.08	Trace	.09	Trace	.12
CO_2	.07	.28	.14	.17	.10	<.05	5.04	<.05	2.64	.34
Total	100	100	99	99	100	100	100	99	99	99
S (aqua regia soluble)	0.06	0.03	0.22	0.08	0.02	0.01	......	0.22	......	0.18
Specific gravity (powder)	2.70	2.68	2.66	2.69	2.73	2.66	......	2.70	......	2.83
Semiquantitative spectrochemical analyses (weight percent)										
Ag	0.000015	0.000015	0.000015	0	0	0	......	0.000015	......	0.00003
B	.003	.007	.007	.007	.007	.003	......	.007	......	.003
Ba	.03	.03	.03	.03	.007	.15	......	.07	......	.07
Be	.00015	.00015	.00015	.00015	0	0	......	.00015	......	0
Ce	0	0	0	0	0	0	......	0	......	.015
Co	.0015	.003	.003	.0015	.003	.003	......	.003	......	.0003
Cr	.007	.007	.007	.003	.003	.003	......	.007	......	.0007
Cu	.0015	.0015	.003	.0015	.0015	.0007	......	.007	......	.015
Ga	.0007	.0007	.0007	.0007	.0007	.0007	......	.0007	......	.0007
La	0	0	0	0	0	0	......	0	......	.007
Nd	0	0	0	0	0	0	......	0	......	.015
Ni	.003	.007	.007	.003	.007	.007	......	.015	......	.003
Pb	.00015	.0003	.0007	.0003	.00015	0	......	.007	......	.015
Sc	.0007	.0007	.0007	.0007	.0007	.0007	......	.0007	......	.0007
Sn	0	0	0	0	0	0	......	.0015	......	.003
Sr	.015	.007	.007	.015	.007	.015	......	.007	......	.015
Sm	0	0	0	0	0	0	......	0	......	.015
V	.003	.007	.007	.003	.007	.003	......	.007	......	.0015
Y	.0015	.0015	.0015	.0015	.0015	.0015	......	.0015	......	.015
Yb	.00015	.00015	.00015	.00015	.00015	.00015	......	.00015	......	.0015
Zr	.007	.007	.007	.007	.007	.007	......	.015	......	.003

1. Graywacke, northeast base of Telegraph Hill, 200 ft west of Kearny St., 50 ft south of Francisco St., San Francisco (sample No. SF-2148).
2. Lithic graywacke, west of James D. Phelan Beach State Park, fresh rock near sea level below *Douvilleiceras*-bearing graywacke (sample No. SF-373).
3. Graywacke, Marin Peninsula, 5,050 ft northwest of Lime Point lighthouse, north end of roadcut west side of U.S. Highway 101 (sample No. SF-2114).
4. Graywacke, south base of Mount Sutro, east end of Laguna Honda (sample No. SF-2141).
5. Volcanic graywacke, 1,000 ft south of top of Buena Vista Park, San Francisco (sample No. SF-2140).
6. Arkosic graywacke, San Francisco South quadrangle, 4,100 ft east of peak 1314, San Bruno Mountain, Macco-P.C.A. quarry (sample No. SF-2122).

6a. Average sandstone, Clarke (1924, p. 30).

7. Shale near east end of Broadway Tunnel, Russian Hill, San Francisco (sample No. SF-1140).

7a. Average shale, Clarke (1924, p. 30).

8. Phosphatic nodule in shale, southeast side of Laguna Honda, San Francisco (sample No. SF-101).

spaced in shales of the Franciscan Formation than in sandstones.

The shales are made up mostly of micaceous minerals in the silt sizes (2–62 microns). However, the shales range from those containing no material greater than silt size to those containing substantial amounts. Most contain more than 15 percent silt-size quartz and feldspar. Carbonaceous material is in sand- to clay-size plates and fibers that are nearly opaque, dark brown in transmitted light, and dark gray to black in reflected light. Pyrite is often found in tiny crystals disseminated in large carbonaceous particles and layers.

The mineral composition of shale is similar to that of the sandstone matrix. Predominating constituents are mica, clay minerals, quartz, feldspar, and carbonaceous material. About half the shale consists of quartz and feldspar. The micaceous cleavage surfaces and the carbonaceous plates and fibers are roughly parallel. The mica crystals are generally not alined in *a* and *b* crystallographic directions. In a slaty shale obtained from the excavation for the Broadway Tunnel in Russian Hill, San Francisco, the mica plates appear to be thicker than those in nonslaty shale.

Microscopic examination shows that the micaceous minerals in the shale contain abundant unidentified inclusions of colorless generally equidimensional crystals, about ½–1 micron in diameter, of moderate refractive index and birefringence. The mica may be partly or wholly authigenic. X-ray diffraction analyses of the smaller-than-2-micron fraction of pulverized and deflocculated fresh unsheared shale show that mica predominates, though chlorite is abundant. Randomly mixed layers of mica, chlorite, vermiculite, or montmorillonite are present in some shales. Kaolinite is generally absent or minor.

Soft, sheared, and plastically deformed shale within shear zones consists predominantly of clay minerals and smaller amounts of pyrite-bearing carbonaceous streaks, nonclay minerals, and sheared rock pieces. Clay minerals are mostly chlorite or randomly mixed layered chlorite-montmorillonite and randomly mixed layered mica-montmorillonite. Some sheared shales are mostly montmorillonite and randomly mixed layered montmorillonite-mica-chlorite.

The chemical composition of shale obtained from the excavation of the Broadway Tunnel is given in table 4. As compared with the average shale, most of the differences are similar to the differences between Franciscan graywacke-type sandstone and Clarke's (1924, p. 30) average sandstone.

Weathered shale consists of mica, montmorillonite and (or) vermiculite, and randomly mixed layered mica-montmorillonite. Hydrothermally altered shale contains these minerals and abundant kaolinite-group clay minerals.

CONGLOMERATE

Conglomerate lenses and pebbly zones, 1 or 2 feet thick and interbedded with sandstone, are rare in San Francisco and on Marin Peninsula but are common on Angel Island, Belvedere Island, and Tiburon Peninsula, where some reach a thickness of about 10 feet. At the north end of Simpton Point on Angel Island, conglomerate beds in sandstone are well exposed. The thickest is a 12-foot bed composed by volume of about one-third well-rounded large clasts and two-thirds matrix of coarse-grained graywacke. The average diameter of the large clasts is approximately 2½ inches and the maximum is 12 inches. Sandstone beds above and below the conglomerate bed contain isolated well-rounded clasts 2–3 inches in diameter.

Conglomerate at approximately the same stratigraphic position is also exposed about 2,400 feet east of Stuart Point. Here it is about 10 feet thick and consists of about 20 percent well-rounded large clasts and 80 percent coarse-grained graywacke matrix. The average diameter of the large clasts is 1½ inches, and the maximum is 4 inches.

Along the beach on Angel Island, halfway between the north end of the serpentine exposure and the point west of Hospital Cove, a pebbly sandstone which is probably at the same stratigraphic position as the conglomerates was described by Ransome (1894, p. 197) as follows: "The pebbles are usually disposed as bands in the sandstone, and not as separate sharply defined beds. They are generally rather flattened and of all sizes up to 10 inches (25 centimeters) in diameter, and 4 inches (10 centimeters) thick."

Pebbles in the conglomerate at Simpton Point, Angel Island, consist of graywacke, 30 percent; shaly sandstone and shale, 20 percent; red, brown, and black chert, 15 percent; black orthoquartzite, 15 percent; and felsite, porphyry, and intermediate volcanic rocks, 20 percent. The pebbles in the conglomerate exposed east of Stuart Point are largely black or dark-gray chert and orthoquartzite and a small amount of graywacke.

Phosphate nodules were found in a shear zone in Franciscan clastic rocks near the east end of Laguna Honda. Nodules are 1–12 inches in diameter. The small nodules are massive. The largest one found consisted of concentric layers, 2–5 mm thick, of brown phosphatic material around an angular chert fragment (2 by 5 by 5 in.) and angular pieces of gray limestone. Both phosphatic material and limestone contained abundant Radiolaria. X-ray diffraction analysis showed the phosphatic layers to consist mostly of carbonate fluorapatite and smaller amounts of chlorite, calcite, quartz, and mica. The chemical composition of a small massive nodule is given in table 4, column 8.

METAMORPHOSED SEDIMENTARY ROCKS

Although their clastic, sedimentary nature is unmistakable, most of the sandstone, shale, and conglomerate of Angel and Belvedere Islands and Tiburon Peninsula are semischists of low metamorphic grade with a foliation more or less parallel to the bedding (fig. 15). They have been metamorphosed under conditions of the zeolite to glaucophane schist facies. The semischists are associated with sedimentary rocks that are not sheared and that otherwise appear to be unmetamorphosed; however, the boundaries between the two types are vague, and to show them separately

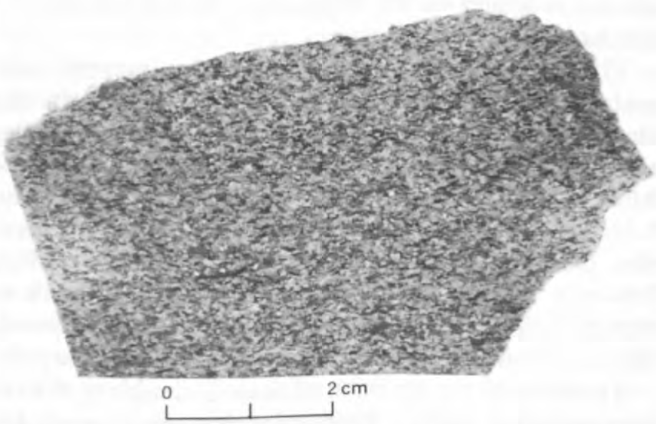

FIGURE 15.—Semichistose coarse-grained graywacke sandstone of the Franciscan Formation. Campbell Point, Angel, Island.

on the geologic map (pl. 1) was impractical. Sedimentary rocks in the vinicity of Quarry Point on Angel Island and on Corinthian Island are unfoliated and relatively unmetamorphosed, though weak metamorphism has formed pumpellyite in part of the matrix and in some of the quartz, feldspar, and volcanic clasts. Metamorphic pumpellyite is also found in the Franciscan sandstone of Alcatraz and Yerba Buena Islands and scattered localities in San Francisco and Marin Peninsula.

The semischists show several degrees of metamorphism. Those most strongly affected that retain sedimentary textures are tough and have a bluish or greenish cast. Foliation in the sandstone is shown by light-colored hard detrital grains of quartz and feldspar, which are commonly elongated and lens and spindle shaped. Foliation is also shown by darker material, representing easily deformed and chemically unstable detritus, and by carbonaceous and micaceous matrix, which appears as crenulated wisps wrapped around the larger harder grains. The shales are generally slaty. Semischistose conglomerates show characteristics of the semischistose sandstones with sheared lens-shaped pebbles.

Variations in degree of metamorphism are best shown in thin section. In the least affected sandstones, some large detrital grains of quartz and feldspar may have undulose extinction, internal cracks, or a fine-grained mosaic texture and a sutured lens-shaped outline. All the matrix and unstable detritus such as shale, greenstone, and micaceous minerals show marked effects. The unstable detritus is flattened and squeezed into streamlined clots, thin layers, veinlets, and complex plications around and between quartz and feldspar grains. Most of this material appears to be recrystallized largely to stilpnomelane, muscovite, and chlorite. In the least metamorphosed rocks it may be difficult to distinguish recrystallized micaceous material from mechanically distorted detrital micaceous material. Sparse biotite is believed to be distorted detrital material, but the microscopic evidence is inconclusive. Magnetite and other iron oxides, as well as ilmenite, leucoxene, and sphene, are commonly found in the micaceous layers. In interlaminated shale and fine-grained sandstone, the laminations are crenulated into tiny folds in which the shale is squeezed into the sandstone at the fold axes. Although much relict quartz and feldspar is present in the sandstone laminae, the shale is recrystallized largely to stilpnomelane, muscovite, quartz, and albite (?), and the rock has a phyllitic sheen.

In some weakly metamorphosed sandstones, some of the matrix and unstable detrital grains are converted to fibrous bundles of exceedingly small amphibole crystals of the riebeckite-glaucophane series, partly replaced by chlorite and containing laths of lawsonite. In places, fibrous amphibole has been recrystallized to large euhedral crystals. Bluish-gray slaty shale consists mostly of fine-grained amphibole needles of the glaucophane-riebeckite series, small amounts of platy stilpnomelane, and albite veinlets.

In sandstones that have been subjected to more severe metamorphism, most of the detrital quartz grains are recrystallized and elongated into a mosaic of small crystals. The dark micaceous aggregates, representing the matrix and unstable detrital grains, are replaced by varied mineral assemblages. Lawsonite-jadeite aggregates are common, and lawsonite-quartz-chlorite aggregates are also present. Stilpnomelane commonly replaces biotite and chlorite. Clots of stilpnomelane-muscovite studded with lawsonite laths are common in sandstones that contain much unmetmorphosed plagioclase. Leucoxene-magnetite aggregates are commonly associated with stilpnomelane. One semischistose sandstone shows jadeite replacing stilpnomelane in aggregates of stilpnomelane and lawsonite. Some metasiltstones near Knox Point consist of lawsonite, stilpnomelane, albite, and quartz. In other sandstones that are closer to serpentine borders where magnesium metasomatism was affective, tremolite instead of lawsonite is present.

A conglomerate exposed at Blunt Point on Angel Island contains bluish sheared pebbles enclosed in a pale-blue-green matrix with a micaceous sheen. Isolated bluish pebbles are also found in semischistose sandstone along the main road on the west-facing slope southwest of Hospital Cove. The conglomerate contains a large variety of low-grade metamorphic mineral assemblages that vary with the composition and texture of the pebbles and their matrix. Lawsonite, in isolated laths and in clots of randomly oriented laths, is widely distributed. Bundles of fine-grained amphibole of the glaucophane-riebeckite series and muscovite plates are common in the matrix. Chlorite, jadeite, hornblende with glaucophane rims, and intergrowths of muscovite-stilpnomelane, zoisite-lawsonite, lawsonite-stilpnomelane are found in some of the pebbles, whereas metaquartzite pebbles have little or none of these minerals. The pebbles and the matrix appear to have been metamorphosed after the conglomerate was deposited, for both appear to be of the same metamorphic grade and metamorphic mineral crystals traverse the boundary between pebbles and matrix.

Jadeite occurs in sandstone on Angel Island as porphyroblasts and as tiny stumpy prisms intergrown with lawsonite. The sandstone also contains quartz, muscovite, biotite, chlorite and, locally, glaucophane and veins and clots of aragonite (Coleman and Lee, 1962, p. 581). Detrital plagioclase is generally absent.

Jadeite-bearing rock is abundant at or near intrusive greenstone. Point-count analyses of thin sections of sandstones between Campbell Point and Simpton Point and west of Quarry Point show 34–56 percent jadeite. Jadeite is also found in some of the semischistose sandstone near Knox Point. Bloxam (1956, p. 489) reported that "Franciscan graywackes are locally jadeitized***" on the shore midway between the point west of Hospital Cove and a greenstone exposure to the south.

Chemical analyses for three sandstones, including a jadeite-bearing semischist, a jadeite-free semischist, and a jadeite-free unmetamorphosed sandstone, are given in table 5. The analyses show that the three sandstones are remarkably similar in composition and indicate that jadeitization and metamorphism took place under isochemical conditions and that sodium metasomatism was not involved.

TABLE 5.—*Chemical composition of sandstone samples of the Franciscan Formation from Angel Island*

[Rapid-rock analyses by Paul Elmore, I. H. Barlow, S. D. Botts, M. S. Mack, and Gillison Chloe. N.d.=not determined]

Sample locality	1	2	3
SiO_2	68.2	69	72.9
Al_2O_3	13.0	11.7	11.3
Fe_2O_3	1.6	1.0	1.1
FeO	2.7	4.2	2.8
MgO	2.4	3.8	2.7
CaO	2.0	1.3	.60
Na_2O	2.2	2.0	3.8
K_2O	2.2	2.3	.90
H_2O^+	3.2	3.3	2.2
H_2O^-	.50	.30	.39
TiO_2	.62	.70	.56
P_2O_5	.10	.17	.12
MnO	.08	.09	.20
CO_2	1.0	.05	.15
Total	100	100	100
S (aqua regia soluble)	N.d.	0.02	N.d.
Specific gravity (powder)	2.75	2.72	2.62

1. Semischistose; estimated 20 percent jadeite by volume. Collected at shoreline 950 ft southeast of Campbell Point at the boundary line of state park (sample No. 80–RGC–58).
2. Semischistose, jadeite free; contains detrital quartz and plagioclase, authigenic muscovite, stilpnomelane, chlorite, lawsonite, and pumpellyite. Collected at shoreline 750 ft southeast of Campbell Point (sample No. S–39–A).
3. Massive, unsheared, unmetamorphosed, jadeite free. Collected 4,000 ft N. 25° W. of Blunt Point lighthouse (sample No. 80–RGC–58–1).

Jadeite porphyroblasts consist of single anhedral to subhedral equant crystals as much as 1.5 mm in diameter or of slightly larger clots of several crystals. The average diameter of most of the porphyroblasts is larger than what is believed to have been the diameter of the largest detrital grains. Jadeite porphyroblasts are distributed fairly evenly and randomly in the sandstone.

Several stages in the development of jadeite porphyroblasts may be seen in thin section. In an early stage, the jadeite appears in straight-sided masses (suggesting relict plagioclase) of a fine-grained aggregate with considerable amounts of finely divided quartz. In a later stage, it is less clouded with quartz inclusions but occurs in single crystals or in clots of a small number of crystals showing prominent cleavage fractures. At a still later stage, it is mostly transparent and free of inclusions, except for large lawsonite laths in some, and appears as large crystals or clots with irregular borders.

Detrital plagioclase is sparse or completely lacking in semischistose sandstone rich in jadeite, whereas jadeite porphyroblasts are sparse or absent in semischistose sandstone having approximately the usual complement of detrital plagioclase. This relationship strongly indicates that plagioclase is involved in the formation of jadeite porphyroblasts; however, the change is evidently not a direct, simple replacement of the albite component of plagioclase by jadeite and quartz, as suggested by de Roever (1955, p. 289) for jadeitized sandstones from the Celebes. Coleman (1965, p. C27) showed that the Angel Island jadeite contains acmite, diopside, and hedenbergite components. Plagioclase can furnish only part of the elements needed to form the jadeite of Angel Island; thus other detrital minerals must have been involved in its formation.

The chemical composition, physical properties, and paragenesis of the jadeite in the metagraywacke sandstones of Angel Island were given by Coleman (1965, p. 25–34). Coleman found that the jadeite contains 86 percent jadeite molecule ($NaAlSi_2O_6$) and that its unit cell volume is larger than pure jadeite. He suggested that this is evidence that the formation of impure jadeite in the metagraywackes of Angel Island requires less pressure than is required to form pure jadeite. Additional evidence of less pressure is the preservation of clastic textures and other sedimentary features in the jadeitized sandstone (Bloxam, 1956, p. 495).

The metamorphic grade under which the semischists formed—though it varied in intensity from place to place—was that of the greenschist facies, comparable with Hutton's (1940, p. 28, 60–61) subzones Chlorite 1 and 2 of the chlorite zone of the Otago area of New Zealand. Blake, Irwin, and Coleman (1967, p. C3–C5) described metagraywackes in northern California and southwestern Oregon similar to those of the San Francisco North quadrangle and placed them in their textural zones 1 and 2. Some of the rocks shown on the geologic map (pl. 1) as metamorphic rocks are also low-grade schists and in addition may have been graywacke-type sediments. These metamorphic rocks, however, differ from the semischists in having been subjected to more intense metamorphism, though nowhere more intense than that of the greenschist or albite-epidote-amphibolite facies. These schists are generally coarser in texture than the semischists, are wholly crystalloblastic, and are without obvious sedimentary features, such as detrital grains. They contain well-developed amphibole crystals of glaucophane-riebeckite and tremolite-actinolite, in addition to lawsonite, muscovite, albite, quartz, and other minerals. They correspond to metagraywackes of textural zone 3 of Blake, Irwin, and Coleman (1967). These schists are unevenly disposed through the semischists, generally at or near intrusive greenstone or serpentine, but many of them are too small to be shown on the geologic map (pl. 1).

Such an erratic distribution of metamorphic intensities is to be expected in an area where rocks that are heated to temperatures in the lower part of the metamorphic range by burial during orogeny are subject to local shearing or to reaction with chemically active waters (Turner, in Williams and others, 1954, p. 209). Evidently, the presence of the greenstone body influenced the formation of jadeite for the sandstone richest in jadeite lies near or at the border of the greenstone. Semischistose sandstones elsewhere generally lack jadeite. Conceivably, the border zone sustained high pressure during orogeny and also provided access for fluids needed to jadeitize the sandstone. The sodium content (table 5) of jadeite-bearing and jadeite-free sandstones from Angel Island indicates that sodium metasomatism was not significant in the formation of jadeite. Bloxam (1956, p. 493–494) found similar evidence at Valley Ford, Calif.

Inasmuch as the semischists have a greater bulk density than unmetamorphosed rocks, pressure probably also was a factor in jadeitization and metamorphism. High pressure is suggested also by veins and clots of aragonite in the jadeitized sandstone, for calcite is converted to aragonite under pressures greater than 4,000 bars (Coleman and Lee, 1962). Nonschistose sandstone contains calcite rather than aragonite.

Blake, Irwin, and Coleman (1969) suggested that the lawsonite- and jadeite-bearing metagraywackes formed at high-pressure low-temperature conditions below a regional low-angle thrust fault. The presence on Angel Island and Tiburon Peninsula of metagraywackes similar to those of textural zones 2 and 3 of Blake, Irwin, and Coleman (1967) suggests that the metagraywackes were not far below the postulated thrust fault.

Hard dark-gray siliceous beds are abundant in sandstone near some greenstone bodies. The siliceous beds are silicified shale beds and quartz veins following bedding planes. They are ⅜–1½ inches thick and are separated by three-fourth of an inch of sandstone in some places and 3–5 feet of sandstone in other places. Where they are abundant and closely spaced, they are cut by abundant white quartz veinlets as much as one-half inch thick.

Weathering of metamorphosed sedimentary rocks produces sandy silty soils as much as 20 feet thick and weathered rock as deep as 70 feet. The chief clay mineral of the soil and weathered rock is vermiculite, which causes the soil to become plastic and lose considerable shearing strength when wet.

OCCURRENCE

Northeastern San Francisco

Clastic rocks of the Franciscan Formation are the predominating bedrock in northeastern San Francisco. Russian, Nob, and Telegraph Hills consist of two sequences of massive sandstone and of two thick sequences of shale and thin-bedded sandstone. The observed thickness of the four units is 3,650 feet. The basal 400 feet of the youngest sequence, a massive sandstone, is exposed on the north side of Russian Hill. It overlies a shale and thin-bedded sandstone sequence, 1,350 feet thick, exposed on the south side of Russian Hill and on the west side of Telegraph Hill. The shale and sandstone sequence in turn overlies a lower massive sandstone 700 feet thick, exposed on the north side of Nob Hill and over most of Telegraph Hill (fig. 16). The oldest sequence is shale and thin-bedded sandstone of which the upper 1,200 feet is exposed. It constitutes most of Nob Hill.

Bedrock on hills such as Rincon Hill and the hills west of Van Ness Avenue is so poorly exposed, primarily because of intense urban development, that recognition of the predominant lithology was impossible. Consequently, the bedrock in those areas has been mapped as undifferentiated sandstone and shale of the Franciscan Formation.

FIGURE 16.—Massive sandstone of the Franciscan Formation. Old quarry face on the northeast side of Telegraph Hill, San Francisco.

Central Highlands of San Francisco

The sandstones exposed in the central highlands of San Francisco also appear to be in two separate stratigraphic positions. The older sandstone is found at the south base of Mount Sutro and south of Laguna Honda. Radiolarian chert, which forms Mount Sutro, separates it from younger sandstone exposed in the hills south of Mission Dolores. The younger sandstone sequence may be the same sandstone as that exposed to the northwest between Buena Vista Park and Mount Olympus. In other parts of this area, thin sandstone lenses are found interbedded with radiolarian chert and greenstone.

The sandstone at Laguna Honda evidently lies nearly horizontal, judging from the attitude of its contact with overlying radiolarian chert; if so, no more than 200 feet of sandstone is exposed here. The sandstone in the hills south of Mission Dolores dips northeastward and is at least 1,000 feet thick. In the area between Buena Vista Park and Mount Olympus, the sandstone is only about 400 feet thick.

Cliff House to Bakers Beach

Clastic rocks of the Franciscan Formation form the 100- to 200-foot-high cliffs along the shore from Cliff House to Bakers Beach and also occur at the north border of Bakers Beach (fig. 17).

In the cliffs from Cliff House to the shear zone west of Lands End, massive sandstone is interbedded with 100-foot-thick sequences of shale and thin-bedded sandstone. The estimated total thickness is 750 feet. Because of its high potassium feldspar content, the sandstone here is believed to be correlative with sandstone exposed at San Bruno Mountain, 6 miles to the southeast. Mapping by Bonilla (1961) in the San Francisco South quadrangle disclosed the northwest-trending City College fault, which separates the potassium feldspar-bearing sandstone at San Bruno Mountain from the potassium feldspar-free sandstone northeast of San Bruno Mountain. The shear zone at Lands End is thought to be an extension of the City College fault and similarly is the east boundary of potassium feldspar-bearing sandstone. East of the

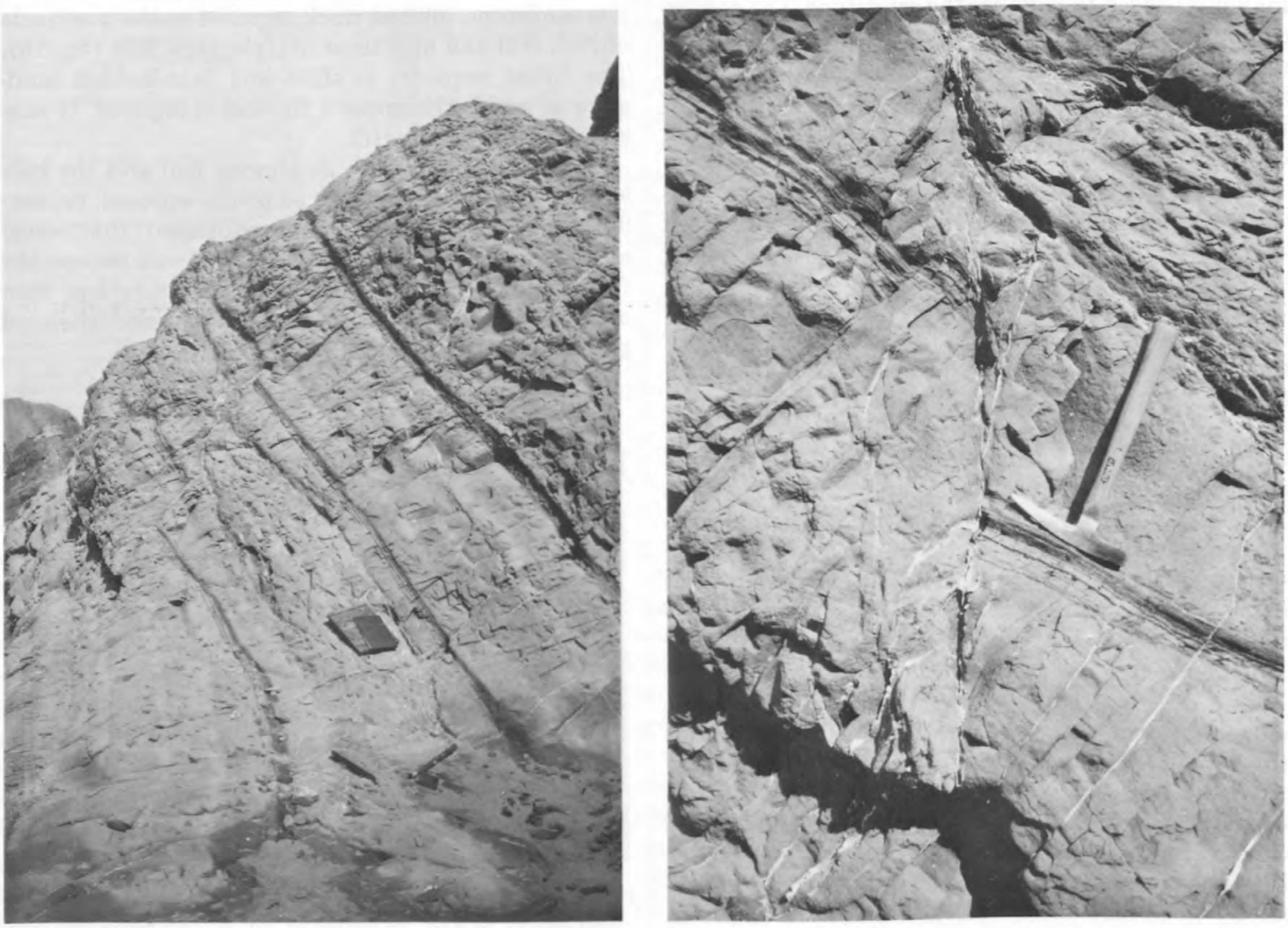

FIGURE 17.—Thick-bedded sandstone, laminated sandstone, siltstone, and shale of the Franciscan Formation. Note a small offset in closeup view (right). Near the north end of Bakers Beach, San Francisco.

shear zone, the sandstone exposed from the east side of the landslide east of Lands End to Bakers Beach is approximately 2,400 feet thick, if the section is a continuous homocline, and dips 30°. This thickness excludes the serpentine at Phelan Beach. In a few places near Bakers Beach, sedimentary features, such as small-scale channels and graded bedding, suggest that part or all of this sequence is overturned.

Fort Point to Potrero Hill

Sedimentary rocks — mostly sandstone — and volcanic and metamorphic rocks occur as tectonic inclusions in a northwest-trending zone of sheared rocks between Fort Point and Potrero Hill. The largest exposed sandstone body is the northeast spur of Potrero Hill. Sandstone predominates in the sheared-rock zone between the U.S. Mint and the Presidio, although most of this area is shown by Lawson (1914) as a continuous body of serpentine.

Marin Peninsula

On Marin Peninsula sandstone occurs in at least three separate sections. The oldest sequence, Lawson's (1914) Cahil Sandstone, now abandoned, is about 1,700 feet thick and is exposed along the northeast shore in a narrow belt that widens on the ridges to the northwest of Sausalito. It is overlain by greenstone and radiolarian chert beds 1,000–3,000 feet thick, which in turn are overlain by younger sandstone, about 1,000 feet thick, exposed from near Lime Point nearly continuously for more than 2 miles along its strike. The roadcut on the west side of U.S. Highway 101, about three-fourths of a mile north of the Golden Gate Bridge, contains an excellent exposure of the lower part of this sandstone (fig. 18). The youngest sandstone sequence crops out about one-third mile west of the second sandstone. It is largely concealed by slope debris and ravine fill, but it is nearly continuous for about one-third mile from the large exposure shown on

FIGURE 18.—Thick-bedded sandstone interbedded with shale and thin-bedded sandstone of the Franciscan Formation. West side of U.S. Highway 101, three-fourths of a mile north of Golden Gate Bridge, Marin Peninsula.

the geologic map (pl. 1) northwest toward the buildings in Fort Baker. Thin belts of sandstone are also exposed to the west and southwest.

Angel and Alcatraz Islands and Tiburon Peninsula

Sandstone is exposed over about two-thirds of Angel Island and makes up the crest of Mount Caroline Livermore (fig. 5). Almost all the clastic rocks here, however, are semischistose. (See page 20.) The southwestward-dipping section from Campbell Point to Hospital Cove is approximately 1,300 feet thick. The northward-dipping section from the south shore, west of Blunt Point, to the top of Mount Caroline Livermore is estimated to be at least 1,850 feet thick. An intervening greenstone body, 350 feet thick, was excluded from this total. Ransome (1894, p. 198) believed that 2,000 feet is a conservative estimate for the exposed thickness of the sandstone on Angel Island.

In the 1860's, sandstone of the Franciscan Formation was quarried on Angel Island and used extensively as a building material. The rock is described as being "used chiefly for purposes where beauty and strength are not absolutely required, for this rock possesses neither qualification in a high degree, although it answers very well for ordinary uses in the mild and equable climate of San Francisco." (Whitney, 1865, p. 77).

Conglomerate is interbedded with sandstone at the north end of Simpton Point on Angel Island. It also is exposed about 2,400 feet east of Stuart Point. A pebbly sandstone crops out along the west shore, north of the serpentine body. All these occurrences probably have the same stratigraphic position. (See p. 20.)

Alcatraz Island, except for a few patches of surficial material, is entirely sandstone and a few minor shale beds. The exposed thickness of rocks is approximately 500 feet.

On Tiburon Peninsula exposed sequences of sandstone and shale are 5–30 feet thick. Much of the southeastern part of Belvedere Island, as well as a narrow belt along the southwest shore, is sandstone that contains small amounts of shale. The exposed thickness of clastic rocks on Belvedere Island is estimated to be 1,000 feet. Most sandstone and shale on Tiburon Peninsula and Belvedere and Corinthian Islands are semischistose.

ORIGIN

Environment of Deposition

A marine environment of deposition for the Franciscan Formation is indicated by fossils and the interbedded greenstones. Though sparse, marine Mollusca are found in clastic rocks, and Radiolaria, today exclusively marine, are found in chert and in some limestone. Radiolarian chert is also found interbedded with greenstone flows which generally show pillow structure, a characteristic of subaqueous eruption.

Formations equivalent in age to the Franciscan, such as the Knoxville Formation of Late Jurassic age and the Lower and Upper Cretaceous beds of the Great Valley sequence, represent slope and shelf sedimentation in the less orogenically active parts of the continental crustal plate that existed in Franciscan time (Irwin, 1957, p. 2292). The juxtaposition of the eugeosynclinal facies and the shelf and slope facies in the modern Coast Ranges is a result of movements of the oceanic and continental crustal plates.

Turbidity currents are thought to be capable of carrying sand to deep-sea basins (Kuenen, 1950, p. 360, 367; Shepard, 1951, p. 53–65). Kopstein (1954, p. 63) suggested also that the high velocities measured on submarine turbidity currents render them capable of carrying "large pieces of gravel." The materials for the sparse conglomerate beds and for the massive nongraded or poorly graded graywacke sandstone beds and the interbedded shale and thin-bedded sandstone sequences were probably transported by turbidity currents. A mass of unconsolidated detritus of various sizes from clay to sand or possibly gravel, lying on a nearshore submarine slope, could be set in motion by an earthquake or by storm waves (Heezen and Ewing, 1955, p. 2505–2514). The ensuing slump or mudflow could become a turbidity current of sufficient energy to transport most of the material en masse (Kuenen, 1951, p. 31). Thin graded beds of sand and mud would be deposited by weaker turbidity currents. Many of the lithologic features of the Franciscan clastic sedimentary rocks, such as graded bedding, small-scale channeling, ripple marks, and cross-bedding, can also be produced by turbidity currents. Thus preponderant evidence suggests a deepwater turbidity current origin for the Franciscan Formation.

As compared with Kopstein's (1954, p. 92–93) tabulation of evidence for deepwater accumulation of graywacke in Harlech Dome, Wales, further evidence for deepwater accumulation in the Franciscan includes the following: (1) Shale layers between graded beds; (2) extremely rare fossils; (3) abundant small-scale current bedding; (4) current-ripple marks; and (5) graded bedding, load casts, flow markings, slump structures, and associated features in some sections. Furthermore, Sanders and Swinchatt (1957, p. 1791) believed that the deepwater hypothesis is correct for the origin of the radiolarian cherts of the Franciscan Formation.

Local large masses of greenstone in the Franciscan Formation have been compared with seamounts (Bailey and others, 1964, p. 43), and limestone associated with greenstone may represent corals and other shallow-water calcareous organisms that grew on the tops of seamounts (E. H. Bailey, oral commun., 1966). Gradation of greenstone agglomerate and tuff into tuffaceous sandstone and nontuffaceous sandstone could have been brought about by reworking and mixing of detritus from land and from pyroclastic rocks erupted during Franciscan time.

SOURCE AREA OF DETRITUS

Clasts in the conglomerates and sandstones provide a few clues to the kinds of rocks present in their source area. The coarse clasts consist of (1) sandstone, shale, and volcanic rocks similar to those of the Franciscan Formation and (2) cherts, quartzites, volcanic, or dike rocks unlike those of the Franciscan Formation. The sandstones of the quadrangle also contain clasts of granitic rocks, metamorphic rocks, and serpentine as well as clasts of the same rock types as the conglomerates. Heavy mineral grains in the sandstone are predominantly mica, chlorite, vermiculite, epidote, clinozoisite, pumpellyite, sphene, and garnet, which are common in low-grade metamorphic rocks and altered volcanic rocks. The heavy mineral fraction of the sandstones contains only small amounts of zircon, rutile, and tourmaline, which are minerals characteristic of granitic and related metamorphic rocks. Chromian spinel found in sandstone near the Golden Gate Bridge and on Angel Island was probably derived from ultramafic rocks or from an older sedimentary rock containing ultramafic-rock detritus.

Abundant clasts of Franciscan-type sandstone, shale, and volcanic rocks in the sandstones and conglomerates suggest "self digestion" of topographically high areas above or below sea level created by local orogeny during the time of accumulation of the Franciscan Formation. The clasts may also have been derived, however, from pre-Franciscan sedimentary and volcanic rocks. In addition, sandstone and conglomerate clasts suggest a source area containing metamorphic and non-Franciscan volcanic rocks. Rocks similar to the clasts are exposed in the Coast Ranges, Klamath Mountains, and Sierra Nevada (fig. 6). Bailey, Irwin, and Jones (1964, p. 39–41) are in agreement with these conclusions.

Taliaferro (1943, p. 136–139, 141) suggested that granodiorite was a prominent rock in the landmass from which the Franciscan Formation was derived. Granodiorite or other granitic rock types, however, were not seen in the Angel Island conglomerates and are rare in other conglomerates in the quadrangle. If detrital grains had been derived from a granodiorite terrane, their composition would be similar to the constituents of the granodiorite and would be present in similar proportions. The freshness of the plagioclase grains and their angularity indicate that mechanical weathering predominated over chemical weathering. The composition of detrital grains is more similar to metamorphic and volcanic rocks.

The average granodiorite, according to Johannsen (1932, p. 321), contains 22 percent potassium feldspar. The granodiorite or quartz diorite of Montara Mountain (14 miles south of the mapped area), which would be typical of a possible local source rock, contains as much as 10 percent potassium feldspar. The complete absence of detrital potassium feldspar in most of the Franciscan sandstones in the map area precludes granodiorite as a prominent rock type in the source area. And as potassium feldspar is generally more stable than plagioclase feldspar, which is present in the sandstone, the absence of potassium feldspar cannot be attributed to differential alteration of the sand grains.

The mapped area is too small and the data are too sparse to determine the direction of the source area from textural coarsening and thickening of conglomerate beds. A few linear structures suggest a westerly current flow, such as casts of striations and grooves on the bottom of sandstone beds in the section nearest the Golden Gate Bridge in Marin County.

AGE

FOSSILS

Fossils have been found at only five localities in clastic rocks of the Franciscan Formation in this quadrangle. The only ones useful for age determination are Cretaceous in age.

At an unnamed point along the shore of the South Bay of the Golden Gate, 800 feet west of James D. Phelan Beach State Park (pl. 1), the ammonite *Douvilleiceras* sp. was found in beds called Marin Sandstone by Lawson. This ammonite is thought to be of late Early Cretaceous (Albian) age (Schlocker and others, 1954, p. 2373). At this same locality, the writer found a gastropod resembling the holotype of *Paladmete perforata* and an undetermined pelecypod, but neither was useful for age designation.

On the beach north of the Needles on Marin Peninsula near the Golden Gate Bridge, *Mantelliceras* sp. was found in float probably derived from nearby sandstone beds. This ammonite is thought to be of Early or early Late Cretaceous age "a little later than that given for the specimen of *Douvilleiceras****" (Hertlein, 1956, p. 1987.).

Pelecypod casts from an unrecorded locality on Alcatraz Island were described by Gabb (1869, p. 193), by Stewart (1930, p. 106), and by Anderson (1938, p.

121). According to Stewart, *Inoceramus ellioti* Gabb is probably Cretaceous in age. Anderson assigned an Early Cretaceous(?) age to *Lucina alcatrazis*.

Bailey, Irwin, and Jones (1964, p. 115–123) discussed fossils in the Franciscan Formation in localities outside the quadrangle.

Gray limestone lenses found in sheared sandstone and shale north of Sausalito contain Radiolaria preserved in calcite and pyrite. Similar Radiolaria are abundant in phosphate nodules found in sheared sandstone and shale near the southeast end of Laguna Honda Reservoir. The Radiolaria are similar in appearance to some of those in the chert and shale described by Hinde (1894, p. 235–240) and by Riedel and Schlocker (1956, p. 357–360). The Radiolaria indicate a Jurassic or Cretaceous age.

In a discussion of the phosphate nodules just mentioned, Dickert (1966, p. 292) attributes to W. R. Evitt the identification of *Marthasterites tribrachiatus* [*recte Discoaster tribrachiatus* Bramlette and Sullivan], a calcareous nannofossil known from the California Eocene. Evitt reexamined the thin section studied by Dickert and reported (W. R. Evitt, oral commun., 1966) that the objects referred to are not *Marthasterites* or triradiate discoasters but are probably radiolarian spines with conspicuously triradiate cross sections. Similar fossils are common in Franciscan cherts north of the Golden Gate in association with abundant Radiolaria. According to Evitt, no age significance should be attached to these triradiate objects; certainly they should not be the basis for suggesting that Tertiary fossils have been identified from Franciscan sedimentary rocks.

Lawson (1914) thought that the oldest formation of his Franciscan Group was the Cahil Sandstone; he thought this sandstone was separated from the overlying Marin Sandstone by the Sausalito Chert. Lawson's Cahil Sandstone contains the foraminiferal Calera Limestone Member, whose type locality is along the Pacific Ocean shoreline 9½ miles south of the map area. Foraminifera from the Calera Limestone are considered to be early Late Cretaceous in age (Kupper, 1956, p. 41). Inasmuch as Lawson referred to the *Douvilleiceras*-bearing sandstone of late Early Cretaceous age as his Marin Sandstone, paleontologic data suggest that his Cahil Sandstone is younger than his Marin Sandstone.

Significance of potassium feldspar content

Bailey and Irwin (1959) and Bailey, Irwin, and Jones (1964, p. 138–141) determined the potassium feldspar content of the thick shelf and slope facies (miogeosynclinal) in the Coast Ranges (Great Valley sequence) along the west border of the Sacramento Valley. This facies represents almost continual deposition from Late Jurassic to Late Cretaceous time. The same workers determined the potassium feldspar content of Mesozoic miogeosynclinal sandstone in other parts of the Coast Ranges. They found that the potassium feldspar content increased systematically with decreasing age of the rocks. The median potassium feldspar content of Upper Jurassic rocks was found to be less than 0.5 percent, Lower Cretaceous rocks 1.1 percent, and Upper Cretaceous rocks 13 percent. Bailey, Irwin, and Jones (1964) suggested that all the sediments were derived from the same source—the ancestral Sierra Nevada and the Klamath Mountains of northwestern California, which were created during the Nevadan orogeny. As the granitic rocks emplaced during the orogeny became increasingly exposed and eroded, the potassium feldspar content of the sediments derived from them increased. Thus the potassium feldspar content should roughly indicate the age of the sediments.

