Title
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Permalink
https://escholarship.org/uc/item/5rh9t1jj

Journal
San Francisco Estuary and Watershed Science, 7(1)

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Publication Date
2009

DOI
https://doi.org/10.15447/sfews.2009v7iss1art2

SEPTEMBER 2009

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Published by the California Bay-Delta Authority Science Program and the John Muir Institute of the Environment

Literature Review of Unconsolidated Sediment in San Francisco Bay and Nearby Pacific Ocean Coast

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ABSTRACT

A review of the geologic literature regarding sedimentation in the San Francisco Bay estuarine system shows that the main part of the bay occupies a structural tectonic depression that developed in Pleistocene time. Eastern parts, including San Pablo Bay and Suisun Bay, have had sedimentation throughout late Mesozoic and Tertiary. Carquinez Strait and the Golden Gate may represent antecedent stream erosion. Sedimentation has included estuarine, alluvial, and eolian deposition. The ages of estuarine deposition includes the modern high sea level stand and earlier Pleistocene interglacial periods. Sediment sources can be generally divided into the Coast Ranges, particularly the Franciscan Complex, and "Sierran." Much of the estuarine system is floored by very fine sediment, with local areas of sand floor. Near the Golden Gate, sediment size decreases in both directions away from the deep channel. Bedforms include sand waves (submarine dunes), flat beds, and rock and boulders. These are interpreted in terms of dominant transport directions. Near the Golden Gate is an ebb-tidal delta on the outside (including San Francisco Bar) and a flood-tidal delta on the inside (parts of Central Bay). The large tidal prism causes strong tidal currents, which in the upper part of the estuary are normally much stronger than river currents, except during large floods. Cultural influences have altered conditions, including hydraulic mining debris, blasting of rocks, dredging of navigation channels, filling of the bay, and commercial sand mining. Many of these have served to decrease the tidal prism, correspondingly decreasing the strength of tidal currents.

KEYWORDS

Tectonic depression, estuarine, alluvial, sources, grain size, bedforms, glacial, tidal

SUGGESTED CITATION

Keller BR. 2009. Literature review of unconsolidated sediment in San Francisco Bay and nearby Pacific Ocean Coast. San Francisco Estuary and Watershed Science [Internet]. Available from: http://repositories.cdlib.org/jmie/sfews/vol7/iss1/art2

INTRODUCTION

Unconsolidated sediment overlies metamorphic and sedimentary bedrock in and near the San Francisco Bay estuarine system, including central San Francisco Bay (Central Bay), the nearby Pacific Ocean coast (open coast), and offshore. While the term "sand" is often used to describe the unconsolidated sediment, it in fact varies in grain size from silt size or smaller to boulders. The sand and larger-sized sediment are of principal interest in this geologic literature review article, which resulted from studies of commercial sand resources. The purpose of this paper is to review the existing literature on the history of sedimentation within San Francisco Bay. As described in greater detail below, in the main north-south part of the bay this sedimentation is a geologically recent phenomenon, compared to the eastern part of the bay and the Central Valley.

Following a review of the geologic processes that have formed the physiographic depression presently occupied by the bay and a review of the depositional units within the depression, the unconsolidated sediment is interpreted in terms of possible sediment source areas, or provenance, which may be generally divided into: the local Coast Range geologic materials, the Franciscan Complex and younger rocks; and the geologic materials carried into the estuarine by the Sacramento River, comprehensively termed "Sierran." Data on grain size and bedforms within the estuarine system are reviewed, as are the changes of glacial and interglacial periods, the effects of tidal and fluvial influences, and the history of cultural influences. Some observations of the author regarding grain size and lithologic characteristics of commercial mined sand are included.