Contradictions unfortunately arise, however, when this dating technique is applied to the Franciscan Formation in the mapped area, with the assumption that the rocks have all been derived from the same source area. Thus, the complete absence of potassium feldspar in most sandstones (fig. 14, table 2) would indicate a Jurassic age; yet, the fossils are of late Early or early Late Cretaceous age. Bailey, Irwin, and Jones (1964, p. 141) suggested, therefore, that the assumption of a similar source for all the rocks is invalid and that the absence of potassium feldspar is not necessarily diagnostic of age.

A notable exception to the general absence of potassium feldspar in Franciscan sandstone is the sandstone in the Point Lobos area, which averages 5–10 percent. On the basis of its high potassium feldspar content and its location southwest of a shear zone thought to be part of the City College fault (see section "Cliff House to Bakers Beach"), this sandstone may be part of the Great Valley sequence sandstone of San Bruno Mountain (Bailey and others, 1964, pl. 1).

The high (about 20 percent) potassium feldspar content of the sandstone of San Bruno Mountain together with such features as well-developed bedding, abundant flow casts and load casts, and general absence of shearing and interbedding greenstone and chert suggest that this sandstone is part of the miogeosynclinal (Great Valley sequence) facies. Lawson (1914, p. 17) also noted that this sandstone "differs from the usual sandstone of the Franciscan."

Thus, until more is known of the structure of the Franciscan Formation and better indications of its age are found, the age of the Franciscan in the quadrangle must be considered to range from probable Jurassic to Early and Late Cretaceous. The probable Jurassic age is suggested by the Jurassic or Cretaceous age of the Radiolaria and by the presence of a great thickness of Franciscan Formation lying structurally below the sandstones containing the Cretaceous fossils.

GREENSTONE

Greenstone is a term often used for dark igneous rocks of indeterminate composition and origin having green alteration products. The greenstone of the San Francisco area is mostly fine- and medium-grained basalt that has been subjected to little or no alteration and basalt that has been subjected to a variety of local and regional conditions of alteration and metamorphism. The most common types are unmetamorphosed moderately fresh basalt and rocks of basaltic chemical composition that consist mostly of pumpellyite, primary pyroxene, albite, and chlorite. Some of these are rich in albite and could be called spilite. The metamorphosed greenstone of Angel Island, Belvedere Island, and Tiburon Peninsula also contains epidote, lawsonite, glaucophane, hydrogarnet, vesuvianite, and pyroxene. The field identity of many of these rocks is obscured by their dense, aphanitic texture, by close fracturing, and by a variety of chemical and mineralogical alterations. The bulk of the greenstones are probably flows and commonly show pillow structure. Pyroclastic rocks are present in smaller volume. Except for thin intrusive rocks in radiolarian chert, intrusive greenstone could not be distinguished from flows.

A long history of volcanism during Franciscan time is indicated by the large masses of greenstone that occur throughout thick sections of clastic rocks and radiolarian chert.

Like other rocks of the Franciscan Formation, greenstone forms the hilly parts of the quadrangle. The widespread alteration of greenstone to rock containing substantial proportions of clay minerals and the almost universal randomly oriented close fracturing of greenstone are important influences on its natural slopes. With a few notable exceptions, greenstone slopes are smooth and subdued. Small landslides of weathered greenstone debris are common.

On Marin Peninsula several large valleys, such as the one draining into Horseshoe Bay and the one draining into the Golden Gate channel west of Lime Point, are bordered by greenstone and presumably have been cut into it (fig. 7). Fresh greenstone is very resistant to erosion in such places and forms the steep sea cliffs and stacks at Stuart, Knox, and Blunt Points on Angel Island, Point Diablo along the Golden Gate channel, Marin Peninsula, and Lands End (figs. 19, 20).

FIGURE 19.—High cliff of greenstone in the Franciscan Formation. Lime Point, Marin Peninsula, viewed north. The cliff rises 400 feet above the water in the Golden Gate. In the middle distance, greenstone underlies white to light-gray slopes; radiolarian chert or graywacke sandstone and shale underlie dark slopes. West (left) side of Golden Gate Bridge tower rests on greenstone; east side rests on radiolarian chert and shale.

FIGURE 20.—Greenstone and radiolarian chert of the Franciscan Formation. Point Diablo, north shore of Golden Gate, Marin Peninsula, on the west edge of the quadrangle. The top of the cliff is 625 feet above sea level. Conspicuously jointed rock at the extremity of the point is greenstone (KJg). It is separated by an east-west shear zone from radiolarian chert (KJc) that makes up the ridge and the light-colored base of the cliff. Greenstone also makes up the central part of the cliff.

MEGASCOPIC FEATURES

Fresh greenstones is dark gray or greenish gray. Moderately altered greenstone is grayish green and grayish olive. The greenstone most commonly exposed is weathered or hydrothermally altered rock of moderate brown, dark yellowish-brown, or moderate reddish-brown colors. Hydrothermally altered greenstone is also grayish orange and light yellow green at and near radiolarian chert contacts.

Iron and manganese oxidation and hydration products are commonly found as thin films of bluish black, brownish black, yellow, orange, or brown on joints in altered greenstone. Brown and yellow-green waxy scaly deposits of nontronite, ½–4 mm thick, are also commonly found in joints. Moderately fresh greenstone may have the deceptive appearance of being highly altered, owing to the presence of thin earthy coatings of nontronite and iron oxides on joints. Most of the freshest pillow basalt near Horseshoe Bay has a unique greenish-gray vitreous or pitchy luster that is caused by a thin film of slightly sheared chlorite on slickensides, joints, or small faults. Fresh fractures in this rock usually reveal a medium- to fine-grained holocrystalline rock.

On Angel and Belvedere Islands and on Tiburon Peninsula, bright blue joint fillings of crocidolite, as much as one-eighth inch thick, are conspicuous in exposures of reddish-brown altered metamorphosed greenstone.

Closely spaced fractures are the most conspicuous structural feature of greenstone (fig. 21). Most of the greenstone is so thoroughly fractured that it shatters easily into pieces ⅛–¼ inch across. Only rare exposures yield coherent pieces more than 2 inches across. Examples of the latter rock are the aphanitic and porphyritic greenstone on Anza Street on the northwest side of Lone Mountain in San Francisco and the fresh aphanitic pillow greenstone exposed in the west roadcut on U.S. Highway 101, 400 feet northwest of the Waldo Tunnel in Marin County. Fracturing may have resulted from violent steam explosions during submarine eruptions, rapid cooling-shrinkage of the hot lava and pyroclastic deposits, or severe and repeated stresses during several orogenic episodes.

FIGURE 21.—Close random fracturing in greenstone of the Franciscan Formation. South side of road to Sausalito, 0.1 mile east of U.S. Highway 101, 0.8 mile north of Lime Point, Marin Peninsula. The wood stake lying on the cut is 1 foot long.

Tectonic breccias occur in 5–40-foot-wide zones bordering some faults. In these zones the rock has been fractured, sheared, and crushed and now consists of rock pieces, ¼–1 inch in diameter, in a matrix of crushed rock of sand and smaller sizes. It is difficult to distinguish such breccias from agglomerates and volcanic breccias. Because of small-scale random fracturing, massive and pillow greenstone at many exposures shows rough surfaces that consist of irregularly shaped ⅛–½-inch projections, which give the rock the appearance of a tectonic or volcanic breccia.

In some exposures of massive greenstones, in contrast with randomly oriented fracturing, fractures at intervals of ½–1 inch are open, parallel, and straight sided. Subparallel, irregular, and discontinuous vesicles also occur in such exposures. Both the fractures and vesicles have drusy linings of calcite, doubly terminated quartz, zeolites, and hematite. These fractures and vesicles apparently formed during and shortly after solidification of the lava.

Pillow structures occur in basalts, in altered rocks of basaltic composition, and in spilites. Pillow structures are rounded bodies 6 inches to 10 feet across in greatest dimension. About half the observed pillows are 8–10 inches thick, 12–18 inches wide, and 18–24 inches long, although some exposures consist predominantly of pillows several times as large. Exposures consisting predominantly of large pillows also contain some smaller more spherical pillows, 6–10 inches in diameter. Small pillows tend to be spheroidal rather than ellipsoidal, although spheroidal pillows 4 feet in diameter have been seen.

The surfaces of adjacent pillows are closely conformable in shape to one another, like mold and cast, but are separated by gaps of clayey material ⅛–12 inches thick. Pillows are generally shaped like a stretched-out bun and usually have a convex top and a flat or concave bottom (fig. 22). The bottom of some pillows projects downward between adjacent underlying pillows. The middle of the upper surface of some pillows is depressed; such pillows commonly are overlain by pillows with convex bottoms that conform in shape to the pillows below. Commonly, a pillow may consist of a thick central part and a thinner appendage.

In the Fort Baker area of Marin County, the bottom surfaces, top surfaces, and longest axes of the pillows are roughly parallel to the bedding of the enclosing rocks (fig. 23).

The outer surface of a fresh pillow commonly consists of a rind of slickensided chloritic material about one-fourth inch thick, evidently derived from glass

FIGURE 22.—Basalt pillows. The basalt here consists of pumpellyite, pyroxene, albite, and chlorite. West side of U.S. Highway 101, 1½ miles north of Golden Gate Bridge, Marin Peninsula.

formed by rapid cooling. Shallow chlorite-lined joints about ½–2 inches apart thoroughly dissect the surface and probably also formed during cooling. Other pillows have a rough, knobby surface. Some pillows show a slight increase in grain size from rim to center, although many fresh pillows are wholly aphanitic or consist wholly or partly of fine- to medium-grained varioles. Many pillows are cut by strong radial joints and veins. The radial joint pattern is considerably modified in many pillows by a swarm of randomly oriented onionskinlike fractures that cut the pillow into pieces not more than one-half inch thick (fig. 24). Although most pillows are not vesicular, the outer 3–4 inches of a few are spotted with sparse vesicles or amygdules as large as three-eighths inch in diameter. Still others have vesicular cores and solid rims.

Pillow structure is readily discerned in fresh and moderately altered greenstone, but it can also be recognized even in highly altered greenstone by strong curving joints that follow the surface of the pillows. Intense shearing and brecciation, however, destroy pillow structure.

Most pillows are separated from each other by soft sheared chloritic or nontronitic clay, which may be easily dug out with the fingers. Rarely, the material between the pillows is massive red or green chert or green, gray, or brown limestone. The separation of the pillows averages 1 inch or less; a greater spacing is not uncommon, but a spacing as great as 1 foot is rare.

Massive greenstone is second to pillow greenstone in abundance. Although its altered and fractured condition does not permit positive identification of flow surfaces or flow jointing or banding, much of this greenstone is believed to have originated as submarine lava flows, for it is closely associated with pillow greenstone, radiolarian chert, and marine sandstone. The better exposed contacts show that the association of massive greenstone with these rocks is probably depositional, although many contacts are abrupt faults perpendicular to the bedding. Tabular bodies of massive and pillow greenstone, 2–5 feet thick, intrude radiolarian chert and shale. At some places they connect with irregular intrusive bodies 10–15 feet in diameter. In a few localities massive greenstone is moderately vesicular or amygdaloidal.

Pyroclastic greenstones are minor in bulk, but they occur in small volume in nearly every greenstone terrane. One of the largest exposures of pyroclastic greenstone is on Marin Peninsula facing Golden Gate channel at the west end of a small elbow beach, 3,500 feet west of Lime Point (fig. 34). The rocks are bedded tuffs, lapilli tuff, agglomerate, and pillow lava, all dip-

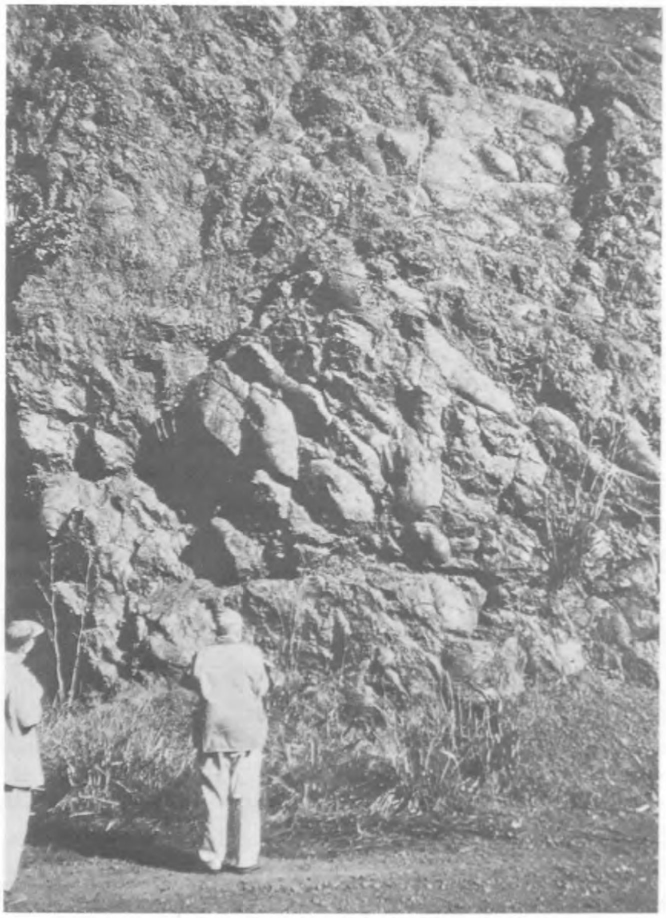

FIGURE 23.—Pillow basalt of the Franciscan Formation, Fort Baker, Marin Peninsula. Dip down to the right (southwest) is suggested by the orientation of the pillows.

ping 35°–45° southwest. The lowermost bed, about 130 feet thick, is mostly grayish-orange laminated tuff containing a few lenses and nodules of red and green chert and a few agglomeratic beds made up of 1–4-inch ejecta. The overlying bed, about 40 feet thick, is predominantly agglomerate, but it contains a few thin flows of pillow lava and a few beds of lapilli tuff. The topmost part of the section, about 80 feet thick, is mostly pillow lava with a minor amount of lapilli tuff. Reddish-brown tuff, lapilli tuff, and agglomerate beds, closely associated with pillow lava, can also be seen at Stuart Point, Knox Point, and northwest of Simpton Point on Angel Island, on Sunset Heights (near 16th Avenue and Moraga Street) in San Francisco, and on Twin Peaks at the south edge of the quadrangle.

In the volcanic breccias and agglomerates, pieces as much as 1 inch in diameter are most abundant; pieces 1–4 inches in diameter are common, but larger pieces are uncommon. Greenstones at the shore between Campbell and Simpton Points on Angel Island contain rounded blocks, as large as 1 foot in diameter, that appear to be ejecta that may be transitional between volcanic breccia and pillow lava.

Tuff beds are sparse. They are of fine to medium grain size. Some of them may have been mapped inadvertently with sandstone and shale of the Franciscan Formation, which they resemble closely and into which many of them grade.

Pipelike bodies of greenstone consisting of unsorted breccia pieces as much as 8 inches in diameter may be volcanic vent fillings.

MINERALOGY-MICROSCOPIC FEATURES

The greenstones of San Francisco are aphanitic to fine-grained altered basalts or altered rocks of basaltic chemical composition. The most common textures in basalt are intergranular, intersertal, or subophitic. Ophitic and hyaloophitic textures are less common. One thin section may show several textures. Glomeroporphyritic clots of pyroxene ophitically enclosing plagioclase laths are common in some pillow basalts. Other pillow basalts contain intergrowths of plagioclase and pyroxene laths that are arranged radially as varioles in the outer half of the pillow. Plagioclase laths in basalt reach lengths of 2 mm and vary from andesine to labradorite (An_{35}–An_{62}). Pyroxene is mostly augite and pigeonitic augite; pigeonite and titaniferous augite are less common. One rock contains aegerine microphenocrysts, whereas the groundmass pyroxene is plumose augite. Magnetite and ilmenite are abundant in basalt. Olivine, now replaced by chlorite, is found in a few basalts. Pyrite is common in small amounts in the freshest basalts; apatite is rare. A medium-grained basalt northwest of Horseshoe Bay contains about 5 percent quartz; its major constituents are labradorite and augite.

The basalts are all altered to varying degrees. Nontronite, chlorite, and leucoxene are common alteration products. Plagioclase cores in some basalts are altered to epidote and micaceous minerals. Veinlets of secondary minerals are abundant and include nontronite, chlorite, calcite, aragonite, quartz, stilpnomelane, hematite, leucoxene, zeolites, pumpellyite, and albite. The occurrence of veinlets of pumpellyite, albite, and laumontite indicates a gradational metamorphism to the zeolite facies (Turner and Verhoogen, 1960, p. 532). Tiny amygdules, about 1 mm in diameter, are found sparsely disseminated in most basalts. Most of them are chlorite and (or) nontronite. Larger amygdules are abundant in some rocks and consist of prehnite, calcite, and mordenite, enclosed and veined by chlorite and nontronite.

The altered rocks of basaltic composition (zeolite facies) contain relict basalt textures preserved mostly by primary pyroxene and by albite (An_0–An_6), chlorite, and pumpellyite. Some rocks contain abundant altered olivine phenocrysts; others may be spilites (Turner and Verhoogen, 1960, p. 258). Pyroxene is generally pigeonitic augite or titaniferous augite, though it is absent in some rocks. Nontronite, stilpnomelane, quartz, calcite, epidote, sphene, amphiboles, zeolites, iron oxides, and leucoxene are also present. Calcic plagioclase is generally sparse.

Greenstones on Rincon Hill, Russian Hill, Lone Mountain, and a few other locations are porphyritic with plagioclase (albite, An_6, to andesine, An_{43}) phenocrysts as much as 5 mm long set in a dense, cryptocrystalline groundmass. Albite is also in the groundmass as microlites or as clear rims on cloudy plagioclase microlites.

Another common type of greenstone is typified by the dense pillow lavas exposed in cuts along U.S. Highway 101, 1,000 feet north of the twin vehicular tunnels in Marin County; this rock consists largely of varioles, a few microphenocrysts, and abundant veinlets. Most of the varioles are radially arranged laths of pumpellyite, diopsidic augite, and albite, small amounts of opaque ores, and sphene. Pyroxene and olivine microphenocrysts are replaced by chlorite and pumpellyite; calcite, quartz, albite, and pumpellyite veins cut the rock. Veinlets of quartz with borders of pumpellyite needles are very common.

WEATHERING AND HYDROTHERMAL ALTERATION

Most exposed greenstone is weathered or hydrothermally altered to brown and orange rock. Fresh gray and green greenstone is rarely seen in natural exposures except at steep shores that are being actively washed by waves. At such places on Marin Peninsula and on Angel Island, the weathered zone is a band 10–40 feet thick. The base of the weathered band is a 1–2-foot-thick transitional zone that is parallel to the configuration of the ground surface at the top of the exposure. Hydrothermally altered greenstone masses generally do not conform to the configuration and may be much thicker than the zone of weathered greenstone. In many places weathered greenstone is hard to distinguish from hydrothermally altered greenstone. The rocks in many natural exposures, moreover, have been affected by both processes.

Hydrothermal alteration in greenstone is most intense in and adjacent to faults and at contacts with radiolarian chert. The zone of hydrothermal alteration along faults may be as much as 50 feet wide. Intense hydrothermal alteration along many contacts with radiolarian chert has converted the greenstone, in an irregular zone 5–20 feet wide, to a soft clayey and sandy material of a distinctive grayish-orange color (fig. 24). Because of its light color and softness, this material resembles an acid tuff; however, hand-lens examination reveals a relict intergranular texture. Wide, gradational, and irregular contacts with fresher massive or pillow lavas also suggest altered greenstone.

The mineralogy of the altered greenstones is variable. In weathering, the chief alteration product is generally nontronite, an iron-bearing member of the swelling-clay group montmorillonite. An early effect of weathering is the conversion of chlorite to vermiculite and nontronite. At a further stage of weathering, feldspars, pyroxene, and other minerals are converted to nontronite.

Hydrothermally altered greenstone contains one or more of the following minerals in the clay-size fraction (smaller than 2 microns): Vermiculite, halloysite, hydrous mica, chlorite, and nontronite. Random mixed-layering of mica, chlorite, and vermiculite is common. In many localities halloysite or hydrous mica is the predominating mineral in the greenstone at contacts with radiolarian chert. The formation of halloysite, a common mineral in hydrothermally altered greenstone, is favored by an acidic environment during alteration (Keller, 1956, p. 2701). Radiolarian chert at contacts with greenstone is often replaced almost entirely by oxidized manganese minerals in a zone a few inches thick. Joints in the adjacent chert and in highly altered greenstone are lined with films of conspicuous black manganese oxide minerals.

The chemical composition of greenstones is given in table 6. The composition of the basalt (analysis 1) is similar to that of the pumpellyite-pyroxene-albite-chlorite rocks (analyses 2, 3, 4), and compositions of both rock types generally fall within the composition range for basalts as given by Kuno, Yamasaki, Iida, and Nagashima (1957, p. 213), Turner and Verhoogen (1960, p. 208, 220), Poldervaart (1955, p. 134), and MacDonald and Katsura (1961, p. 362).

OCCURRENCE

MARIN PENINSULA

On Marin Peninsula, the greatest thickness of greenstone in the quadrangle, totaling 4,800 feet, is exposed at several stratigraphic positions in the thick southwestward-dipping section of the Franciscan Formation. Here the greenstone consists predominantly of pillow lavas but also includes massive greenstone and pyroclastic rocks. The lowermost mass exposed along the shore of San Francisco Bay west of Yellow Bluff is at least 1,700 feet thick; it may be as much as 2,700 feet thick if it underlies the Quaternary deposits in the valley north of Horseshoe Bay.

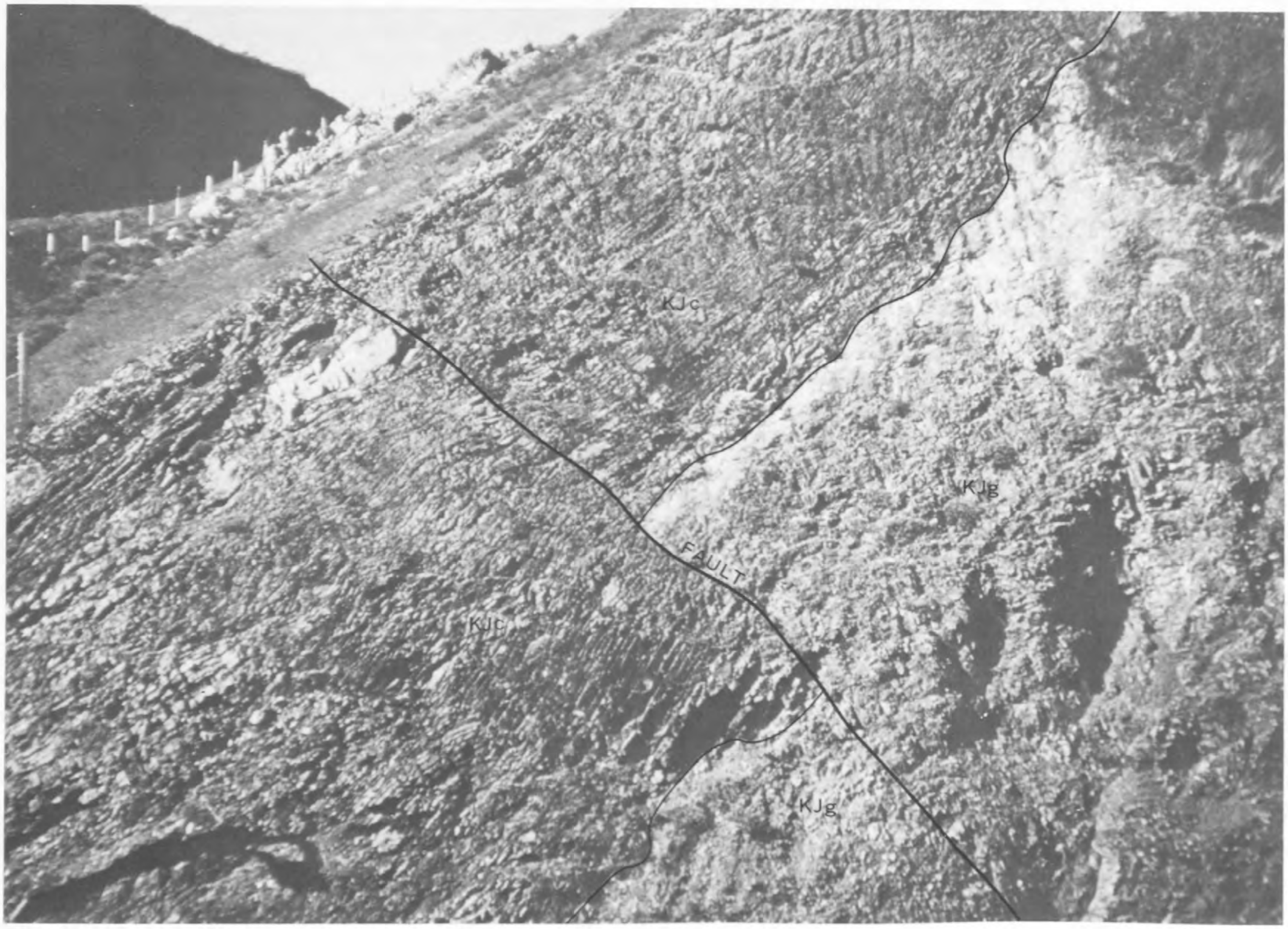

FIGURE 24.—Radiolarian chert, KJc, overlying basaltic greenstone, KJg, all within the Franciscan Formation. The contact is offset by a small fault. Light-colored greenstone at the contact is almost completely altered to clay minerals. North roadcut on lateral road to Sausalito, 400 feet east of U.S. Highway 101, 1.2 miles north of Lime Point, Marin Peninsula.

Radiolarian chert north of Horseshoe Bay is interbedded with this greenstone. The chert increases in thickness northward, and at a point 1½ miles northwest of Yellow Bluff, the greenstone lenses out (pl. 1). Such large variations in thickness over short distances and close association with radiolarian chert are characteristic of greenstone. Unaltered basalt containing augite and labradorite is especially abundant, though erratically distributed, near Lime Point and west of Horseshoe Bay.

San Francisco

The largest mass of greenstone in San Francisco, approximately 2,400 feet thick, is exposed from Twin Peaks southward into the adjoining quadrangle. Two greenstone bodies, 700–1,000 feet thick, are found in the hills between Portola Drive and Valencia Street. Unaltered basalt containing augite and labradorite is also erratically distributed in this area.

A large mass of greenstone may underlie the cover of dune sand at Buena Vista Park hill. Small exposures of greenstone are found widely scattered in other parts of San Francisco.

A small body of porphyritic dacite breccia near Lands End and one of medium-grained hornblende quartz keratophyre along Market Street east of Twin Peaks are included with the greenstones, but nothing is known of their field relations with other rock types.

In contrast with the great volume of greenstone interbedded with the sedimentary rocks elsewhere, greenstone is almost completely absent from the clastic rocks exposed between Rincon Hill and the Presidio. Volcanism, therefore, was largely inactive when these rocks were deposited; these rocks probably are not the same age as the Franciscan Formation a short distance to the north on Marin Peninsula and a short distance to the south at Twin Peaks and vicinity, unless—as seems unlikely—volcanic centers were so localized that erupted material did not reach this area.

TABLE 6.—*Analyses of greenstone samples of the Franciscan Formation*

[Chemical analyses (rapid rock methods) by Paul Elmore, Samuel Botts, I. H. Barlow, and Gillison Chloe. Semiquantitative spectrochemical analyses by H. W. Worthing. Looked for but not found: As, Au, Be, Bi, Cd, Ce, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Lu, Nb, Nd, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sn, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

	1	2	3	3a	4	4a	5
Chemical analysis (weight percent)							
SiO_2	47.8	49.3	42.6	45.6	44.9	46.2	43.3
Al_2O_3	12.5	17.3	15.2	16.3	15.9	16.4	14.4
Fe_2O_3	4.8	2.6	5.7	6.1	3.9	4.0	4.0
FeO	11.7	5.5	4.4	4.7	6.6	6.8	5.6
MgO	4.8	3.7	4.8	5.1	7.9	8.1	10.9
CaO	8.3	10.8	15.8	13.3	8.5	7.2	5.2
Na_2O	3.0	3.8	3.1	3.3	2.7	2.8	.14
K_2O	.30	.25	.02	.02	.76	.78	2.0
H_2O+	2.3	3.8	3.8	4.1	5.0	5.2	7.4
H_2O-	.36	.22	.4	.4	1.2	1.2	1.7
TiO_2	3.3	1.6	.76	.81	.95	.98	.62
P_2O_5	.35	.22	.08	.09	.08	.08	.04
MnO	.26	.14	.18	.19	.22	.23	.20
CO_2	$<.05$	$<.05$	2.7	....	1.2	....	1.2
Total	100	99	100	100	100	100	100
S (aqua regia soluble)	0.22	0.01	0.03	....	0.01	....	0.02
Specific gravity (powder)	3.04	2.97	3.02	....	2.86	....	2.76
Semiquantitative spectrochemical analyses (weight percent)							
Ag	0.00003	0	0.000015	....	0	....	0
B	.003	.003	.007	....	0.003	....	.003
Ba	.015	.003	.003	....	.15	....	.015
Co	.007	.007	.007	....	.003	....	.003
Cr	.0015	.03	.03	....	.007	....	.015
Cu	.007	.003	.003	....	.007	....	.007
Ga	.0007	.0007	.0007	....	.0007	....	.0007
Li	.03	0	0	....	0	....	0
Mo	.0007	0	.0003	....	0	....	0
Ni	.015	.015	.03	....	.015	....	.015
Pb	0	.00015	0	....	.0015	....	0
Sc	.0015	.0015	.0015	....	.0007	....	.0015
Sr	.015	.003	.03	....	.003	....	.015
V	.03	.015	.015	....	.003	....	.007
Y	.003	.0015	.0007	....	.0003	....	.0007
Yb	.0003	.00015	0	....	0	....	0
Zr	.015	.007	.003	....	.0015	....	.0015

1. Basalt, 0.4 mile north of Lime Point, Marin Peninsula (sample No. 60-804).
2. Pumpellyite-pyroxene-albite-chlorite-quartz rock. Spilite(?) northwest slope of Lone Mountain, San Francisco (sample No. SF-97).
3. Pumpellyite-pyroxene-albite-chlorite rock. Core of pillow 1.55 miles north of Lime Point, Marin Peninsula; west cut along U.S. Highway 101 (sample No. 60-805).

3a. Analysis No. 3 recast by subtracting $CaCO_3$ corresponding to CO_2 content.
4. Rim of same pillow as rock of analysis No. 3 (sample No. 60-806).
4a. Analysis No. 4 recast by subtracting $CaCO_3$ corresponding to CO_2 content.
5. Matrix between pillows of locality of analyses No. 3 and 4 (sample No. 60-808).

ANGEL ISLAND AND VICINITY

The exposed thickness of greenstone on Belvedere Island is approximately 1,800 feet. Greenstone at Stuart and Knox Points on Angel Island may be a southeastern extension of this body, which may have been separated from the greenstone on Marin Peninsula by folding and erosion. The arcuate exposure of greenstone in the central part of Angel Island ranges in thickness from 100 feet at its western exposure to a maximum of 600 feet southwest of Mount Caroline Livermore and about 400 feet near Simpton Point, its eastern exposure. This eastern exposure may be a northeastern extension of the greenstone of Stuart and Knox Points, it may be stratigraphically higher, or it may be partly intrusive.

Ransome (1894, p. 201) believed that the central Angel Island greenstone body intrudes sandstone of the Franciscan Formation, but the presence of pyroclastic and pillow-form phases at several widely scattered places suggests that it is partly or wholly volcanic or a shallow plutonic body intrusive into soft sediments on the sea floor. Unfortunately, the only well-exposed contact between this body and sandstone is near Campbell Point, where faulting obscures their relations. Intrusion, admittedly, is suggested by the swarms of ½–1½-inch-thick calcite-quartz veins in the sandstone and the increase in size and abundance of these veins as the greenstone body is approached. Ransome (1894, p. 201) also suggested that "the irregular shape of the*** (greenstone body) and the accompanying contact metamorphism, prove it to be a true sill and not an interbedded flow." He evidently believed it was a sill rather than a dike because of the general conformity of the greenstone-sandstone contact with the sandstone bedding. The rocks ascribed by Ransome (1894, p. 211) to contact metamorphism are glaucophane-bearing metagreenstones that are found sporadically in small isolated masses along greenstone borders, but also within the greenstone body. Jadeitization of Franciscan sandstone also seems to be strongest at and near the greenstone border. The author believes that similar metamorphic processes affected the entire greenstone body and other rock masses far from its borders after emplacement. The extensive calcite-quartz veining may also be related to a later action.

Pillow lavas and volcanic breccia are seen at several places in the sill-like body. These features are more likely to develop under extrusive conditions than under intrusive conditions. East of the large valley between Campbell and Simpton Points, the greenstone is a breccia containing reworked, rounded pieces as much as 10 inches in diameter. The largest part of the greenstone body, however, does not show pillow or breccia development and may indeed be intrusive, but evidence for its intrusive nature is inconclusive.

The central Angel Island greenstone body is mostly metagreenstone, but it also contains dense variolitic greenstone. Chemical composition of the central Angel Island greenstone body is given by Ransome (1894, p. 231) and Bloxam (1960, p. 564). They showed that greenstones and metagreenstones of this body are generally similar in composition and that they are similar in composition range. (See table 6.) This similarity suggests that the formation of metagreenstones from greenstones was mainly isochemical.

The greenstone in central Angel Island, and most other greenstones in these areas, are either similar in texture and mineralogy to the dense variolitic greenstone (see greenstone discussion on "Mineralogy-Microscopic Features") or they are slightly more metamorphosed or hydrothermally altered.

The metagreenstones generally consist of phenocrysts or large feathery plates of pyroxene as much as 3 mm in diameter in a matrix of small feathery pyroxene plates, lawsonite, blue amphibole of the glaucophane-riebeckite series, stilpnomelane, opaque ores, and sphene. Pyroxene is augite, titanaugite, diopsidic augite, and diopside-jadeite. In some rocks it is partly or almost completely replaced by blue amphibole of the glaucophane-riebeckite series, chlorite, lawsonite, pumpellyite, iron oxides, stilpnomelane, nontronite, clinozoisite, zoisite, muscovite, albite, calcite, and quartz. These secondary minerals are also found in the matrix. Skeletal pyrite is commonly intergrown with pyroxene.

ORIGIN

Greenstone of the Franciscan Formation is a product of volcanism. It was emplaced as lava flows, tuffs, agglomerates, and associated dikes, sills, and plugs. Volcanism was active repeatedly during Franciscan time. Most if not all the volcanic rocks were erupted on the sea floor, for pillow structure is widespread, marine chert and limestone are found in the space between some pillows, and the greenstone flows and pyroclastics are interbedded with marine sediments. Pillow structure is also developed by shallow intrusion of flows into wet unconsolidated sediments; small sills and dikes, 2–10 feet thick and showing pillow structure, intrude radiolarian chert at several localities. Such intrusives may have been parts of flows that sank into the soft siliceous gel that later hardened into chert.

Tuffaceous greenstone grades into graywacke at several localities where ash was deposited concomitantly with graywacke. Volcanic graywackes are largely reworked ash and lapilli.

Coarse lapilli and ejecta greater than about 4 inches in diameter are evidence of local vents. Indeed, some masses of brecciated greenstone may be plugs or necks of Franciscan volcanoes.

Metamorphosed and altered basalt is present in almost every greenstone body shown on the geologic map (pl. 1). Its erratic distribution, however, indicates great local variations in conditions of alteration and metamorphism, including (1) deuteric or hydrothermal alteration from the action of volcanic emanations (Williams and others, 1955, p. 59), (2) the reaction of hot volcanic rocks with hot sea water, and (3) low-grade metamorphism of the zeolite, greenschist, and glaucophane schist facies (Turner and Verhoogen, 1960, p. 531–544). The common greenstone mineral assemblage of primary pyroxene and pumpellyite, albite, and chlorite would probably be created if basalt were subjected to zeolite-facies metamorphism (Turner and Verhoogen, 1960, p. 532). Much of the greenstone of Angel and Belvedere Islands and Tiburon Peninsula probably was metamorphosed under the slightly greater pressures and temperatures of the greenschist and glaucophane schist facies, as indicated by lawsonite, glaucophane, epidote, and metamorphic pyroxene.

RADIOLARIAN CHERT AND SHALE

The radiolarian chert and shale of the Franciscan Formation consist predominantly of thin alternating beds of chert and siliceous shale. In places these sedimentary rocks make up sections more than 1,000 feet thick. Radiolarian remains are common in the chert and less common in the shale. Massive generally isolated shale-free bodies of chert 4–25 feet thick, as well as thin-bedded shale-free cherts, are also included in this map unit. Interbedded chert and shale predominate, however, and in this report the term "chert" is occasionally used for all three types. The larger deposits of radiolarian chert are closely associated with greenstone. Like other map units in the Franciscan Formation in this quadrangle, this unit is primarily lithologic and has limited stratigraphic significance, for it occurs at several stratigraphic positions in the Franciscan Formation. Moreover, rocks at various stratigraphic positions are similar in appearance; no distinct characteristics distinguish one radiolarian chert section from another.

Davis (1918b, p. 239–408) and Bailey, Irwin, and Jones (1964, p. 55–68) include descriptions of deposits outside the San Francisco North quadrangle.

The radiolarian chert and shale unit generally forms topographically high areas because the chert resists weathering and hydrothermal alteration. The contact of radiolarian chert and shale with other rock types usually is easily recognized, for this unit commonly stands 3–10 feet higher than the adjoining rock. All the peaks in the central highland area of San Francisco are underlain by radiolarian chert and shale. Most of the higher ridges of Marin Peninsula, including the highest point in the quadrangle, are also underlain by this rock.

MEGASCOPIC FEATURES

Color of the radiolarian chert and shale varies with the content and state of oxidation of iron and manganese. The most common colors of fresh thin-bedded radiolarian chert are dusky red to dark reddish brown. Grayish-green chert is found in small volume. Generally, the associated shale has the same color as the chert, except where it is altered.

Under hydrothermal reducing action, the red and brown chert becomes grayish green, dark greenish gray, or grayish yellow green. Hydrothermal activity and weathering may also remove iron and manganese, giving the chert and shale a white, very light gray, grayish-orange, or light-bluish-gray color. In many places hydrothermal activity and weathering were limited and variable from place to place, and only part of the rock was affected. Mottled cherts are formed in this manner; they commonly are green, gray, and white adjacent to joints and along the bedding surfaces. The joints themselves and the shale between the chert beds are often stained with yellow and brown iron oxides or black or bluish-black manganese oxides.

Some single chert beds in a chert and shale sequence contain distinctly colored blebs of red, orange, yellow, and brown chert elongated parallel to the bedding with irregular but sharp and tightly bonded borders (fig. 25). Other red chert beds contain pale-gray and pale-green irregular color bands that are generally parallel to the bedding and probably are formed by hydrothermal alteration or weathering.

Near some greenstone bodies, radiolarian chert that is enriched in manganese is colored very dusky red; the associated shale is dusky brown or almost black. Chert colors, however, are difficult to distinguish because of the masking effects of numerous fractures lined with black manganese oxides. Bright red, bright orange, bright yellow, and brown mottling of chert and shale beds may be heat effects caused by contact with molten basalt.

Massive chert interbedded with thin-bedded chert is generally paler in color than the associated thin-bedded chert and shale. Gray, white, pale green, and yellowish orange are common colors of massive chert.

Metacherts of Angel Island and Tiburon and Belvedere Peninsulas are commonly medium dark gray, brownish gray, and bluish gray.

Radiolarian chert consists typically of alternating thin beds of chert and shale. Chert beds are generally 1–5 inches thick. Some beds, however, are much thicker. Rare single chert beds, 1–25 feet thick, are interbedded with chert and shale of normal thickness. Shale beds range from mere films to beds about three-fourths inch thick (fig. 26); they seldom exceed 1 or 2 inches in thickness. Very rare ones exceed 1 foot.

The chert is aphanitic and hard. Fresh unfractured chert is difficult to break and, on breaking, yields sharp edges and conchoidal to hackly surfaces. Fractures, however, are almost universal in chert of the Franciscan Formation. In most places the fractures are cemented, and the rock as a whole is fairly tough; nevertheless, it readily breaks to coherent pieces generally 1–3 inches in diameter. In a few places adjoining faults, the rock is severely fractured and breaks down to small splinters. Individual chert beds generally lack fissility, for fractures or surfaces of weakness parallel to the bedding are uncommon.

Clastic micaceous silt-size and smaller particles occur on bedding surfaces of the shale. These particles give the shale its poor to moderate fissility. The shale is fairly well indurated, although somewhat brittle; however, some of it can be scratched with the finger-

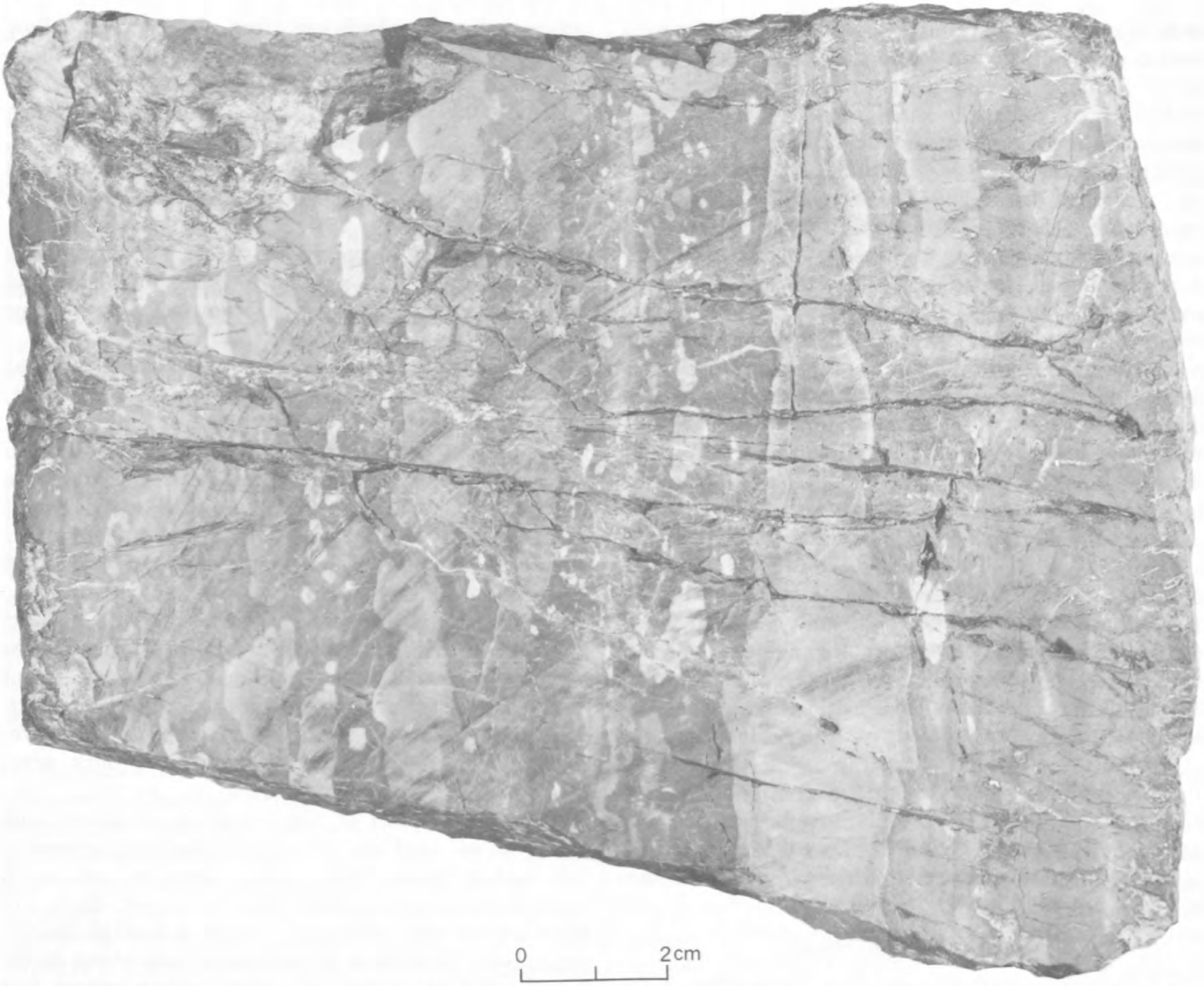

FIGURE 25.—Internal structure of radiolarian chert bed of the Franciscan Formation, 6½ inches thick. Isolated blebs that appear to be light gray on the photograph are really moderate yellow (5*Y* 7/6) in a moderate-reddish-brown (10*R* 4/4) to dusky-red (5*R* 3/4) matrix. Structural features are elongated parallel to bedding. Structure suggests this rock formed from silica gel masses that differed in amount, particle size, and state of oxidation and hydration of iron and manganese oxides. From quarry on Sausalito lateral, one-half mile northwest of Yellow Bluff, Marin County.

nail and all of it with a steel blade, in contrast with the chert, which cannot be scratched with a steel blade. Most shale remains hard when soaked in water for long periods of time. Where shale between chert layers is 1 inch or more thick, it often contains thin distinct layers rich in Radiolaria; these layers are somewhat harder than the average. Most chert beds are sharply bounded by interbedded shale, although some highly ferruginous chert grades into shale.

Pinching, swelling, and lensing of chert beds are very common and take many forms. An individual chert bed may have bulges two to three times its minimum thickness a few inches to 1 foot apart (fig. 27). The underlying and overlying chert beds are generally pinched at the point of the bulge, but the thickness of the interlayered shale beds is affected only slightly. As a chert bed lenses out and terminates, adjacent chert beds thicken or bend towards each other, whereas the two shale beds enclosing a wedged-out chert bed merge into one shale bed only slightly thicker than either of the individual shale beds. Or, the lensing ends of two chert beds may overlap; so, the thickness of adjacent chert beds remains unchanged. Each shale bed is generally less than 25 feet long in horizontal exposure. Bedding irregularities are also described and illustrated by Davis (1918b, p. 248–252), Taliaferro and Hudson (1943, p. 227–229), and Bailey, Irwin, and Jones (1964, p. 55–68).

FIGURE 26.—Radiolarian chert and shale of the Franciscan Formation. Note pinching, swelling, and wedging out of individual chert beds. Twin Peaks, San Francisco.

FIGURE 27.—Pinching and swelling in radiolarian chert beds of the Franciscan Formation. Raveled shale bed (undercut zone in shadow between the man's hands) is unusually thick. On lateral road to Sausalito from U.S. Highway 101, three-fourths mile north of Lime Point, Marin Peninsula.

Small tight rounded folds and sharp chevron folds are common in radiolarian chert and shale, although many exposures show only nonfolded bedding or a gentle waviness of bedding (fig. 28). Bedding surfaces of chert are generally curved rather than flat because of the small-scale tight folding and because of pinching and swelling. Attitude measurements on small exposures of radiolarian chert beds, therefore, must be used with caution in deciphering the broad structural features of the Franciscan Formation. Where exposures are extensive, as on Twin Peaks and in Fort Baker on Marin Peninsula, local contortions as well as consistent attitudes can be recognized.

FIGURE 28.—Chevron folds in radiolarian chert of the Franciscan Formation 2 miles northwest of Golden Gate Bridge, Marin Peninsula.

The most common cause of contorted bedding in chert probably is submarine slumping of beds prior to hardening. In places, disturbance of incompletely hardened beds may have been caused by volcanic activity, such as flow movement or intrusive action. In other places, crumpling of chert appears to have preceded volcanic activity. Contorted bedding also occurs in the vicinity of large faults. Small faults that show displacements of a few inches to 1 foot are confined to the axis of small folds and evidently ruptured during folding. Possible drag folding related to the formation of major folds in the Franciscan Formation can be seen in some localities, particularly on Marin Peninsula (fig. 29).

Massive chert generally produces large bold bare exposures. In favorable exposures it is seen to be interbedded with thin-bedded radiolarian chert and shale. In less favorable exposures it commonly is isolated and is surrounded by slope debris and other surficial deposits that obscure its relation to other rock units. Massive chert bodies are generally wedge shaped with blunt ends and may have very irregular borders within thin-bedded radiolarian chert and shale sections. At many exposures thin-bedded chert and shale terminate abruptly against massive, thick-bedded, or obscurely bedded chert lenses.

The largest known exposure of a single chert bed in a section of thin-bedded chert and shale is on Sunset Heights in San Francisco along 14th Avenue, 600 feet east of the intersection of Noriega Street and 16th Avenue (fig. 30). It is approximately 500 feet long and 25 feet in maximum thickness. It has an irregular bottom and lies partly on thin-bedded chert and partly on pale-green shale. The shale is as much as

FIGURE 29.—Radiolarian chert containing possible drag folding. *Above,* Radiolarian chert at Lime Point, as seen looking northwest along the strike of the Franciscan Formation. Greenstone lies under the left side of the Golden Gate Bridge tower and the high cliff on the left of the tower. Chert lies below the right side of the bridge tower and is exposed in the cliff to the right of the tower. A light-colored zone in the cliff across the road from the buildings is chert containing jarosite derived from the alteration of pyrite. *Opposite,* Possible drag folding in the chert exposed in the cliff to the right of the bridge tower. Chert beds are 1–4 inches thick. Dark part at upper right-hand corner is bottom of bridge.

1 foot thick where it fills the irregular space between massive and thin-bedded chert, and its bedding is parallel to that of the underlying thin-bedded chert.

Some chert immediately adjacent to greenstone or chert completely enclosed by greenstone differs from typical bedded chert. The differences may be from heat and chemical effects of the erupting molten greenstone acting on the typical thin-bedded chert or on siliceous gel prior to consolidation. The effect on some chert is brecciation and quartz veining, the absence of the shale partings, and no change in color (fig. 31). The chert layer next to greenstone is generally 1 foot or more thick; adjoining chert beds are less than 4 inches. Stronger effects, usually seen on chert enclosed by greenstone, are extensive brecciation, quartz veining, a color change to pale or bright red, orange, yellow, green, and brown, and a drusy coating of tiny quartz crystals on joints. Microscopic examination of thin sections of this rock show that new minerals have formed.

Fractures are numerous in thin-bedded chert and shale, especially in the chert. They are commonly nearly perpendicular to the bedding. Fractures intersect each other at various angles up to 90°, but most of them are more or less alined in a limited number of directions. Parallel fractures are generally ⅛–½ inch apart.

Some fractures are slightly open fissures and commonly are lined with manganese and (or) iron oxides. The rock splits readily along such fractures. Other fractures are tightly cemented, generally with quartz, or less commonly with calcite, gypsum, zeolites, and other minerals. About half the fractures in a typical chert bed are filled with white quartz veins that are generally less than one-eighth in thick. Thicker quartz veins penetrate the interbedded shale about an eighth inch; thus bedding surfaces of many chert beds from which the shale has been removed have a prominent reticulate pattern of raised quartz veins. Chert rarely breaks along quartz-cemented fractures; the brittle-

FIGURE 29.—Continued.

ness of chert stems from its tendency to break along incipient uncemented fractures. At faults, chert may be so minutely fractured that it can easily be shattered by the fingers into small splinters generally elongated perpendicular to the bedding.

Fractures parallel to the bedding in chert are uncommon. They do appear in some chert beds as one or two conspicuous uncemented joints. Many cherts contain numerous tiny discontinuous quartz veins or possible fossil spicules, either in a plane parallel to the bedding or very irregular in shape but generally parallel to the bedding. They are generally less than 0.5 mm wide and less than 10 mm long, but they give the chert a laminated appearance.

Most massive chert bodies are not as brittle as thin-bedded chert. On close examination massive chert bodies are generally found to be highly brecciated and thoroughly recemented with one or more generations of quartz and chalcedony. Massive chert at most contacts with greenstone contains numerous quartz veins as much as 1–2 inches thick. These veins are more irregular than quartz veins in thin-bedded chert.

CHEMICAL COMPOSITION

The chemical composition of chert and related shale is given in table 7. Silica is the predominant constituent. In chert, silica is almost entirely chalcedony and quartz. In shale, the content of silica, chalcedony, and quartz varies with the Radiolaria content. In shale containing no Radiolaria, only about half the silica is represented by these minerals and the rest is combined in silicates. In the cherts, SiO_2 content is well above 90 percent; a massive chert at Grand View Park is nearly pure SiO_2 (table 7, analysis 6).

Fe_2O_3 and Al_2O_3 are generally next in order of abundance, except in green chert which evidently was subjected to iron leaching and reducing conditions (analysis 4). The three constituents, SiO_2, Al_2O_3, and

FIGURE 30.—Massive chert in the Franciscan Formation. The bottom of a massive chert bed, 25 feet thick, interbedded with thin-bedded chert and shale. Material between massive chert and thin-bedded chert is green hydrothermally altered shale containing quartz, mica, and kaolinite. The chert bed below the shale in the middle of the photograph is about 2 inches thick. West side of Sunset Heights, San Francisco; 14th Avenue near Ortega Street.

FIGURE 31.—Quartz veins in radiolarian chert lying on altered greenstone. Twin Peaks, San Francisco.

Fe_2O_3, make up more than 97 percent of the cherts. Besides SiO_2, the shales contain substantial quantities of Al_2O_3, Fe_2O_3, and K_2O. As in the red cherts, iron is mostly in the ferric state of oxidation, though FeO is nearly 1 percent in a green shale which appears to have been a red shale reduced by hydrothermal fluids. Shale differs from chert in having less SiO_2 and more Fe_2O_3, FeO, MgO, K_2O, H_2O, P_2O_5, and MnO. Minor-element content as measured by spectrochemical analysis also differs. Shale contains more Cr, Sr, V, Y, and Zr and contains the following elements which are either absent from chert or are below the limits of detection: Be, Ce, Ga, La, Mo, Nb, Nd, Pb, Sc, and Yb. Minor-element content of chert generally substantiates Krauskopf's (1955, p. 427) statement that the few analyses available to him indicate negligible

TABLE 7.—*Analyses of radiolarian chert and shale samples of the Franciscan Formation*

[Chemical analyses (rapid rock methods) by Paul Elmore, Samuel Botts, I. H. Barlow, and Gillison Chloe. Semiquantitative spectrochemical analyses by H. W. Worthing. Looked for but not found: As, Au, Bi, Cd, Cs, Dy, Er, Eu, Gd, Ge, Hr, Hg, Ho, In, Ir, Li, Lu, Os, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Zn]

	1	2	3	4	5	6	7	8	9	10	11
Chemical analyses (weight percent)											
SiO_2	93.5	95.9	94.7	96.5	93	97.4	40.1	60.9	58.4	66.7	66.3
Al_2O_3	.96	1.1	1.1	1.5	2	.47	10.9	13.1	14.3	14.1	15.9
Fe_2O_3	2.8	1.7	2.7	.34	2.4	1.3	27.6	9.2	7.4	6.5	3.3
FeO	<.05	.34	.22	.38	<.05	.26	<.05	1	<.05	.58	.96
MgO	.11	.10	.14	.16	.13	<.05	3.5	2.3	3.3	1.6	1.8
CaO	.42	.05	.06	.17	.11	.05	.53	<.05	2	.05	<.05
Na_2O	.01	.02	.01	.11	.11	.01	.12	.08	1.7	.10	.18
K_2O	.08	.26	.37	.26	.41	.04	4.5	4.9	3.9	3.8	4.9
H_2O^+	.72	.70	.63	.65	1	.55	4.8	4.6	3.1	4	4.3
H_2O^-	.22	.11	.16	.15	.26	.07	2.2	2	2	1.2	1.3
TiO_2	.04	.06	.06	.08	.12	.03	.76	.92	.66	.81	.76
P_2O_5	.03	.02	.03	.04	.05	.04	.14	.14	1.3	.09	.27
MnO	1.3	.05	.05	.03	.40	.02	4.8	.11	1.4	.10	.08
CO_2	<.05	<.05	<.05	<.05	<.05	<.05	.08	<.05	<.05	<.05	<.05
Total	100	100	100	100	100	100	100	99	99	100	100
S (aqua regia soluble)	0.01	0.00	0.01	0.01	0.01	0.02	0.00	0.02	0.03	0.01	0.02
Specific gravity (powder)	2.68	2.66	2.65	2.63	2.64	2.64	2.97	2.73	2.66	2.69	2.66
Semiquantitative spectrochemical analyses (weight percent)											
Ag	0.00007	0	0	0	0.000015	0	0.0007	0	0.00015	0.000015	0
B	0	.003	0	.003	.003	.003	.007	.003	.003	.007	.015
Ba	.07	.03	.015	.15	.15	.007	.3	.03	.15	.07	.015
Be	0	0	0	0	0	.00015	.00015	.00015	.00015	.00015	0
Ce	0	0	0	0	0	0	.015	.015	.03	.015	.015
Co	.0003	0	.00015	.00015	.003	.0007	.003	.0015	.03	.0015	.003
Cr	.0003	.0003	.0003	.0003	.0003	.0003	.003	.007	.0015	.003	.003
Cu	.015	.0015	.0015	.0015	.003	.003	.03	.015	.015	.007	.0015
Ga	0	0	0	0	0	0	.0007	.0007	.0007	.0007	.0007
La	0	0	0	0	0	0	.007	.007	.015	0	.003
Mo	0	0	0	0	0	0	.0015	.0007	.0003	0	0
Nb	0	0	0	0	0	0	.0003	.0003	.0003	.0007	.0003
Nd	0	0	0	0	0	0	.015	.015	.015	0	0
Ni	.007	.003	.003	.003	.007	.003	.07	.007	.03	.007	.015
Pb	0	0	0	0	.00015	0	.015	.003	.0015	.0003	0
Sc	0	0	0	0	.0007	0	.0015	.0015	.003	.0015	.0015
Sn	0	0	0	0	.0007	0	.003	.0007	.0003	0	0
Sr	.0007	.0003	.0003	.0015	0	0	.007	.0007	.15	.15	.007
V	.0015	.0015	.0015	.0007	.0015	.0007	.007	.15	.003	.007	.03
Y	.0007	0	0	0	.0003	0	.003	.003	.015	.003	.0015
Yb	0	0	0	0	0	0	.0003	.0003	.0015	.0003	.00015
Zr	.0007	.0015	.0015	.0015	.0015	.0007	.015	.015	.015	.015	.015

1. Chert, thin-bedded; much iron and manganese oxides on joints; Twin Peaks, San Francisco (sample No. 60–800).
2. Chert, thin-bedded; on Sausalito Lateral, 3,500 ft west of Yellow Bluff, Marin Peninsula (sample No. 60–802).
3. Chert, thin-bedded; on Sausalito Lateral, 3,000 ft northwest of Yellow Bluff, Marin Peninsula (sample No. SF–1970).
4. Chert, thin-bedded, green; west cut U.S. Highway 101, 8,500 ft northwest of Yellow Bluff (sample No. SF–2043).
5. Chert, thin-bedded; 600 ft east of 16th Ave., 1,100 ft north of Ortega St., Grand View Park, San Francisco (sample No. SF–2145).
6. Chert, massive; 600 ft east of 16th Ave., 500 ft north of Ortega St., San Francisco (sample No. SF–2143).
7. Shale bedded with chert of analysis 1 (sample No. 60–801).
8. Shale bedded with chert of analysis 2 (sample No. 60–803).
9. Shale bed; 1 ft thick; bedded with chert; east cut U.S. Highway 101, 3,750 ft west of Yellow Bluff (sample No. SF–2111).
10. Shale bedded with chert of analysis 5 (sample No. SF–2145A).
11. Shale, green; 1 ft thick; below massive chert of analysis 6 and above thin-bedded chert (sample No. SF–1941).

amounts of rare metals (minor elements) in chert. However, the shales interbedded with chert of the San Francisco North quadrangle show the following maximum enrichment factors (the ratio of the minor element content to the crustal abundance of the element, see Krauskopf, 1955, p. 417–428): Ba, 12; Co, 13; Cu, 4; Mo, 15; Ni, 11; Pb, 9; rare earths including Y, 5; Sr, 5; V, 10. The shales interbedded with cherts differ from gray shales interbedded with sandstones of the Franciscan Formation (table 7, analysis 8) mostly in having more Fe_2O_3 and K_2O and less FeO and Na_2O.

MICROSCOPIC FEATURES

CHERT

Thin-bedded chert consists of a matrix of chalcedony and cryptocrystalline to microcrystalline quartz enclosing Radiolaria and a small amount of spicules. The fossils also consist of chalcedony and quartz. Veinlets that cut the matrix and the fossils consist of quartz, chalcedony, and subordinate amounts of calcite, gypsum, stilpnomelane, chlorite, kaolinite, rare-earth phosphates, and zeolites. In some cherts the matrix appears to be isotropic or shows only scattered specks of light under crossed nicols. This material is thought to be largely quartz of exceedingly small grain size for the following reasons: (1) The index of refraction is approximately 1.535, slightly lower than those of quartz, but far above that of opal and (2) X-ray diffraction powder analysis shows only quartz spacings and does not contain spacings of beta-cristobalite, which are obtained by X-ray diffraction analysis of most opals. Previously, Lawson (1895, p. 422), Davis (1918b, p. 255), and Taliaferro and Hudson (1943, p. 231) reported that some cherts of the

Franciscan Formation are composed of amorphous silica.

Most grains of chalcedony and quartz in the fossils and veinlets are at least 3 and generally more than 10 times larger than grains in the matrix. The veinlets contain the largest grains of quartz, some being more than 0.5 mm in diameter. Veinlets in some chert are calcite or gypsum with a thin border of quartz. Small patches of stilpnomelane and chlorite are common. Iron and manganese oxides and rare-earth phosphates rich in cerium coat joints in some cherts.

The matrix of the typical red thin-bedded chert is heavily charged with tiny brownish-red particles. The fossils and the veinlets are relatively free of these particles.

The proportion of fossils to matrix varies within a single chert bed and from bed to bed. In some chert beds fossils are so crowded that they touch each other. Few if any are seen in light-colored pigment-free chert beds or in the pigment-free parts of otherwise red chert beds rich in fossils. Radiolaria generally appear in thin sections as sharply defined clear circular or conical areas, 0.04–0.5 mm in diameter, of relatively coarse chalcedony and more rarely of microcrystalline quartz. The rim of many fossils is equigranular microcrystalline quartz enclosing a large core of one or several grains of chalcedony, each grain consisting of a sheaf of fibers of negative optical elongation (length fast) radiating from the edge or center of the grain. The chalcedony and quartz that preserve the former chambers and pores within radiolarian tests usually contain some red pigmentation, in contrast with the clear parts of the rest of the test. Spines and other delicate surface ornamentation are generally absent.

As would be expected, the color of the chert varies with the amount of pigment in the matrix: the dusky cherts contain more pigment than the light-colored ones. Parts of the matrix of dusky-red chert appear opaque under the microscope because they are so heavily charged with pigment. The pigment particles are mostly embedded in chalcedony and quartz grains and to some extent between these grains. At high magnification the pigment in red chert is seen to consist mostly of equidimensional and elongated rounded transparent reddish and brownish crystals that average 1 micron in diameter. They have a moderate to high index of refraction. Most of them appear isotropic under crossed nicols, but some, particularly the thin laths, show a moderate to high birefringence. Definitive studies of the pigment have not been reported, but published descriptions of these red chert beds identify the pigment as hematite or iron oxide (Davis, 1918b, p. 254; Taliaferro and Hudson, 1943, p. 150, 227, 231; Williams and others, 1954, fig. 124A, p. 363). Taliaferro and Hudson (1943, p. 232) found that manganese oxide and carbonate are also coloring agents. Davis (1918b, p. 258, 260) reported finding pyrite in green and gray chert and a glauconitelike mineral in chert from Point Richmond, 3.5 miles north of Angel Island.

X-ray diffraction powder patterns of typical red thin-bedded shale-free chert show much quartz, small amounts of hematite (alpha-Fe_2O_3), goethite, possibly lepidocrocite, and small amounts of minerals with spacings suggestive of poorly crystalline micalike and chloritelike structures. These minerals no doubt account for much of the Al_2O_3, MgO, K_2O, Na_2O, and H_2O, and for some of the iron shown in table 7. Taliaferro and Hudson (1943, p. 232) suggested that "the alumina, magnesia, lime, and alkalies represent the small amount of fine clayey detritus mechanically entangled when the colloidal silica was flocculated." Silicates in the veinlets also account for part of these components.

Microscopic examination of thin sections of the brown cherts of Angel Island and vicinity reveal abundant Radiolaria remains in the form of clear circular quartz-crystal aggregates that are slightly coarser in texture than the inclusion-filled quartz crystals that surround them. Also, some radiolarian structures are outlined by lepidocrocite, which may represent altered pyrite. The quartz surrounding the Radiolaria is crowded with tiny pale-yellow-green to colorless slightly pleochroic hornblende (rarely aegerine) needles, 2–20 microns long, and stumpy, euhedral hexagonal prisms of apatite, 3–10 microns in diameter. The apatite may be recrystallized from the chitinous organic remains found in shale interbedded with unmetamorphosed chert. Veins of magnetite, mostly altered to lepidocrocite, and of stilpnomelane are common.

Pale-blue chert is interbedded, or irregularly interspersed, with the brown variety. It appears to be slightly more metamorphosed than the brown variety, for no radiolarian remains were found in it and much of the quartz appears to be recrystallized. It also contains abundant hornblende needles, some of them partly altered to stilpnomelane, and small amounts of epidote, crossite, and lepidocrocite pseudomorphing magnetite. Shale, interbedded with either pale-blue or brown chert, is dark blue in color and is completely recrystallized. It consists predominantly of various types of blue amphiboles of the glaucophane-riebeckite series and stilpnomelane and minor amounts of aegerine, hornblende, sphene, and lepidocrocite.

The metacherts described here probably formed under conditions similar to those for Hutton's (1940, p. 27–28) subzone Chlorite 1 of the chlorite zone.

Microscopic examination of baked chert shows differences from unbaked chert. Most of the baked rock consists of microcrystalline quartz or large spherules of chalcedony. Radiolaria are generally obliterated but are recognized in some baked cherts. Colorless isotropic material is absent. Baking tended to recrystallize the pigment into larger particles than exist in the unbaked chert. The particles may take the form of long irregular veinlets of magnetite, 0.4 mm in maximum thickness, or of euhedral crystals of magnetite, and unidentified opaque or deep yellowish-brown isotropic crystals of high refractive index. The pigment in the baked cherts is generally segregated into sharply defined clots and concentric shells leaving nearly clear irregularly shaped masses of quartz crystals between the pigmented clots. The pigment is generally confined to chalcedony and cryptocrystalline quartz of the finest grain size in the chert, whereas relatively unpigmented quartz is the coarsest in grain size, some crystals being nearly 1 mm in diameter.

Silicate minerals are common products of baking. Unidentified microlites and unidentified long hairlike crystals, as well as larger crystals of hornblende, pumpellyite, epidote, aegerine, and stilpnomelane, are often found in these rocks. Hornblende with $Z =$ dark to moderate yellow brown, $X = Y =$ pale yellow brown to pale brownish yellow, $Z \wedge c = 15°$, birefringence $= 0.010$ is common in chert found lying between pillows of basalt in a roadcut 2,000 feet northwest of Horseshoe Bay.

Massive chert lenses are petrographically different from the thin-bedded chert that encloses them. Microscopic examination shows that massive chert consists largely of microcrystalline quartz and relatively coarse chalcedony spherules; the pigment appears to be in crystals larger than those in the typical red thin-bedded chert. Taliaferro and Hudson (1943, p. 260), however, found some massive chert to be partly opaline. Irregular veins and clots of unpigmented relatively coarse anhedral to euhedral quartz crystals, as large as 1 mm in diameter, are found throughout the massive chert; so, the rock appears to be a breccia of older pigmented rock recemented with the clear coarse quartz. Radiolaria are not recognized with the hand lens and are obscure and sparse in thin sections examined under the microscope. Their apparent scarcity may be explained by the difficulty of seeing them against generally pale background of massive chert. Their scarcity, however, may be real and may be related to the origin of massive chert. Massive chert may contain a greater proportion of chemically precipitated silica than is found in typical thin-bedded chert.

Shale

A few thin sections of shale interbedded with chert from the Twin Peaks area show that shale there consists mostly of (1) flakes and wavy veins of a micaceous mineral showing dark-reddish-brown (Y, Z) to moderate-reddish-brown (X) colors and (2) lens-shaped aggregates of tiny micaceous crystals that show a weak aggregate pleochroism in moderate brown hues. Present in smaller but variable amounts are veins and disseminated particles of dark-red-brown nearly opaque hematite and silt-size grains of quartz and colorless mica. The mica flakes and micaceous crystals, the lens-shaped aggregates, and the veins parallel the bedding, except in shale containing Radiolaria and spicules where their orientation near the fossils is parallel to the surface of the fossils.

X-ray diffraction analysis of the shale indicates the presence of large amounts of mica, most of which is poorly crystallized or randomly interlayered with other micaceous minerals, moderate amounts of a chlorite-like mineral, and hematite, goethite, and quartz. No expanding-lattice clay mineral was detected. Feldspar is present in very small amounts or is absent.

Radiolaria and spicules are sparse in most shale, but thin beds of shale containing as much as 70 percent Radiolaria and spicules are interbedded with Radiolaria-free shale. Radiolaria range in diameter from 0.2 to 0.05 mm. As in the chert, the Radiolaria are preserved in microcrystalline quartz and chalcedony which contain red pigment inclusions in former chambers of the test. Radiolaria replaced by calcium carbonate were also found in the chert of a phosphatic nodule near Laguna Honda. Taliaferro and Hudson (1943, p. 260) found that Radiolaria in their "Franciscan-Knoxville" radiolarian shales collected at a number of localities in the Coast Ranges are invariably replaced by calcium carbonate.

Most shales also contain a small amount of carbon having relict plant-cell structures. Some red shales contain a small amount of light-bluish-white curved thin shells, as much as 1 mm in size, that resemble chitinous parts of arthropods and tiny shark's teeth. These remains are preserved as carbonate fluorapatite.

Green shale found between massive and thin-bedded chert on Sunset Heights in San Francisco consists of about 40 percent hydrous mica, 40 percent quartz, and 20 percent kaolinite.

HYDROTHERMAL ALTERATION

Radiolarian chert and shale are hydrothermally altered along faults and along greenstone bodies. Chert becomes either grayish orange or light gray, and shale generally is grayish orange. In some localities the rock is green from ferrous iron alteration products. In some chert sections the color changes and other effects of hydrothermal alteration are confined to bands along joints; these give the rocks a mottled appearance. Hydrothermal effects may follow the bedding of sections 1–25 feet thick in the midst of a section of unaltered beds or may cross the bedding (fig. 32).

Altered chert beds generally preserve much of the hardness of fresh chert beds. Altered shale beds soften and are generally plastic when wet. X-ray diffraction analyses of the <2-micron fraction of hydrothermally altered shale show mica, kaolinite, and montmorillonite. The mica is poorly crystalline or randomly interlayered with expandible clay minerals.

In some places hydrothermal alteration has converted both chert and shale into a soft clayey material containing quartz, montmorillonite, kaolinite, mica, and the hydrous iron silicate hisingerite. The clay is plastic and weak when wet.

At some wide fault zones the chert is thoroughly shattered and has the properties of a friable sandy material or a clayey, moderately plastic material. Clay minerals in fault gouge consist mostly of mica, with subordinate amounts of random mixed-layered mica-montmorillonite (mostly mica) and kaolinite.

Fresh radiolarian chert near zones of hydrothermal alteration commonly contains veinlets of quartz and well-crystallized kaolinite.

WEATHERING

Most exposures of radiolarian chert and shale show virtually no weathering effects except for raveling of the shale towards the ground surface (fig. 33). The physical properties of the chert beds appear to be little affected by weathering, although the slight disintegration of the interbedded shale decreases the shearing strength of the whole rock mass. At some exposures, weathering has leached out iron, removed some of the silica, and colored the surface of the chert light red brown to white to a depth of 1 mm. Radiolaria stand out in relief on such surfaces (Davis, 1918b, p. 261). In discussing oxidation of manganese ores in Franciscan chert, Taliaferro and Hudson (1943, p. 270) evidently believed that manganiferous chert may be oxidized by weathering processes to a depth of several feet, although they gave no depth figures and stated that the maximum migration of manganese, leaving behind porous cores of silica, is only a few inches.

FIGURE 32.—Irregular band of hydrothermally altered radiolarian chert of the Franciscan Formation within a section of unaltered chert. Light chert is altered; dark chert is fresh. Northwest Mount Sutro, University of California Medical Center, San Francisco.

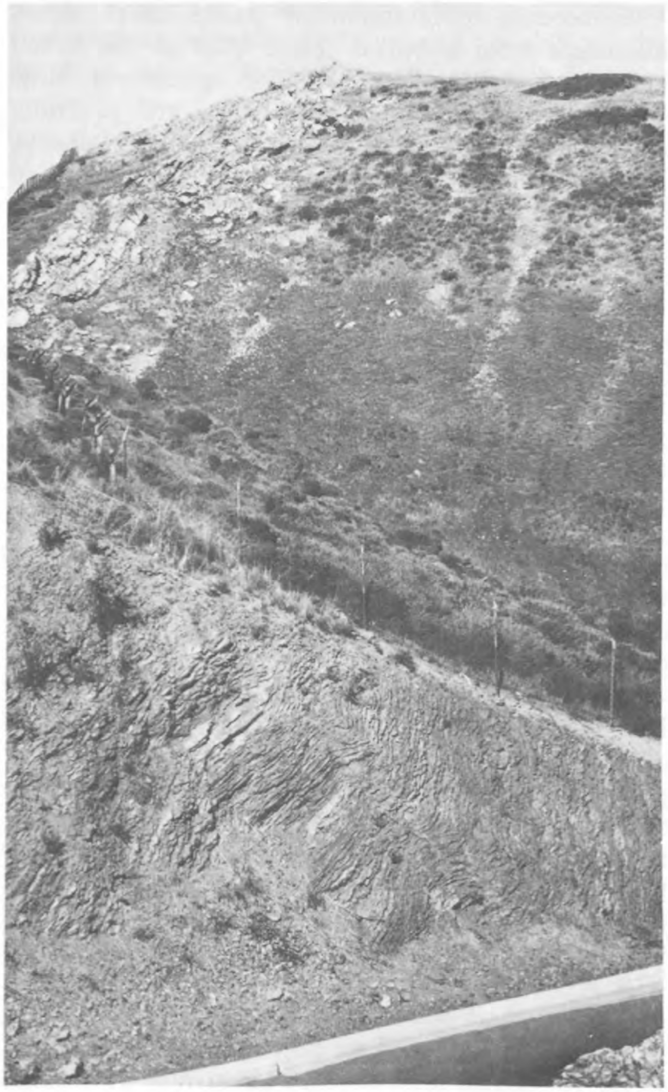

FIGURE 33.—Radiolarian chert and shale. Near the east side of U.S. Highway 101, three-fourths mile north of Golden Gate Bridge, Marin Peninsula. Note the thin soil cover and raveling of thin-bedded chert and shale in foreground, thick chert beds in background.

ORIGIN

Chert is a marine deposit, but its environment of deposition on the sea floor, the source of silica, and the manner in which the silica becomes chert are largely unsettled questions.

The probability of a deep-sea origin for the graywacke sandstone and shale through turbidity current transportation of detritus also dictates a probable deep-sea environment for the radiolarian chert with which they are interbedded (Sanders and Swinchatt, 1957). The ultimate source of the silica is believed to be the greenstones of the Franciscan Formation. The close association in time and space of greenstone and radiolarian chert of the Franciscan Formation of the Coast Ranges is given by Taliaferro and Hudson (1943, p. 273–274) as the strongest evidence for this belief. They stated that chert did not begin to form until volcanism started, that the maximum development of the chert coincides with maximum volcanism, and that where volcanic rocks decrease laterally and disappear, interbedded chert does likewise. In the San Francisco North quadrangle, chert is indeed generally found near greenstone and is absent or sparse where greenstone is absent.

ORIGIN OF SILICA

Silica in chert can be supplied by silica-secreting organisms or by inorganic processes. Bramlette (1946, p. 37–55) presented strong evidence for the derivation of porcelaneous and cherty rocks of the Miocene Monterey Formation in the California Coast Ranges from diatoms through a diagenetic alteration process that dissolves finely divided opal of diatoms in diatomaceous deposits and reprecipitates it nearby and that is accompanied by moderate load and dynamic metamorphism.

Taliaferro and Hudson (1943, p. 233–234) believed the silica is derived from submarine springs, which they expect are common during volcanism, and from the reaction of hot sea water and hot lava or pyroclastics. Rhythmically bedded chert and shale lenses may have been originally bottom oozes consisting of colloidal silica and small amounts of colloidal iron, aluminum, manganese compounds, and other substances, mixed with clayey material and the siliceous organisms that flourished in the silica-rich waters. When colloidal silica changes from a sol to a gel, it tends to free itself of impurities. Thus the shale interbedded with the chert represents layers of impurities segregated by flocculation of silica. In aging and syneresis, water is lost and the gel hardens rapidly (Taliaferro, 1933, p. 50; 1934, p. 221–227).

Results of experimental investigations of the solubility and precipitation of silica by Krauskopf (1956; 1967, p. 166–170) and White, Brannock, and Murata (1956, p. 27–59) show that silica forms true solutions in water, mostly in the form of dispersed molecules of monosilicic acid, H_4SiO_4. Amorphous and colloidal silica is more soluble than crystalline silica (tridymite, cristobalite, chalcedony); quartz has the lowest solubility. In supersaturated solutions, colloidal silica, in amounts equal to the excess over true solution equilibrium concentration, forms slowly at low temperatures and rapidly near and above 100°C. The amount of soluble silica found in sea water (1–10 ppm) is far below the experimentally determined solubility of amorphous silica in sea water (100–110 ppm at 22°–27°C; 280–310 ppm at 85°–95°C, according to Krauskopf, 1956, p. 13). Removal of silica by Radiolaria, diatoms, and siliceous sponges probably accounts for much of this difference. The remarkable undersaturation of soluble silica in sea water would seem, at first glance, to be strong evidence against the inorganic origin of chert by flocculation of colloidal silica. But the undersaturation is true only of sea water that has been analyzed. Sampling has not been extended to sea water in regions of submarine volcanic activity where hot sea water is in contact with hot molten or solidified volcanic volcanic rocks and where springs are expected to be numerous and the silica content is expected to be high, especially in quiet basins. Determination of the release of silica, aluminum, iron, magnesium, and other elements from molten lava to heated sea water should yield data especially pertinent to the origin of chert. The high temperature of such waters would greatly increase the solubility of silica, and cooling of the water would cause supersaturation and rapid formation of colloidal silica. Thus Krauskopf (1956, p. 23) suggested that the cherts commonly associated with pillow lavas may have an inorganic origin by flocculation of colloidal silica, although he added that Bramlette's hypothesis of diagenetic alteration for the opaline cherts of the Monterey Formation is in good agreement with experimentally determined behavior of silica.

ORIGIN OF CHERT

Both organic and inorganic processes may have formed the chert of the Franciscan Formation. The Franciscan cherts are closely associated in the field with contemporaneous volcanic rocks and also contain abundant Radiolaria. Part of the silica in Franciscan chert is obviously radiolarian skeletons and spicules. Thus the problem of the origin of the additional silica that fills and encloses the Radiolaria and spicules and that has no recognizable organic structure remains unsolved. The amount of silica is large in some cherts in which no fossils are apparent, but even those crowded with Radiolaria and spicules probably contain

30–50 percent of silica showing no organic structures. Hinde remarked (1894, p. 238) "the fossilization, which has been sufficient to obliterate most of the radiolarian structure, would completely destroy all traces of the smaller and more delicate diatoms," and he suggested this process also occurred in the cherts. In addition, Bramlette (1946, p. 55) suggested "that the Radiolaria preserved in the cherts of the Franciscan Formation represent only the heavier-shelled forms of the Radiolaria or other siliceous organisms originally present." This difference in behavior of silica in different organisms has been confirmed experimentally by D. E. White (oral commun., 1956), who stated that the form and stability of silica vary among silica-secreting organisms and that the silica of diatomite is unstable, fairly soluble, and very readily crystallized to chalcedony or quartz. He also suggested that in Radiolaria skeletons the silica of the spines is more soluble than the remaining silica. Thus some of the silica of the Franciscan chert not involved in organic structures may represent diatoms and other unstable organic silica remains whose organic origin has been obliterated.

Origin of shale

The shale that is rhythmically bedded with Franciscan chert differs considerably from the shale that is interbedded with graywacke sandstone of the Franciscan Formation. Individual shale beds in chert seldom reach 25 feet in length, whereas a shale bed in sandstone extends 100 feet or more. Shale in chert generally has more total iron, commonly ferric, as hydrated or anhydrous iron oxide. Shale in sandstone has mostly ferrous iron in silicate minerals. Na_2O is lower and K_2O is higher in the shale in chert. There is a notable lack of feldspars, as shown by X-ray diffraction analysis. These peculiarities indicate to the writer that the shale in chert probably did not form by sedimentation of detritus. Its formation by the little-known colloidal process by which impurities in silica gel tend to be pushed aside and segregated into bands better explains its characteristics. Other than the fossils, most of the constituents of the shale, as well as of the chert, are thought to have been derived by rapid chemical precipitation from cooling sea water. The sea water was able to acquire these constituents in solution by reaction with hot molten or freshly solidified volcanic rocks (Bailey and others, 1964, p. 66–67). The precipitates would be mostly colloidal in size and would be mixed with skeletons of siliceous organisms, and possibly a small amount of detritus sinks to the sea floor. Most of the micaceous minerals may have formed incipient crystals during precipitation from the cooling sea water and may have grown later by diagenesis. The bulk of the deposit consisted of silica gel, which lost water, shrank, and coagulated under the weight of overlying sediments; eventually it hardened into chert.

Origin of color

The red color of the chert and the shale is probably the original color of these rocks. It is caused by fine particles of ferric oxide, probably precipitated from sea water as colloidal ferric hydroxide. Two factors may have induced precipitation: (1) a lowering of temperature and consequent lowering of solubility of Fe with respect to the minerals and (2) a change from acidic conditions of sea water in contact with erupting volcanic rocks to the alkaline conditions of average sea water (Hem and Skougstad, 1960, p. 96). The high oxygen content of sea water at great depths (Sverdrup and others, 1946, p. 748, 753) would promote the oxidation of any ferrous ions in sea water, especially at the high pH of average sea water (Huber, 1958, p. 133). Nevertheless, shales associated with graywacke sandstone deposited at the same depth of sea water contain more ferrous iron, in the form of silicates, magnetite, and pyrite, than ferric iron probably because of a local negative Eh (redox potential) created by the presence of detrital carbonaceous material.

AGE

Radiolaria and spicules are common (as much as 70 percent) in the chert and in some shale but are sparse in most shale. Radiolaria can be seen in chert by hand-lens examination of wet fresh fractures. They appear as dark-gray clear round or conical masses tightly cemented in the rock. On weathered surfaces they have relief. In shale they appear with the hand lens as tiny pellets or leave pits where they were detached. Most of them are between 0.5 and 0.05 mm in diameter. Delicate structures, such as slender external spines, are rare and are seen only in thin sections of chert or on chert surfaces that have been etched for a few minutes in hydrofluoric acid. Obscure chitinous material is found in some shale.

Radiolaria in the cherts of the Franciscan Formation were first described by Hinde (1894), who identified several genera in cherts from Angel Island and from Buri-Buri Ridge, 6–10 miles south of the quadrangle. Preservation was too poor to permit identification of species. Hinde (1894, p. 237–238) noted a similarity in character of the rock, mode of preservation of the Radiolaria, and abundance of the genus *Dictyomitra* in the cherts of the Franciscan Formation and in the red radiolarian jaspers and chert of Jurassic and Cretaceous age from the Tyrol, from Switzerland, from Hungary, and other places.

Riedel and Schlocker (1956) described several genera of Radiolaria found in shale interbedded with red radiolarian chert of the Franciscan Formation at Belmont, 18 miles southeast of the San Francisco North quadrangle. The Radiolaria there are somewhat better preserved than those found in cherts in the San Francisco North quadrangle. Some are similar to Jurassic species of other parts of the world, others are similar to Cretaceous species. Radiolaria are not yet useful in dividing the Franciscan Formation. Pessagno (1970, p. 130) recognized tentative radiolarian zones in the Great Valley sequence and suggested that the zone may be used for the Franciscan Formation.

Two typical red thin-bedded radiolarian chert and shale sections, 10–20 feet thick, are interbedded with sandstone and shale west of James D. Phelan Beach State Park. They are separated stratigraphically 400–600 feet from the *Douvilleiceras*-bearing sandstone of Albian age. Part or all of the sedimentary rock sequence in this area is overturned, and it is not known whether the radiolarian chert and shale sections are older or younger than the Albian sandstone.

A

B

FIGURE 34.—Franciscan Formation exposed on north shore of Golden Gate, Marin Peninsula. *A*, View between Golden Gate Bridge and Point Diablo. Cliff left (west) of bridge is greenstone. Cliff near left edge exposes radiolarian chert on left and greenstone on right. *B*, Close view of wooded ravine (see *A* for location) 0.6 mile west of Golden Gate Bridge. Radiolarian chert exposed as barren rock east (right) of the ravine and forms hogback west (left) of the ravine. Pyroclastic greenstone exposed immediately west of ravine. Note dip to west in chert and pyroclastic rocks in 400-foot cliff. Colluvium generally underlies dark brush.

OCCURRENCE

MARIN PENINSULA

On Marin Peninsula, radiolarian chert and shale occur in thick zones interbedded with sandstone and greenstone at several stratigraphic positions (fig. 34). Between Lime Point and Horseshoe Bay, the two radiolarian chert sections, separated by a thick sandstone section, vary in thickness from about 50 to more than 500 feet. They can be followed along the strike for about 2 miles, which, according to Taliaferro (1943, p. 149), is an exceptional persistence for chert beds of the Franciscan Formation. Several other thick sections of radiolarian chert lies stratigraphically above and below these sections (fig. 34).

ANGEL ISLAND AND VICINITY

Relatively small bodies and lenses of chert are widely distributed on Angel and Belvedere Islands and on Tiburon Peninsula. Most of the chert shown in these areas is slightly to moderately metamorphosed, although it retains most of the field appearance of bedded chert and associated shale. The chert north of Hospital Cove on Angel Island is the least metamorphosed. These chert bodies are unsheared. They are pale reddish or greenish brown or pale blue. The largest mass is 2,000 feet east of Stuart Point. Sheared metachert is shown as metamorphic rocks. These rocks are brown and rich in aegerine and (or) stilpnomelane or are dark blue and rich in amphiboles of the glaucophane-riebeckite series.

SAN FRANCISCO

The largest exposures of radiolarian chert in San Francisco are the central highlands area near the south border of the quadrangle. Sunset Heights, Mount Sutro, Twin Peaks, Mount Olympus, and Corona Heights owe their height and boldness in large part to the presence of radiolarian chert (figs. 35, 36, 37). The maximum thickness is exposed on Mount Sutro, where this unit may be as much as 1,600 feet thick. The same section is exposed on Mount Olympus and Twin Peaks. It appears to lens out rapidly westward and is separated by sandstone and greenstone from a younger radiolarian chert section, approximately 800 feet thick, exposed at Corona Heights and on 18th Street at Mission Park. The sandstone underlying this younger section contains numerous lenses of radiolarian chert, many of them less than 50 feet thick and 400 feet long. Small lenses of radiolarian chert are also found interbedded with sandstone along the shore between Fort Point and Lands End. Somewhat larger radiolarian chert bodies are in the east half of Golden Gate Park.