Place names that are mentioned in the text are shown in map view in Figure 1. For further information on geographic locations, a road map such as AAA California Regional Series "San Francisco Bay" may be useful. For geologic features, either the California Geologic Survey 1:250,000 scale Geologic Map of California (San Francisco – San Jose Quadrangle, Wagner and others 1990; Santa Rosa Quadrangle, Wagner and Bortugno 1982) or Plate 2 of Jachens and others (2002) may be useful. For bathymetric features, NOAA charts 18560 and 18649 may be useful, as well as the multibeam representations of Chin and others (2004) and Barnard and others (2006a, 2006b, 2007a). These sources should all be readily available, while much of the older literature may be difficult to locate.

In the main north-south part of the bay, the development of a structural trough and the deposition of sediment within it have occurred in Quaternary time. Quaternary time is divided into the Pleistocene, from 1,806,000 years before present to 11,500 years before present, and Holocene, from 11,500 years before present to the present (see http://geomaps.wr.usgs.gov/sfgeo/quaternary/stories/what_is.html). Slightly different values are often given for these time periods, with values such as two or three million years before present for the start of Pleistocene commonly cited. The abbreviations "Ma" for millions of years before present and "Ka" for thousands of years before present are commonly used.

Sedimentation in the eastern part of the bay and in the Central Valley has occurred for a much longer period of time, from Mesozoic time (approximately 248 Ma to 65 Ma, see http://geology.er.usgs.gov/paleo/glossary.shtml) through Tertiary time (65 Ma to the start of Pleistocene time). Tertiary time is divided into five subdivisions, of which Miocene (23.8 to 5.3 Ma) and Pliocene (5.3 to 1.8 Ma) are the most recent and are mentioned here. The older rocks underlying sediments in the north-south part of the bay, collectively known as "bedrock," are of Mesozoic and Tertiary age.

The very precise values of time cited above for Pleistocene and Holocene are based on measurements of radioactive decay of elements in igneous rocks (for the Pleistocene) or in fossils (probably used for the Holocene). In much of the literature on sedimentation in and near the bay, however, more general age terms are used, based on stratigraphic correlations or types of fossils. For the Pleistocene, commonly used terms are early (or lower), middle (or mid), and late (or upper) Pleistocene.

Metric units are used, except where the original source used English units, in which case the equivalent metric units is indicated as well.