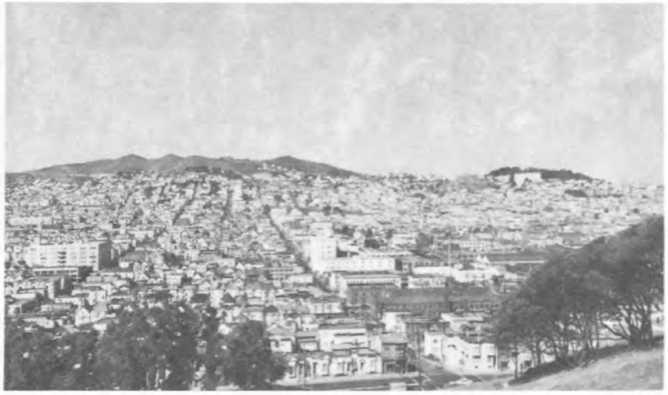

FIGURE 35.—Central highlands area of San Francisco, viewed west from Potrero Hill. Peaks underlain by radiolarian chert in the Franciscan Formation are, from left to right, Twin Peaks, Mount Sutro, and Corona Heights (barren hill below and to right of small cloud).

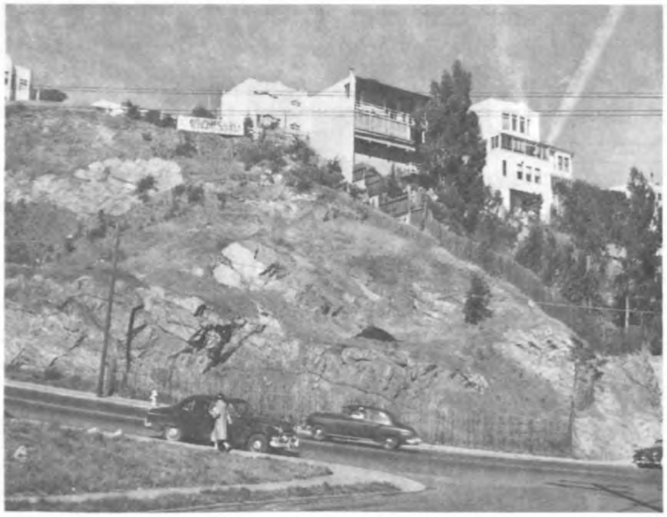

FIGURE 36.—Radiolarian chert and sandstone in the Franciscan Formation, 17th Street, Mount Olympus area, San Francisco, viewed northwest.

FIGURE 37.—Radiolarian chert and shale, Sunset Heights, San Francisco, near Ortega Street and 14th Avenue. Dune sand lies on the chert at top of hill at elevation of 600 feet above sea level.

Although contortions are common in the radiolarian chert of Sunset Heights, persistent bedding attitudes indicate that this rock dips eastward, which would place it below sandstone of the Franciscan Formation exposed at the base of Mount Sutro at Laguna Honda Reservoir and also below the radiolarian chert of Mount Sutro. On the other hand, it may be part of the Mount Sutro chert section repeated by a normal fault now concealed by dune sand, west of Seventh Avenue. If the radiolarian chert of Sunset Heights is a separate section, it is at least 400 feet thick. Lawson (1914, San Francisco quadrangle, structure-sections plate) showed it to be 950 feet thick in Sunset Heights.

METAMORPHIC ROCKS

Metamorphic rocks of the Franciscan Formation include slate, phyllonite, phyllite, fine- to coarse-grained schist, and fine- to medium-grained granular hornfelslike or granulitelike rocks that lack foliation, for which the name granofels (Goldsmith, 1959, p. 109) is useful. On the basis of field appearance, rocks mapped as metamorphic rocks were judged to be of somewhat higher metamorphic grade than the semischists, metacherts, and metagreenstones described. Rock types mapped as metamorphic rocks in one area, however, may be mapped as other bedrock units elsewhere. Relict textures and structures that suggest parentage are present in many of the metamorphic rocks, but because details of mineralogy, chemical composition, and fabric of the rocks are lacking, ideas as to parentage and metamorphic processes are speculative.

Metamorphic rocks are most prevalent on Angel and Belvedere Islands and on Tiburon Peninsula. Almost everywhere in these places—Quarry Point excepted—the clastic sedimentary rocks are semischists, and other Franciscan rock types are metamorphosed to varying degrees. Completely recrystallized schists are also common. Metamorphic rocks from Tiburon Peninsula north of this quadrangle are described by Lawson (1914, p. 7) and Taliaferro (1943, p. 162–166). Several bodies 2–10 feet in diameter in San Francisco are included on the geologic map (pl. 1) in the sheared rocks unit or in serpentine. Some offshore rocks north of Bakers Beach and west of Lands End are metamorphic rocks within the Fort Point–Hunters Point or City College shear zones, respectively.

On the basis of their field occurrence, the metamorphic rocks are placed into three categories: (1)

Rocks on serpentine borders; (2) rocks included within serpentine; and (3) rocks distant from known serpentine bodies.

METAMORPHIC ROCKS ON SERPENTINE BORDERS

The major metamorphic rock types near serpentine borders are fine-grained tough greenish-brown, bluish-gray, and dark-yellowish- and dark-reddish-brown phyllites, schists, and less-foliated rocks. Many of the rocks have little tendency to split along the foliation. Foliation generally strikes northwestward, parallel to the bedding of nearby strata. Near the south shore of Angel Island dips are northeastward. Minor crenulations have maximum amplitudes and wave-lengths of about 8 inches. They generally trend and plunge northwest, but they vary considerably over distances of less than 5 feet.

Metamorphic rocks on serpentine borders include the following assemblages (minerals listed in decreasing order of abundance; minerals making up less than 5 percent of rock listed as minor):

Group I:
- Tremolite-albite-chlorite with minor pumpellyite, sphene, and oxidized pyrite cubes.
- Tremolite-albite-sphene with minor muscovite, chlorite, and oxidized pyrite cubes.
- Albite-stilpnomelane-tremolite with minor sphene and calcite.
- Tremolite (sodic)-albite-stilpnomelane-sphene.
- Tremolite (sodic)-albite-sphene with minor epidote, muscovite, chlorite.
- Albite-stilpnomelane-actinolite with glaucophane rims, chlorite with minor pyrite.
- Quartz-tremolite-stilpnomelane with minor muscovite, sphene, magnetite, calcite, and garnet.

Group II:
- Tremolite-chlorite.
- Tremolite.

Group III:
- Quartz-muscovite-stilpnomelane-crossite schist (fine-grained, silvery to brownish-gray with dark-blue rosettes of crossite).
- Quartz-garnet-hematite-stilpnomelane with minor clinozoisite and glaucophane (fine grained, dark brownish gray) with thin micaceous layers of muscovite-chlorite-iron oxide.
- Quartz-albite-crossite schist with minor muscovite, sphene, stilpnomelane, magnetite, oxidized pyrite cubes, and apatite (fine grained, silvery to dark bluish gray).
- Quartz-chlorite with minor muscovite (fine grained, green).
- Quartz-garnet with minor stilpnomelane, muscovite, glaucophane, and sphene (fine grained, dark brownish gray).
- Stilpnomelane-quartz-albite with minor glaucophane (fine grained, reddish brown, with thin blue glaucophane-rich streaks).

Group IV:
- Pumpellyite-albite-sphene rock with minor clinopyroxene (relict microphenocrysts) and chlorite (very fine grained, tough, slightly schistose, greenish gray).
- Clinopyroxene (diopside-jadeite)-albite-sphene rock with minor chlorite (very fine grained, tough, slightly schistose, greenish gray).
- Tremolite-albite-clinozoisite-epidote rock with minor sphene, stilpnomelane, and pyrite (fine grained, tough, slightly schistose, greenish gray).

Group II rocks are less abundant but more conspicuous than group I rocks. They are very fine grained white to silvery light-gray schists with small-scale crenulations (1/8–1/2-in. amplitude) and well-developed cleavage parallel to the foliation. Some are in elongated pods and veins in shear zones between serpentine and the darker rocks of group I. Tremolite and tremolite-chlorite rock are generally soft and talcose. Groups III and IV are not as common but form distinct metamorphic assemblages. The largest exposed bodies of metamorphic rocks are on the borders of serpentine along the south shore of Angel Island (fig. 38). Inland to the northwest along the west side of a large serpentine body, however, the bodies are isolated and do not form a continuous belt adjacent to the serpentine.

Along the south shore of Angel Island, metamorphic rocks border both sides of the serpentine dike (pl. 1). The smaller body, east of the serpentine, is mostly fine grained light-green rock consisting of the first two assemblages listed in group I. Schistosity in this body is shown by layers 1 or 2 inches thick, but individual layers are tough and only slightly schistose. The larger, western body consists of a large variety of metamorphic rocks and includes most of the assemblages in groups I–IV. Schistosity is developed to various degrees. Some rocks show closely spaced highly schistose micaceous layers; others, rich in quartz, albite, and other nonmicaceous minerals, are tough and show only moderate or little tendency to break along the schistosity. Rocks of group IV are present in minor volume.

PARENT ROCK TYPES

Metamorphic rocks along serpentine borders are believed to be metamorphic equivalents of sedimentary and igneous rocks of the Franciscan Formation. The highly tremolitic rocks of groups I and II may have

FIGURE 38.—Serpentine body and metamorphic rocks on Angel Island. Upper photograph is view northwest across Raccoon Strait and along Tiburon Peninsula. Serpentine is light band in center partly covered with trees. Metamorphic rocks form headlands on shore at right. Lower photograph is of the same part of the serpentine body showing its ridge topographic expression, as viewed from a boat southwest of Knox Point (white lighthouse building on shoreline at left). Serpentine ridge is light-colored mostly barren ridge between the shore cliffs and the skyline.

been subjected to magnesium metasomatism, or they may be metamorphosed serpentine or peridotite. Group III rocks are probably metamorphosed cherts or arkosic wackes. Group IV rocks are probably metamorphosed greenstones.

A rock abundant near the west border of the serpentine along the south shoreline of Angel Island consists of alternating reddish-brown stilpnomelane-rich beds 1–3 inches thick and bluish- and brownish-gray quartz-rich beds cut by numerous quartz veinlets and pigmented with crossite, glaucophane, garnet, and stilpnomelane. Mineral composition and bedding strongly indicate that the rock was originally interbedded chert and shale. Thus, quartz veinlets in the quartz-rich layers appear to be relicts of quartz veinlets in the original chert. This metamorphic rock differs from typical Franciscan chert in that the quartz-rich layers and stilpnomelane-rich layers are nearly the same thickness, whereas unmetamorphosed chert layers are typically 3 inches thick and the shaly layers are only one-fourth inch thick. The difference in thickness may be caused by metamorphism.

METAMORPHIC ROCKS WITHIN SERPENTINE BODIES

A great variety of metamorphic rocks occur as inclusions in all the serpentine bodies. They are especially abundant on Angel Island but are sparse in San Francisco. The inclusions vary in size from about 2 inches to 20 feet in diameter and include a variety of textures and compositions. They appear to have a random distribution with respect to serpentine borders; foliation and lineation are random in some inclusions. All these features are compatible with the belief that the inclusions formed under varying physical and chemical conditions before reaching their present position. Similar tectonic inclusions in serpentine are described by Brothers (1954, p. 616) from the Berkeley Hills, 8 miles northeast of Angel Island. The inclusions in the San Francisco North quadrangle are believed to be metamorphosed rocks of the Franciscan Formation and metamorphosed serpentine and gabbro-diabase.

Inclusions are classified here according to their mineralogy and probable parentage into five groups:

Group I:
- Quartz-crossite.
- Quartz-crossite-stilpnomelane.
- Quartz-hornblende (with crossite aureoles)-sphene-garnet with minor stilpnomelane and cut by veins of albite-stilpnomelane-muscovite.
- Quartz-stilpnomelane-hornblende (with glaucophane and crossite aureoles) with minor sphene and albite.
- Quartz-albite-hornblende (with crossite aureoles)-aegerine with minor sphene, stilpnomelane, and hematite.

Group II:
- Garnet-chlorite-vesuvianite with minor sphene.
- Garnet-chlorite-diopsidic augite-sphene.
- Garnet-chlorite-vesuvianite-calcite with minor magnetite and pyrite.
- Diopside-chlorite with minor sphene.
- Diopside-chlorite with minor sphene and garnet.
- Chlorite-diopside-zoisite-sphene.
- Clinozoisite-diopside-garnet-vesuvianite with minor sphene and chlorite.
- Diopside-garnet-prehnite-chlorite-sphene.

Group III:
- Pumpellyite-pigeonite-chlorite-sphene with minor stilpnomelane.
- Pumpellyite-albite-sphene and minor calcite and chlorite.
- Chlorite-sphene-andesine (An_{44}).

Group IV:
- Hornblende-albite-clinozoisite-diopside-sphene with minor stilpnomelane and muscovite.
- Clinozoisite-diopside-sphene with minor chlorite and stilpnomelane.

Group V:

- Tremolite-chlorite.
- Actinolite-glaucophane-chlorite-pumpellyite with minor calcite, muscovite, and sphene.
- Albite-actinolite with minor chlorite and sphene.
- Chlorite-actinolite with minor sphene.
- Chlorite-magnetite-apatite.
- Chlorite-magnetite-sphene-apatite.
- Chlorite-sphene with minor stilpnomelane.
- Talc-chlorite-hornblende (sodic) with minor sphene, pyrite, and stilpnomelane.

Rocks in group I are medium- to dark-bluish-gray or brownish-gray fine-grained somewhat brittle schists. Most of them contain more than 50 percent quartz and in addition are cut by numerous quartz veins. They are probably metamorphosed cherts or arkosic wackes.

Rocks in group II are dark greenish gray to light yellowish gray, aphanitic to medium grained, and exceedingly tough. Typically, they are spheroidal inclusions 1½–4 feet in diameter. They show no foliation. Most of them have a light-colored core and a 1–3-inch-thick medium- to dark-gray rim. The dark rim consists mostly of chlorite and magnetite. Garnet composition, determined by use of Sriramadas' (1957, p. 295–296) and Winchell and Winchell's (1951, p. 493) graphs, shows grossularite-andradite (40–70 percent grossularite) and garnet-hydrogarnet of the same grossularite-andradite range, but with 1–1.2 moles of water. Many rodingites show a relict porphyritic texture with phenocrysts replaced by metamorphic minerals, althrough some of the clinopyroxene appears to be primary phenocrysts. One inclusion contained euhedral plagioclase laths replaced by chlorite, garnet, and vesuvianite in a groundmass that shows structures identical to those found in tachylitic, pyroclastic, and pillow greenstone preserved mostly by cloudy garnet-hydrogarnet (of grossularite-andradite composition). Greenstone structures are also preserved, mostly as chlorite and magnetite, in the dark rim.

Rocks in group II are believed to be metamorphosed igneous rocks and possibly sediments of the graywacke type. Their mineralogy indicates that calcium was added to them. Their composition and their occurrence as inclusions in serpentine suggests that they are rodingites. Rodingites have been described throughout the world as calcium-enriched gabbros or diorites intrusive into serpentine. Rodingites on Angel Island do not intrude serpentine; rather, they are tectonic inclusions in serpentine and are intruded by serpentine (antigorite) veins. Thus the rock from which they were altered to rodingite is older than serpentine (Schlocker, 1960). The source of additional calcium needed to form rodingite and the conditions under which calcium was concentrated in the cores of the inclusions and magnesium was concentrated in the dark rim are not known. Calcium is thought to come either from solutions left after crystallization of ultrabasic "magma" or from pyroxenes in peridotite and may have been released during serpentinization (Turner and Verhoogen, 1951, p. 488). The presence of calcium-bearing pyroxenes such as diallage (diopside) in the serpentine of the San Francisco area indicates that the latter source is possible here. The diopside-garnet-prehnite-chlorite-sphene rock and the diopside-chlorite-zoisite-sphene rock were inclusions in serpentine and landslides north of Bakers Beach.

Rocks of group III are grayish-green aphanitic to fine-grained exceedingly tough unfoliated metagreenstones. They are generally cut by blue veinlets of crocidolite.

Rocks in group IV are green to greenish-gray fine- to medium-grained granoblastic metadiabase-gabbros. They are commonly cut by pumpellyite, quartz, and albite veins.

Rocks of group V include types that are rich in magnesium minerals. They have various colors that range from dark greenish gray to pale pearly green and various textures that range from aphanitic hornfelsic at one extreme to coarse-grained porphyroblastic schistose at the other. They may have been subjected to magnesium metasomatism. Parentage is unknown, but some of them may be metaserpentines or metaperidotites. The actinolite-glaucophane-chlorite-pumpellyite rock was found in serpentine in San Francisco near the intersection of Euclid and Masonic Avenues.

METAMORPHIC ROCKS DISTANT FROM KNOWN SERPENTINE BODIES

Some metamorphic rocks have erratic distributions within semischists and relatively unmetamorphosed rocks of the Franciscan Formation of Angel and Belvedere Islands and Tiburon Peninsula. They are particularly abundant on Angel Island, within and near the centrally located greenstone body, although a number of them are found near Blunt Point, near a small exposure of pillow greenstone (pl. 1). They are generally elongated bodies less than 1 to more than 5 feet thick and mostly too small to show on the geologic map (pl. 1). Schistosity, where shown, is more or less parallel to the bedding of nearby stratified rocks. Some of the metamorphic rocks occupy shear zones, and high shearing stresses may have been important in their formation. A hydrothermal origin is also suggested by the following characteristics: (1) Crocidolite on joints in unmetamorphosed unsheared greenstone; (2) veins of albite, quartz, calcite, pumpellyite, amphiboles, chlorite, stilpnomelane, and opaque ore minerals in metamorphic rocks; (3) rapid changes in texture and mineralogy over short distances; and (4) concentration of metamorphic rock bodies in and near the largest greenstone body exposed on Angel Island. (For more information on these processes, see Turner and Verhoogen, 1951, p. 244, 472.)

Similar observations were made by Borg (1956, p. 1581). She used these as evidence that hydrothermal metamorphism formed glaucophane schists and eclogites in the Franciscan Formation near Healdsburg, Calif., 60 miles northwest of San Francisco. Nevertheless, Borg (1956, p. 1563, 1581) concluded that the metamorphism was not accompanied by metasomatism, after she had compared chemical analyses of unmetamorphosed parent rock types and the metamorphic equivalents and found them to be similar. The analyses given in table 5 show that this is also true of unmetamorphosed sandstone and jadeitized sandstone of Angel Island.

The rocks not directly related to serpentine bodies are further segregated according to their mineralogy and (or) parentage into the following groups:

Group I:

- Quartz-crossite with minor stilpnomelane.
- Quartz-crossite-aegerine.
- Quartz-aegerine-stilpnomelane with minor riebeckite and sphene.
- Quartz-aegerine-magnetite with minor stilpnomelane.
- Quartz-garnet-stilpnomelane with minor muscovite, hornblende (sodic), and hematite.

Group II:

- Blue amphibole (glaucophane-riebeckite series)-lawsonite - pumpellyite - stilpnomelane - albite - chlorite with minor sphene
- Blue amphibole (glaucophane-riebeckite series)-lawsonite-sphene with minor stilpnomelane
- Glaucophane - pyroxene (diopside - jadeite) -chlorite-sphene with minor clinozoisite, muscovite, and stilpnomelane
- Clinozoisite - chlorite - lawsonite - stilpnomelane - pyroxene (diopside-jadeite)-sphene with minor muscovite, cut by veins of lawsonite-stilpnomelane-chlorite with minor muscovite
- Glaucophane - lawsonite - albite - sphene cut by quartz and calcite veins
- Hornblende (hastingsite)-lawsonite with minor muscovite and sphene, cut by veins of lawsonite with minor chlorite and by veins of albite with minor hornblende.
- Tremolite (sodic)-lawsonite-pyroxene (diopside-jadeite) with minor chlorite, stilpnomelane, glaucophane, and lepidocrocite.

Group III:

- Glaucophane-albite-chlorite-muscovite with minor sphene.
- Glaucophane - chlorite - pumpellyite - sphene with minor muscovite, stilpnomelane, lawsonite, and apatite (garnet porphyroblasts completely altered to chlorite, muscovite, pumpellyite, sphene, and stilpnomelane).
- Glaucophane-clinozoisitic epidote-stilpnomelane with minor muscovite and sphene, cut by veins of calcite.
- Albite-hornblende (with glaucophane aureoles)-muscovite with minor chlorite, clinozoisite, garnet, pyrite, and lepidocrocite.
- Albite-hornblende-chlorite with minor sphene, leucoxene, ilmenite, and magnetite, cut by veins of albite, hornblende, and chlorite.
- Albite-amphibole (sodic hornblende to tremolite) with minor chlorite, muscovite, and sphene, cut by veins of coarse-grained albite.

Group I rocks are predominantly fine grained metacherts. Quartz makes up three-fourths of most of them. Those rich in crossite are blue; those rich in aegerine are yellowish or reddish brown or grayish red. Some rocks contain both minerals as segregated masses or as yellowish and reddish brown rosettes streaked with blue. The last assemblage listed in group I is mostly light gray with subordinate brown flakes. Some rocks in group I are interbedded with relatively unmetamorphosed chert, especially on Belvedere Island, where blue semischistose metacherts are interbedded with colorless to red nonschistose chert.

Group II rocks are predominantly fine- to coarse-grained metagreenstones that are within, and at the borders of, the large greenstone body on Angel Island. The first two assemblages listed are blue fine-grained breccia fragments in a sheared partly metamorphosed greenstone that it enclosed within relatively unmetamorphosed greenstone breccia. The glaucophane-lawsonite-albite-sphene rock is a blue fine-grained tectonic inclusion more than 20 feet in diameter in the shear zone west of Lands End.

Group III rocks are fine- to coarse-grained blue or grayish-green generally micaceous completely recrystallized schists. On Angel Island they are spatially related to the large greenstone body and crop out at the unnamed point 3,000 feet north of Blunt Point. Parentage and conditions of metamorphism are uncertain. Because of the lack of chemical analyses, guesses about their parentage cannot be very selective. Their association with greenstone and sandstone and their mineralogy suggest that they are probably metamorphosed greenstone or arkosic wacke. The presence of late stilpnomelane and late pumpellyite suggests that chlorite zone conditions prevailed for some of them at a late stage of metamorphism.

TECTONIC SETTING OF METAMORPHIC ROCKS

Metamorphic rocks of Angel Island are part of an irregular northwestward-trending zone of metamorphic rocks, occurring mostly as tectonic inclusions, that follows the Tiburon Peninsula syncline for at least 6 miles and includes Tiburon Peninsula and Belvedere Island. Perhaps this belt was an exceptionally strong axis of downwarping in which the Franciscan rocks were metamorphosed to varying degrees, depending on local conditions of shear, water-vapor pressure, temperature, and chemical environment. The tectonic inclusions within and on the border of serpentine evidently were emplaced during shearing. Lack of schistosity in the numerous rodingite inclusions in serpentine suggests that they were enriched in calcium after reaching their present position. Metamorphic rocks within semischists and relatively unmetamorphosed rocks of the Franciscan Formation in most places appear to be tectonic inclusions, but exposures are not complete enough to confirm this for all occurrences.

Metamorphic rocks in San Francisco are tectonic inclusions within the Hunters Point–Fort Point and the City College shear zones.

Ransome (1894, p. 211, 222) believed that the metamorphic rocks of Angel Island were formed by "local contact metamorphism" along intrusive borders of greenstone and serpentine. He explained the greater abundance of metamorphic rocks on the west side of the serpentine dike as due to greater intensity of metamorphic processes on the upper side of the dike. His report on the geology of Angel Island first clearly described the transition of the unmetamorphosed rocks into metamorphosed rocks and the close spatial relations of the metamorphic rocks and the mafic and ultramafic intrusive rocks. Early thinking on the origin of the Franciscan metamorphic rocks was also indicated by Ransome (1894, p. 211):

> As the existing literature on Coast Range geology makes no mention of "glaucophane schists" arising from local contact metamorphism, and generally assigns them, together with the radiolarian cherts and much of the serpentine, to widespread regional metamorphism, the results arrived at in this paper have been to a certain extent forced upon the writer against certain preconceived notions drawn from reading.

Taliaferro (1943, p. 168, 182) believed that the metamorphic rocks are the result of local pneumatolytic metamorphism or metasomatism accomplished by emanations from mafic and ultramafic intrusives and that the schistosity is relict bedding. The writer believes that metamorphism was accomplished by one or more of the following: Hydrothermal solutions, metasomatism, local shear, or hydrostatic pressure.

HYDROTHERMAL ALTERATION AND WEATHERING

The metamorphic rock body exposed about 750 feet northeast of Knox Point is altered to a grayish-orange crumbly schist composed mostly of muscovite, vermiculite, quartz, and albite, and of a small amount of glaucophane. Small patches of partly altered bluish glaucophane-rich schist within the altered schist suggest that some or all of the vermiculite was derived from glaucophane. The schist and underlying greenstone are believed to be hydrothermally altered.

Weathering of metamorphic rocks has been slight.

SHEARED ROCKS

Zones of intense shearing that include several types of bedrock are distinguished on the geologic map (pl. 1) from zones of intense shearing in but one rock type. These shear zones generally consist of a mixture of hard blocks of bedrock, from less than 1 inch to 25 feet or more in diameter, in a soft intensely sheared matrix. The largest of these blocks is about 0.4 mile by 0.6 mile, in the Potrero Hill area. The blocks are generally rounded and surrounded by slickensided shear surfaces. The matrix is cut by abundant closely spaced shear surfaces. It consists generally of incompetent serpentine or shale that has broken down and generally moved plastically. Other incompetent material, such as hydrothermally altered rock, is found locally, but sheared shale is the only matrix material in many zones (fig. 11). Sheared serpentine and sheared shale resemble each other superficially, and they are difficult to distinguish in the field. Because of this resemblance, serpentine has been erroneously reported in previous literature in some areas.

Shearing of Franciscan rocks is greatest in shale, especially at and near serpentine borders, and the width of shear zones varies considerably. In some places, shear zones between the Franciscan Formation and serpentine are gradational, are more than 100 feet wide, and consist of an intimate mixture of serpentine and other rock types. In other places, shear zones are sharply defined and are only 3–5 feet wide, and the Franciscan rocks beyond are relatively undisturbed. Serpentine in many shear zones is converted to black waxy bentonite veins consisting predominantly of montmorillonite mixed with fragments of unaltered serpentine.

The color of shear zones is generally black or gray tinged with green. The color is determined by the sheared matrix. In sheared shale, carbon in thin disseminated streaks and films is believed to be partly responsible for the black and gray color. Chlorite is formed, in part, during shearing and gives the green tinge.

OCCURRENCE

The largest bodies of sheared rocks form the ridge between the U.S. Mint and the intersection of Presidio Avenue and Geary Boulevard. These rocks are predominantly clastic rocks and serpentine, but they include small bodies of radiolarian chert, greenstone, gabbro-diabase, and metamorphic rocks. Some of the clastic rock bodies are more than 1,000 feet long. Rock-type relationships are similar to those on the northeast slopes of Potrero Hill, where tectonic inclusions of sandstone occur in serpentine. Franciscan rocks, however, appear to be more abundant than serpentine. Depicting rock types within shear zones on the geologic map (pl. 1) generally is not feasible because the zones are very complex and mostly concealed by homes and streets in this area. The sheared rock relationship south of California Street and west of Presidio Avenue is considerably generalized from a detailed field map at a scale of 1:2,400 prepared by M. G. Bonilla and the writer when this area was being subdivided.

In a shear zone in the Point Lobos–Lands End area, a large variety of Franciscan bedrock is represented, including a few glaucophane-bearing metamorphic rocks with subordinate amounts of silica-carbonate rock and serpentine. The shear zone is tentatively thought to be the northern extension of the City College fault. (See p. 92.) Bodies of sheared rocks also occur on the north slope of Twin Peaks, Lone Mountain, on the west slope of Mount Sutro, and at Point Diablo.

SERPENTINE

Serpentine derived from peridotite occurs in San Francisco, on Angel and Belvedere Islands, and on Tiburon Peninsula. The peridotite was largely harzburgite; a small part of it was dunite. The present position of much of the serpentine is believed to be due to tectonic movement at relatively low temperatures. Most of the serpentine is sheared, but in a few places it is largely massive and unsheared. A few small bodies of clinopyroxenite and gabbro-diabase are found in the serpentine.

Serpentine in San Francisco is exposed in a shear zone about 1½ miles wide that extends from the southeast corner of the quadrangle across the city to the shoreline southwest and east of Fort Point. Other occurrences are below the south tower of Golden Gate Bridge, at James D. Phelan Beach State Park, in shear zones in the Lands End area, and in Lincoln Park. A serpentine body, about 600 feet thick, crosses the southwest part of Angel Island (fig. 38). Small serpentine exposures occur southwest of this body, along the southwest shore of Belvedere Island, and on Tiburon Peninsula.

In the San Francisco North quadrangle, as in the Coast Ranges generally, large bodies of serpentine form ridges (fig. 39). Serpentine and mixtures of serpentine and sheared rocks of the Franciscan Formation form the ridges of Potrero Hill, Alamo Square, and much of the high area of Fort Scott in the Presidio and continue for half a mile northwest of Fort Point as a submarine ridge to a point about midway in the Golden Gate channel (Carlson and others, 1970; Carlson and McCulloch, 1970). On Angel Island, serpentine is generally exposed in ridges (fig. 44) and spurs except at the northwest end of the island where it underlies a valley. Small bodies of serpentine do not generally form ridges.

Serpentine is apparently resistant to erosion, despite its generally sheared character. This is evidently due to its stability in the weathering environment and its consequent lack of a thick soil mantle. It is also due partly to its property of retaining cohesiveness after shearing by yielding to tectonic forces in generally plastic manner, instead of by shattering. It yields easily, however, to strong and continuous erosion processes, such as wave attack at the base of the cliffs. Most of the serpentine cliffs south of Bakers Beach are involved in landslides.

Another possible explanation for the tendency of serpentine to form ridges is that some Coast Ranges serpentine bodies appear to be under stress and are moving upward and laterally over adjoining more competent rock.

MEGASCOPIC FEATURES

Most serpentine is strongly sheared and fractured (fig. 40). Typical exposures include spheroidal knobs of hard serpentine with a polished, slickensided rind in a waxy, crumbly, thoroughly sheared matrix (fig. 41).

FIGURE 39.—Shoreline along Bakers Beach, the Presidio, Fort Point, and vicinity, view northeast. The cliffs south of Fort Point (far left) are huge landslides mostly in serpentine. The hill on the skyline is mostly underlain by serpentine. Bakers Beach is in the middle distance. Raised beach sands were found in the excavation for sewers for the houses on the far right on the distant slope of the Presidio. Franciscan sandstone exposed in near cliffs.

FIGURE 40.—Serpentine in a landslide. Fort Point Rock area, San Francisco, viewed southwestward from Golden Gate Bridge. The serpentine was strongly sheared before landsliding.

FIGURE 41.—Serpentine nodule in sheared serpentine. West end of Crissy Field, Presidio, San Francisco.

The knobs vary in diameter from a fraction of an inch to 6 feet or more. The sheared matrix generally constitutes 30 percent or more of the entire rock. In some places, bands of serpentine several hundred feet wide consist largely of sheared serpentine and a few unsheared nodules. In a few exposures, however, the serpentine consists of massive blocks, 2 feet or more in size, and less than 10 percent sheared serpentine. Such serpentine is shown separately on the geologic map (pl. 1) for the Potrero Hill serpentine mass and for the small serpentine body on Divisadero Street near Duboce Avenue and is also present within other serpentine bodies.

The color of serpentine varies widely and is evidently dependent on the composition of the parent peridotite, on the serpentinization process, and on the degree and type of alteration and shearing. Most commonly, coherent knobs and massive serpentine derived from harzburgite are bluish gray mottled with dark green and brown. Some especially hard ones are black, or greenish or bluish black. Somewhat crumbly ones are grayish green, and the abundant joints are black or dark blue. Hard, massive serpentine thought to be derived from dunite is mostly grayish green, grayish yellow green, or mottled grayish green and reddish brown. The predominating surface color of a knob, generally lighter than the interior color, is light greenish or bluish gray, but some knob surfaces are black or dark blue. The hard knobs with a black interior may have a white or yellow rind. The color of the sheared matrix surrounding the knobs, also generally lighter than the interior of the knobs, is mostly light greenish or bluish gray, or grayish yellow. Strongly sheared and altered serpentine may be dark gray or white.

On Angel Island many slickensided ellipsoidal knobs are embedded in sheared serpentine. These knobs are tough dark-gray to grayish-green serpentine that shows a very fine to fine-grained drusy to sugary appearance on a fresh fracture. Hard inclusions of metamorphic rocks are exceedingly common in sheared serpentine of Angel Island, also, but they are sparse in sheared serpentine in San Francisco.

MINERALOGY AND PETROGRAPHY

The spheroidal knobs and blocks of serpentine derived from harzburgite are generally studded with green, submetallic bronze-brown, or dark-brown crystals as much as 1 cm in diameter. These crystals have a good cleavage or parting, and they constitute 5–15 percent of the rock. They are either unaltered or partly altered pyroxene, or they are bastitic serpentine completely replacing pyroxene. Where the pyroxene is largely fresh, relict olivine appears as tiny corroded crystals in the cores of mesh-texture serpentine. The pyroxene is orthorhombic, generally enstatite. Palache (1894, p. 166–167), Ransome (1894, p. 221), and Taliaferro (1943, p. 154) also reported the presence of a small amount of the clinopyroxene diallage. The pyroxene is completely serpentinized in some bastite pseudomorphs, and so the original pyroxene could not be identified; however, the clinopyroxene content is believed to have been small, and thus the peridotite prior to serpentinization was harzburgite.

Serpentine believed to have been derived from dunite shows no relict pyroxene. It is not as common as serpentine derived from harzburgite. It is present on the west side of Potrero Hill.

Microscopic examination of thin sections shows that most serpentine from San Francisco consists predominantly of fibrous serpentine minerals. They commonly show mesh texture with length-fast alpha serpentine borders and length-slow gamma serpentine cores. The description and illustrations of this texture and its variations given by Francis (1956, p. 201–226) for a serpentine body in Scotland are equally applicable to the serpentine of this quadrangle. In some San Francisco serpentine, the cores of the meshes are isotropic. This material has been referred to previously as an amorphous mineraloid "serpophite," but Francis (1956, p. 219) explained that the isotropism is caused either by a matted growth of gamma serpentine fibers or by the $2V$ of the serpentine mineral passing through 90°. Alpha serpentine handpicked by Francis (1956, p. 208–210) yielded an X-ray diffraction pattern of chrysotile.

Several color and textural varieties of hard nodules from the serpentine of the San Francisco North quadrangle were investigated by X-ray diffraction. The criteria given by Whittaker and Zussman (1956, p. 107–126) were used to distinguish serpentine minerals. The results, given in table 8, show that clinochrysotile, lizardite, and orthochrysotile are the predominating serpentine minerals in most serpentine in San Francisco. Antigorite predominates in the serpentine sampled on Angel and Belvedere Islands. Brucite is absent except in some serpentines, where it may be present in trace amounts. Table 8 also gives bulk density of serpentines. The bulk density of serpentines from the Potrero Hill and U.S. Mint areas ranges from 2.1 to 2.4. In the Fort Point area serpentine partly altered to montmorillonite has a value of 1.14, whereas serpentines containing unserpentinized enstatite reach values of 2.65. The antigorite-bearing serpentines of Angel and Belvedere Islands have a bulk-density range of 2.44–2.66.

Mesh-texture serpentine is evidently derived from olivine, for some of it contains tiny corroded olivine relicts in the cores of the meshes and magnetite veinlets, 0.01–0.03 mm thick, which divide the rock into polygonal areas and which are believed to have been derived by exsolution along fractures in olivine at the time of serpentinization. The areas outlined by the magnetite veinlets generally include five to 10 meshes, but the magnetite veinlets usually follow the border of the outer meshes of the group. Nontronite and possibly bowlingite or stilpnomelane are present in some veinlets instead of magnetite. It is not known whether they are alteration products or magnetite or whether they formed in lieu of magnetite during serpentinization. Opaque iron ore dust is found in the cores of some of the meshes. Chromite or picotite appears sparsely in irregular masses, some of which, especially the iron-rich opaque chromites, have rims of nontronite or, more commonly, kämmererite.

BASTITE

Altered pyroxene or "bastite" serpentine is readily recognized in thin section by (1) the presence of closely spaced straight parallel veinlets of magnetite, bowlingite, or nontronite that follow cleavage or parting fractures in the original pyroxene, (2) one or two common extinction directions of the serpentine within the altered pyroxene, and (3) lack of mesh texture that is common in the matrix surrounding replaced pyroxene. An X-ray diffraction powder pattern of a serpentinized pyroxene, handpicked from a brown serpentine from the U.S. Mint area, showed mostly spacings of lizardite. Zussman (in Whittacker and Zussman, 1956, p. 123) reported that two of three bastites he studied gave X-ray diffraction powder patterns of lizardite; the third bastite gave a pattern of chrysotile.

RELICT OLIVINE AND ORTHOPYROXENE

Optical measurements (table 9) of the relict olivine and orthopyroxene confirm the presence of iron in the original peridotite, although the FeO/MgO ratio, indi-

TABLE 8.—*Partial mineral composition and bulk density of serpentine*

[Mineral composition based on X-ray diffraction and thin section examination; magnetite and chrome-spinel present in all serpentine. M=major constituent; m=minor constituent; Tr. (?)=identification of minor constituent is uncertain; n.d.=not determined]

Sample No.	Description	Bulk density	Lizardite	Clinochrysotile	Orthochrysotile	Antigorite	Splintery antigorite	Brucite	Chlorite	Enstatite	Olivine	Pyroaurite	Montmorillonite
Potrero Hill area:													
SF- 237; -1525	Light yellow green, compact, porcelaneous, mesh texture	2.1–2.3	M		M								
2133	Dark greenish gray, mesh texture	2.41	M	M									
274	Light yellowish gray, asbestiform fibers, brittle, 1½ in. long	n.d.					M						
289	White, waxy to fibrous compact veins	n.d.		M									
319	Grayish green, compact, mesh texture	2.31	M	M	m			Tr. (?)					
1119	Light blue green, opaline	2.30	M		M								
1501	Dark yellowish green, bastitic and mesh texture	2.40		M	M								
2025	Grayish yellow green, compact, chalcedonic	2.30	M	m	M								
2050	Mottled dark green and yellowish brown, mesh texture, compact, hard	2.28	M	M									
2213	Dark greenish gray, strongly sheared, crumbly	2.36	M	M					m				
322	Brown, resinous, strongly sheared, crumbly	2.37	M	M									
U.S. Mint area:													
SF- 174	Mottled dark brown and dark gray, bastitic, hard	2.37	m	M	M					m	m		
1947	Pale yellow green, mesh texture, friable	2.01	M	M				Tr. (?)					
1950	Pale olive, mesh texture, moderately firm to friable	2.07	M	M								M	
1951	Dusky yellow green, resinous	2.2	M	M									m
1953	Greenish gray with pale greenish yellow mesh cores	2.28	M	M				Tr. (?)					
1954	Mottled dark green and dark gray, bastitic	2.42	M	M									
1955	Pale blue, chalcedonic rind on bastitic serpentine	2.18	M	M								m	
1958	Mottled greenish yellow, olive, and dark greenish gray, bastitic	2.21	m	M									
Fort Point–Presidio area:													
SF–1986	Light greenish gray, friable	1.14	M	M					m				M
2056	Black, bastitic, hard	2.58	Tr. (?)	M				Tr. (?)		M			
2208	Dark greenish gray, bastitic, white powdery coating	2.34	M	M	M							[1]m	
1949	Black, bastitic, hard	2.65	M	M				Tr. (?)		m			
Angel Island and Belvedere Island:													
SF- 696	Mottled light yellow green and dusky blue, sheared but hard	2.62	m	m		M			m				
2209	Mottled pale greenish yellow and black, sheared but hard	2.58		m		M							
B–26	Mottled pale yellow green and dusky blue, sheared but hard	2.54	m	M		m							
51	Mottled dark greenish gray and light yellow green, sheared but hard	2.66	m	m		M							
S–10	Dark gray, fine grained, hard	2.65				M			m				
11	Mottled moderate yellow green and black, sheared but hard	2.52	m	m		M			m				
12	Mottled pale green, dusky blue, and white, hard	2.52				M	m						
44	Mottled medium gray and yellow green, hard	2.44	M	M		M							
57	Mottled dark gray and pale yellow green, hard	2.63	m	m		M							

[1]On coating.

TABLE 9.—*Optical properties of olivine and orthopyroxene and suggested composition*

Mineral	Locality	Refractive index and composition	2V and composition
Olivine	Divisadero St. and Duboce Ave.	Not determined	84°; $MgSiO_4$=75 percent.[1]
Orthopyroxene	do	Alpha=1.655–$MgSiO_3$=99 percent;[2] gamma=1.666–$MgSiO_3$=97 percent.	80°; $MgSiO_3$=81 percent.[2]
Orthopyroxene	South edge of Potrero Hill.	Alpha=1.669–$MgSiO_3$=88 percent; gamma=1.676–$MgSiO_3$=90 percent.	Not determined.

[1]From charts of Poldervaart (1950, p. 1073).
[2]From charts of Kuno (1954, p. 40).

cate by optics of enstatite, is lower than that indicated by olivine.

BLUE COLOR OF SERPENTINE

The characteristic blue coloring of much serpentine is in thin films and crusts along shear surfaces. Its composition was not investigated in detail, but it appears to be a finely disseminated mixture of magnetite crystals, smaller than 2 microns in diameter, and serpentine minerals.

ANTIGORITIC SERPENTINE

Serpentine composed largely of antigorite is found on Angel and Belvedere Islands as hard rounded knobs within soft sheared serpentine or as sheared, but coherent, serpentine containing tight slickensided joints throughout. The hard knobs are mottled dark-gray and pale-yellow-green fine-grained rock resembling basalt in hand specimen appearance. Under the microscope they are seen to consist mostly of plates of antigorite that average 0.1 mm in diameter and 0.006 mm in thickness. The largest plates are 0.4 mm in diameter and 0.05 mm in thickness. Veins and vague clots and segregations of antigorite crystals of the same general size make up the rock. Some rocks appear to show a vague foliation of the antigorite plates; others show a rectangular arrangement in which some plates are perpendicular to others. Magnetite crystals are generally larger than in mesh-texture serpentine, though in some serpentine they appear to outline meshes or are parallel to relict olivine or pyroxene crystallographic directions. In other antigoritic serpentine magnetite is in large isolated crystals or clots as much as 2 mm in diameter surrounded by 2–5 mm of magnetite-free antigorite. Chlorite appears to pseudomorph pyroxene and contains parallel bands of magnetite euhedra and antigorite plates.

Evidence for the partial conversion of mesh-texture serpentine to antigoritic serpentine is seen in thin sections of some serpentines from Angel Island consisting of a matrix of antigorite plates within which walls of the meshes appear collapsed and broken into subparallel groups containing very little mesh core material. The supposed collapsed mesh-wall material is similar to the sheared mesh-texture described by Francis (1956, p. 218–220). X-ray diffraction analysis of serpentine consisting partly of collapsed mesh walls shows the presence of antigorite, clinochrysotile, and lizardite (entries S–11 and S–44, table 8).