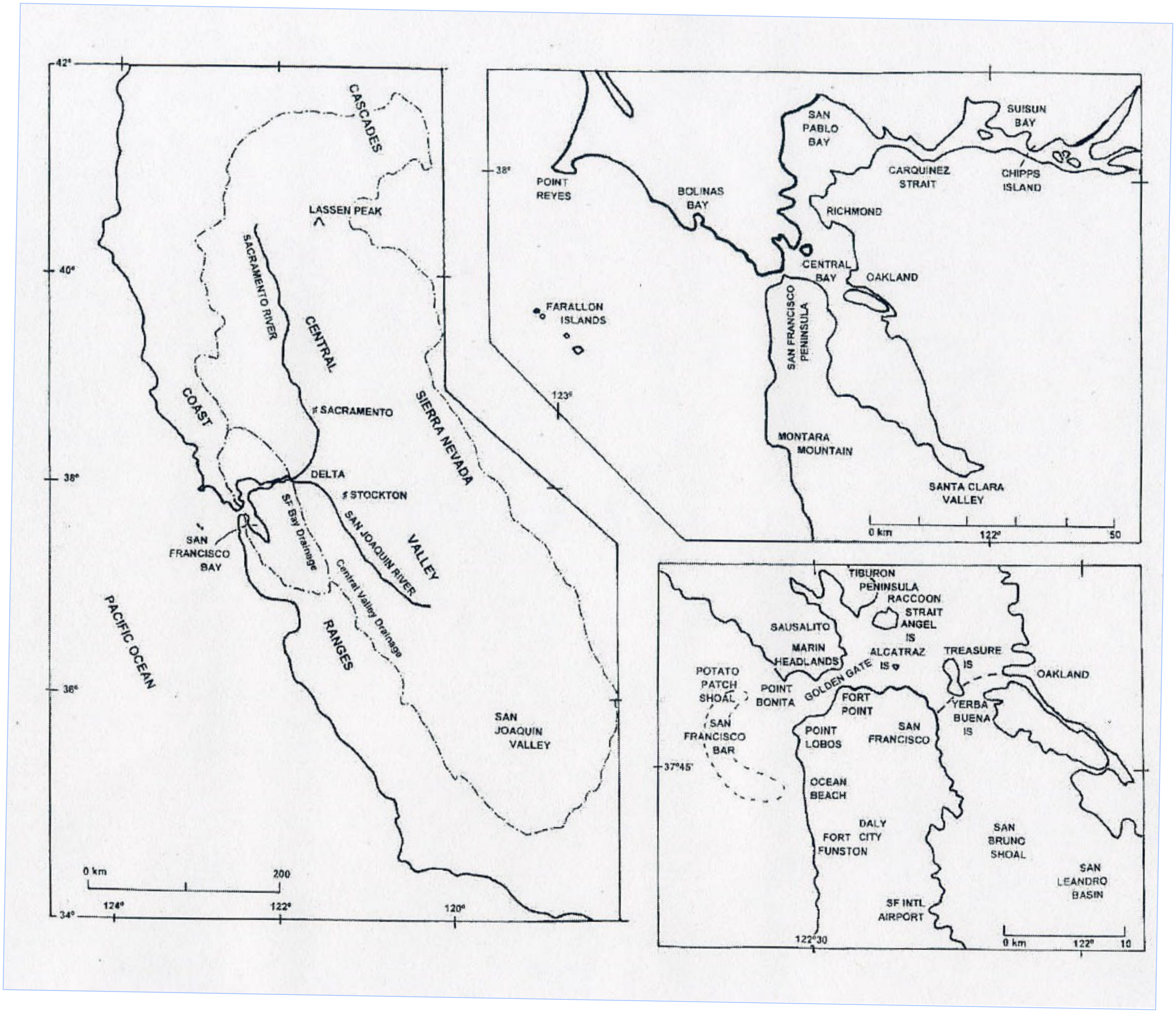

Figure 1 Map of locations mentioned in text. Left – large scale features, with drainage areas after Porterfield (1980). Upper right – San Francisco Bay estuarine system and nearby coastal area. Lower right – Central Bay and area offshore of Golden Gate. The dashed line near Oakland is bridge crossing where subsurface samples were collected..

MID PLEISTOCENE FORMATION OF THE PHYSIOGRAPHIC DEPRESSION

The San Francisco Bay estuary as a physiographic depression appears to have been formed mainly by tectonic motions, with some influence or erosion by running water. It is a geologically young feature, having existed only during Quaternary time (Pleistocene and Holocene) and having been both an on-land river valley, with alluvial sedimentary deposition, and a marine bay, with estuarine deposition, depending on changes in the elevation of sea level throughout its history.

Summarizing the interpretation of Louderback (1951), in Miocene and Pliocene time the present location of the ridges and depressions east of the main north-south part of the bay formed the west flank of a marine embayment that filled the present location of San Joaquin Valley, connected to the Pacific Ocean somewhere to the south. The location of the main part of the present bay was elevated above sea level, with drainage of its east side to the embayment on the east. In late Pliocene time the embayment became non-marine, and its western flank was uplifted and folded.

In late Pliocene to Pleistocene time, some marine sediments were deposited on the southwest and west side of what is now the San Francisco Peninsula, forming the Merced Formation (see geologic map of Figure 2), presumably connected to the ocean to the south or west. Hall (1966) interpreted a change in heavy minerals between the lower and upper member of the Merced Formation to indicate that the deposition of the upper member, in mid Pleistocene time, marked the inception of drainage from the Central Valley through the San Francisco Bay system. This stratigraphic horizon, and the location of the Rockland ash, are shown in the cross sections of Clifton and others (1998).