VEINS IN SERPENTINE

Late veinlets of cross-fiber chrysotile are common in the mesh-texture serpentine but are sparse in the antigoritic serpentine of Angel and Belvedere Islands. These veinlets vary from dark-green through light-yellow-green silky asbestiform fibers to white and pale-blue compact porcelaneous material. X-ray diffraction analysis shows clinochrysotile is present in all and orthochrysotile and lizardite in some. The porcelaneous rinds on hard serpentine knobs are also largely clinochrysotile.

Many knobs have a strongly fibrous rind, as much as one-half inch thick, of fibers alined parallel to the knob surface. In a few places this material has the appearance of cross-fiber chrysotile asbestos, but the fibers lack the flexibility of asbestos and break when bent. The fibrous rinds generally give the X-ray diffraction pattern of splintery antigorite (Whittaker and Zussman, 1956, p. 121), though a few are mixtures of chrysotile and lizardite. The fibrous rinds may have formed by shearing of cross-fiber chrysotile veinlets, which evidently are planes of weakness that become shear surfaces during tectonic movement. Some rinds show gradation from cross-fiber chrysotile veinlets to parallel-fiber splintery antigorite. The clinochrysotile rinds may have formed during shearing of massive serpentine and may not be related to the presence of previously existing veinlets.

On many serpentine knobs, late cross-fiber chrysotile veinlets, about 2 mm in maximum thickness, are oriented radially, at right angles to the knob surface. Such veinlets characteristically wedge out 1 or 2 inches from the surface of the knob. A pleochroic green and brownish-yellow mineral, chlorite or ferrostilpnomelane, accompanies the chrysotile in some veins. These veins appear to have formed by filling of shrinkage fractures, but no cause for such shrinking is known. Many knobs are cut by three-dimensional rectangular networks of late subparallel chrysotile veinlets (fig. 42).

Veins of carbonates and magnetite are common in serpentine. The common carbonate veins are hydromagnesite ($Mg_4CO_3(OH)_2 \cdot 3H_2O$) and magnesite ($MgCO_3$). They are conspicuously white veins and zones of nodules that reach 3 inches in thickness. Xonotlite, $Ca_6(Si_6O_{17})(OH_2)$, ($\alpha = \beta = 1.582 \pm 0.002$; $\gamma = 1.593 \pm 0.002$), occurs as radial fibrous sheaves resembling pectolite in veins with carbonates.

Calcite ($CaCO_3$) in brown and white veins is common in some places. Aragonite ($CaCO_3$) is found as bladed crystals on joints in serpentine nodules at several places on the east slope of Potrero Hill. Aragonite also occurs as anastomosing cross-fiber veinlets, as much as one-half inch thick, and as euhedral crystals in the serpentine near Fort Point Rock. Aragonite is also reported in serpentine at Hoboken, N.J. (Palache and others, 1951, p. 190). The crystallization of aragonite rather than calcite from aqueous solution is evidently favored by the presence of magnesium salts and a temperature of 30°–70°C (Palache and others, 1951, p. 191). Such conditions were evidently met during hydrothermal alteration of the serpentine.

Along Webster Street, at the U.S. Mint, sockets remaining in sheared serpentine matrix after the removal of hard knobs have a ¼-inch-thick lining of magnesite, possibly derived from chrysotile or splintery antigorite. Thin sections of serpentine from Potereo Hill show veinlets of cross-fiber chrysotile grading to fibrous magnesite.

SHEARED SERPENTINE

In San Francisco the sheared matrix enclosing the hard ellipsoidal knobs of serpentine contains the same serpentine minerals that are found in the knobs. Soft sheared matrix of antigoritic serpentine knobs on Angel

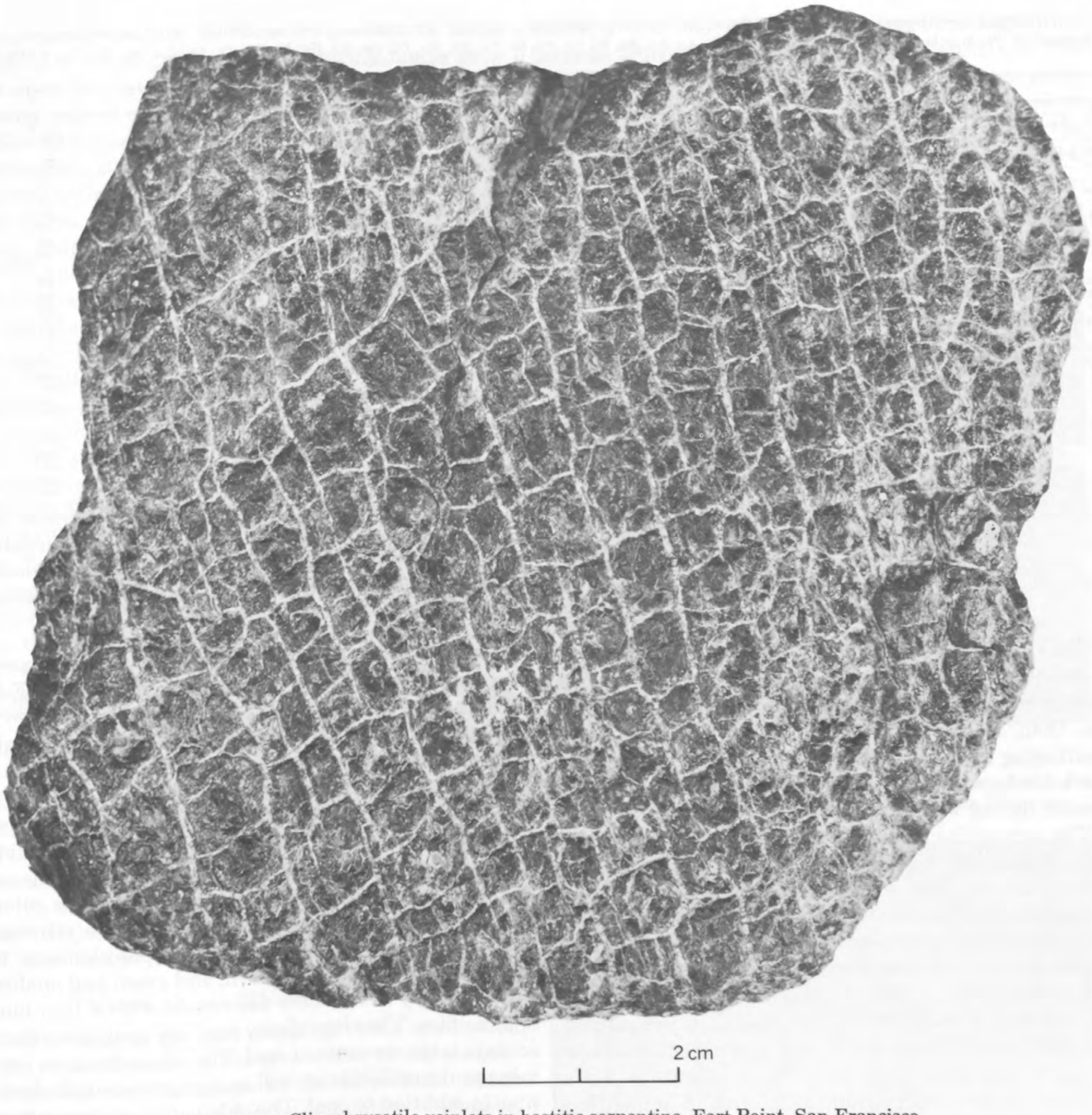

FIGURE 42.—Clinochrysotile veinlets in bastitic serpentine. Fort Point, San Francisco.

Island and Belvedere were not analyzed. Montmorillonite is common and in some sheared serpentine may be a major constituent. Talc is present locally. A light-blue to white strongly sheared friable serpentine is found in several places in the quadrangle. It swells and becomes plastic when wet and consists mostly of clinochrysotile and pyroaurite. No montmorillonite could be found in this material. The swelling and plasticity seems to be related to the clinochrysotile which forms a fluffy sediment and colloidal suspension when agitated in water.

CHEMICAL COMPOSITION

The approximate chemical composition of serpentines was obtained by semiquantitative emission spectrochemical analysis (table 10). The nickel, chromium, cobalt, and scandium contents are compatible with the results of Faust, Murata, and Fahey (1956, p. 318–320) on ultrabasic rocks of eastern United States and of Europe. Page (1968) and Page and Coleman (1967) gave partial chemical composition of serpentine from Tiburon Peninsula and complete chemical composition of serpentine minerals from other localities.

TABLE 10.—*Approximate semiquantitative spectrochemical analyses of serpentine and nontronite veins in serpentine*

[Analyst: H. W. Worthing. Looked for but not found: As, Au, Be, Bi, Cd, Ce, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Lu, Nb, Nd, Os, P, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Yb, Zn. M=major constituent > 10 percent]

	1	2	3	4	5	6	7
Si	M	M	M	M	M	M	M
Al	0.3	0.3	0.3	0.3	0.07	3	1.5
Fe	7	7	7	7	7	7	7
Mg	M	M	M	M	M	3	1.5
Ca	.015	.07	.7	.15	.03	.07	.15
Na	0	0	0	.03	.015	.03	.15
K	0	0	0	0	0	.7	.7
Ti	.015	.0015	.003	.003	.0007	.07	.07
Mn	.07	.07	.15	.15	.7	.7	.07
Ag	0	0	0	0	0	0	.000015
B	.003	.007	.003	.007	0	.003	.007
Ba	.0003	.00015	.0003	.00015	.0003	.0015	.003
Co	.007	.007	.007	.007	.007	.003	.003
Cr	.07	.07	.07	.07	.07	.03	.015
Cu	.0003	.0007	.0015	.0007	.0007	.0007	.0015
Ga	0	0	0	0	0	.00015	.00015
Mo	0	0	0	0	0	.0007	.0007
Ni	.3	.3	.3	.3	.3	.3	.3
Pb	0	0	.00015	0	0	0	.0015
Sc	.0003	.0003	.0003	.0007	.0003	.0015	.0015
Sn	0	0	0	.0003	0	.0003	.0003
Sr	0	0	.0007	.0003	0	.0003	.0003
V	.003	.003	.0015	.003	.003	.003	.003
Y	0	0	0	0	0	0	.0003
Zr	.0007	.0015	.0007	.0015	.0015	.003	.007

1. Serpentine; mostly antigorite; Angel Island (sample No. SF–1604).
2. Serpentinized harzburgite; no primary minerals; shattered bluish nodule; U.S. Mint, San Francisco (sample No. SF–1956).
3. Serpentinized harzburgite; tough brownish nodule. Most of enstatite is unserpentinized; small amount of primary olivine; U.S. Mint, San Francisco (sample No. SF–1957).
4. Serpentinized harzburgite; tough rock. Most of enstatite is unserpentinized; small amount of primary olivine; late veins of chrysotile and stilpnomelane; Fort Point, San Francisco (sample No. SF–2056).
5. Serpentinized dunite showing mesh texture; no primary minerals; Potrero Hill near San Francisco Hospital (sample No. SF–2133).
6. Nontronite vein in serpentine; Potrero Hill, 18th and James Lick Freeway (sample No. SF–1851).
7. Nontronite vein in serpentine; Ellis and Gough Streets, San Francisco (sample No. SF–2134).

WEATHERING AND HYDROTHERMAL ALTERATION

Soil development on serpentine is very slight, and only in a few places does the surficial mantle, generally less than 1 foot thick, appear to be soil formed by weathering processes. The white or yellow rind on black knobs of hard harzburgite serpentine may have formed during weathering.

The serpentine at and near Fort Point is altered to hydromagnesite, pyroaurite ($Mg_6Fe_2CO_3(OH)_{16}{\cdot}4H_2O$), coalingite ($Mg_{10}Fe_2CO_3(OH)_{24}{\cdot}2H_2O$), and nesquehonite, $MgCO_3{\cdot}3H_2O$ (Mumpton, 1965). The hydromagnesite forms white nodules as much as half an inch in diameter in a talcose matrix of serpentine and pyroaurite. Coalingite occurs in golden brown veinlets 1–2 mm thick in serpentine largely altered to pyroaurite. Nesquehonite forms a white soft surface efflorescence at moist places in serpentine. Eakle (1901, p. 316) reported barite and gypsum in fissures in serpentine near Fort Point. Sheared serpentine at the Hunters Point area is altered to a white soft talcose mixture of pyroaurite and clinochrysotile. The altered serpentine is in bodies as much as 3 feet thick. When wet the mixture is plastic.

Mixtures of epsomite and hexahydrite commonly occur as a white soft powdery efflorescence on protected surfaces of serpentine. Chromite, shiny black on fresh fractures, is sparsely scattered in the serpentine in crystals as much as 4 mm in diameter. Locally, in serpentinized dunite, it is concentrated in thin bands of blebs 1–10 mm in diameter. Millerite and pyrite are commonly disseminated on sheared surfaces in serpentine, especially near contacts with the Franciscan Formation; they have not been found together. Octahedra of magnetite as much as 2 mm in diameter commonly stud shear surfaces. Gray and brown montmorillonitic clay minerals are common in serpentine.

At many places in San Francisco, serpentine contains a variety of alteration products in the form of opaline spheroidal nodules, mammillary and botryoidal masses, and crusts. In hand specimen some of these are colorless, glassy, and transparent. Others are white, vitreous, and opaque; pale yellowish brown porcelaneous to earthy; or mottled blue, brown, and green and opaline with a greasy cast. Many are coated with a thin blue opaline film. The clear glassy ones are opal; the others contain large amounts of opal. The white ones also contain montmorillonite as well as manganese oxide dendrites in addition to opal. The pale-yellowish-brown porcelaneous to earthy ones contain larger mounts of montmorillonite admixed with opal. Earthy nodules in some places have been largely destroyed, leaving thoroughly pitted serpentine. The mottled opaline material is a mixture of opal and serpentine minerals. Serpentine containing the opaline material generally shows other signs of alteration, such as gossanlike cellular iron oxide-rich segregations and abundant soft waxy brown segregations of montmorillonite. Alteration to opal appears to be related to weathering.

At many places serpentine is hydrothermally altered as well as strongly sheared along its contact with the

Franciscan Formation. A common product of these processes is a dark-gray bentonite which is moderately hard when dry but exceedingly plastic when wet. This material consists largely of montmorillonite. Montmorillonite masses vary in thickness from 1 or 2 inches to more than 20 feet. The large bodies of this material contain knobs of serpentine and Franciscan rocks. In some places, such as on Parker Avenue near DeAnza Street, white talc segregations are associated with the montmorillonite.

Hydrothermal alteration within serpentine bodies has also changed serpentine into soft crumbly porous brown-to-white material of bulk density less than 2. The alteration zones vary from distinct veins, ½–1 foot in thickness, to bodies several hundred feet in size having indistinct borders and containing segregations of fresh hard serpentine. Alteration of the sheared matrix of serpentine is apparently more pronounced and more widespread than alteration of the knobs.

Nickelian nontronite is found as brown crumbly veins 1–12 inches thick; semiquantitative X-ray spectrochemical analyses by the writer indicate that the nickel content of the nontronite is several times greater than that in unaltered serpentine. Semiquantitative analyses of two nontronite veins are given in table 10 (samples 6, 7). The analyses indicate that the altering solutions added Al, Na, K, Ti, Ba, Ga, Mo, Sc, and Zr to the serpentine and diluted or removed Mg, Co, and Cr.

Silica-carbonate rock, a product of extreme hydrothermal alteration of serpentine, is rare. It is an exceedingly tough rock consisting of a complex network of veins and masses of quartz, chalcedony, opal, carbonates (generally magnesite), and limonite. Silica-carbonate bodies, 5–15 feet in diameter, are seen at the U.S. Mint and at the Lands End landslide area.

SHAPE OF SERPENTINE BODIES

At one stage of the field mapping, shear orientation in the serpentine seemed to give a clue to the manner of intrusion and the shape of the serpentine. Shear orientation is best shown by the elongation of sheared hard knobs. In the soft matrix between the knobs, shear orientation is influenced by the knobs and is generally parallel to the surface of the knobs. In general, however, shear orientation varies greatly over short distances, and no meaningful pattern evolved except, perhaps, in Potrero Hill, where most of the shearing dips eastward or is horizontal or vertical and could be interpreted to suggest that the serpentine was intruded by low-angle shearing or thrusting (fig. 43).

Unfortunately, because of poor exposures, the structure of the Franciscan Formation adjacent to the serpentine belt of San Francisco is unknown. Lawson (1895, p. 450–453; 1914, p. 6) believed the serpentine between Potrero Hill and Fort Point consists of two nearly flat lying sheets separated by a continuous sheet of sandstone about 160 feet thick and "in places so warped that they are more or less discordant with the stratification planes of the Franciscan rocks" (1914, p. 6). No field evidence was found for Lawson's continuous sheet of sandstone. Instead, the sandstone bodies in the serpentine are believed to be tectonic inclusions completely within serpentine (fig. 44).

FIGURE 43.—Sheared serpentine containing large augens of altered and sheared gabbro-diabase. West side of Potrero Hill, James Lick Freeway near 19th Street, San Francisco.

FIGURE 44.—Serpentine, light gray, on the left and sandstone, dark gray, on the right, separated by a shear zone containing both rock types. Boys are at the edge of the serpentine and are left of sheared serpentine, sandstone, and shale. The sandstone is a huge tectonic inclusion in serpentine. East side of Potrero Hill, San Francisco. Iowa Street, south of 20th Street.

Irwin's (1964, p. C–1, C–9) suggestion that serpentine belts mark westward-overriding low-angle thrust faults may very well apply to the Hunters Point–Fort Point and City College shear zones. The hypothesis would be strengthened if the Franciscan Formation lying northeast of the Hunters Point–Fort Point shear zone should prove to be considerably different in age from those west of the zone. No evidence to support an age difference was found.

The border of the serpentine body on Angel Island appears to dip southwestward, whereas the adjoining sandstone dips northeastward. Ransome (1894, p. 219) described this body as a dike dipping about 55° southwestward.

Conclusions could not be reached regarding the subsurface shape of the serpentine bodies in the quadrangle.

ORIGIN

Microscopic examination shows that most of the serpentine was derived from harzburgite and some from dunite. Evidence is sparse on the early intrusive relations of the peridotite and serpentine and on the time of serpentinization. The peridotite and serpentine in the quadrangle are classified as of the alpine type because they generally occur with spilitic volcanic rocks, radiolarian chert, and graywackes in an orogenic zone (Hess, 1955, p. 392; Turner and Verhoogen, 1951, p. 239–240). The peridotite and serpentine are believed to come from the upper mantle, from which they were raised into the crust and eventually to the surface along deep faults or folds that extended into the mantle (Irwin, 1964; Hess, 1955, p. 403; DeSitter, 1956, p. 360–361). Bailey, Blake, and Jones (1970) believed the peridotite and serpentine were derived from the oceanic mantle and became the basal part of the ophiolite sequence of the oceanic crust upon which the Great Valley sequence and the Franciscan Formation were deposited. They stated that since middle-Cretaceous time the Franciscan Formation has been thrust (subducted) under the serpentine of the oceanic crust upon which the Great Valley sequence was deposited. The serpentine bodies of the quadrangle, however, do not appear to be part of an ophiolite sequence, for they lack an overlying layer of mafic volcanic rocks. The serpentine bodies apparently lie wholly on or within the Franciscan Formation, with the possible exception of the serpentine in the shear zone of Lands End which, as part of the City College shear zone, separates the Great Valley sequence of San Bruno Mountain and Point Lobos from the Franciscan Formation to the northeast. (See fig. 62.) Serpentine in the Fort Point–Potrero Hill–Hunters Point shear zone may have been derived from the upper mantle, for the shear zone may be a northeasterly dipping thrust fault created by underthrusting (due to sea-floor spreading) the predominantly radiolarian chert and greenstone block southwest of the zone below the predominantly graywacke and shale block on the northeast. (See fig. 62.)

Although the borders of serpentine bodies in this quadrangle are poorly exposed and hydrothermally altered, some evidence was found to suggest that the serpentine reached its present position by tectonic stresses acting on more or less solid serpentine. Contacts between serpentine and the Franciscan Formation, wherever they were seen, are strongly sheared. Blocks of Franciscan Formation lying within serpentine have sheared slickensided exterior surfaces. The random attitude of bedding planes in such blocks suggest that they are tectonic inclusions. Furthermore, the common occurrence of serpentine as a sheared matrix enclosing ellipsoidal slickensided knobs is best explained as a response of solid material of low strength to shearing stresses. Finally, the adjoining rocks of the Franciscan Formation do not show the metamorphism that would be expected at the high temperatures needed to maintain a molten peridotite or serpentine magma (Turner and Verhoogen, 1951, p. 244–252).

Serpentine forms by hydration of peridotite by chemical reactions similar to the following for olivine and water (Turner and Verhoogen, 1951, p. 250):

$$\underset{\text{(olivine)}}{5Mg_2SiO_4} + \underset{\text{(water)}}{4H_2O} \rightleftharpoons \underset{\text{(serpentine)}}{2Mg_3Si_2O_5(OH)_4} + 4MgO + SiO_2$$

If MgO and SiO_2 are removed in solution, the volume of olivine is almost the same as the volume of the serpentine formed from it. If the MgO and SiO_2 contents remain the same before and after serpentinization, a volume gain of more than 50 percent is possible. The preservation of cleavage and parting of serpentinized enstatite in the harzburgite knobs in San Francisco indicates little or no volume change on a microscopic scale during serpentinization. Coleman (1971, p. 910) suggested that both constant-volume and constant-composition processes may operate in serpentinization. He finds that the most common products of serpentinization of alpine-type ultramafics are clinochrysotile, lizardite, antigorite, brucite, and magnetite. Coleman (1971, p. 908) gave reactions for serpentinization of olivine that show that SiO_2 must be added or MgO removed in order to convert olivine to serpentine by hydration. The excess MgO can be removed from the reaction by forming brucite. Judging from the absence of brucite in serpentine derived from dunite in the quadrangle, SiO_2 was added or MgO was removed during serpentinization. After using data from laboratory investigations of the system MgO-SiO_2-FeO-Fe_2O_3-H_2O, Coleman suggested that most serpentine derived from alpine-type ultramafic rocks in orogenic zones probably formed between 100° and 300°C and that antigorite-bearing serpentine may have formed between 300° and 550°C in deeper levels of the crust than those at which lizardite and clinochrysotile form. Barnes and O'Neil (1969) suggested that serpentinization is taking place at present at and near the surface.

AGE

Serpentine in the quadrangle is probably slightly younger than the rocks in which it was injected, but almost no time data are available. The serpentine at James D. Phelan Beach State Park probably reached its present position by tectonic injection into sandstone containing *Douvilleiceras* sp. of Early Cretaceous Albian age. Thus, the serpentine injection here may be post-Albian.

The presence of rare detrital grains of picotite and orthopyroxene in some Franciscan sandstone means that ultramafic rocks were exposed, though scarce, during Franciscan time.

In his study of the Coast Ranges, Taliaferro (1943, p. 153–154) found sills and plugs of serpentine in the Franciscan Formation and also in and nearly to the top of the Late Jurassic Knoxville Formation (Great Valley sequence of Bailey and others, 1964). He believed they "were emplaced as peridotite before the sediments had been uplifted from the basin of deposition," but also stated that "some of the stratigraphically higher sills were largely serpentinized before complete emplacement***."

In a study of the Klamath Mountains and northern Coast Ranges, Irwin (1964, p. C–1) suggested that ultramafic rocks, including serpentine, were emplaced during the Nevadan (Late Jurassic) and Coast Range (probably Late Cretaceous) orogenies.

PYROXENITE

Several masses of pyroxenite as much as 10 feet across were found in the serpentine on the south slope of Potrero Hill and along the shore north of Bakers Beach. The pyroxenite is a tough grayish- to yellowish-green coarse-grained rock that contains crystals as much as 7 mm long. It consists largely of diallage with small amounts of tiny euhedral to subhedral magnetite crystals. The diallage is slightly altered to chlorite and leucoxene. Pyroxenites have a hypidiomorphic texture, modified by postsolidification forces to a cataclastic texture. This texture is shown by breccia zones between some of the diallage crystals and by veinlike breccia zones.

A tough greenish rock on the shore about half a mile south of Fort Point is regarded as a metapyroxenite. The rock contains relict pyroxene that is ragged and has been largely replaced by chlorite and by smaller amounts of clinozoisite and sphene under chlorite-zone metamorphic conditions that may have existed during serpentinization.

A tough pale-green rock encased in altered serpentine, one-eighth mile east of Fort Point, consists of diopside, chlorite, and prehnite. It may be an altered gabbro. Ransome (1894, p. 221–222) found pyroxenite in the serpentine on Angel Island. He stated that the pyroxene crystals are "10 mm or so in length***" and identified them as diallage. Crandall (1907, p. 19) found both diallage and enstatite in pyroxenite from the Presidio area.

GABBRO

Small bodies of fine- to medium-grained gabbro are widely scattered in the serpentine. They vary in size from 5 feet in diameter for small equidimensional bodies to elongate bodies 100 feet by 20 feet. Only the larger ones are shown on the geologic map (pl. 1). Gabbro is dark gray where freshest and brown where weathered. Most bodies have sharp slickensided contacts with serpentine; the small bodies are rounded by shearing, and the elongated ones are randomly oriented. They are probably tectonic inclusions. Because some of the bodies have a linear arrangement and a decrease in grain size from their centers outward, Palache (1894, p. 172) suggested that they are intrusive bodies that were disrupted by movement of the serpentine. At most places no contact effects are seen on the adjoining serpentine.

The gabbro is tougher and less fractured than the serpentine and tends to crop out in relief 2–5 feet above the serpentine. On Angel Island metagabbro is so tough, so fracture free, and so rounded that it is difficult to obtain a hand specimen. At one locality on Potrero Hill, gabbro altered mostly to prehnite is in sharp contact with fresh gabbro.

The texture of the gabbro varies from allotriomorphic granular to subophitic; rocks with the latter texture have the field appearance of a diabase. The predominating constituents are plagioclase laths (white to colorless), which generally make up one-half to two-thirds of the rock, and ferromagnesian minerals (dark), which rarely make up more than half of the rock. The gabbro of Potrero Hill in San Francisco has a slight foliation. The plagioclase is labradorite, An_{60}, mostly altered and replaced by chlorite, muscovite, zoisite, and unidentified clay minerals. The ferromagnesian mineral is predominantly hornblende, in generally equidimentional crystals about 1 mm in diameter ($Z \wedge C = 20°$; X=pale brown; Y=light brown; Z=moderate to slightly greenish brown to light brown). All the hornblende may be secondary after pyroxene, for a few crystals of colorless pyroxene ($Z \wedge C = 48°$), partly altered to hornblende, are identified in thin sections. Part of the ferromagnesian minerals is replaced by chlorite and nontronite. Present in small amounts are stumpy apatite prisms, rounded blebs of monazite, and magnetite and ilmenite filling the space between plagioclase and hornblende crystals.

A medium-grained gabbro at the Presidio, San Francisco, is about 90 percent hornblende ($Z \wedge C = 21°$; X=pale brown; Y=light brown; Z=light bluish green). Most of the remainder is clinozoisite, actinolite, epidote, and albite. Monazite blebs are abundant in the hornblende. Actinolite needles have grown into the albite from the borders of hornblende crystals.

Xonotlite and pumpellyite veinlets are common in gabbro. In a sheared and altered unidentified "basic rock" inclusion in serpentine near Fort Point, Eakle (1901, p. 316) found veins of pectolite and datolite. The rock was not found by the writer, but it has been described (Murdock and Webb, 1956, p. 137) as an "altered diabase dike." On Angel Island a fresh metagabbro consists of about two-thirds andesine laths (An_{42}) and one-third pigeonite. The pigeonite generally has rugged edges where it is partly replaced by actinolite and chlorite; in one body the pigeonite was completely replaced by actinolite. The andesine is crowded with needles and stumpy prisms of a colorless to pale-brown amphibole. About 2 percent leucoxene replaces skeletal ilmenite. Skeletal pyrite is also present. The gabbros of Angel Island and Tiburon Peninsula are also cut by pumpellyite and chlorite veinlets.

Palache (1894, p. 173–178) found orthorhombic and monoclinic pyroxene in some of the gabbro of Potrero Hill and named the rock hypersthene diabase. He also found the hornblendic variety, which he classed as epidiorite.

Gabbro generally crops out as fresh tough rock. In some places it has a weathering mantle, 1–3 feet thick, consisting of material high in nontronite and vermiculite.

The gabbro may represent acidic segregations of a periodotite magma richer than usual in SiO_2, CaO, and Na_2O. If such segregations formed they probably had a lower temperature of crystallization that the peridotite and thus may be slightly younger than the peridotite.

If serpentinization quickly followed crystallization of peridotite, gabbro may also be younger than serpentine. This possible age difference may explain why it is not serpentinized. As seen today, most of the bodies are tectonic inclusions in serpentine.

Because the gabbro of Angel Island shows no contact effects on the adjoining serpentine, Ransome (1894, p. 227–231) suggested that it is older than the peridotite. Palache (1894, p. 172) suggested that the gabbro bodies of Potrero Hill are parts of one or more continuous dikes or sills that intruded the serpentine or peridotite and were broken into the present detached masses by movement of the serpentine. Some rodingites on Angel Island and the prehnitized gabbro of Potrero Hill are metamorphosed gabbro.

SURFICIAL DEPOSITS

Surficial deposits of late Pleistocene and Holocene age cover approximately 80 percent of the land area of the quadrangle. They have a maximum thickness of approximately 300 feet. The Tertiary Period is not represented in the quadrangle, other than the possible occurrence of Pliocene deposits in the oldest deposits below San Francisco Bay. The oldest of the surficial deposits, the Colma Formation, is a complex of Pleistocene coastal sediments, which include marine estuary deposits, beach deposits, and—at higher elevations—eolian, stream, and colluvial (slope debris) deposits. Dune sands cover more than half the city of San Francisco. They are the most widespread surficial deposit and reach thicknesses of 150 feet. Most dunes were actively moving in historic time.

Most hill slopes are mantled with debris (colluvium) derived from underlying rock and represent in part old landslide deposits. Ravines are partly filled with colluvium from adjoining slopes. Modern alluvium is uncommon in the quadrangle because of the absence of large streams. Alluvium is shown on plate 1 only in small deposits on Twin Peaks where it is related to a slightly older than modern drainage system that existed there when rainfall was greater than it is now. Modern landslide deposits are widely distributed on bedrock hills and along sea cliffs, though many of them are too small to show on plate 1.

Mud and clay of San Francisco Bay are unconsolidated sediments containing clay- and silt-size detritus and large amounts of water. They have accumulated to thicknesses greater than 100 feet in the bay along the east shore of San Francisco and along the north shore of Sausalito and Belvedere Island.

Artificial fill covers more than 3 square miles and is as much as 60 feet thick in some places. It consists of dune sand, colluvium, spoil from excavations and quarries, bay mud, and the general garbage of an urban area.

COLMA FORMATION

The Colma Formation is a group of unconsolidated sandy estuarine and coastal deposits of Pleistocene age. It was first named by Schlocker, Bonilla, and Radbruch (1958). Its type locality is south of the town of Colma, approximately 6 miles south of the quadrangle. Typical exposures are on the west side of El Camino Real extending 0.7 miles southeast of the intersection of El Camino Real with Hickey Boulevard. The lower part of the Colma Formation is exposed in depositional contact on the Merced Formation, approximately 3.6 miles south of the quadrangle. This exposure, designated a reference locality, is on the east side of the road leading to Thornton Beach State Park, about 0.15 miles southwest of the intersection of Alemany and Skyline Boulevards and between 200 and 225 feet above sea level. The Colma probably records several different periods of sedimentation related to periods of relatively high sea level. The isolated exposures within the San Francisco North quadrangle can be correlated with each other and with the type Colma on the basis of gross similarity in physical properties and stratigraphic position.

The Colma Formation was first recognized by the author and his colleague, M. G. Bonilla, in the Lake Merced area near the Pacific Ocean, about 1 mile south of the quadrangle. There the Colma is a nearly flat lying friable sand that lies unconformably on the steeply tilted fossiliferous marine Merced Formation of Pliocene and early Pleistocene age and unconformably below Pleistocene(?) and Holocene dune sand. In the San Francisco North quadrangle, widespread poorly consolidated bedded sand deposits are correlated with the Colma Formation rather than with the Merced Formation of the Lake Merced area because they are approximately horizontally bedded and lie immediately below latest Pleistocene and Holocene deposits. They also lack the shale beds and marine invertebrate megafossils that are common in the Merced Formation. For practical mapping purposes, silt, clay, and poorly sorted rubble intercalated with bedded sand were placed in the Colma Formation. Silt, clay, and rubble not associated with bedded sand were generally mapped as slope debris and ravine fill, though they may have been deposited contemporaneously with part of the Colma Formation.

MEGASCOPIC FEATURES

Bedding in the Colma Formation is generally easy to discern, for individual beds are 1–3 inches thick. Some of the Colma deposits, however, such as the one at map locality 6 in the Presidio (pl. 2*A*), are obscurely bedded. Bedding is revealed mostly by variations in the proportion of the silt-clay matrix relative to sand grains and the resulting variations in cohesiveness and cementation. Cohesiveness increases as the proportions of silt and clay increase; however, the silt-clay matrix does not generally exceed 20 percent by weight. The variations in cohesiveness are soon revealed in fresh cuts by rainwash sculpturing. The sandy beds are more readily eroded than the clayey beds, which stand out in relief a fraction of an inch to several inches from the sandy beds. Bedding is accentuated in some places by color differences which probably are caused by variations in the permeability of individual beds and by resulting differences in the amount of iron oxide stain deposited by interstratal solutions. The source of the iron is largely grains of iron-bearing heavy minerals concentrated in thin nonpersistent layers. Bedding may appear as an abrupt change in sand grain size. Rarely, a few pebbles, as much as 1 inch in diameter, are sparsely distributed in a one-pebble-thick layer in the midst of clayey sand. Bedding is rarely shown by clay beds.

Thinly bedded clayey sands in the Colma Formation commonly display a slight waviness of bedding with an amplitude of 1–6 inches and a wavelength of ½–3 feet (fig. 45). The waviness probably records uneven compaction rather than the environment of deposition. Crossbedding or inclined torrential bedding intercalated with near-horizontal bedding is especially common on the south slopes of Twin Peaks (fig. 46). Locally crumpled bedding between parallel nearly horizontal undisturbed beds 1–2 feet apart probably records subaqueous slumping.

The Colma Formation is generally yellowish or reddish brown. On Angel Island it is predominantly light gray, as are beds on the west slope of Russian Hill uncovered in the excavation for the Broadway Tunnel. On Twin Peaks the Colma Formation is mostly yellowish or reddish brown, but cuts disclose gray uncemented sand deposits resembling channel fillings, 15–25 feet wide. In a few places in San Francisco, the top 3–5 feet of the Colma Formation immediately underlying dune sand is gray to black, owing to organic carbonaceous material. Richard Janda (written commun., 1967) believed that the fresh Colma Formation is light gray or light brownish gray. The common yellowish- and reddish-brown colors, he believed, are due to weathering. He also believed soil stratigraphy may be useful in dividing the formation.

The Colma Formation is chiefly moderately sorted fine to medium sand with small to moderate amounts of detrital silt and clay (pl. 2B–E). Beds of silty clay ½–5 feet thick and coarse rubble containing gravel as large as cobbles are interbedded with the sand in a few places. Locally, rubble beds make up a minor part of the formation.

By using the method described by Inman (1952), Inman and Chamberlain (1955, p. 109), and Folk and Ward (1957), 13 samples of the Colma Formation were analyzed; the results are given on plates 2D and 2E. They show the following ranges in characteristics:

FIGURE 45.—Colma Formation (Qc) overlying greenstone of the Franciscan Formation (KJg), Sutro Reservoir, San Francisco. The light-colored streak dipping to left is interpreted as a zone of considerable ground-water chemical activity that altered the Colma Formation to clay and ironstone, possibly an old soil developed on a surface cut on older rocks of the Colma Formation to the right and later buried by younger Colma to left. Photograph below is a closeup view showing bedding and the inclined clay-ironstone zone.

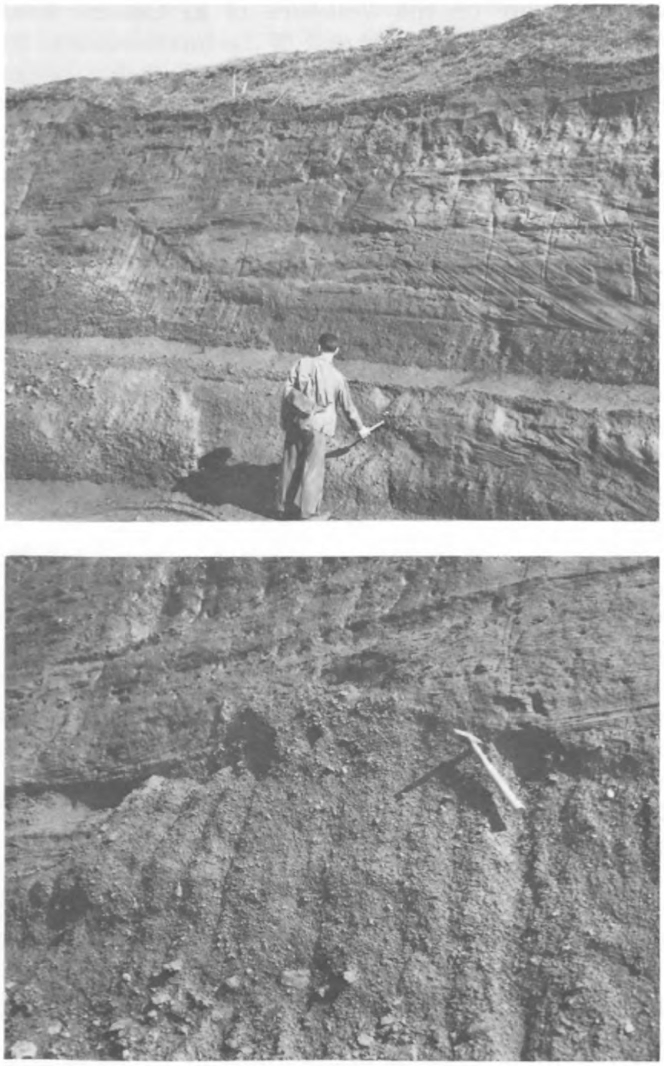

FIGURE 46.—Rubble deposits and crossbedding in the Colma Formation. In upper photograph contact with greenstone of the Franciscan Formation is 3 feet to left of man. Lower photograph is closeup view of well-bedded sand overlying poorly bedded rubble deposit containing large greenstone pieces. The rubble may be an old landslide deposit; the sand is a stream or lake deposit. South slope Twin Peaks, San Francisco.

Median diameter:
- Md 0.183–0.270 mm
- Mdϕ 2.45–1.89 phi units

Sorting:
- Trask So 1.18–1.85
- Phi deviation $\sigma\phi$ 0.44–1.91

Skewness:
- Trask Sk 0.625–1.019
- Phi $\alpha\phi$ + 0.02–0.76

Conclusions on the significance of these characteristics are given elsewhere.

COMPOSITION AND PHYSICAL PROPERTIES

Most of the sand grains of the Colma Formation are (in decreasing order of abundance) rock fragments, quartz, and feldspar (pl. 2*F*). Rock fragments are generally locally derived. For example, those in the Colma Formation at map locality 2 on Angel Island consist mostly of metamorphic rocks similar to those found in the underlying Franciscan Formation. Sand grains from locality 9 in San Francisco consist mostly of chert and from locality 11A of altered greenstone, nontronitic clay, and some chert. Heavy minerals make up 10–25 percent of the sand grains (pl. 2*F*). The predominant heavy minerals (in decreasing order of abundance) are green hornblende, augite, clinozoisite-epidote, brown hornblende, hypersthene, and ilmenite. Locally, dark layers of heavy minerals 1/16–1/4 inch thick are abundant. Particles smaller than 2 microns consist of varying proportions of montmorillonite, chlorite, and mica and random and regular mixed layered clay minerals of all three. In most sands, black, carbonaceous silt-size material, probably representing plant remains, is present, generally in amounts less than 1 percent. In a few exposures in San Francisco, dark-gray to black peat, clayey sand, or sandy clay occurs at the top of the Colma Formation immediately below dune sand. Peaty layers less than 1 foot thick were also penetrated by a few borings in the Colma Formation. Rubble beds were derived locally and consist of whatever rocks were available from nearby Franciscan Formation exposures in Colma time.

Most sand grains in the formation are medium size and coarser, are generally subangular to subrounded, and have polished surfaces. About 5–15 percent of the grains are angular; an equal portion are well rounded and have frosted surfaces. Feldspar, heavy minerals, serpentine, and rock fragments—including chert and microporphyritic igneous rocks—are generally better rounded than quartz; however, a small number of quartz grains also are well rounded and have frosted surfaces.

Cementation and porosity of the sands of the Colma Formation vary with the clay content. Most sands of the Colma Formation are friable or only weakly cemented. A 25-foot-thick deposit of gray fairly clean sand interbedded with brown clayey sand at Sutro Reservoir is uncemented. Porosity of the Colma Formation sand is generally moderate to high because of the moderately good sorting, the large proportion of subrounded and rounded grains in the sand sizes, and the lack of enough fine sizes to fill the spaces between sand grains. Some porous sands are cemented only at points of contact of the 1/2–1-mm-thick clay shells around each grain. In a few places the clay matrix completely fills the space between sand grains, and the sediment has low porosity. Sand grains and clay cement are generally iron stained. Oxidation of black layers of iron-bearing heavy minerals produces a tough, low-porosity ironstone 1–3 inches thick.

WEATHERING

Widespread orange and brown iron stains, with green and gray patches, and sporadic ironstone layers are evidence for oxidation and reduction which, in surficial deposits such as the Colma Formation, are probably related to weathering processes. Most of the clayey material in sand of the Colma Formation appears to be detrital, though a small amount of clay may represent alteration of sand grains. Evidence that the clay is detrital is indicated by the freshness of the feldspar and rock grains and by fairly abrupt variations in clay content from bed to bed. Soil development varies, but it usually appears to be slight to moderate, for distinct soil horizons generally are present only as a 1-foot-thick light- to medium-gray top layer. In a few places the soil-forming process has been intense, such as on the west side of Russian Hill and near Lombard and Divisadero Streets, where clayey sand grades upward into a sandy silty clay layer about 10 feet thick. The bottom half of the sandy silty clay layer is compact, but the top half is vesicular, has columnar structure, resembles loess in appearance, and is evidently the B soil horizon. The A horizon is poorly represented by small 1-foot-thick patches of gray clayey silty sand.

Weathering is also shown by etching of pyroxenes and hornblende. Almost all pyroxene grains in the Colma Formation have well-developed, long, delicate sawtooth terminations. In contrast, the pyroxene grains in the modern beaches and dunes have only tiny, short sawtooth terminations or no such terminations. Hornblende grains in the Colma Formation generally show good cleavage faces, in contrast with grains in modern beach and dune sand which are generally well rounded.

Strong etching of pyroxene comparable to that found in the Colma Formation was illustrated by Bradley (1957, p. 434, fig. 10). Though he examined modern beach sands, he found etched pyroxene only in old marine deposits lying on an elevated 100-foot marine terrace at Santa Cruz, Calif.

The dark-gray to black, carbonaceous clayey material found at the top of the Colma, underlying dune sand in a few places in San Francisco, may represent an old soil that developed in or near local marshes or lakes.

OCCURRENCE

The Colma Formation is widely distributed on Angel Island and in San Francisco. It was not recognized on

Tiburon and Marin Peninsulas or on Belvedere Island, although Quaternary deposits at these localities may be of the same age as the Colma Formation. The thickness of the Colma Formation varies greatly over short distances and is difficult to estimate. On many slopes its nearly horizontal bedding may be exposed in a continuous section through elevation differences of 100 or 200 feet, yet thicknesses measured at right angles to the bedding or the slope at individual points are considerably less. Thicknesses are less variable and generally are greater in broad valleys at low elevations than on the slopes.