The formation of a canyon in the area of Carquinez Strait is ascribed by Louderback (1951) to “a remarkable west-trending downfold of the strata which has been recognized in the older rocks (Upper Cretaceous)” that was eroded as a canyon in mid or late Pleistocene time. The flow of the Sacramento River (combined Sacramento and San Joaquin rivers) through Carquinez Strait started about this time. Sarna-Wojcicki and others (1985) presented a more precise dating of the beginning of flow out of the Central Valley, based on the end of the prior existence of large inland lake that deposited a unit called the Corcoran Clay in the Central Valley, and was then overlain by volcanic deposits including the Rockland ash, which was transported by water through Carquinez Strait, giving a date of establishment of that external drainage of approximately 0.6 Ma. More recent dating of the Rockland ash (Lanphere and others 2004) indicates that its age is approximately 0.57 to 0.60 Ma, so the establishment of the drainage may be slightly younger than indicated by Sarna-Wojcicki and others (1985). This would correspond to mid to late Pleistocene time.

Louderback (1951) cites a mid Pleistocene “disturbance” as resulting in uplift of the bay area, with differential uplift producing a trough in the center, into which sediment was deposited. Thus, in this view, the area of low elevation is mainly a result of tectonic motions, not erosion. Taliaferro (1951) cited late middle or early upper Pliocene deposition of the Merced formation and volcanic rocks. However, Taliaferro (1951) indicated that the Merced formation basin was tectonically destroyed and that in late Pleistocene time the main part of San Francisco Bay (west and south of Carquinez Strait) experienced “down-warping” that has continued to recent times.

The 1951 papers cited in the previous paragraph, while providing a good review of stratigraphic units, were written before the understanding of strike-slip faulting and plate tectonics. There is an extensive more recent literature regarding Quaternary tectonic displacement, a review of which is beyond the scope of this article. However, a summary in Jachens and others (2002) indicates that the location of central and southern San Francisco Bay is within the San Francisco Bay tectonic block, which also includes the San Francisco Peninsula and Marin Headlands. As shown in Figure 2 and Figure 3, this block lies between the San Andreas Fault on the west and the Hayward Fault on the east, both part of the wider zone of plate transform motion called the San Andreas Fault system (Parsons and others 2002). No active fault is identified within the San Francisco Bay