The Colma Formation is exposed discontinuously on the east and southeast shores of Angel Island (fig. 47), where exposures range in altitude from sea level to about 325 feet. It may also be represented in the unconsolidated deposits that fill the valley of Hospital Cove. Maximum observed thickness in the quadrangle is 75 feet.

FIGURE 47.—Colma Formation on the southeast slope of Angel Island, about 250 feet above sea level.

In San Francisco the Colma Formation is exposed discontinuously from about sea level to an elevation of about 550 feet, and it is recognized in boreholes more than 100 feet below sea level. The most extensive exposures are on the southwest and northeast slopes of the ridge occupied by the Presidio Golf Course and reservoir, where the deposits are confined to elevations below 280 feet (pl. 1). Sands of the Colma Formation near Mountain Lake are at least 30 feet thick. In the Presidio north of Kahn Playground, small youthful valleys appear to be cut entirely in the Colma Formation, which is at least 60 feet thick.

On the slopes between the Presidio and Russian and Nob Hills, the Colma Formation is found in small sporadic exposures below about 200 feet elevation and in boreholes. The top of a 42-foot-thick clayey sand, believed to be the Colma Formation, was penetrated in a boring at 42.2 feet below mean sea level at Fort Mason near the southeast corner of the pier at the end of Laguna Street. The formation was found to be more than 30 feet thick in the excavation for the twin vehicular tunnels on Broadway near Hyde Street.

The Colma Formation is believed to be present on the lower slopes and valleys in eastern San Francisco below an elevation of 100–200 feet, in the area between North Point and the south edge of the quadrangle. At the Ferry Building in a boring below 102 feet of mud and clay, a sand layer, 38 feet thick, is correlated with the Colma Formation.

Small patches of the Colma Formation rest on the bluff behind Bakers Beach and on the sea cliffs westward and southward towards the Cliff House. These are slightly consolidated nearly horizontally bedded sand. Most of these patches are too small to show on the geologic map (pl. 1). In the valley north of the Cliff House, the formation is 30 feet thick. Southeast of the Cliff House the Colma Formation overlies sandstone of the Franciscan Formation and is overlain by dune sand. Here, the basal part consists of coarse sandstone rubble derived from the underlying Franciscan Formation. The Colma Formation is at least 40 feet thick; it appears to thicken southward, and it dips gently southward toward Golden Gate Park.

On the north slope of Mount Sutro, the Colma Formation is exposed north of Parnassus Avenue. It was penetrated south of Parnassus Avenue in borings made to investigate foundation conditions below the University of California Medical Center Building (Moffet Hospital). South of Mount Sutro and west of Twin Peaks, the formation is found at elevations as high as 550 feet. On the south slope of Twin Peaks, the formation fills a channel cut in greenstone of the Franciscan Formation (fig. 48). In the excavation for Sutro reser-

FIGURE 48.—Colma Formation filling a channel cut in greenstone. South slope of Twin Peaks, San Francisco.

voir, a 75-foot-thick section of the formation was exposed (fig. 45).

ORIGIN

The Colma Formation appears to have been deposited mostly by water and gravity and, to a lesser extent, by wind in a variety of coastal environments. At elevations above 250 feet, the Colma Formation commonly is massively bedded or steeply crossbedded and is believed to consist mostly of stream, colluvial, and eolian deposits (figs. 46, 48). In contrast, at lower elevations the Colma Formation consists mostly of moderately well sorted sands, usually with persistent horizontal stratification but in some places with intercalated steeply inclined crossbeds. The lower sediments probably accumulated in an extensive complex of shallow bays, inlets, and channels such as would exist if sea level were 35–100 feet higher than now. Deposition in water is also suggested by local contorted layers, 1–2 feet thick, interbedded with undisturbed beds; the contortions appear to have formed by slumping in water.

Intercalations of bedded moderately sorted marine sands with clay and with massive poorly sorted continental sediments indicate fluctuations in the transportation and sedimentation processes, in the strength of water currents at the site of deposition, in the location of the shoreline, and in the character and amount of material supplied to the basins of deposition.

The environment of deposition of the Colma Formation can be inferred from the size-distribution diagram (pl. 2*D*). Most of the data shown are for marine sands believed to have been deposited at the lower elevations. Data for dune sand and modern beach sand are also shown on the diagrams. Dune sands are distinguished from beach sand by their smaller median grain diameter and by better sorting. ($\sigma\phi$ for dune sands is less than 0.5; $\sigma\phi$ for beach sands is greater than 0.5.) Sediments of the Colma Formation—whether the whole sediment or only sand fraction is considered—have about the same range in median grain diameter as dune sands; however, they are generally not as well sorted, and their frequency distribution curve is generally skewed towards finer grain sizes. Stewart (1958, p. 2589, 2595) found that marsh sediments of lagoon borders have sorting and skewness values comparable to those of the Colma Formation, though his samples were of finer grain (median phi diameter about 3–6) and the Colma does not contain enough organic matter to be a marsh sediment. Inman and Chamberlain (1955, p. 114, 119) referred to sediments of median phi diameter about 3–4, sorting $\sigma\phi$ values greater than 1.5, and positive skewness, $\alpha\phi$, values as transition sand and suggested that such sediments probably result from basic differences between modes of transport of sand and of silt and clay. They found transition sand about ¼–1 mile offshore from a beach north of Point La Jolla, San Diego County, Calif., and within shallow bays behind barrier beach sand islands near Rockport, Tex.

The grain-size distribution of the Colma Formation may be due to deposition and mixing of silt and clay in estuaries to which sand was transported before or during the existence of the estuary. The sites of Colma estuaries, before the rise in sea level that created them, may have been covered by dune sand, by the Merced Formation, or by sand brought in by the ancient Sacramento-San Joaquin River. The similarity in ranges of median diameters of the sand fraction of the Colma Formation and of dune sand suggests that some sand may have reached Colma estuaries by wind. Sand of median diameters like those of the Colma Formation may also have been brought by water currents less vigorous than breakers on a beach.

The poorly consolidated Merced Formation is rich in sand grains of sizes found in the Colma Formation (M. G. Bonilla, oral commun., 1961) and is the most likely source of much of the Colma Formation. The Merced Formation was deposited over a wide area west of the present shoreline and as far north as Point Reyes Peninsula and is approximately 5,000 feet thick. Its initial volume appears to have been large enough to have supplied detritus for a large part of the Colma Formation. The folding of the Merced probably brought it above sea level and made it available as a source of the Colma. The predominance of hornblende in the Colma Formation in San Francisco (pl. 2*F*) is evidence that its main source was not the local Franciscan Formation, in which hornblende is scarce (table 3). However, the content of hornblende and other minerals in the Merced Formation is similar to that in the Colma Formation and supports the belief that some or most of the Colma Formation was derived from the Merced Formation or from the same source as the Merced Formation. Where the Colma Formation lies on the Merced Formation, west of Lake Merced, it is difficult to distinguish one formation from the other.

Another possible source of the Colma Formation is the detritus carried by the Sacramento–San Joaquin River. Drainage from the Great Valley into the San Francisco Bay area is believed to have started by early Pleistocene time and to have been the source of the upper member (Pleistocene) of the Merced Formation (Hall, 1965, p. 152, 153). Because sea level may have been high when the Colma was deposited, the ancient Sacramento–San Joaquin River may have reached the estuary that existed then far upstream from the site of deposition of the Colma Formation on the San Francisco Peninsula, much as the present river reaches tidewater east of Suisun Bay. Thus the silt and clay sizes in the Colma Formation may have been partly contributed by the ancient Sacramento–San Joaquin River drainage from the Great Valley of that time.

The sandiness of the Colma Formation may be explained also by its deposition in basins and channels swept by tidal currents. Sands are deposited where tidal currents are vigorous, such as those in the central parts of San Francisco Bay and in parts of Golden Gate channel. Muds are deposited along the fringes of the bay where currents are weak. Muddy sands are deposited under intermediate conditions or where rocky headlands furnish sand that mingles locally with muds (Louderback, 1939, p. 784–793; 1951, p. 91; Inman and Chamberlain, 1955, p. 119). The few frosted and well-rounded sand grains in the Colma Formation suggest wind action on a beach, or they may have been derived from the Merced Formation.

The Colma Formation was thought previously to have been deposited in an offshore marine environment (Lawson, 1895, p. 463; Ashley, 1896, p. 354) or in swamps, lagoons, lakes, flood plains, and dune fields (Martin, 1916, p. 226). The author believes the Colma Formation now found below an elevation of 200 feet was deposited in a complex estuary swept by vigorous tidal currents.

A eustatic rise of sea level and a local rise of the crust after deposition explain the presence of marine Colma deposits of late Pleistocene age several hundred feet above sea level. Sea level should have been higher than now whenever less glacial ice existed than exists today. During at least one interglacial period, ice was less extensive than it is today (Louderback, 1951, p. 86; Kuenen, 1955, p. 201; Kuenen, 1950, p. 539). Hopkins, MacNeil, and Leopold (1960) and McCulloch, Taylor, and Rubin (1965, p. 446) showed that in the Nome and Kotzebue Sound areas, Alaska, the rise in sea level during Sangamon time was only about 35–40 feet. Hopkins, MacNeil, and Leopold (1960, p. 49) showed that in the Nome area the greatest eustatic rise of sea level during a Pleistocene (preKansan(?)) interglacial period was approximately 100 feet. Thus the marine deposits in the quadrangle presently above an elevation of 100 feet probably reached their present position partly by tectonic uplift.

If sea level were 35–100 feet higher than it is today, sandy sediments of the Colma Formation could have accumulated on beaches or in shallow marine water near the shore, as well as in basins several miles offshore covered by sea water several hundred feet deep. Thus the Colma Formation in the Presidio area, which is now more than 200 feet above sea level, may have been deposited at the same time as the Colma Formation now lying more than 100 feet below sea level at the Ferry Building.

Smith (1960, p. 160) suggested that the Colma Formation records depositional episodes related to several different sea levels. He separated a unit from the Colma Formation which he believed represents beach and dune deposits related to his Colma marine terrace. He traced this marine terrace for more than 15 miles at elevations between 200 and 300 feet above sea level on the bay side of San Francisco Peninsula south of Lake Merced. Above this lower terrace he found terraces 400 feet and 500 feet above sea level. Deposits on the 400-foot terrace resemble the Colma Formation. No deposits were found on the higher terrace. Smith believed the terrace between 200 and 300 feet above sea level was cut during the high sea level of the Sangamon Interglaciation.

Lawson (1895, p. 463) recognized the beds here called the Colma Formation as his "Terrace Formations." He described these beds as occurring from an altitude of about 750 feet down to sea level and thought they represented marine deposits. In the San Francisco Folio, Lawson (1914, p. 15) abandoned the term "Terrace Formations" but mentioned a deposit in the Lake Merced area of "light-yellow sands, about 200 feet thick, which probably lies unconformably upon the Merced***" and suggested that it may be the correlative of the Alameda Formation, a Pleistocene marine and continental formation found on the east shore of and in San Francisco Bay. He explained that he did not show the deposit in the Lake Merced area on a geologic map because it could not be easily distinguished from the underlying Merced Formation.

Marine megafossils have not been found in the Colma Formation at lower elevations where the formation is believed to have been deposited in a marine environment. Perhaps strong currents and a sandy bottom were unfavorable for marine life, as they are today. Evidence for the presence of leaching acidic solutions is found in decomposed sand grains bearing iron such as magnetite, which occur almost everywhere in the Colma Formation. Such acidic solutions could decompose marine shells, which are largely calcium carbonate, more readily and more completely than they could decompose magnetite and other iron oxides. Smith (1960, p. 153) also suggested leaching by ground water as an explanation for the lack of fossil shells in marine sediments of Colma age on former wave-cut platforms 2–25 miles south of the quadrangle.

CORRELATION WITH NEARBY DEPOSITS

Sand lying below bay mud along the bay shore east of San Francisco is included in the Colma Formation, although it could not be traced continuously from the Colma Formation on the Pacific Ocean and Golden Gate channel sides of San Francisco Peninsula. On their geologic cross section that extends from the bay onto San Francisco near the south border of the quadrangle, Trask and Rolston (1951, p. 1085) designated the sand below bay mud as the Merritt Sand. It was designated the "sand layer" in the Islais Creek area at the southeast corner of the San Francisco North quadrangle by Radbruch and Schlocker (1958); they correlated the upper part of the layer with the Merritt Sand and Temescal Formation. On the east side of San Francisco Bay, Radbruch (1957) showed that the marine type Merritt Sand grades into and interfingers eastward with alluvial-fan deposits of the Temescal Formation, which she found to be the same unit as the upper member of the San Antonio Formation. Similar facies are found on the west shore of the bay in San Francisco where the marine Colma Formation of lower elevations—here correlated with the Merritt Sand—interfingers with and grades into the continental Colma Formation of mostly higher elevations.

Pleistocene marine deposits are also above sea level on the east side of San Francisco Bay (Louderback, 1951, p. 86). Similar deposits were not seen on the Marin Peninsula, though small patches of them were seen in the vicinity of Point Bonita west of the quadrangle. They are lacking from Marin Peninsula because such unconsolidated deposits could easily have been removed by erosion of the steep slopes when sea level dropped. The same cause may explain the absence of the Colma Formation on the steep slopes on the north side of Angel Island. Some of the deposits at elevations of 200 feet and lower on Yerba Buena Island, designated "reworked colluvium" by Radbruch (1957), resemble the Colma Formation and may have a marine origin.

Abraded marine and nonmarine diatoms and sponge spicules are present, but no specific identifications have been made. Part or all of the diatoms could have been derived from older sediments. Vertebrate remains are reported from what may be the Colma Formation. Hay (1927, p. 5, 210) reported that a bone now lost, apparently a fragment of a tibia of a large ground sloth, was found before 1853 at a depth of 23 feet on Pacific Street between Kearney and Montgomery Streets. Stock (1925, p. 201–202) reported that a humerus of *Mylodon* (probably *Paramylodon*, a ground sloth) was found in excavations for the Twin Peaks Tunnel at a depth of 60 feet, about 300 feet west of 18th Street. Hay (1927, p. 210) concluded that the material from the two localities comes from Lawson's San Antonio Formation and represents the Aftonian Interglaciation.

Peabody (1945, p. 60–63) described a vertebrate fauna of late Pleistocene age from a deposit that he believed to be slightly older than Lawson's "Terrace Formations" (the Colma Formation of Schlocker and others, 1958, and of this report). The bones were found above Mussel Rock on the ocean shore 6 miles south of the quadrangle. Peabody (1945, p. 60) reported that the bones are in a stream deposit of gray sand and gravel resting on the Merced Formation and overlain by Lawson's "Terrace Formations" of reddish-brown horizontally bedded sand. Field mapping in the Mussel Rock area by M. G. Bonilla (oral commun., 1958) indicates an obscure relationship of the fossiliferous sand and gravel and the overlying reddish-brown sand to the Colma Formation. Savage (1951) listed other vertebrates from the San Francisco Bay region to which he assigned an "undifferentiated Pleistocene" age. They were found in deposits that may be the same age as the Colma Formation.

A tree identified by Rowland W. Brown as a juniper or redcedar, probably *Juniperus californica*, was found in the excavation for the Broadway Tunnel on the west slope of Russian Hill near Hyde Street in a sand thought to be the Colma Formation. Duplicate carbon-14 age determinations by J. L. Kulp in 1954 gave an age greater than 30,000 years (sample designation: Lamont No. 227).

The Colma Formation is tentatively assigned a late Pleistocene age.

AGE RELATION TO THE ANCIENT SACRAMENTO RIVER

The shape of the exposed and buried parts of the bedrock surface shown on the bedrock-surface map (pl. 3) is strikingly similar to the pattern of valleys and ridges made by stream erosion. Most of the valleys are tributaries of the large valley, now Golden Gate channel, that was carved between San Francisco and Marin Peninsulas by the ancient Sacramento River which emptied into the Pacific Ocean at various distances west of Point Lobos. The ancient channel of the Sacramento River and some of its tributaries is shown on maps by Trask (1956, p. 17). The bedrock-surface map of central San Francisco Bay by Carlson and McCulloch (1970) shows channels in bedrock that may represent old stream channels. Louderback (1951, p. 82) suggested that Golden Gate channel was carved perhaps in early Pleistocene time or perhaps during a middle Pleistocene disturbance inasmuch as it maintained its flow across the slowly rising land west of the Great Valley. Thus, some of the sedimentary deposits mapped as Colma Formation may have been transported by the ancient Sacramento River before the crustal rise or at an early stage of the rise.

Sea level is estimated to have been about 228–406 feet below present sea level during the Wisconsin Glaciation and 325–390 feet below present sea level during a pre-Wisconsin glaciation (Flint, 1947, p. 437; Moore and Shumway, 1959, p. 373; Curray, 1965, p. 725; Milliman and Emery, 1968). The present shoreline would shift 34–39 miles westward if sea level were lowered to the present 300-foot-depth contour (U.S. Coast and Geodetic Survey, 1941), and this lower base level would result in vigorous erosion of the present bottom. The present-day buried valleys on San Francisco and Marin Peninsulas must have been carved when sea level was lower, during a maximum glacial stage, or earlier during a middle Pleistocene disturbance, as postulated by Louderback (1951, p. 82).

The Colma Formation and its age equivalent, the Merritt Sand, are the upper part of the natural fill in these buried valleys. For example, the bedrock floor of the buried valley below the Ferry Building is more than 270 feet below sea level; however, the bottom of the Colma Formation at this place is 127 feet higher. Thus, at the Ferry Building the Colma Formation was deposited after the valley was carved, and it subsequently was filled with 127 feet of sediments older than the Colma. It is also likely that several periods of erosion and filling during successive glacial and interglacial stages intervened between the time of the carving of the valley and the deposition of the Colma Formation. After its deposition, the Colma Formation was also cut by valleys graded to a sea level lower than the present level.

RELATED DEPOSITS

Some Quaternary deposits around San Pablo, Suisun, Tomales, and Monterey Bays (fig. 1) are tentatively correlated with the Colma Formation.

The Millerton Formation of late Pleistocene age at Tomales Bay consists of interbedded marine and continental beds (Weaver, 1949a, p. 99–103; Weaver, 1949b, p. 51–52). The marine beds contain a large molluscan fauna, and the continental beds contain a large flora. Weaver (1949b, p. 52) believed the fossils "indicate a climate slightly warmer than that which prevails today, possibly representing an interglacial epoch." Richards and Thurber (1966, p. 1092) determined an apparent age of 55,000 years by the Th^{230}/U^{234} method on mollusks from the Millerton Formation and suggested that the mollusks "could easily have been deposited during the last interglacial stage or earlier." The Millerton Formation contains seven vertebrate genera, including *Bison* (Weaver, 1949a, p. 103), and is therefore of Rancholabrean mammalian age (Savage, 1951, p. 289), which spans the Illinoian Glaciation, the Sangamon Interglaciation, and the Wisconsin Glaciation (Hibbard and others, 1965, p. 514).

Fossiliferous marine sand and associated sandy clay and gravel, assigned to the Millerton Formation by Weaver (1949a, p. 101), are found in nearly horizontal beds in San Pablo and Suisun Bays. Weaver (1949a, p. 103–106) also named several nearby continental deposits, the Huichica, Glen Ellen, and Montezuma Formations, which are partly contemporaneous with the Millerton Formation.

The Aromas Red Sands of Allen (1946, p. 18, 43–45), exposed over a wide area near Monterey Bay, are similar in field appearance and lithology to the sands of the Colma Formation. Allen believed "They were laid down by the action of both wind and waves, on a low-lying plain, as lagoonal deposits, sand dunes, and bars. After uplift, the oxidation and solution of the magnetite in the sand resulted in the development of red colors, cementation, and reprecipitation of hematite." Although no fossils have been found, Allen (1946, p. 45) suggested that the Aromas is "at least as late as middle Pleistocene in age."

OLDER BEACH DEPOSITS

In May 1952 a fresh-appearing beach sand about 100 feet above sea level was exposed below a 5–10-foot cover of dune sand in a deep trench on the Presidio Military Reservation. The sand is pale yellowish brown (10*YR* 6/2), loose, and fine to medium. It is believed to be a beach deposit because of the nearly horizontal bedding and the persistence of thickness and inclination of the beds for several hundred feet (fig. 49). These features are in marked contrast to corresponding features of dune bedding (Thompson, 1937, p. 747–751; McKee, 1953, p. 20, 25). In many places the bedding resembles Thompson's (1937, p. 732) type A

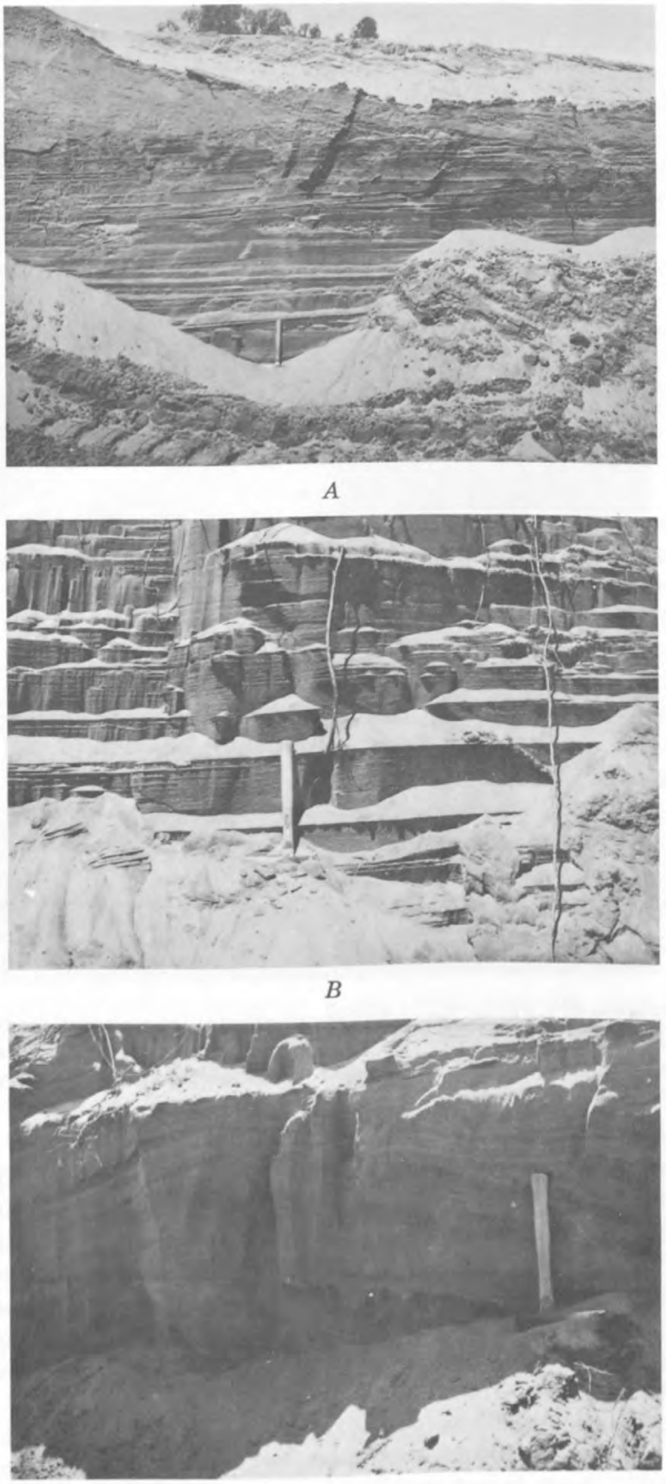

FIGURE 49.—Raised older beach deposit covered by dune sand. Southwest corner of the Presidio, San Francisco. Bakers Beach is one-fourth of a mile to the left. A, The raised beach deposit below dune deposits as exposed in north wall of sewer trench. Elevation approximately 150 feet above sea level. B, Closeup view of the raised beach deposit showing regularity of bedding. C, Closeup view of dune sand covering raised beach deposit. Note crossbedding in dune sand.

cross-lamination found on the upper foreshore of modern California beaches, where laminae of low landward dip are truncated by an erosional surface of low seaward dip. In the Presidio the dip of the bedding of the raised beach deposit increases to as much as 20° eastward, suggesting a facies change that may represent backshore beach deposits (McKee, 1953, p. 14, 19). These sands, in turn, grade into sands showing classic dune crossbedding.

Grain-size distribution of sand from the raised beach is similar to modern beach sands and modern dune sands (pl. 2*C–E*). Most of the deposit has a median diameter near the lower limit of the medium sand size, but sands of maximum eastward dip (pl. 2*A*, map locality 19, sample 1434) have a median diameter near the lower limit of the coarse size. Sorting is good, except for the coarse sand, which is only moderately sorted.

The shape, roundness, and frosting of grains of the raised beach sand are more similar to those of dune sand than to those of modern beach sand; mineral composition is similar to that of both modern beach sand and dune sand. Intensity of etching of pyroxenes is between that shown by dune sand and that shown by modern beach sand. About 1–2 percent of the pyroxene grains show long sawtooth terminations with blunted points. Most of the pyroxene grains show only tiny sawtooth terminations or show none.

AGE

The older beach deposit, like the Colma Formation, was probably deposited during an interglaciation when sea level was higher. Properties of the grains and their size distribution suggest that the raised beach sand consists mostly of dune sand blown from a beach west of it and below it and that the dune sand entered the beach environment during a high stand of the sea. The raised beach sand may be younger than the Colma Formation, for it appears to be completely unaltered and unconsolidated and contains tiny shell fragments, whereas sands of the Colma Formation are generally weathered to a darker brown color, have a fair cohesion, and have no shell fragments. The contrast in etching of pyroxene grains is also striking, for the strong etching seen in almost all pyroxene in the Colma Formation is rare in pyroxene of the raised beach sand. On the other hand, the raised beach sand may be a relatively unweathered part of the Colma Formation, the weathered part having been removed by wind action.

The stratigraphic relations of the raised older beach sand and the Colma Formation were not directly observed and remain obscure. The Colma is exposed at the same elevation 2,500 feet east of the raised beach sand and also near sea level 1,000 feet west of it. If the raised beach deposit is younger than the Colma Formation, why is it not more extensive and why is it not found elsewhere above the Colma? Perhaps some deposits thought to be dune sands, penetrated in boreholes, are part of the raised beach deposit.

Because it is unaltered, the raised beach sand appears to be younger than marine sands on the Half Moon Bay marine terrace, described by Smith (1960, p. 46). If the raised beach sand is younger and if Smith's (1960, p. 186) Sangamon age designation for the Half Moon Bay terrace is correct, the raised beach sand is Wisconsin in age. Sea level during Wisconsin time, however, was lower than present sea level (Hopkins, 1959, p. 7). Consequently, if the raised beach sand is indeed Wisconsin in age, it reached its present elevation by uplift rather than by deposition during a sea level higher than present sea level. On the other hand, the raised beach sand may have been deposited during Sangamon time, which was the latest time when sea level was substantially above present sea level. If the sand is Sangamon in age, then the Colma Formation and possibly the Half Moon Bay terrace are related to earlier interglaciation.

MODERN BEACH DEPOSITS

Sands and coarser beach deposits are numerous along all the shores except the east edges of San Francisco and Sausalito. Most beaches are small and are confined to coves and inlets. The largest, Ocean Beach, extends for nearly 8 miles south of the Cliff House (figs. 50, 51). The next largest, Bakers Beach, is more than half a mile long, west of the Presidio. Beach deposits that at one time bordered nearly all the shore between Fort Point and Telegraph Hill are now largely buried under artificial fill.

Beach deposits vary in thickness and areal extent, depending on the nature of the waves and the supply of sediments, both of which vary from hour to hour and season to season. An excess of sediments permits beach building, and an inadequate supply of sediments for some wave conditions causes beach erosion. Energetic storm waves may cause considerable erosion in a few hours (Trask, 1959, p. 21). Deposits on the smaller beaches probably are not more than 20 feet thick, but those along Ocean Beach and Bakers Beach may be considerably thicker.

Beaches of predominantly coarse gravel and cobbles with some sand and fine gravel are found in a few coves on both sides of the Golden Gate and on Tiburon Peninsula and Belvedere and Angel Islands. The principal materials of gravel beaches on the north side of the Golden Gate channel are radiolarian chert and greenstone. Some beach deposits consist of boulders of intact greenstone pillows that have become detached and fallen from exposures above the shore. Rocks 5–10 feet in diameter are common on the beach between Fort Point Rock and Bakers Beach and west of Lands End where debris of sheared rocks or serpentine has fallen to the shore. Locally abundant are concrete pieces derived from construction waste dumped into the sea.

FIGURE 50.—Ocean Beach, viewed southeastward from the Cliff House area. The seawall serves as a barrier to the eastward movement of windblown sand.

FIGURE 51.—Ocean Beach looking northward from a point about 1 mile south of the San Francisco North quadrangle. Note slight development of berm. Photograph taken in February 1962.

Trask (1959) examined Ocean Beach at five stations (pl. 2*A*) at 2–6-week intervals from July 1956 to June 1957 and found many changes during that time. Beaches generally were built upward and seaward during summer and fall and were eroded during winter and spring.

Sand, the predominant beach deposit, is yellowish brown (10*YR* 6/4) to light gray (*N*7) speckled with a few white shell fragments and abundant dark-gray, green, and brown grains. The median diameter of sand grains is in the medium to coarse size ranges. Sorting is moderate as measured by the phi deviation measure, $\sigma\phi$, which ranges from 0.60 to 0.95 (pl. 2*C–E*). The Trask sorting coefficient ranges from 1.34 to 1.55. The phi skewness measure, $\alpha\phi$, shows that most of the analyzed sands have a size-frequency curve skewed slightly to moderately on the larger grain size side of the mode.

Trask (1959) gave median diameters and Trask coefficients of sorting for about 500 sand samples collected along Ocean Beach on various parts of the beaches at his stations (pl. 2A) during 1 year. The average median diameters ranged from 0.191 mm (fine) to 0.497 mm (medium). These extremes were obtained from sands collected on one beach (station J) in September (fine) and April (medium). The median diameters were generally larger in winter and spring than in summer and fall. Average median diameter for the year at all the stations were in the medium sand size range. At any given time of sampling, grain size did not vary significantly at different parts of the beach.

The sorting values suggest a progressive increase in sorting to the south along Ocean Beach. Sorting was best in summer and fall.

Sand grains are mostly quartz, feldspar, and rock fragments. The rock fragments from the sample taken at map locality 15 (pl. 2*A*) consist mostly of chert, quartzite, porphyries, felsite, and some serpentine. Heavy minerals, chiefly ilmenite, chromite, green and brown hornblende, augite, and hypersthene, make up about one-fifth to one-third of the sand. Black sands—natural concentrates of heavy minerals—are found from time to time on Ocean Beach about 1 mile south of the quadrangle. More than half of the dark grains have a secific gravity below 2.82; these include chert, quartzite, porphyry, felsite, and serpentine. A small amount of gold has been recovered from these sands (DeGroot, 1890, p. 545–547; Day and Richards, 1905, p. 1188; Davis, 1949, p. 107). Modern mollusk and echinoid shells are abundant locally on the beach surface, but they are generally rare in the sand below the surface. Flat rounded cobbles of fossiliferous sandstone of the Merced Formation are occasionally found on Ocean Beach. Sand along the north shore of the Golden Gate are mostly dark brown and consist mostly of radiolarian chert and greenstone grains.

Most of the quartz and feldspar grains are slightly elongated, are subangular to subround, and have polished surfaces. A small percentage are angular or well rounded and have dull pitted surfaces. Some grains show these features on only part of the grain. The dark grains, whether heavy or light, are generally better rounded than quartz and feldspar grains; a large percentage of the dark grains are well rounded and have polished surfaces. Many of the heavy mineral grains, chiefly hornblende, pyroxene, and zircon, are rod shaped. Pyroxene grains generally have tiny or blunted sawtooth terminations, a few have long, delicate sawtooth terminations, and a few have no such terminations.

SOURCE OF SAND ON OCEAN BEACH

The chief sources of sand on Ocean Beach and in the related dunes that extend 6 miles eastward are the poorly consolidated Merced Formation along the shore south of this quadrangle and the Colma Formation and younger Quaternary rocks. These sources are exposed for several miles along the shore to the south in steep cliffs that reach heights of 500 feet. Active landsliding of these cliffs furnishes large volumes of sediment to the shore at their feet (Bonilla, 1959, p. 29; 1960, landslide location map).

Direct evidence for the derivation of beach sand from these older formations is furnished by the sand grains. The similarity in mineral composition of sand of Ocean Beach and sand of the Colma Formation (pl. 2*F*) and Merced Formation suggests these formations are sources of the beach sand. Hornblende is abundant in the beach sands and indicates that the local hornblende-poor sandstone of the Franciscan Formation is not an important source. Hornblende, however, as well as other minerals, may have reached Ocean Beach from other sources, such as the quartz diorite of Montara Mountain 9 miles south of San Francisco. Bradley (1957, p. 434) indicated that pyroxene grains are not etched in the active beach environment. The abundance of etched pyroxene grains, some strongly etched, on Ocean Beach indicates a derivation from older sand deposits such as the Colma and Merced Formation, in which almost all pyroxenes are strongly etched.

In the past, beach sand may also have been derived from the vast Sacramento–San Joaquin drainage area. During Quaternary glaciations sea level is thought to have been 228–406 feet lower than now (Moore and Shumway, 1959, p. 373; Hopkins, 1959, p. 7; Kuenen, 1955, p. 197; Kuenen, 1950, p. 537; Flint, 1947, p. 437). The shoreline during these times would have been about 30 miles west of Ocean Beach. Thus, the Sacramento River would have carried sediments into the sea to form a delta many miles west of the Golden Gate. Sand from the river would probably have furnished much material for beaches near its mouth and for dunes east of the shore. With rising sea level, the locus of deltaic, beach, and dune deposition would have shifted eastward. The delta then would have retreated to its present location east of Carquinez Strait as the ocean covered the lower course of the river. The wide sandy sea-bottom plain between the present shoreline and the

Farallon Islands is probably a relict of these former deltas, beaches, and dunes. Some or much of the sand on Ocean Beach, Bakers Beach, and the beaches between Fort Point and Black Point and the sand in the offshore bar across the mouth of the Golden Gate may, thus, be derived from land far to the east.

Although direct measurements of sand drift have not been made, some northward movement parallel to the shore probably has occurred for several reasons. Waves frequently strike Ocean Beach at an angle from the south (Trask, 1959, p. 24). Richard Janda (written commun., 1967) also suggested that a north-moving current may be related to strong prevailing winds from the southwest and west and the relatively straight north-south trend of the coast. The U.S. Coast and Geodetic Survey (1943, p. 32–33; Gilbert, 1917, p. 69) reported a weak offshore current that flows south-southeastward, following the trend of the coast, but near the shore the Survey reported a weak current that flows northward, except when winds blow southward. The north-flowing inshore current in the San Francisco area is explained in part as an eddy, formed in the lee of the Point Reyes salient of the coastline, counter to the general southward circulation of the California part of the eastern Pacific Ocean (Davis, 1933, p. 19–20; Howard, 1951, p. 105).

Moore (1965, p. 55–56) concluded from a study of heavy minerals in recent coastal sediments west of Marin and San Francisco Counties that (1) longshore transport is only of local importance at the present time; (2) sand in more than 90–120 feet of water originates from an earlier period of sedimentation than that of the modern coast; (3) the bay bar sand is derived from San Francisco Bay; (4) the beaches south of the Golden Gate owe their composition at least partly to offshore sands mixed with local sediments by the surf; and (5) longshore movement south of the bay bar is to the south.

Yancey and Lee (1972) placed the modern beach sediments of the west and north coast of San Francisco in their hornblende-augite-hypersthene heavy-mineral assemblage, which they believe results from mixing of sediments derived from volcanic, metamorphic, and sedimentary rocks of the Central Valley of California.

DUNE SAND

Dune sand underlies more than half of the city of San Francisco, but the only other occurrence in the quadrangle is a small deposit behind a small sandy beach on the east shore of Angel Island south of Quarry Point. Prevailing westerly winds swept the sand from Ocean Beach, Bakers Beach, and possibly from a former beach west of Black Point as far eastward as the former Yerba Buena Cove, which was between Rincon and Telegraph Hills and has been artificially filled. Winds from the east created the small dune on Angel Island. Dune sand is more than 600 feet above sea level at Sunset Heights and Grand View Parks and covers the 575-foot summit of Buena Vista Park. On Nob Hill, near its east border, dune sand is nearly 300 feet above sea level.

Dune sand in the Civic Center area (fig. 52) and surrounding parts of Hayes Valley reaches thicknesses greater than 100 feet. Dune sand, 5–40 feet thick, covers the west slope of Mount Sutro north of Kirkham Street. Maximum thickness of dune sand is approximately 150 feet. Elevation differences of 75 feet were measured from dune crests to interdune troughs in the area now occupied by the Mark Twain School and A. P. Giannini Junior High School on Ortega Street prior to the development of that area in 1952, and the total thickness of sand was greater than 100 feet. Dune sand mantling the prominent hills and ridges is much thicker on the east (lee) side than on the west and is thin or absent on the crests.

Dune sand is absent from the west slopes of Mount Sutro on the lee side of the Grand View–Sunset Heights Parks ridge. The extensive area of hills and lowlands east of the Mount Sutro–Mount Olympus–Twin Peaks highland was also protected from windblown sand.

At the present time, manmade barriers confine most wind transportation of sand to a narrow zone near Ocean Beach. Active dunes were observed by the author in 1937 in the Sunset District west of 33d Avenue and as late as 1951 in the area west of Sunset Boulevard and south of Ortega Street (figs. 53, 54). They were of the transverse-ridge type (Cooper, 1958, p. 27–49; 1967, p. 42–52). The U.S. Coast Survey map

FIGURE 52.—Dune sand exposed in excavation for Brooks Hall. Civic Center, San Francisco.

FIGURE 53.—Sand dunes in Sunset District of San Francisco. Notch in skyline in center of photograph is site of San Andreas fault in Marin County. View northwest toward Bolinas Bay.

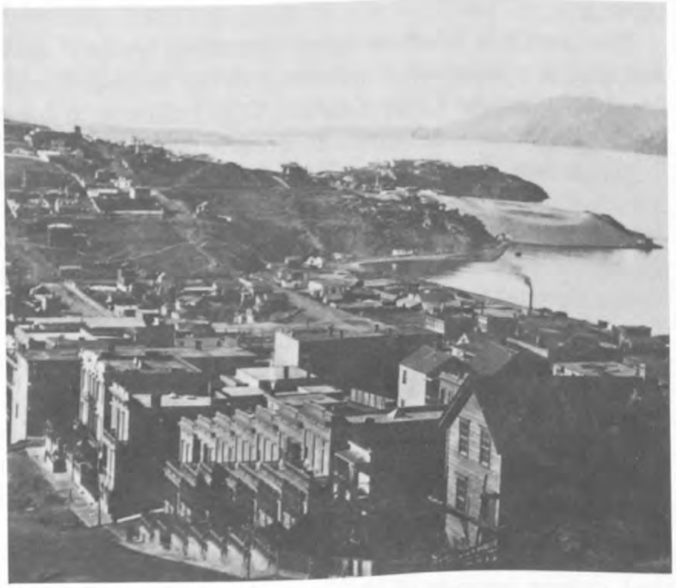

FIGURE 54.—Unstable embankment of dune sand on the lee side of Sunset Heights, near Moraga Street and Funston Avenue, San Francisco, left by excavation for pad for house. Sand was blown over top of hill, which is 666 feet above sea level. View west.

of San Francisco published in 1853 (fig. 62) shows ridges that probably are longitudinal dunes in the present Civic Center–Market Street area. The dunes near Aquatic Park are shown in a photograph taken about 1878 (fig. 55).

Dune sand is fine to medium and well sorted (pl. 2*C–F*). Median diameter decreases sharply from beach sands to adjoining dune sands. A decrease in median grain diameter and an increase in sorting were expected from west to east across the peninsula; however, no consistent variation was seen in the dune sand samples. Dune sand in the central part of the peninsula generally shows positive phi skewness, whereas samples closer to the Pacific Ocean beaches and samples closer to the

FIGURE 55.—Sand dune in Aquatic Park area near intersection of Columbus Avenue and Beach Street, San Francisco. Photograph taken in 1878 or earlier looking northwest to Golden Gate from Telegraph Hill. (Photograph from Professor William S. Cooper, Boulder, Colo.)

San Francisco Bay show negative phi skewness or zero phi skewness. Because variations in parameters are expected in different parts of a single dune, the inconsistency may be due to a failure to select samples from the same parts of dunes, though a negative phi skewness of the western dune sand may be an inheritance from beach sands. It is also possible that samples were taken from different generations of dunes; these may have formed under slightly different conditions of wind and source of sand.

Dune sands show considerable local variations in shape, roundness, surface texture, and mineralogy. As in the beach sands, most grains are generally equant in shape, though such heavy minerals as hornblende, pyroxene, and zircon are rod shaped. Most grains are subround or subangular. Polished surfaces are more common than dull pitted surfaces. In all dune deposits, however, some well-rounded grains with dull pitted surfaces are present; in a few deposits they are predominant. In general, the larger grains are more rounded than the smaller grains, and dark grains are more rounded than light-colored grains of the same size. The dark grains have greater roundness because they are generally of greater specific gravity or are more easily scratched than the light-colored grains (Pettijohn, 1949, p. 428). Textures of rocks that are now grains in the dune sand may have some influence on rounding, for dark-red-brown fine chert grains in the dune sand are generally more rounded than grains of single quartz crystals of the same size and specific gravity. Magnetite, ilmenite, chromite, sphene, monazite, and apatite are especially well rounded, even in sizes smaller than 100 mesh (0.149 mm in diameter), whereas in the same deposit quartz and feldspar grains of the same size are generally angular or subangular.

Roundness of quartz grains between 50 and 70 mesh (0.295–0.206 mm in diameter) was determined by O. M. Schmidt, using Power's (1953) visual method for beach sands (pl. 2*A*, *E*, samples 1688S, 1690) and dune sands (samples 1293, 811, 1483, 1253, 2001, 1249). Roundness increases sharply between beach sands and the nearest dune sands and increases slightly and gradually from west to east in the dune sands. The sharp increase in roundness between beach sand and dune sand was also observed in other areas by Beal and Shepard (1956), who suggested that the wind tends to select the more rounded grains for transportation. Pettijohn (1949, p. 422) also suggested that shape sorting may be more important than abrasion in causing a greater roundness of dune sands compared with sands from which they were derived.

Pyroxene grains with sawtooth terminations are common in the dune sands near Ocean Beach. According to R. C. Gervacio, graduate student at Stanford University (oral commun., 1957), such pyroxene grains progressively decrease in abundance eastward.

Bradley (1957, p. 434) found a progressive increase of etching of pyroxene grains with increasing time of subaerial weathering in a marine terrace deposit at Santa Cruz, Calif. He indicated that etching of pyroxene does not take place on active modern beaches.

Mineral composition of sand grains in two dunes from the quadrangle and from a dune at Edgemar, 8.7 miles south of Point Lobos, is given on plate 2*F*. Feldspar and rock fragments, chiefly chert and quartz in varying proportions, make up 70–85 percent of the dune sands. The remaining grains are heavy minerals, in approximate order of abundance, hornblende, clinozoisite-epidote, ilmenite, magnetite, augite, hypersthene, and chromite. Hornblende, chromite, and ilmenite are the most common heavy minerals in the Edgemar dune sand. A very slight iron staining of the surface of quartz and feldspar grains and the abundance of dark grains give dune sand its prevailing color of moderate yellowish brown, though active dunes commonly are light gray.