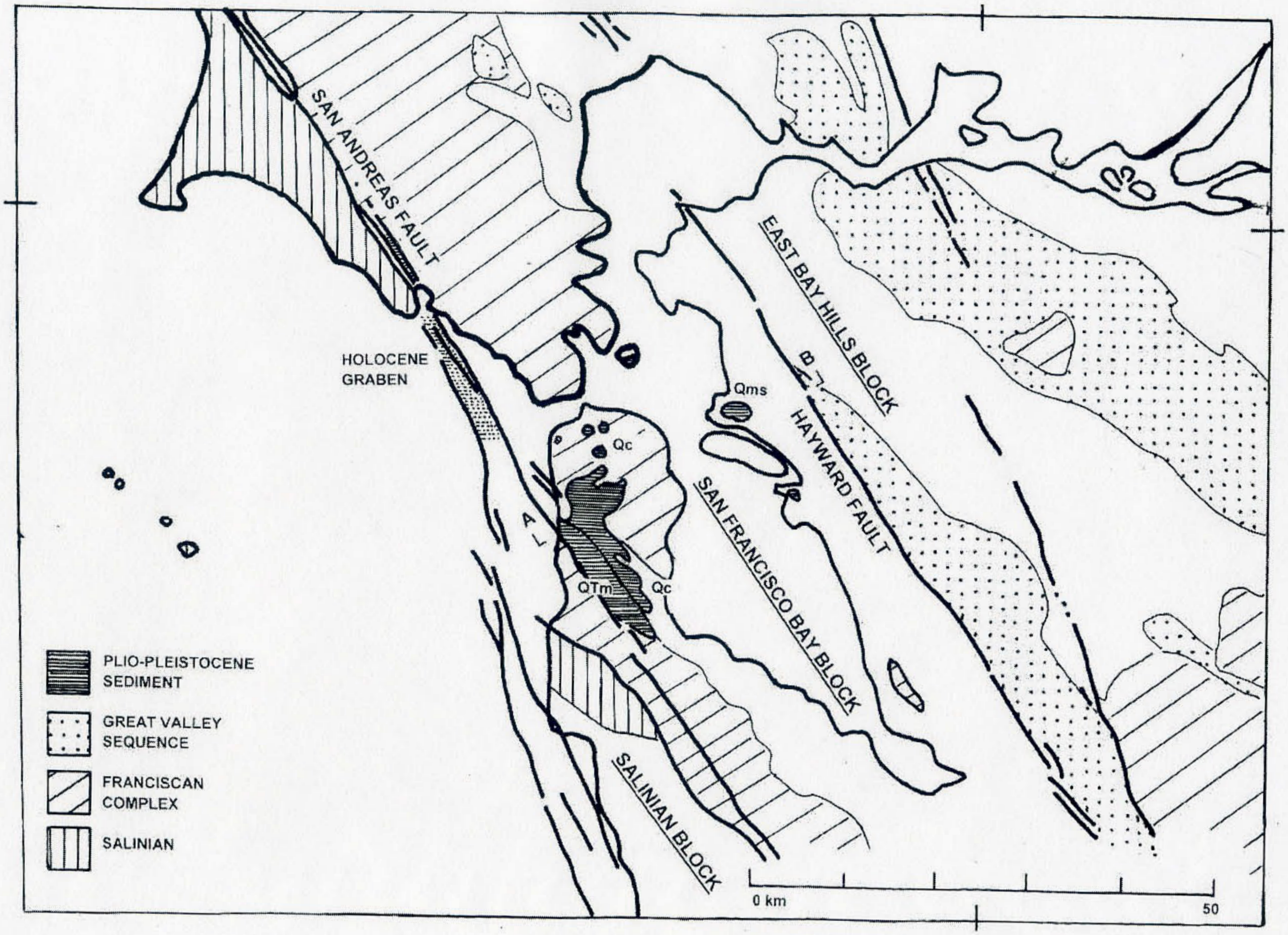

Figure 2 Geologic map, modified from Blake and others (1984) and Jachens (2002). The Plio-Peistocene sedimentary units are: QTm – Merced Formation of Wagner and others (1990); Qc – Colma Formation of Schlocker (1974), southern extension as shown by Atwater and others (1977); Qms – Merritt Sand of Graymer (2000). The letter A and B show the location of the ends of the cross section of Figure 3.