ORIGIN AND AGE

The extensive dunes in San Francisco are due to a favorable combination of wind, supply of sand, coastal topography, and limited plant cover. Strong eastward onshore winds are frequent along the west shore of San Francisco Peninsula. The greatest source of dune sand, Ocean Beach, is continuously replenished by longshore currents and by the surf carrying sand shoreward. Bakers Beach, too, is probably supplied by sand from the surf and tidal currents. Some of the sand for Bakers Beach and the beach east of Fort Point may come from the large area of sand waves on the bottom of the bay between Angel Island and San Francisco, formed by the action of tidal currents moving from the bay to the ocean (pl. 1).

The topography east of Ocean Beach and Bakers Beach is either nearly level, such as at Golden Gate Park, or rises gently. The level topography and the present—and possibly past—absence of a forest of large trees offer no marked obstruction to wind and sand movement within at least 2 miles of the shore. Dune sand above the high cliffs between Point Lobos and Bakers Beach was probably blown by occasional east winds from dune sand lying on the gentle slopes in back of the beaches.

Two sections of dune sand separated by bay mud and clay are penetrated in borings in the Market Street area, east of the Civic Center. This indicates a long history of dune activity. Intensive development of dunes in San Francisco took place more than once during the Holocene and perhaps in the Pleistocene (Cooper, 1967, p. 49–50). However, belts of progressively older dunes away from the beach such as those in the Santa Maria coast area, 230 miles south of San Francisco, were not seen in San Francisco (Woodring and Bramlette, 1950, p. 116; Cooper, 1958, p. 136). Numerous accounts of San Francisco during and following the gold rush of 1849 illustrate and discuss dunes between Nob and Rincon Hills and in the western part of San Francisco near the present Golden Gate Park (Brewer, 1930, p. 499; Weinstein, 1967, p. 38–39).

Cooper (1958, p. 130; 1967, p. 113–115) suggested that during periods of rising sea level, dune development is especially active. He believed that the coastal dunes of California, Oregon, and Washington are related to major sea level changes—a rise in sea level, some 5,000–6,000 years ago, and a succeeding period of virtually stable sea level. He also suggested that sea level changes from earlier Pleistocene glaciations would have influenced dune activity. Thus, it is probable that dunes of San Francisco are not all of the same age. For example, some of the dunes on the east side and central part of the peninsula may be older than dunes closer to the ocean on the west side of the peninsula.

SLOPE DEBRIS AND RAVINE FILL

Most slopes in the quadrangle are mantled by unconsolidated debris derived from weathered underlying material and transported by mass-movement processes. These deposits have been mapped wherever they are known to be more than about 5 feet thick. Locally, this unit includes soils developed on bedrock as well as minor amounts of alluvial, eolian, and landslide materials. Slope debris thickens progressively downhill to an observed maximum of 18 feet; locally, it probably attains thicknesses three or four times as great.

Most of the ravines are partly filled with material derived from the adjoining slopes. These deposits vary in thickness from a few feet to more than 30 feet. Locally, especially on Marin Peninsula, they are interbedded with and grade into stream alluvium. In many places throughout the quadrangle, roadcuts in gently rounded, mature slopes have revealed deep, steep-sided ravines that have been completely buried by slope debris (fig. 10).

Slope debris and ravine fill consist of a mixture of angular rock fragments in a matrix of sand, silt, and clay (pl. 2*B*). The physical properties of the slope debris are partly dependent upon the underlying bedrock. On many slopes in northern San Francisco, where the bedrock is predominantly sandstone and shale of the Franciscan Formation, most of the material is in the sand-to-clay size range with minor amounts of gravel-size material. Elsewhere in San Francisco and on Marin Peninsula, where radiolarian chert is a common bedrock and where slopes are generally steeper and transportation of surface materials more vigorous, slope debris and ravine fill contain a large percentage of gravel- and cobble-size radiolarian chert pieces and appreciable quantities of greenstone and sandstone (fig. 56). Slope debris on or below greenstone or sandstone and shale bedrock is generally much thicker than that derived mostly from radiolarian chert and shale bedrock.

Slope debris may include deposits of different ages. Some roadcuts in slope debris on Marin Peninsula show unconformable layers of distinct lithologies. In many areas slope debris is apparently the youngest material of the slope. On some of the lower slopes and along the wide shelving shores, however, the ravine fill is overlain by marine deposits and is probably late Pleistocene in age. Material identical in lithology with the modern slope debris has also been observed below and interbedded with the Colma Formation. Material in the buried ravines is somewhat older than modern slope debris. The buried ravines were evidently formed during a period of vigorous erosion, such as would occur at the time of a lower Pleistocene sea level when, also, the intensity and amount of precipitation was probably greater than now. The ravines were probably then filled during the early part of the succeeding interglacial period. Transportation of material downslope and into ravines was mostly by such colluvial processes as creep, mud flowage, and debris flowage.

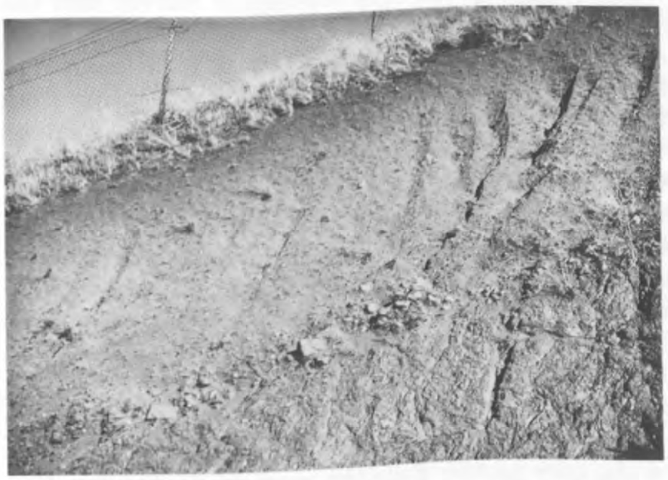

FIGURE 56.—Slope debris on weathered greenstone of the Franciscan Formation. Gravel pieces are chert derived from upslope. Note slight soil development at top.

SAN FRANCISCO BAY SEDIMENTS

San Francisco Bay and the Golden Gate channel, which cover more than half the quadrangle, are underlain by modern sediments, though in places these are only a few inches thick. Bay sediments also underlie areas of artificial fill along the fringes of the bay. Sediments and sedimentation in San Francisco Bay are currently (1969) under investigation by the U.S. Geological Survey. This report summarizes results of other investigations and results of the author's examination of San Francisco Bay sediments.

Sediment studies in San Francisco Bay have been reported by Sumner, Louderback, Schmitt, and Johnston (1914), Gilbert (1917), Packard (1918), Bailey (1921), Miller, Ramage, and Lazier (1928), Louderback (1939; 1951, p. 88–93), Trask and Rolston (1951), Trask (1956), Arden (1961), George Porterfield, N. L. Hawley, and C. A. Dunham (written commun., 1961), Einstein and Krone (1961), Krone (1962; 1963), Arnal and Conomos (1963), Kvenvolden (1962), U.S. Army Corps of Engineers (1963), Smith (1963; 1966), Conomos (1963), Treasher (1963), Mitchell (1963), Storrs, Selleck, and Pearson (1965), Slater (1965), Reese (1965), Means (1965), Gram (1966), Selleck, Pearson, Glenne, and Storrs (1966), Meade (1967), and Quinterno (1968).

Data in this paragraph on sediment volume and movement is taken from Smith (1966, p. 10) and Selleck, Pearson, Glenne, and Storrs (1966, p. 34). The annual sediment inflow to the bay system, including the delta area east of Suisun Bay, is estimated to be between 6.2 and 8 million cubic yards. The combined San Joaquin–Sacramento Rivers supply about 85 percent by weight of sediments that enter the bay; much of the remainder is carried into the bay by Napa River and Alameda Creek. About 1.8 million cubic yards of sediment is deposited each year in the delta area. More than half the total sediment volume enters the bay during February, March, and April. Ebb tides tend to move sediments towards the Golden Gate; approximately 30 percent of the sediments entering the bay is swept out to sea.

Smith (1966, p. 15) gave the following data on grain size of sediments. The approximate grain-size distribution of sediments entering the bay from all streams is 57 percent clay, 29 percent silt, and 14 percent sand. The composition of sediments in suspension in bay water is 57 percent clay and 43 percent silt. Much of the sand-size material is deposited in the delta and in Suisun Bay, but some is carried into San Pablo Bay and southward.

Colloidal clay particles suspended in fresh water flocculate where the salinity is approximately 1,000 parts per million. The interface between fresh water and water of this salinity value varies in position depending on the volume of fresh water entering the bay. During periods of severe storms and high runoff, the fresh-water—saline-water interface may reach the Golden Gate, but it is generally in San Pablo Bay or in the adjoining Carquinez Strait. A large proportion of suspended sediments settle out in San Pablo Bay because of flocculation of colloidal particles and because of the large areas of relatively quiet water there compared to Carquinez Strait and Suisun Bay. Deposition in the bay system is generally greatest at water depths of 10–30 feet and outside of tidal channels. Deposition also takes place at times in water less than 10 feet deep, but these shallow-water deposits are generally eroded by water made turbulent by wind. Part of the material kept in suspension by tidal currents and other turbulent water, and deposits stirred up, eroded, and resuspended by these waters, are carried out to sea through the Golden Gate. Or they are carried to the south arm of the bay, where they form thick deposits in places where the water is quiet.

Sand and locally gravel, therefore, are deposited in the tidal channels. Bedrock, as well as gravel and sand, may be exposed where strong ebb currents are concentrated into narrow powerful currents by shoreline projections. In the San Francisco North quadrangle, such areas are found near Campbell and Stuart Points on Angel Island, Peninsula Point on Belvedere Island, east and south of Alcatraz Island, and in the Golden Gate channel. Smith (1963, figs. 6D, *E*) presented data indicating considerable scour in the period 1855–95 in much of the area between Belvedere Island and San Francisco west of Alcatraz Island and in the period 1850–1956 along the east shore of San Francisco between China Basin and Hunters Point.

Vigorous tidal currents prevent deposition of silt and clay in much of the part of San Francisco Bay lying within the quadrangle. Tidal currents are especially strong and widespread in this part of the bay because this area is the distribution point of the flood tidal currents and the joining point of the ebb tidal currents passing through the Golden Gate channel. Bottom sampling by the U.S. Coast and Geodetic Survey (1959) yielded rock, gravel, and sandy sediments over much of this area. Mud and clay deposits, however, are thick in other places where tidal currents and water turbulence have been weak during the Holocene. Trask (1956, p. 18) showed the general distribution of present-day sediments in San Francisco Bay, based on U.S. Coast and Geodetic Survey charts. The author found about 1 foot of gravel overlying Franciscan sandstone and shale near the northwest end of Raccoon Strait. The gravel pieces, 1–6 inches in diameter, consist largely of Franciscan sandstone and some gastropod shells. Most gravel pieces were coated with Bryozoa.

Holocene mud and clay deposits in the San Francisco North quadrangle reach thicknesses of more than 80 feet along the east shore of the city of San Francisco, including the part now covered by artificial fill (Radbruch and Schlocker, 1958; Goldman, 1969a, pl. 4). These fine-grained deposits are more than 120 feet thick about 2,500 feet northeast of the Ferry Building. Mud is more than 100 feet thick in the center of Richardson Bay at the northwest corner of the quadrangle. Mud is about 40 feet thick near the shore of Sausalito and may be 40–60 feet thick in the northeastern part of the quadrangle, east of Angel Island.

TRANSVERSE SAND BARS

Soundings by the U.S. Geological Survey and the U.S. Coast and Geodetic Survey suggest that between Angel Island and San Francisco, sand is distributed in transverse bars or giant ripple marks resulting from turbulent interaction of ebb and flood tidal currents (Gibson, 1951; Shepard, 1952, p. 1909; Carlson and others, 1970). The approximate boundary of the area of transverse sand bars is shown on plate 1. Detailed soundings of a small area about 1 mile southwest of Alcatraz Island show sand bars oriented approximately due north to N. 30° E. Bar crests are at depths of 50–60 feet, and the average distance between crests is 240 feet. Their height is approximately 6 feet. In Raccoon Strait similar bars are 17 feet high. The swifter westerly ebb current is believed to make the east slopes of the bars gentler than the west slopes. Shallow borings by the U.S. Bureau of Mines and the State of California Division of Bay Toll Crossings, observed by the author in 1965, show that the youngest deposit located about 1 mile northeast of Alcatraz Island is medium sand at least 8 feet thick.

BAY MUD AND CLAY

Bay mud and clay are being deposited in San Francisco Bay at the present time. In their natural state they are generally olive gray (5*Y* 3/2) to dark bluish gray (5*B* 3/1), and they range from soft, plastic, and nearly fluid to moderately firm—about like modeling clay. When dried, the color lightens typically to light greenish gray (5*GY* 7/1) or light olive gray (5*Y* 6/1), and the material becomes fairly tough and somewhat brittle. Bedding is not readily apparent in some mud and clay, but in others it is shown by sand partings, 1–3 mm thick, separating clay layers 0.5–20 cm thick or by flattened plant remains. The general particle-size content of the bay mud and clay is 30–60 percent clay-size particles (<2 microns), 30–65 percent silt-size particles (<62–>2 microns), and 1–10 percent sand-side particles (<2,000–>62 microns).

Lenses and irregular segregations, 1 cm to several meters thick, of fine to coarse sand or mollusk shells are common in the mud and clay in some places. The sand generally has a low silt and clay content. The shell lenses range from a 1-inch-thick layer of a few isolated clam shells in mud or sand, generally both valves being present, to concentrations of shells 3 feet thick in a clay or sand matrix. Shell lenses are mainly in the top 30 feet of the bay mud and clay, according to Hart (1966, p. 43). The shells are mostly pelecypods and minor amounts of gastropods. Although radiocarbon analysis indicates that shells in thickest lenses are approximately 2,400 years old, the shells are the same species as those living in the bay today (Packard, 1918, p. 236–244). Shell layers as much as 3 feet thick, composed entirely of whole or fragmentary separated pelecypod valves, are found on beaches along the bay south of San Francisco. They were probably concentrated by strong waves and tidal currents that washed away the mud and silt. Buried and preserved, such lenses in time will become coquinas. Goldman (1969b, fig. 1) showed the distribution of shell deposits in San Francisco Bay.

Organic remains such as diatoms, peaty plant fragments, Radiolaria, Foraminifera, sponge spicules, Bryozoa coccoliths, mollusk shells, and so forth are common and even abundant at some localities. Diatoms are especially common and make up 20 percent by volume of some mud and clay. Carbonaceous plant remains commonly make up 3–10 percent of the volume of bay muds and clays. Conspicuously peaty sediments, in scattered lenses about 1 inch to about 1 foot thick, contain brownish-black layers of plant remains $\frac{1}{16}$–$\frac{1}{4}$ inch thick and as much as 5 inches long. A persistent peat zone is found at the base of the bay mud and clay in the vicinity of the San Mateo Bridge, commonly as a concentrated layer less than 1 foot thick but locally as a disseminated zone 4 feet thick (Story and others, 1966, p. 48–49).

Water content in bay mud and clay ranges from about 30 to 92 percent; percentages between 50 and 60 percent are common in the uppermost 60–100 feet. The high percentage of water and the plasticity of the sediments stem from their montmorillonite content. When wetted, montmorillonite absorbs water, expands, and becomes plastic. X-ray diffraction analysis of particles smaller than 2 microns from these sediments, from near the east shore of San Francisco and from Richardson Bay, shows about 50–60 percent montmorillonite, about 20–30 percent mica, and about 10–20 percent chlorite. Smaller percentages consist of mica and chlorite randomly interlayered with montmorillonite or regularly interlayered montmorillonite and mica (1:1), quartz, and plagioclase. The presence or absence of a small amount of kaolinite could not be ascertained because of the difficulty of detecting small amounts of kaolinite in the presence of much larger amounts of chlorite. A moderate amount of kaolinite, however, was found by the author in mud collected north of Suisun Bay. The silt-size fraction of the mud and clay also has a high montmorillonite content, but it differs from the clay-size fraction in having a much larger proportion of nonclay minerals—mostly quartz and plagioclase feldspar and minor potassium feldspars and organic remains. Sand grains are mostly quartz and plagioclase feldspar and minor potassium feldspar, rock fragments, and shell fragments.

Preliminary examination of bay muds from a limited number of localities from depths of 1–30 feet shows that the sand and silt grains generally include $\frac{1}{2}$–5 percent heavy minerals (specific gravity >2.86). These minerals include, in approximate order of abundance: green hornblende, augite, tremolite-actinolite, pyrite, brown hornblende, micas, clinozoisite, epidote, chlorite, glaucophane, jadeite, lawsonite, hypersthene, sphene, oxyhornblende, garnet, zoisite, zircon, apatite, tourmaline, calcite, and anatase. Pyrite, crystallized around diatoms and other organic remains, occurs in drusy spheres, 10–30 microns in diameter, intergrown spheres, and elongate barbs. Irregular round grains, resembling glauconite in form, green or brown in color, and consisting of aggregates of tiny translucent crystals, make up about 1–3 percent of the heavy minerals. Analyses by X-ray diffraction and optical microscopy showed that some of them are ankerite. Gram (1966, p. 131) reported 3.1–23.5 percent glauconitic material in sand-size grains of bottom samples obtained from an area between Hunters Point and the San Mateo Bridge. The jadeite, which was abundant in one sample, is the variety showing strong dispersion of the bisectrices and a texture of crystal aggregates similar to the jadeite in metasandstones of Angel Island and the Diablo Range. A program of heavy-mineral analyses of bay sediments from widespread localities and depths would yield information on sediment source and geologic history of the bay.

ENGINEERING PROPERTIES OF BAY MUD AND CLAY

Use of the bay mud and clay for foundation purposes demands careful engineering design to avoid shear failures and differential settlement problems. The problems are related to the high content of both water and the swelling clay mineral montmorillonite, which together cause low shearing strengths, high voids ratios, low specific gravity, high consolidation under load, and high drying shrinkage. Mitchell (1963, p. 26) summarized these and other properties in a table that shows a range of shearing strength of 100–1,200 pounds per square foot. Engineering properties of bay mud and clay are also discussed in Goldman (1969a, p. 20–23), Lee and Praszker (1969), Seed (1969), Steinbrugge (1969), Schlocker (1969, p. 25), Wigginton (1969), San Francisco Bay Conservation and Development Commission (1967), Treasher (1963), U.S. Army Corps of Engineers (1963), Roberts and Darragh (1963), Langston, Trask, and Pask (1958), Radbruch and Schlocker (1958), California Department of Public Works (1955), Lee (1953), and Trask and Rolston (1951) (fig. 57).

Treasher (1963, p. 23) found a marked increase in strength of bay mud 40–70 feet below the top of the mud. The lower, slightly stiffer mud is slightly overconsolidated. According to him, the increased strength is the result of desiccation during a glacial period of low sea level. The top 2–4 feet of bay mud loses water and gains strength in areas that have been diked off and drained.

STRATIGRAPHIC CORRELATION, FOSSILS, AND AGE

Bay mud and clay lie on other Quaternary deposits or on bedrock (fig. 56; pl. 1, section C–C′). Trask and Rolston (1951, p. 1085, 1086) showed bay mud lying on Merritt Sand in an east-west cross section at the southeast corner of the San Francisco North quadrangle and bay mud overlying undifferentiated Merritt Sand, Posey, and San Antonio Formations in a cross section parallel to and 300 feet north of the San Francisco–Oakland Bay Bridge. The foundation excavation for the Headworks Building of the Southeast Sewage Treatment Plant, near the shore of the bay half a mile south of the quadrangle, and logs of nearby boreholes indicate that the bay mud and clay lie unconformably on the eroded surface of sand deposits that may belong

FIGURE 57.—Bay mud, showing desiccation cracks, lying under artificial fill (dune sand). Foundation area Crown-Zellerbach Building, Bush and Battery Streets, San Francisco.

to the Colma Formation. These sand deposits are massive, brown, and clayey (described by the author in Radbruch and Schlocker, 1958). They may be part of the same fossil soil zone that is developed also on sand below bay mud and clay found by Story, Wessels, and Wolfe (1966, p. 49) in numerous boreholes in the vicinity of the San Mateo Bridge. Clays older than the soft uppermost bay mud and clay (informally called younger bay mud and clay by Radbruch and Schlocker, 1958) lie below or are interbedded with the sand deposits (Radbruch and Schlocker, 1958). Older bay clays also lie below a sand layer in the area between Rincon Hill and Telegraph Hill in San Francisco, but according to Treasher (1963, p. 21) this sand forms scattered lenses in San Francisco Bay rather than a continuous blanket on older bay clay. In some areas the younger bay mud and clay (Treasher's semiconsolidated mud) directly overlie older, stiffer bay clay. The older bay clay is distinct from the overlying younger clay and mud because it is generally highly overconsolidated, from 1.5 to 3 tons per square foot (Trask and Rolston, 1951, p. 1096–1097).

Fossils found in the younger bay mud and clay are of species living today. They include mollusks and a large assemblage of microscopic flora and fauna. Preliminary work on diatoms obtained from boreholes in eastern San Francisco shows both marine and fresh-water species in some mud samples and only marine species in others. Kenneth E. Lohman (oral commun., 1955) briefly examined the diatoms and suggested that the muds containing both marine and fresh-water diatoms were deposited under brackish-water conditions.

For two core samples of bay mud obtained by the Corps of Engineers, U.S. Army, about 1 mile east of the quadrangle and 2 miles south of its north boundary and collected 11 and 20.5 feet below the sediment surface, Kvenvolden (1962, p. 1645) reported the following radiocarbon dates from unspecified organic material: 6,210±175 and 7,925±810 B.P. (before present), respectively.

Shell and peat in bay mud obtained 6–9 miles southeast of the quadrangle were dated by Story, Wessels, and Wolfe (1966, p. 47). Radiocarbon ages ranged from 2,420±180 to 7,360±320 B.P. for samples 2–50.5 feet below the top of the bay mud. These radiocarbon ages confirm the belief that the modern deposition of mud began after the Wisconsin Glaciation about 14,000 years ago, when sea level began to rise with the melting of ice (Milliman and Emery, 1968, p. 1121–1123). Treasher (1963, p. 23) suggested that semiconsolidated bay mud was deposited during a pre-Wisconsin interstadial high stand of sea level, was slightly overconsolidated by desiccation during a brief exposure to air during the subsequent Wisconsin Glaciation, and was inundated again and covered by the uppermost bay mud after the Wisconsin Glaciation. Older bay clays may have been deposited during periods of high sea level associated with the Sangamon and earlier interglaciations.

Great volumes of the uppermost soft mud were no doubt deposited during the days of hydraulic mining of gold when huge amounts of debris were fed into the Sacramento River. Gilbert (1917, p. 48–49) stated that the chief deposit in the bay from mining debris is mud. He also estimated that in the period 1849–1914, 50 million cubic yards of sediments, mostly of grains smaller than fine sand and mostly derived from mining debris, reached the ocean. As early as 1862, many years before hydraulic mining reached its peak, Brewer (1930, p. 295) wrote as follows:

> Previous to 1848 the river (the Sacramento) was noted for the purity of its waters, flowing from the mountains as clear as crystal; but, since the discovery of gold, the "washings" render it as muddy and turbid as is the Ohio at spring flood—in fact it is perfectly "riley", discoloring even the waters of the great bay into which it empties.

ALLUVIUM

Alluvium, which is material transported and deposited by running water, is only sparsely present in the quadrangle. Alluvium is distinguished with difficulty from slope debris and ravine fill, which were transported by creep and landsliding. Evidently streams are too small to transport enough slope debris and ravine fill to create substantial deposits of alluvium. In San Francisco the high porosity of the dune sand may have inhibited substantial surface flow. Alluvium that formed in the last few hundred years may be represented by the deposits in the valley at Horseshoe Bay and in the southwest-trending valley of an intermittent stream in the west-central part of Marin Peninsula. The bed of the largest intermittent stream in San Francisco, Lobos Creek, is dune sand, artificial fill, and Colma Formation. Valleys on the east flank of Twin Peaks contained streams that flowed into the bay when the city was founded in 1776, but the stream beds now are covered with slope debris or artificial fill.

Several deposits of alluvium were mapped on the west slopes of Twin Peaks (fig. 58). They have a maximum observed thickness of 15 feet and are interbedded with and grade laterally and vertically into slope debris and ravine fill. Most of these deposits are related to slightly older drainage systems than the present ones and are now moderately dissected. Similar alluvial deposits occur in many other parts of the quadrangle, but they are not shown on the map (pl. 1) because they are largely or entirely concealed by other surficial deposits or by artificial fill and manmade structures. Most of the alluvium is composed of medium silty clayey sand; clean medium sand occurs locally. Allu-

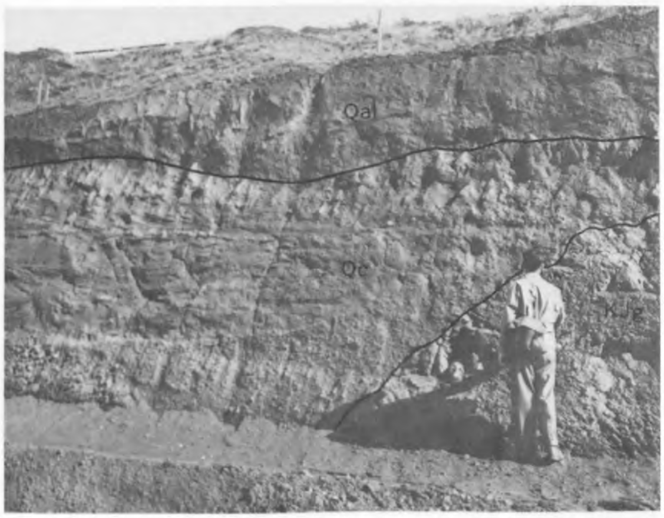

FIGURE 58.—Alluvium (Qal) lying on Colma Formation (Qc). Greenstone (Kjg) at right. West slope of Twin Peaks, San Francisco.

vium is generally better sorted than slope debris and ravine fill. Chert and greenstone pebbles are locally abundant in the alluvium, especially near the heads of the valleys.

LANDSLIDE DEPOSITS

Landslide deposits are widespread throughout the quadrangle, and they indicate that landsliding is one of the principal agents of erosion. The deposits mapped as landslides, however, are rather local features that were formed by relatively recent landsliding. Landslide topographic features, such as shear-failure scarps or hummocky topography, are visible, even though some of them are considerably modified by erosion. Spoon-shaped cliffs like the one just west of the Golden Gate Bridge tower (fig. 19) may have been shaped by landsliding.

In the downward and outward movement of slope-forming material that constitutes landsliding, part of the potential energy of the slope is converted to kinetic energy and friction; the subsequent landslide deposit has correspondingly less potential energy, and so many slopes are more stable after landsliding than before. Thus, if a slope is to remain unstable over a long period of time, the landslide deposits must be removed. In the San Francisco North quadrangle, instability is usually perpetuated by rainwash and stream erosion, especially during large storms, that rework and move landslide deposits downslope or completely remove them from the landslide-sculptured slope. For this reason the activity of landsliding is directly proportional to the activity of other agents of erosion. Consequently, some other Quaternary deposits, especially some of the Colma Formation and slope debris and ravine fill, are reworked landslide deposits, but they are older than the landslide deposits designated as such on the map (pl. 1).

Though landslides are widely distributed in the quadrangle, the small volume of landslide deposits shown on the geologic map (pl. 1) may seem to belie the important role of landsliding as an agent of erosion. Local construction activities have obscured many of the distinctive topographic features of landslides. On the other hand, abundant manmade structures afford numerous known survey points for measuring even slight landslide movements.

Landslide processes are succinctly discussed by Varnes (1958, p. 42–45), who pointed out the following:

> The process of landsliding is essentially a continuous series of events from cause to effect. ***
>
> Very seldom, if ever, can a slide be attributed to a single definite cause. The process leading to the development of the slide has its beginning with the formation of the rock itself, when its basic physical properties are determined, and includes all the subsequent events of crustal movement, erosion, and weathering, until some action, perhaps trivial, sets a mass of it in motion downhill. The last action cannot be regarded as the one and only cause, even though it was necessary in the chain of events.

Because most slides involve failure of slope materials under shear stress, a logical account of causes of landsliding would deal with (1) factors that contribute to high shear stress and (2) factors that contribute to low shear strengths. These factors are outlined in detail by Varnes (1958, p. 42–45). Removal of lateral and underlying support is the most common factor that contributes to high shearing stress in a slope. It includes actions of erosion, of previous landsliding, and of man. A variety of factors leads to low shear strengths, including the initial state of the slope material, subsequent changes brought on by weathering, and other physicochemical reactions. In addition, water is an important factor in slope stability, for it contributes both to high shear stress and low shear strength.

The numerous landslides in the quadrangle owe their existence to several factors: an irregular hilly terrain with gentle to steep slopes underlain in many areas by unconsolidated surficial deposits or by badly sheared and shattered bedrock, a relative abundance of highly plastic and swelling clay in all the foregoing materials, occasional periods of prolonged rainfall, occasional earthquakes, and the continuous disturbance and alteration of the original terrain by man.

The distribution of landslides in the quadrangle is shown on plates 2 and 3. Slopes underlain by strongly sheared Franciscan rocks, by serpentine, and by the sheared-rock map unit are especially prone to landsliding. The largest landslides are in sheared serpentine

FIGURE 59.—Steeply cut slopes in serpentine, Potrero Hill, San Francisco. Cut face to right of stairway has remained intact for many years except for minor sloughing and raveling. Slope beneath and to left of stairway was probably the site of a small landslide.

and in Franciscan rocks in the Lands End area and in the sheared serpentine south of the Golden Gate Bridge. Wave action periodically reactivates some of these slides by removing the supporting material at their bases. Serpentine, contrary to popular belief, is not especially prone to landsliding everywhere, because the large serpentine body of Potrero Hill is almost completely free of landslides (fig. 59). Harding (1969, p. 66) pointed out that "areas of obvious potential instability can be mapped on a regional scale, however, the corollary, mapping whole hillside areas as stable on the basis of rock type, cannot safely be done."

Many landslides too small to be shown on the geologic map (pl. 1) are numerous in the slope debris and ravine fill, especially along roadcuts. Soil moisture in ravine fill is believed to be a primary cause for sliding, although the actual movement may be triggered by other factors.

CHARACTERISTICS OF LANDSLIDES

Slides range from rockfalls at one extreme to mudflows at the other; earthflows and debris flows are the commonest types. Many landslides, however, are complex; their upper parts are rockslides, debris slides, or rotational slumps, and their lower parts are earthflows or debris flows (figs. 60, 61). A few rockfall deposits are found below steep quarry faces and along steep rocky shores. Characteristics of landslides are given on plate 3.

FIGURE 60.—Landslide in center of photograph is a slump and debris slide in its upper part and a debris flow in its lower part (No. 93, pl. 3). Note fracturing of sandstone of the Franciscan Formation. South Bay part of Golden Gate, San Francisco, looking southeast. (Barney Peterson, photographer, used with permission of the San Francisco Chronicle.)

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> Previous to 1848 the river (the Sacramento) was noted for the purity of its waters, flowing from the mountains as clear as crystal; but, since the discovery of gold, the "washings" render it as muddy and turbid as is the Ohio at spring flood—in fact it is perfectly "riley", discoloring even the waters of the great bay into which it empties.

ALLUVIUM

Alluvium, which is material transported and deposited by running water, is only sparsely present in the quadrangle. Alluvium is distinguished with difficulty from slope debris and ravine fill, which were transported by creep and landsliding. Evidently streams are too small to transport enough slope debris and ravine fill to create substantial deposits of alluvium. In San Francisco the high porosity of the dune sand may have inhibited substantial surface flow. Alluvium that formed in the last few hundred years may be represented by the deposits in the valley at Horseshoe Bay and in the southwest-trending valley of an intermittent stream in the west-central part of Marin Peninsula. The bed of the largest intermittent stream in San Francisco, Lobos Creek, is dune sand, artificial fill, and Colma Formation. Valleys on the east flank of Twin Peaks contained streams that flowed into the bay when the city was founded in 1776, but the stream beds now are covered with slope debris or artificial fill.

Several deposits of alluvium were mapped on the west slopes of Twin Peaks (fig. 58). They have a maximum observed thickness of 15 feet and are interbedded with and grade laterally and vertically into slope debris and ravine fill. Most of these deposits are related to slightly older drainage systems than the present ones and are now moderately dissected. Similar alluvial deposits occur in many other parts of the quadrangle, but they are not shown on the map (pl. 1) because they are largely or entirely concealed by other surficial deposits or by artificial fill and manmade structures. Most of the alluvium is composed of medium silty clayey sand; clean medium sand occurs locally. Allu-

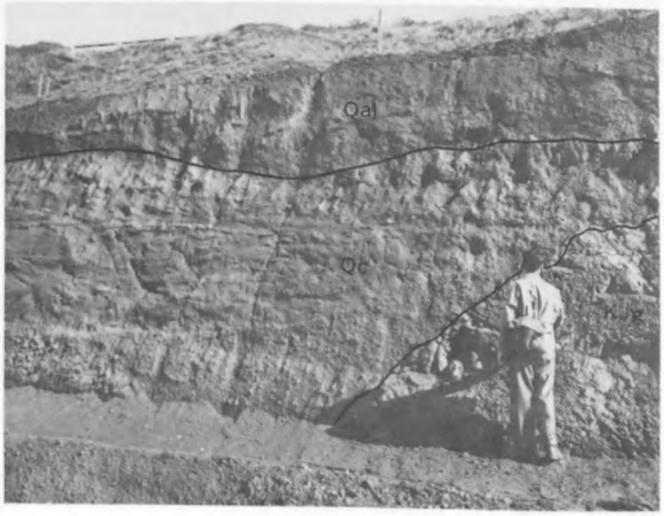

FIGURE 58.—Alluvium (Qal) lying on Colma Formation (Qc). Greenstone (Kjg) at right. West slope of Twin Peaks, San Francisco.

vium is generally better sorted than slope debris and ravine fill. Chert and greenstone pebbles are locally abundant in the alluvium, especially near the heads of the valleys.

LANDSLIDE DEPOSITS

Landslide deposits are widespread throughout the quadrangle, and they indicate that landsliding is one of the principal agents of erosion. The deposits mapped as landslides, however, are rather local features that were formed by relatively recent landsliding. Landslide topographic features, such as shear-failure scarps or hummocky topography, are visible, even though some of them are considerably modified by erosion. Spoon-shaped cliffs like the one just west of the Golden Gate Bridge tower (fig. 19) may have been shaped by landsliding.

In the downward and outward movement of slope-forming material that constitutes landsliding, part of the potential energy of the slope is converted to kinetic energy and friction; the subsequent landslide deposit has correspondingly less potential energy, and so many slopes are more stable after landsliding than before. Thus, if a slope is to remain unstable over a long period of time, the landslide deposits must be removed. In the San Francisco North quadrangle, instability is usually perpetuated by rainwash and stream erosion, especially during large storms, that rework and move landslide deposits downslope or completely remove them from the landslide-sculptured slope. For this reason the activity of landsliding is directly proportional to the activity of other agents of erosion. Consequently, some other Quaternary deposits, especially some of the Colma Formation and slope debris and ravine fill, are reworked landslide deposits, but they are older than the landslide deposits designated as such on the map (pl. 1).

Though landslides are widely distributed in the quadrangle, the small volume of landslide deposits shown on the geologic map (pl. 1) may seem to belie the important role of landsliding as an agent of erosion. Local construction activities have obscured many of the distinctive topographic features of landslides. On the other hand, abundant manmade structures afford numerous known survey points for measuring even slight landslide movements.

Landslide processes are succinctly discussed by Varnes (1958, p. 42–45), who pointed out the following:

> The process of landsliding is essentially a continuous series of events from cause to effect. ***
>
> Very seldom, if ever, can a slide be attributed to a single definite cause. The process leading to the development of the slide has its beginning with the formation of the rock itself, when its basic physical properties are determined, and includes all the subsequent events of crustal movement, erosion, and weathering, until some action, perhaps trivial, sets a mass of it in motion downhill. The last action cannot be regarded as the one and only cause, even though it was necessary in the chain of events.

Because most slides involve failure of slope materials under shear stress, a logical account of causes of landsliding would deal with (1) factors that contribute to high shear stress and (2) factors that contribute to low shear strengths. These factors are outlined in detail by Varnes (1958, p. 42–45). Removal of lateral and underlying support is the most common factor that contributes to high shearing stress in a slope. It includes actions of erosion, of previous landsliding, and of man. A variety of factors leads to low shear strengths, including the initial state of the slope material, subsequent changes brought on by weathering, and other physicochemical reactions. In addition, water is an important factor in slope stability, for it contributes both to high shear stress and low shear strength.

The numerous landslides in the quadrangle owe their existence to several factors: an irregular hilly terrain with gentle to steep slopes underlain in many areas by unconsolidated surficial deposits or by badly sheared and shattered bedrock, a relative abundance of highly plastic and swelling clay in all the foregoing materials, occasional periods of prolonged rainfall, occasional earthquakes, and the continuous disturbance and alteration of the original terrain by man.

The distribution of landslides in the quadrangle is shown on plates 2 and 3. Slopes underlain by strongly sheared Franciscan rocks, by serpentine, and by the sheared-rock map unit are especially prone to landsliding. The largest landslides are in sheared serpentine

FIGURE 59.—Steeply cut slopes in serpentine, Potrero Hill, San Francisco. Cut face to right of stairway has remained intact for many years except for minor sloughing and raveling. Slope beneath and to left of stairway was probably the site of a small landslide.

and in Franciscan rocks in the Lands End area and in the sheared serpentine south of the Golden Gate Bridge. Wave action periodically reactivates some of these slides by removing the supporting material at their bases. Serpentine, contrary to popular belief, is not especially prone to landsliding everywhere, because the large serpentine body of Potrero Hill is almost completely free of landslides (fig. 59). Harding (1969, p. 66) pointed out that "areas of obvious potential instability can be mapped on a regional scale, however, the corollary, mapping whole hillside areas as stable on the basis of rock type, cannot safely be done."

Many landslides too small to be shown on the geologic map (pl. 1) are numerous in the slope debris and ravine fill, especially along roadcuts. Soil moisture in ravine fill is believed to be a primary cause for sliding, although the actual movement may be triggered by other factors.

CHARACTERISTICS OF LANDSLIDES

Slides range from rockfalls at one extreme to mudflows at the other; earthflows and debris flows are the commonest types. Many landslides, however, are complex; their upper parts are rockslides, debris slides, or rotational slumps, and their lower parts are earthflows or debris flows (figs. 60, 61). A few rockfall deposits are found below steep quarry faces and along steep rocky shores. Characteristics of landslides are given on plate 3.

FIGURE 60.—Landslide in center of photograph is a slump and debris slide in its upper part and a debris flow in its lower part (No. 93, pl. 3). Note fracturing of sandstone of the Franciscan Formation. South Bay part of Golden Gate, San Francisco, looking southeast. (Barney Peterson, photographer, used with permission of the San Francisco Chronicle.)

FIGURE 61.—Landslide in which soft sheared sandstone and shale, below radiolarian chert, is moving downhill as a rotational slump and debris slide (No. 51, pl. 3). Toe of slide above roadcut has bulged the surface and is calving onto road. One mile northwest of Lime Point, Marin Peninsula.

The frequency of landsliding differs greatly for the various lithologic units. About 60 percent of the landslides involve surficial deposits and weathered and sheared bedrock. More than half the landslides in bedrock, including sheared and weathered rock, involve sandstone of the Franciscan Formation, 21 percent involve greenstone, 8 percent involve radiolarian chert, and 9 percent involve serpentine. Bonilla (1960) obtained similar results in an analysis of landslides in the San Francisco South quadrangle. These percentages, however, do not take into account the size of slides, nor the relative area of exposure of each type. Serpentine slides are among the largest in the quadrangle. Landslides involving radiolarian chert are generally of small size. A more satisfactory statistical comparison of the tendency of various materials to slide would evaluate dimensions or volume of slides and the relative abundance of the various lithologic units. Proper evaluation of slope stability can be made only by considering such local factors as degree of shearing and chemical alteration, steepness of slope and groundwater conditions, as well as the initial state of the rock.

The frequency of types of landslide movement follows. Each type of movement in a complex landslide is counted as a separate landslide in the tabulation.

Type of movement	Percent of total landslides
Earthflow	28
Debris flow	24
Debris slide	22
Rotational slump	13
Rockfall	5
Sand flow	3
Block glide	2
Mudflow	2
Debris avalanche	1
	100

The slope angle before sliding ranges widely for sandstone of the Franciscan Formation, but it averages 35°; for greenstone it averages 31°. These averages, of course, cannot be used to design slopes at individual construction sites. The lower slope angle of greenstone probably reflects the tendency of greenstone to alter by weathering and related processes more readily than does sandstone. Greenstone alteration products, moreover, consist mostly of easily sheared clay minerals including large proportions of swelling clay.

Landslide deposits vary widely in composition. Because earthflows and debris flows are the commonest types of slides, most deposits consist of heterogeneous unstratified mixtures of rock, sand, silt, and clay in proportions that vary within each landslide and from one landslide to another.

In the large landslide half a mile north of Lime Point on Marin Peninsula (pl. 3, Nos. 12, 13, 48, 52), most of the landslide debris is stabilized, though some of it near the bases of the slides has moved since about 1940.

One of the earliest published accounts of slope instability was that of Captain Beechey who visited San Francisco in 1827. In his "Narrative of a Voyage to the Pacific and Beering's Strait" (Beechey, 1831, p. 345), he reported the following at Fort Point: "The fort, which we passed upon our right, mounts nine guns, and is built upon a promontory on the south side of the entrance, apparently so near to the precipice, that one side will, before long, be precipitated over it by the gradual breaking away of the rock."

ARTIFICIAL FILL

The practice of creating land by dumping artificial fill on the gently shelving tidal flats along the east and north margins of the San Francisco Peninsula was begun before 1850. Flatland has been at a premium since the Gold Rush first made San Francisco a center of growth and development. More than 3 square miles of the most valuable land in San Francisco originated in this way (pl. 1; fig. 62). The average thickness of the fill north of China Basin is about 10 feet; south of China Basin it reaches a maximum thickness of about 60 feet. Similarly, large areas of land have been made in the Sausalito-Tiburon area. The thicknesses of arti-

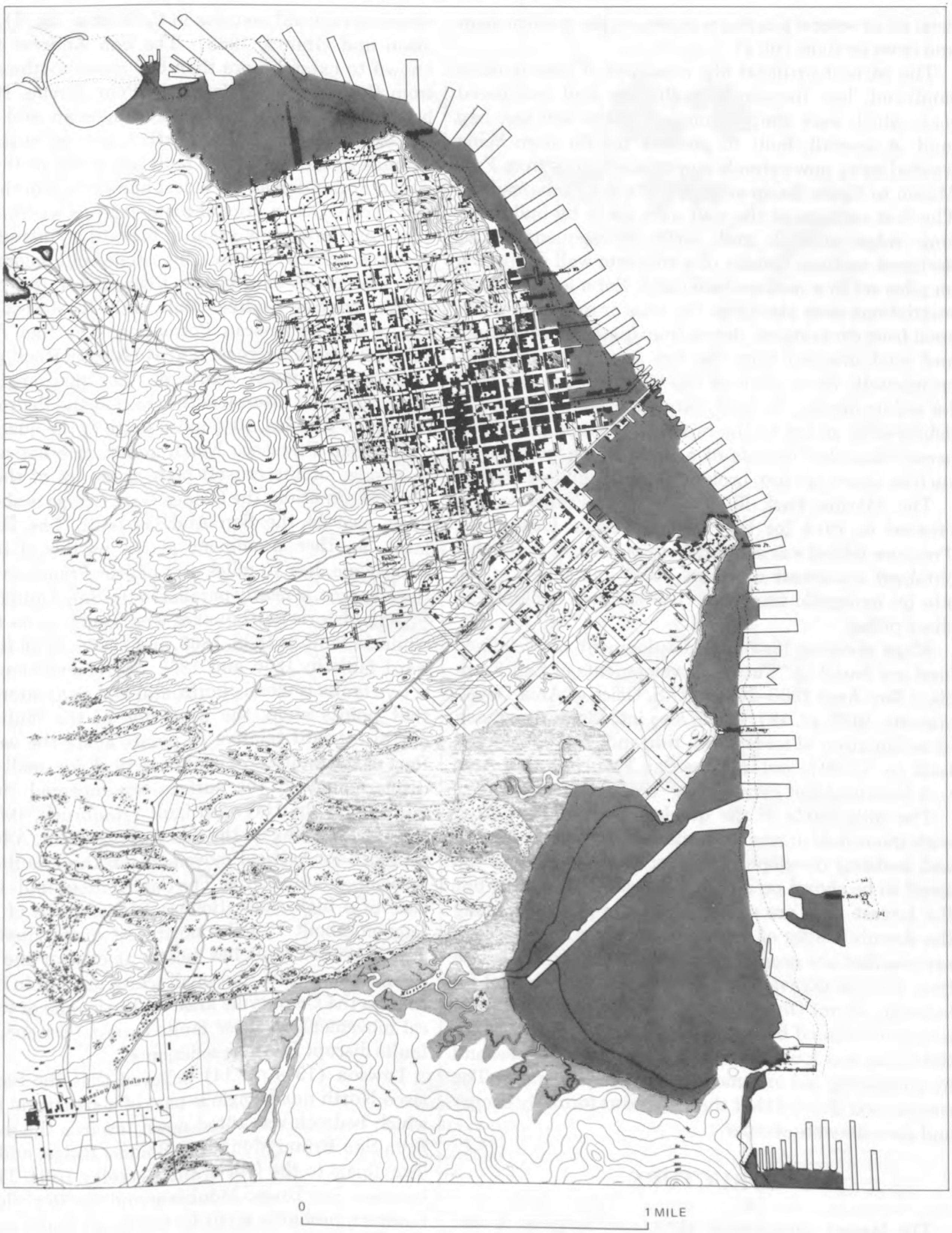

FIGURE 62.—Map showing shoreline of San Francisco in 1853, present shoreline, and areas formerly covered by water that are now artificially filled (shaded). Base modified from Chart 627, U.S. Coast and Geodetic Survey (formerly U.S. Coast Survey).

ficial fill at several places are shown on the geologic map and cross sections (pl. 1).

The earliest artificial fills consisted of nearby dune sand and, less frequently, colluvium and weathered rock, which were simply dumped on the soft wet bay mud. A seawall, built to prevent the fill from being washed away now extends more than 3 miles from Fort Mason to China Basin and supports the Embarcadero. The first sections of the wall were made by building a long ridge of rock and earth. Subsequent better designed sections consist of a concrete wall supported on piles set in a rock embankment. For a long time, no restrictions were placed on the type or quantity of fill; spoil from excavations, debris from quarries, dune sand, and mud dredged from the bay were dumped indiscriminately. Some parts of the fill area were also used for public dumps; so, fairly large deposits of manmade debris were added to the mixture, including miscellaneous discarded objects of a large urban population, such as shoes, bottles, broken pottery, and bed frames.

The Marina Park fill area in San Francisco was created in 1913 for the Panama-Pacific Exposition. Treasure Island was created from sandy bay sediments obtained southwest of Blunt Point and piped to the site by hydraulic transport. The site was enclosed by sheet piling.

Maps showing historical development of reclaimed land are found in "Future Developments of San Francisco Bay Area 1960–2020" (U.S. Office of Area Development, 1959, pl. 19), which also includes a discussion of reclamation of marshland, tideland, and submerged land (p. 75–94), and in "The San Francisco Bay Area —A Metropolis in Perspective" (Scott, 1959, p. 37).

The hilly parts of the quadrangle are also dotted with thousands of small fills made in the course of road and building development. Most of these fills are too small to be shown on a map at a scale of 1:24,000, but the largest ones are shown. They are generally along the downhill sides of major roads or are in large deep ravines that are used as dumps for rock and soil waste from nearby excavations. A large area of artificial fill between Mount Olympus and Golden Gate Park is now largely concealed by urban development. Evidence for the filling was found by studying logs of boreholes and by comparing old and modern topographic maps. The comparison showed that the valley was formerly deeper and its walls were steeper.

STRUCTURE

The largest conspicuous structural features in and bordering the San Francisco North quadrangle are northwest-trending faults and shear zones (figs. 1, 63), including the San Andreas fault—one of the most persistent structural features in California (fig. 6) (Dickinson and Grantz, 1968). The San Andreas fault is known to extend more than 600 miles northwestward from the Gulf of California to Point Arena. It is the boundary between the North American and Pacific Ocean crustal plates. The North American crustal plate extends to the east of the fault and contains the Franciscan Formation as the oldest known rock in this area; the Pacific Ocean crustal plate extends westward and contains Cretaceous granitic rocks that intrude older gneisses, schists, marbles, limestone, and dolomite. On San Francisco Peninsula the Pilarcitos fault, which lies west of the San Andreas fault, is the local west boundary of the Franciscan Formation. The San Andreas fault intersects the coast north of Mussel Rock, approximately 5½ miles south of the quadrangle. The Pilarcitos fault intersects the coast at the Pedro Valley district of Pacifica, 10½ miles south of the quadrangle.

The San Francisco North quadrangle lies near the west edge of the crustal plate made up of the Franciscan Formation; the Golden Gate Bridge is about 6½ miles east of the San Andreas fault. The Hayward fault, another prominent active northwest-trending shear zone, lies 10 miles east of San Francisco and, in the bay area, is nearly parallel to the San Andreas fault. Strong historic earthquakes were centered on the San Andreas fault in 1838, 1865, and 1906 and on the Hayward fault in 1836 and 1868. Movement along these active faults is mostly horizontal and right lateral, such that points along the west side of the faults move northwestward relative to points along the east side. Part of the fault movement is vertical, for small vertical displacement of the surface accompanied the 1868 faulting on the Hayward fault (Radbruch, 1967) and the 1906 faulting on the San Andreas fault. Additional evidence for vertical movement on these faults is the associated fault scarps. The San Andreas fault is at the base of a high ridge, Bolinas Ridge, north of Bolinas Lagoon, about 12 miles northwest of the quadrangle. The Hayward fault lies mostly at or near the base of the Berkeley Hills, and small scarps are within the fault zone in the Centerville area. At least some of the vertical movement on these faults is post-Pliocene, for the faults disrupt Pliocene sediments.

Lawson (1914, p. 14) believed that the San Francisco North quadrangle is part of a structural block in which bedrock was tilted down towards the northeast from San Bruno Mountain, Bolinas Ridge, and Mount Tamalpais to the foot of the Berkeley Hills. The crust between San Bruno Mountain and the Berkeley Hills, however, probably is cut by numerous faults and probably has not acted as a rigid block. The presence of bedrock far above sea level on Angel Island, at El Cerrito, at Potrero San Pablo in Richmond, at Red Rock

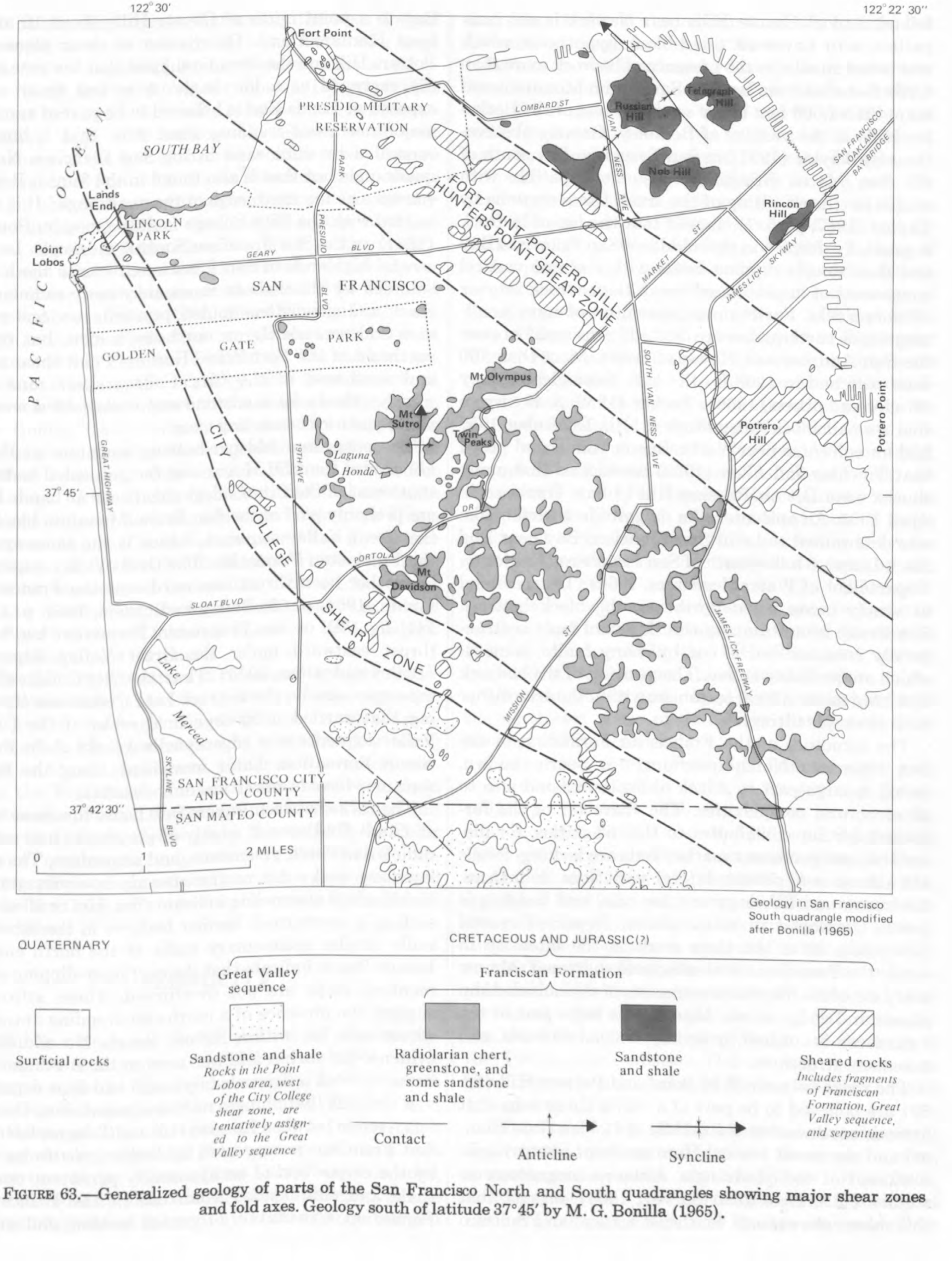

FIGURE 63.—Generalized geology of parts of the San Francisco North and South quadrangles showing major shear zones and fold axes. Geology south of latitude 37°45′ by M. G. Bonilla (1965).

Island, and at Coyote Hills near Newark is not compatible with Lawson's tilted-block hypothesis, which was based mostly on the presence of bedrock more than 1,000 feet above sea level at San Bruno Mountain and more than 1,000 feet below sea level west of the Berkeley Hills in the vicinity of Berkeley. Gravity observations by Taylor (1957) in San Francisco Bay south of the San Mateo Bridge are also incompatible with simple northeast tilting of the crust. Cross sections by Taylor (1957, pl. 5–7) showed that the top of bedrock is generally deepest in the middle of San Francisco Bay and that steeply-dipping faults with a strong vertical component of displacement break the bedrock into six or more blocks. Furthermore, epicenters of many small-magnitude earthquakes are located in the area between the San Andreas and Hayward faults. More than 100 were recorded in 1968 by the U.S. Geological Survey (Roller and others, 1968). Tocher (1959, p. 48) wrote that a small shock (magnitude 2.1) in December 1956 had an epicenter near Yerba Buena Island and noted that Townley and Allen (1939) mentioned that many shocks were felt on Russian Hill in San Francisco in April 1905. An epicenter of a magnitude 4 earthquake was determined to be in San Francisco Bay near Red Rock Island, 8 miles north of San Francisco (California Department of Water Resources, 1964). Thus, instead of simply being tilted northeast, the block between San Bruno Mountain and the Hayward fault is structurally complex and is cut by many faults, some of which are probably active. The position of the bedrock is related more to local tectonism within the area rather than to simple tilting.

The structure of the Franciscan Formation in the San Francisco North quadrangle is poorly known, owing in large part to a lack of exposures and also to its structural complexities. The character of the formation further contributes to the difficulties, for distinctive and persistent marker beds are lacking, fossils are almost nonexistent, lateral variations in texture, thickness, and lithology are the rule, and bedding is poorly developed in many places. Repeated crustal movements have left their mark in the intensity to which the Franciscan is sheared and shattered. Almost every exposure has one or more sets of slickensided slip planes and gouge zones. Moreover, a large part of the Franciscan is covered by water, surficial deposits, and manmade structures.

The rocks between Fort Point and Potrero Hill (fig. 62) are believed to be part of a major shear zone that extends northwest to the middle of Golden Gate channel and southeast toward Hunters Point about 1 mile southeast of the quadrangle. Airborne magnetometer studies (U.S. Geological Survey, 1966) suggest that this shear zone extends southeast across San Francisco Bay to a point north of Coyote Hills about 16 miles from Hunters Point. Orientation of shear planes in Potrero Hill and the Presidio suggest that the zone may dip eastward at a low angle. A second shear zone exposed at Lands End is believed to be part of another major northwest-trending shear zone that is largely concealed by dune sand in the San Francisco North quadrangle but that is also found in the Sunset Reservoir area at the south edge of the quadrangle. It is correlated with the City College fault mapped by Bonilla (1961) in the San Francisco South quadrangle. In the central highlands of San Francisco, rocks in the block bounded by these shear zones are mostly radiolarian chert and greenstone folded primarily on east-west axes and secondarily on north-south axes, but rocks northeast of the Fort Point–Hunters Point shear zone and southwest of the City College shear zone are mostly graywacke sandstone and shale folded mostly along northwest-trending axes.

The potassium feldspar-bearing sandstone at Point Lobos and the Cliff House and the concealed bedrock southwest of the City College shear zone at Lands End are probably part of the San Bruno Mountain block of the Great Valley sequence, which is the same age as the Franciscan Formation. The Great Valley sequence has either been thrust westward over the Franciscan (Irwin, 1964, p. 66; Bailey and others, 1964, p. 123–141, fig. 72) or the Franciscan Formation has been thrust eastward under the Great Valley sequence (Bailey and others, 1970). Thus, the City College shear zone may also be the locus of Late Cretaceous thrusting that carried miogeosynclinal rocks of the Great Valley sequence over eugeosynclinal rocks of the Franciscan Formation. Later movement along the same zone may have been vertical or horizontal.

The rocks between Bakers Beach and the shear zone at Lands End consist mostly of graywacke and minor radiolarian chert, greenstone, and serpentine. The sedimentary rocks dip northeastward; however, graded bedding and channeling indicate that part or all of the section is overturned. Similar features in the lithologically similar sedimentary rocks at the north end of Bakers Beach indicate that the northeast-dipping sedimentary rocks are not overturned. These attitudes suggest the presence of a northwest-trending anticline whose axis lies within Bakers Beach. No additional evidence for such a fold was seen to the southeast because bedrock is concealed by beach and dune deposits.

A syncline that plunges northwestward along Columbus Avenue between Russian Hill and Telegraph Hill in San Francisco is suggested by bedding attitudes and by the disposition of an apparently persistent unit of shale and thin-bedded sandstone of the Franciscan Formation. Orientation of graded bedding and small-scale channeling suggest that locally the west limb of the syncline is overturned. Opposing flanks of a large anticline are suggested by northeasterly dips on Alcatraz Island and southwesterly dips on Telegraph Hill. Meager structural data indicate one or more northwest-trending large folds between the Columbus Avenue syncline and the belt of sheared rocks between Potrero Hill and Fort Point. On Marin Peninsula the immense section of southwestward-dipping sediments and greenstone apparently forms the limb of a large anticline whose axis lies in Richardson Bay (pl. 1, section *A–A′*). On Angel Island the principal structure is a broad syncline whose axis plunges northwestward to Hospital Cove and beyond along the middle of Tiburon Peninsula.

No satisfactory structural correlation exists between Marin and San Francisco Peninsulas. The marked contrast in stratigraphy, lithology, and local structures between the two suggest that a major fault exists in the Golden Gate channel, but no other supporting evidence was found, with the possible exception of the westward-trending shear zone at Point Diablo. The alinement of the Richardson Bay anticlinal axis with the axis between Alcatraz Island and Telegraph Hill is one possible link. The radiolarian chert and greenstone southwest of the Fort Point–Hunters Point shear zone may be represented by similar rocks in the Point Bonita quadrangle. Rocks in both areas are folded mostly on east-west fold axes (Lawson, 1914, geologic map of Tamalpais 15′ quad.).

Another interpretation of the structural link across the Golden Gate is that the Columbus Avenue syncline is a part of the Angel Island–Tiburon Peninsula syncline offset 2 miles westward by a northeast-trending fault south of Angel Island. Under such an interpretation the Fort Point–Hunters Point shear zone could continue in offset as the serpentine of Angel Island and Tiburon. However, fieldwork by the author in the Point Bonita quadrangle indicates that the Fort Point–Hunters Point shear zone may continue northwestward across the Golden Gate to the shear zone of the Bonita Cove area.

SEISMICITY

The San Francisco North quadrangle lies between the active San Andreas and Hayward faults and is within a region of high seismic activity, in which earth tremors are frequent and unpredictable. The five largest earthquakes since 1800, as well as many other strong shocks, originated from movement on or near these two faults. Parts of the Calaveras fault zone, located about 20 miles east of the quadrangle, are also active. Epicenters located by seismographs suggest that other faults in the bay area are also active, but data are too meager to identify them.

Surface ground breakage by historic fault movement during earthquakes has occurred on the San Andreas fault (Lawson and others, 1908) and on the Hayward fault (Radbruch, 1967). No field evidence of recent fault movement has been found in the quadrangle.

Epicenters for small earthquakes in and near the quadrangle are shown on maps by Byerly (1951, p. 159) for the periods 1930–41 and 1947–48 and by Tocher (1959, p. 46) for the period 1942–57. None of these epicenters are located in the quadrangle, though several are shown in nearby areas. The epicenter of the strongest shock recorded between 1930 and 1957, that of March 22, 1957, Richter magnitude 5.3, is near Mussel Rock where the San Andreas fault intersects the Pacific Ocean shore 5½ miles south of the quadrangle. Several other epicenters of weaker shocks are also near Mussel Rock and west of Golden Gate, generally along the alinement of the San Andreas fault; one epicenter is about 1 mile south of Twin Peaks; one is on the shore of the bay near Islais Creek; two are near Hunters Point, 2 miles southeast and 3 miles southwest of the point; and three are within 1–4 miles west and northwest of the northwest corner of the quadrangle. Except for the March 22, 1957, earthquake, all shocks were only strong enough to rattle windows and doors and occurred during the period 1930–41. During 1968 the U.S. Geological Survey recorded six epicenters of microearthquakes in the quadrangle (Roller and others, 1968), all located near the northwest shore of San Francisco between Fort Mason and Hunters Point.

Earthquake history of the San Francisco Bay area is discussed by Tocher (1959, p. 39–48) and Byerly (1951, p. 141–160). The five largest known earthquakes are those of June 10, 1836, and October 21, 1868, which originated from movements along the Hayward fault, and those of June 1838, October 8, 1865, and April 18, 1906, which originated from movements along the San Andreas fault. Serious damage to structures in San Francisco is recorded for the 1865, 1868, and 1906 earthquakes. Almost no information is available on damage to structures from the 1836 and 1838 earthquakes because the population of San Francisco was small and structures were few, though the walls of the Presidio and Mission Dolores were reported to have been seriously damaged by the 1838 earthquake (Louderback, 1947).

Effects of the 1906 earthquake have been extensively documented in many publications. Some of the more comprehensive reports are by Gilbert, Humphrey, Sewell, and Soule (1907), by the American Society of Civil Engineers (1907), and by Lawson and others

(1908). Though structures were damaged in all parts of the city, much of the damage was moderate. Nevertheless, in the heavily built-up northeastern part of the city, from North Point to Townsend Street and from the Embarcadero to an irregular line approximately along Van Ness Avenue to the intersection of Dolores and 20th Streets, destruction by the earthquake and the resulting fire was a great catastrophe. About 400 lives were lost in the city, and estimates of total damage range from $350 million to $1 billion. Estimates of the loss due to the earthquake exclusive of the fire range from 5 to 20 percent of the total damage.

In San Francisco the relationship between damage to manmade structures and geology was investigated by Wood (1933, p. 67–82; 1908, p. 220–245; see also Lawson and others, 1908, atlas map 19). Though Wood postulated a general increase in intensity of shaking towards the fault, he found that damage to structures was influenced mostly by the geology of their foundations. The least damage was in hilly areas of the city where buildings were founded on or near Franciscan Formation bedrock. Damage was 5–10 times greater in the areas where structures were founded on artificial fill lying on bay sediments (Duke, 1958, p. 9). Wood found that some of the damage in the filled-in areas was caused by settling of poorly consolidated material. Another pertinent observation on damage to structures in the filled-in areas was made by the American Society of Civil Engineers (1932, p. 40): "No class 'A' building founded on well-driven piles or well-placed concrete piers suffered any material injury due to the earthquake; serious damage or collapse occurred only in poorly constructed buildings erected on soft foundations in the 'filled-in' areas." Steinbrugge (1968) discussed relations of building damage to foundation material, earthquake risk zoning, and building code ordinances requirements for earthquake resistant design.

For the Alaska earthquake of March 27, 1964, damage was also greatest in areas underlain by thick saturated unconsolidated deposits, whereas there was no significant damage to structures founded on indurated bedrock or on bedrock with a thin veneer of unconsolidated deposits (Eckel, 1970, p. 29). Damage was related more to local geology than to distance from the epicenter (Eckel, 1970, p. 29).

A rough appraisal of earthquake stability of the geologic units in the quadrangle is given in table 11.

A cooperative effort of the Earthquake Engineering Research Institute, the National Science Foundation, the National Center for Earthquake Research (NCER) of the U.S. Geological Survey, and several State of California agencies is being made to place more than 40 instruments in and near the quadrangle to record motion during strong local earthquakes. These instruments will obtain data on shaking characteristics of various types of geologic rock units, surficial and bedrock, in various geologic environments.

Measurements made by the National Center for Earthquake Research in and south of this quadrangle of ground motion generated by underground nuclear explosions in Nevada show good correlation of motion amplitude with geologic setting of the recording site. Maximum horizontal ground velocities at sites underlain by bay mud generally increased with thickness of bay mud and were as much as ten times greater than those recorded on nearby bedrock (Borcherdt, 1970).

Additional information on the behavior of foundations in the San Francisco Bay area during earthquakes is given by Bonilla (1970), Seed (1970), and Cluff and Bolt (1969).

ENGINEERING GEOLOGY

The San Francisco North quadrangle, particularly the city of San Francisco, is blanketed by various kinds of unconsolidated surficial deposits through which protrude scattered patches of more durable bedrock. The quadrangle is between two major active faults and is therefore subject to frequent earth tremors. Other geologic phenomena peculiar to the quadrangle are two broad zones of sheared rock, many landslides, and large areas of land that have been reclaimed by covering soft mud with artificial fill. All these features are of concern to the engineering geologist and the engineer because of the special problems they pose individually and in combination with each other.

The differences in permeability, shearing strength, bearing capacity, and other engineering properties between bedrock and surficial deposits are generally large, and in addition, these properties may vary considerably over short distances within a single bedrock or surficial deposit map unit. At some sites on the heavily utilized land areas, heavy structures have been built partly on soft bay mud and partly on hard sandstone of the Franciscan Formation. Proper use of such sites for foundation purposes demands careful exploration and engineering design. Even construction sites entirely on the Franciscan Formation encompass shear zones consisting of soft clayey material studded with hard rocks. These zones are a few inches to many feet wide. Thus, many building sites are founded on rocks with differing bearing capacities and resistances to seismic shocks.

Wood (1933; 1908) concluded that the damage to structures in the 1906 earthquake was controlled mostly by the foundation of the building. Buildings founded on bedrock were the least damaged, and buildings on well-designed and well-placed piles or concrete footings or mats in soft saturated poorly consolidated bay or marsh sediments did not suffer material damage. Serious damage occurred only in poorly constructed buildings erected on soft foundations in the filled-in areas. On the other hand, Steinbrugge (1968, p. 30) observed that damage from the July 28, 1957, earthquake in Mexico City, which is founded on soft wet expansible lake clays, was mostly to tall reinforced concrete buildings, whereas 1–2 story "collapse hazard" buildings performed well. These and other observations made in a worldwide study make it apparent that the natural period of vibration of the foundation and the engineering structure, as well as the nature of the earthquake vibrations and the foundation material, must be considered in design and construction.

In addition to the increased earthquake effects to buildings on artificial fill, differential subsidence is a second serious problem. In less than 60 years, poorly made fill has settled more than 7 feet (fig. 64) (Bonilla and Schlocker, 1966, p. 452). To avert possible subsidence, construction of modern fills should be preceded by careful study of the properties and ground-water conditions of the fill foundation, and only selected materials should be laid under controlled conditions. Engineering problems of reclaimed land in the northeastern part of the city are discussed in "Subsidence and the Foundation Problem in San Francisco" (American Society of Civil Engineers, 1932, p. 24–36). Less serious engineering problems in areas of artificial fill along the fringes of the bay are raised by the old pilings and sunken ships which are found in pile driving and caisson sinking. Also, old garbage dumps present foundation excavation problems because of the variation in strength and bearing capacity of miscellaneous objects in the dump.

FIGURE 64.—Differential settlement of buildings on artificial fill in former Mission Swamp. Photograph taken shortly after street, sidewalk, and sewerline were raised to former level before subsidence. Near Sixth and Folsom Streets, San Francisco.

Because of the great contrast in engineering behavior between bedrock and surficial deposits, the location of the buried bedrock surface (pl. 3) and the generalized engineering characteristics of all the exposed rock units (table 11) are important in planning structures. The contours shown on the bedrock map are based largely on records of borings made for foundation purposes, water wells, and on records of tunnel excavations. Most of them are unpublished. Some of the logs are given as abbreviated notations on the geologic map (pl. 1), and some are published in "Selected Logs of Borings" (Institute of Transportation and Traffic Engineering, 1951) and in "Subsidence and the Foundation Problems in San Francisco" (American Society of Civil Engineers, 1932). As a further aid in evaluating the exposed bedrock surface for possible construction sites, the locations of faults, shear zones, and known landslides are also shown on plate 3.

Engineering properties of San Francisco Bay sediments are discussed briefly in the section "San Francisco Bay Sediments," where the reader will find references to other more detailed discussions. Engineering properties of other geologic map units in the quadrangle are discussed by Trask and Rolston (1951), Lee (1953), California Department of Public Works (1955), and Schlocker (1969; 1970). The reader should also consult the sections "Landslide Deposits" and "Seismicity" for additional material on engineering geology.

In conclusion, each construction site within the quadrangle presents a unique combination of such conditions as topography, hydrology, and foundation materials. Foundation materials, in turn, vary in degree of consolidation, fracturing, and chemical alteration. The bedrock surface map (pl. 3) and the table summarizing the characteristics of rock units (table 11) provide only a general framework on which to base plans for particular site investigations. The information is generalized, covers a large area, and does not supplant detailed site investigations—both field and laboratory—that are necessary for evaluating specific sites for specific structures. It is hoped that the presentation of these data will serve as a reminder to stimulate the acquisition of precise geologic data for use in the proper location and design of structures.

TABLE 11.—*Generalized description of*

[Franciscan Formation extends

Name and map symbol (pl. 1)	Lithology	Weathering, soil development alteration	Permeability	Workability	Slope stability
Artificial fill (Qaf).	Mostly dune sand but includes silt, clay, rock waste, manmade debris, and organic waste.	None.	High, except where clayey materials predominate.	Generally easy to remove except locally in tangles of ship timbers and other manmade debris.	Generally low because most fills are uncemented and lie near or below the water table.
Landslide deposits (Ql, Qlo, Qly).	Variable. Rock pieces of all sizes in sand, silt, and clay matrix.	None or very little.	Variable, but generally high.	Variable, but generally easy to excavate and compact.	Slopes cut in landslide deposits generally unstable. Although some undisturbed natural slopes of landslide deposits are stable for many years, sliding may be reactivated by changes in stress or strength conditions.
Alluvium (Qal).	Gray silty clayey medium sand; fine to medium sand; clayey silt; some pebbles. Grades to slope debris and ravine fill. Older alluvium is rich in plant fragments. Bedding obscure.	No well-developed soils; top 1–2 ft of older alluvium has abundant plant fragments and higher silt content than lower portions.	Generally moderate; fairly high in sand.	Easily excavated with hand or power equipment, such as bulldozer, front-end loader, backhoe, or scraper. Generally easy to compact, except where silt and organic content is high.	Clayey material stands in steep or vertical cuts for several months when dry. Subject to severe gullying. Sandy alluvium unstable in steep cuts.
Modern and older beach deposits (Qb, Qob).	Gray well-sorted medium to coarse sand. A few small gravel beaches.	None.	High.	Easily excavated with hand or power equipment. Compacts rapidly; compaction density increased by water flooding and vibration. Owing to high water table, deep excavations require pumping.	Generally unstable and free running, especially on slopes greater than about 30°. Susceptible to wind and rain erosion. Excavation walls more than 2 or 3 ft in height require support.
Slope debris and ravine fill (Qsr).	Light-yellow to reddish-brown unsorted rock fragments, gravel, sand, silt, and clay in various proportions. Clayey parts exhibit moderate swelling and plasticity when wet.	Generally none, but a slight weathering of top 2–4 ft seen in older material on Marin Peninsula.	Variable, but generally moderate to low.	Generally easily excavated and compacted with power equipment.	Stands in steep to vertical cuts for several months when dry. Generally unstable and prone to sliding when wet. Gullying severe.
Bay mud and clay (Qm).	Gray silty organic (lignitic and diatomaceous) clay with minor amounts of sand; locally, lenses of sand, peat, or shell fragments. Soft and plastic near top, moderately stiff at depth. Shrinks and becomes hard when dried during excavation; plastic and swells when rewetted.	None.	Very low, except sand lenses.	Excavated with power equipment, such as dragline and clamshell bucket, bulldozer, front-end loader, or backhoe. Sheet piling generally required for excavation. Highly compressible, difficult to compact. One method of placing artificial fill is to push aside surface layers of soft mud to avoid trapping it below the fill. Another method is to place a thin layer of fill on the undisturbed top layer of mud that has been somewhat consolidated by drying for a few years.	Generally unstable; where above water table, has moderate stability at 1:1 cut slope for foundation excavations for several months during dry season.
Dune sand (Qd).	Yellowish-brown to light-gray well-sorted fine to medium sand. Quartz, feldspar, and hornblende are chief minerals.	Slight to none. Most grains coated with film of iron oxide. Minor amounts of carbonaceous plant matter disseminated locally in top 2–3 ft.	High. In most places zone of saturation is deep.	Easily excavated. Compacts rapidly; compaction density increased by water flooding and vibration.	Generally unstable and free running. Slopes steeper than 30° generally unstable. Susceptible to wind and rain erosion. Lagging required to support excavation walls more than 2 or 3 ft high.
Colma Formation (Qc).	Light-brown to orange fine to medium sand with minor amounts of clay. Evenly spaced horizontal or nearly horizontal bedding and crossbedding. Beds 1–3 in. thick. Cobble-size rubble beds rare. Low swelling and plasticity when wetted.	Moderate to slight soil development; in places soil identified only by presence of organic matter, increase in silt and clay content, and iron staining.	Variable from low to high in adjacent beds. Found above and below water table.	Easily excavated by hand or power equipment. Scraper with light ripping or no ripping used on large grading jobs. Easily compacted.	Fair to good, except for silt- and clay-free layers, which are unstable in cut slopes greater than 30°. Excavated vertical faces stand for several weeks to several months when dry.
Serpentine (sp, sph).	Mostly soft friable sheared rock enclosing hard spheroidal knobs of unsheared serpentine (sp). Rarely massive and tough (sph). Various colors but generally greenish-gray, blue, or brown.	Soil generally absent or less than 1 ft thick. Locally, 5–10-ft-thick mantle of dark-gray clayey material containing much high-swelling montmorillonite; probably derived from sheared and hydrothermally altered serpentine. This material is "adobelike" and develops deep shrinkage cracks on drying.	Low to moderate	Sheared serpentine excavated readily with power equipment. Massive serpentine may require heavy ripping, blasting, or equivalent. Mixtures of massive and sheared serpentine excavated with light to moderate ripping.	Massive serpentine stable in steep or vertical cuts. Cut slopes in sheared serpentine should not exceed 1:1, and embankment height should be limited. Serpentine at and near other bedrock types generally sheared and altered, and slope stability low. Nodules of hard serpentine tend to fall out of sheared matrix.

engineering properties of map units
from KJss through KJm]

Earthquake stability	Shearing strength; foundation conditions	Possible or reported use	Unit weight (pounds per cubic foot)[1]	Unified soil classification group symbol[2]
Poor to fair. Most movement where thick, poorly compacted, and overlying soft bay mud and clay. Fair where thin, well compacted, and overlying firm materials.	Generally moderate shearing strength, but exceedingly variable depending on composition, method of placement, age, thickness, underlying material, and history following placement, such as ground-water conditions, loading and so forth. In 1906 earthquake the greatest damage to structures was inflicted in areas of artificial fill overlying bay mud and clay along east shore of city.	Used extensively for construction material and foundation purposes. See Putnam (1947, p. 271–278) for estimating storm wave heights in San Francisco Bay and for planning building locations on artificial fill on edge of bay.	Variable within wide limits.	Variable within. wide limits.
Low.	Generally unsuitable for foundations.	Rockfalls possible local source of pervious fill, riprap, and so forth.	Highly variable.	Variable. GC to CH.
Moderate.	Moderate to high in sandy alluvium; low where deposits are predominantly clay and silt or high in plant fragments. To safeguard foundations, clay-filled surface and subsurface channels should be adequately drained.	Surface material possible source of topsoil for lawns and gardens.	100–114	SM, SC, SW, OL.
Probably moderate.	Moderate to high shearing strength where confined. Susceptible to wave erosion on beach. Uniform sands have lower shearing strength than well-graded sands.	Blending sand for concrete aggregate; fill.	105–110	SP.
Moderate.	Variable. Deposits with relatively high clay content are weak and plastic when wet; sandy and gravelly deposits have moderate to high strength.	Fill.	104–124.	CL, SM, SC, rarely GC and GM.
Very low; structures erected on artificial fill overlying bay mud and clay severely damaged in earthquakes of 1865, 1868, and 1906.	Low shearing strength. An older bay clay, lying below Colma Formation, is firm and preconsolidated in most places and has moderate shearing strength.	Although of very poor quality, bay mud and clay have been used for fill behind part of Embarcadero seawall. Recent shell deposits and underlying clay and mud dredged from bay for manufacture of cement. Blended with better quality clay to make structural clay ceramic products. May be suitable for making foundry sand.	43–98 (older bay mud).	CL, CH.
Probably moderate.	Moderate to high shearing strength when confined.	Fair quality fill. Admixed with clay to make foundry sand. Small tonnages used as blending sand in concrete aggregate.	65–102 at surface; 110 compacted.	SP.
Probably moderate to high.	Moderate to high shearing strength. Used for pile and caisson support.	Good quality fill.	105–130.	Mostly SP; some is SC, SM.
High.	Shearing strength high in massive rock but decreases with increasing proportion of shearing and alteration. Thoroughly sheared and altered serpentine has low shearing strength. Veins of soft altered material in hard serpentine may present special problems.	Massive and moderately sheared serpentine widely used for fill; highly sheared and altered rock is unsuitable.	78 (sheared and altered) –158 (massive) (See table 8).	Some is CL, CH.

See footnotes at end of table, p. 99.

TABLE 11.—*Generalized description of*

Name and map symbol (pl. 1)	Lithology	Weathering, soil development, alteration	Permeability	Workability	Slope stability
Gabbro and diabase (gb).	Gray coarse- to fine-grained equigranular and diabasic igneous rock that occurs as segregations in serpentine.	Observed weathering depth is less than 3 ft. Moderately altered in places, mostly to prehnite. Weathered rock is speckled brown and orange and ranges from crumbly to moderately hard; generally nonswelling.	Low, except where fractured.	Generally requires heavy ripping or blasting except where altered.	Variable; high where fresh; moderate to low where altered.
Sandstone (KJss).	Gray tough nonporous fine- to coarse-grained thick-bedded sandstone and minor thin-bedded shale. Conglomerate beds rare. Pervasive nearly random fracturing to ½–2 in. blocks, but locally, blocks between major fractures are 1 ft or more in size.	Maximum depths of weathering observed, 60 ft; average 30 ft. Soils well developed locally, with 1–18-ft-thick B horizon of sandy clay. A and B horizons high in swelling clay minerals montmorillonite and vermiculite, but sand content keeps swelling low to moderate. Partly altered rock, C horizon, is brown or orange, friable, and nonswelling.	Generally low; moderate to high in fractured rock.	Altered rock excavated readily by ripping. Backhoe trenching is generally slow; highly altered rock trenched rapidly by backhoe. Fresh to moderately fresh rock generally excavated by heavy ripping; massive rock usually requires blasting.	Fresh or moderately fresh rock stable in vertical cuts. Blocks may fall from vertical faces in jointed sandstone. Moderately sheared and fractured sandstone stable in cut slopes of 55°. Badly altered, sheared, fractured sandstone tends to slump and slide, especially when wet.
Shale and thin-bedded sandstone (KJsh).	Dark-gray shale interbedded with dark-gray fine-grained sandstone. Beds generally 2–5 in. thick; paper-thin laminations locally common. Sheared rock is slaty or reduced to soft, friable, and mashed material enclosing hard nodules.	Maximum depth of weathering observed, 30 ft. Well-developed soils with thick clayey B horizon. A and B horizons of moderate to high swelling and (or) plasticity when wetted. Altered and sheared shale generally of high swelling and (or) plasticity when wetted.	Low, except where fractured.	Fresh rock excavated by moderate to heavy ripping; blasting required in some places. Support required for excavation walls and tunnels. Altered rock excavated by ripper, front-end loader, bulldozer, or equivalent.	Steep cut slopes tend to ravel, but are fairly stable for long periods except where extensively sheared, fractured, and altered. Sliding likely on bedding dipping in same direction as cut slope.
Radiolarian chert and shale (KJc).	Reddish-brown alternate beds of hard chert, 1–5 in. thick, and brittle friable shale as much as ½ in. thick. Includes thick irregular masses of unstratified chert with brecciated structure. Some altered chert is badly fractured and splintery.	Slight; cherts whiten from removal of iron and become more broken along joints; shale more broken than chert. Hydrothermal alteration to orange and white, but durable, rock; pronounced in some places, especially in fault zones, to white plastic clay of little or low swell when wetted.	Low, except where fractured.	Bedded chert generally excavated by moderate ripping. Massive chert may require blasting.	Generally stable in steep cuts, except for minor raveling. Sheared and hydrothermally altered zones may slide in steep cuts. Dip slopes should be cut at lower angle than dip of beds. Commonly chert lies on badly altered greenstone and may slide on slip surface developed in greenstone.
Greenstone (KJg).	Greenish-gray aphanitic to medium-grained volcanic rocks. Predominantly basalt flows, agglomerates, and tuffs. Pillow lavas, locally interbedded with radiolarian chert, are common. Most natural exposures are reddish-brown soft crumbly altered rock; hard tough unaltered rock limited to deep excavation. Some rock altered to soft clay that swells when wet.	Maximum depth of weathering observed, 40 ft. Soil well developed and reddish brown or grayish orange in color, containing iron-rich swelling clay, though swelling and plasticity low to moderate when wetted. Hydrothermal alteration common to clayey material containing halloysite and of low to moderate swelling and plasticity when wetted.	Low, except where fractured.	Altered greenstone can be excavated by light to moderate ripping. Fresh massive greenstone requires heavy ripping or blasting.	Fresh and moderately fresh rock stable in steep cuts, but lava pillows may fall out of weak matrix. Altered rock stable at 1:1 or gentler slopes depending on degree of alteration and fracturing and such local conditions as ground water and height of slope.
Metamorphic rocks (KJm).	Hard fine- to coarse-grained slate, schist, and granofels.	Only moderate to slight soil development observed in quadrangle. Partly altered rock on Angel Island contains much vermiculite.	Low, except where fractured.	Generally excavated by heavy ripping or blasting.	Steep cut slopes are stable. Dip slopes should be cut lower than angle of schistosity.
Sheared rocks, undifferenciated (Ks).	Hard rocks of the Franciscan Formation, as much as hundreds of feet in diameter, in a soft and crumbly matrix of sheared shale and serpentine.	Moderate to well-developed soil. Hydrothermal alteration common. Swelling and plasticity on wetting is moderate to high in shale and serpentine matrix as well as in soils and hydrothermally altered materials.	Low.	Soft material easily excavated by light to moderate ripping; large, hard inclusions generally require heavy ripping or blasting.	Generally low, especially when wet (matrix); stable in steep cuts where hard rock inclusions are large enough.

engineering properties of map units—Continued

Earthquake stability	Shearing strength; foundation conditions	Possible or reported use	Unit weight (pounds per cubic foot)[1]	Unified soil classification group symbol[2]
Generally high.	Generally moderate to high shearing strength.	Good quality fill. Possible limited source of concrete aggregate and large size riprap.	180–192 (fresh); 160 (altered).	
High.	Shearing strength is high except in badly shattered and altered rock.	Fresh rock suitable for good quality fill, road metal, riprap, concrete aggregate. Moderately altered rock suitable for fill. Highly altered rock has been used for impervious lining of reservoir.	128–144.	
High in fresh rock. Probably moderate in thoroughly sheared or altered rock.	Shearing strength high in fresh rock. Foundations on badly sheared, altered rock may require pile support.	Fresh rock and much moderately altered rock suitable for fill. Calcined, expanded shale is source of light-weight aggregate. Shale used to make common bricks. Possible use in manufacturing of cement.	127–142.	
High.	Generally moderate to high shearing strength, except where badly altered.	Widely and successfully used as fill and road metal. Suitability of chert for concrete aggregate questionable (Goldman and Klein, 1959).	166 (fresh); 151 (moderately altered); 110 (badly altered).	
High.	Shearing strength high in relatively fresh rock, low in altered clayrich rock.	Moderately altered greenstone with associated chert and shale, known locally as "redrock," is used as fill and road metal. Fills of badly altered greenstone are prone to sliding on moderate or steep slopes. Relatively fresh rock is possible source of concrete aggregate and riprap.	113 (thoroughly altered) to 185 (fresh).	
High.	High shearing strength except where parallel to cleavage or schistosity.	Good quality fill, road metal, large-size riprap, concrete aggregate.	169–195.	
Moderate.	Matrix has low to moderate shearing strength. Large rock fragments found in exploratory borings may give false impression of sound foundation conditions.	Used extensively for low quality fill. Hard rock inclusions used for good quality fill and large riprap.	78–110 (matrix); 125–170 (rock fragments).	Some is CL, CH.

[1]Pounds of dry material per cubic foot of original material.
[2]Classification used by U.S. Bureau of Reclamation (1953) and U.S. Army Corps of Engineers (1953).

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