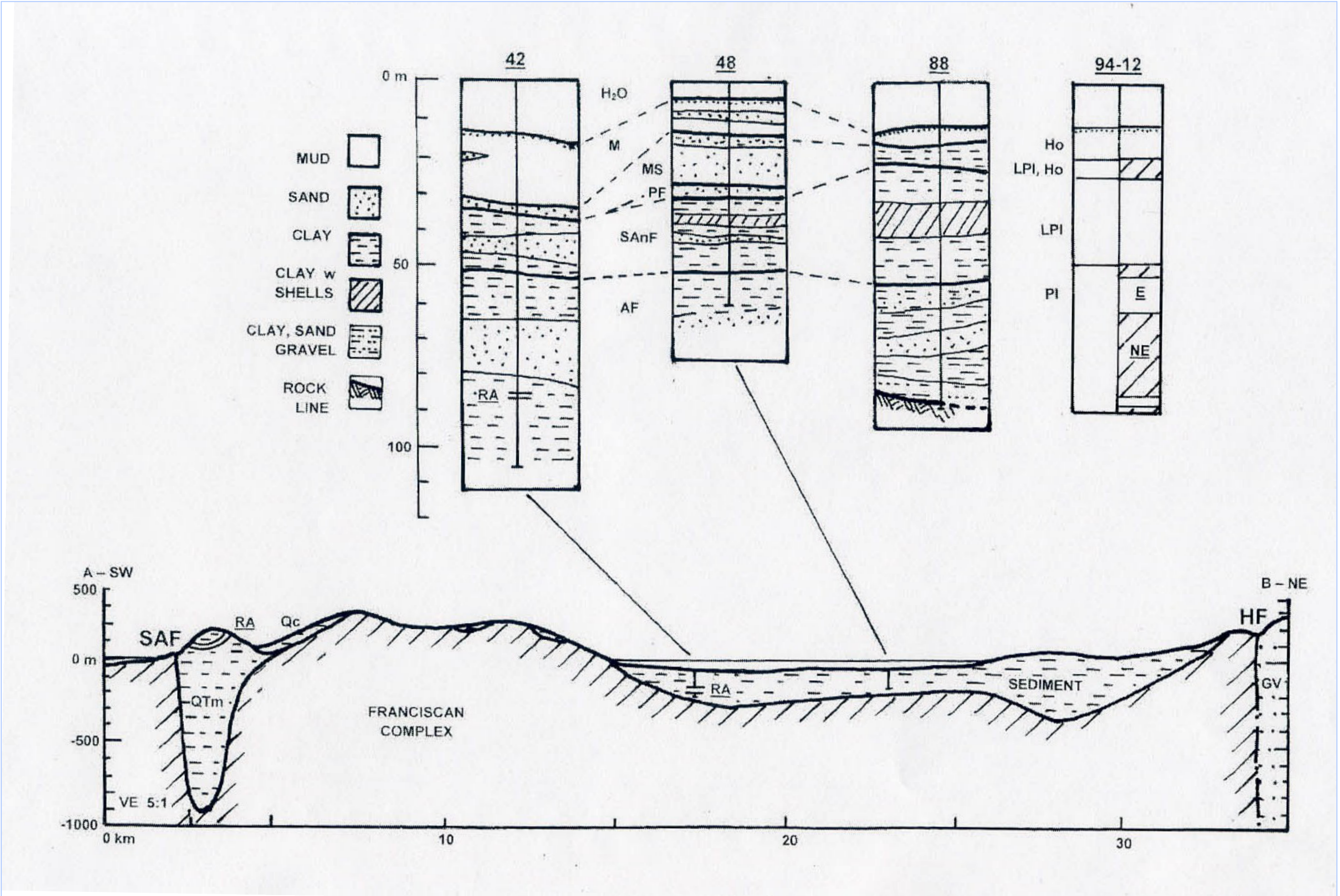

Figure 3 Cross section with borehole interpretations. In the cross section: SAF – San Andreas Fault; QTm – Merced Formation; RA – Rockland ash; Qc – Colma Formation; HF – Hayward Fault; GV – Great Valley Sequence. Boreholes 42, 48, and 88 are from Trask and Rolston (1951). Borehole 94-12 is from McGann and others (2002). Boreholes 42 and 48 are on this cross section ("southern crossing" of Trask and Rolston (1951), whereas boreholes 88 and 94-12 are very close to each other, north of this section, east of Yerba Buena Island (on bridge crossing – Figure 1). Trask and Rolston (1951) interpreted the boreholes with textural terms and formation names, whereas McGann and others (2002) used geologic ages and four cycles of estuarine (E) and nonestuarine (NE) conditions. The formations of Trask and Rolston are: M – Mud; MS – Merritt Sand; PF – Posey Formation; SAnF – San Antonio Formation; AF – Alameda Formation. The geologic periods of McGann and others (2002) are: Ho – Holocene; LPL, Ho – Latest Pleistocene and Holocene; LPI – Late Pleistocene; PI – Pleistocene.

block, so the topographic trough of the main part of the bay is apparently not an independent down-dropped area, but could possibly represent a down-to-the-east horizontal rotation of the block, which would correspond to Taliaferro's (1951) "downwarping" or Louderback's (1951) "tilting of great earth blocks."

Atwater and others (1977) documented at least 100 m of tectonic subsidence of Quaternary sediments in southern San Francisco Bay, but did not interpret this in terms of tilting of a block or relate it to fault motion. Schlocker (1974) interpreted Pleistocene marine Colma Formation deposits on land at elevations up to several hundred feet (over 500 ft, 150 m on Twin Peaks) to be the result of tectonic uplift, in addition to possible high sea level stands. Thus, the total eastward tilt of the block (as suggested by Louderback [1951]) at the latitude of San Francisco, if it is such, is a few hundred meters, a very small fraction of the horizontal fault motion. These spatial relations are shown schematically in Figure 3.

This configuration of the main part of the bay as a shallow structural depression is in marked contrast to the configuration of San Pablo Bay, which is a significant structural depression, with 2+ km of Tertiary and Quaternary fill east of the Hayward Fault (Wright and Smith 1992; Jachens and others 2002). San Pablo Bay and Suisun Bay are separated by Carquinez Strait, where the channel is eroded into Mesozoic bedrock (Jachens and others 2002), also called the Great Valley Sequence (Blake and others 1984), including both Mesozoic and early Tertiary sedimentary rocks.

SEDIMENTATION IN THE BAY

As reviewed above, the geologic evidence indicates that the main north-south trending part of San Francisco Bay became a structural depression where sediment could be deposited in mid to late Pleistocene time, or approximately one million years ago. During and since that time, sea level has experienced a number of eustatic (world-wide) changes, due to water being incorporated in glaciers during low sea level stands, or melted into sea water during high stands. These fluctuations in sea level have been greater than 100 m of vertical change, with the present being a high stand. A structural depression, such as the bay, that has less than the approximately 100 m of vertical relief, would be an on-land valley during low sea level stands, and a marine embayment during high sea level stands.

Beneath the part of the floor of San Francisco Bay between the San Francisco Peninsula on the west and Oakland and other cities on the east, very detailed information on sedimentary deposits is available locally from cores collected during construction of the bridges that cross it (Trask and Rolston 1951; Goldman 1967, 1969; Atwater and others 1977; McGann and others 2002), whereas elsewhere there is much less information.

In terms of Quaternary sediment in the main bay trough, at various locations mid-Pleistocene mammal fossils, including bison, mammoths, and horses are found in alluvial deposits, both above and below present sea level (Louderback 1951). The source of the sediment in which the fossils are found is interpreted to be erosion of the bordering hills and reworking of the alluvial deposits themselves, so these represent eras of the depression as an on-land valley.

On land near Oakland and beneath the bay between Oakland and San Francisco a series of sedimentary units is recognized, but the nomenclature has been inconsistent. Those under the bay were described on the basis of borings for the original Bay Bridge, called the "parallel crossing," and for an alternate proposed route called the "southern crossing" (Trask and Rolston 1951). These authors used formation names from nearby on-land deposits; from oldest to youngest, the Alameda Formation, San Antonio Formation, Posey Formation, Merritt sand (or Formation), and mud (commonly also called Bay Mud). The more recent studies (Atwater and others 1977; McGann and others 2002) use descriptive terms (estuarine, alluvial, eolian) for the sedimentary units, with correlation to the previously used formation names (see Figure 3). Goldman (1969) included a table comparing the earlier formation names with descriptive terms used in then "recent studies" by the Army Corps of Engineers. The geologic map of the Oakland area of Graymer (2000) has only the Merritt sand as a surficial unit, while cross sections shown in Rogers (1997) show the San Antonio Formation as a surficial as well as subsurface unit and Alameda Formation only in the subsurface. Atwater and others (1977) indicated that some of the units that had been interpreted by Trask and Rolston (1951) as being alluvial (on-land deposits) were actually estuarine (marine deposits) but had been desiccated, giving the appearance of being alluvial. Atwater and others (1977) also presented borehole data for the Dumbarton and San Mateo bridges.

A study of microfossils from essentially the same location as the "parallel crossing" (Bay Bridge) of Trask and Rolston (1951) was presented in McGann and others (2002), based on samples from the construction of the retrofitted Bay Bridge. McGann and others (2000) did not use formation names, but presented stratigraphic columns for individual cores with microfossils and biofacies that were labeled with the time units Pleistocene, late Pleistocene, latest Pleistocene, latest Pleistocene and Holocene, and Holocene and indicated to represent the paleo-environments estuarine, non estuarine, and alluvial or estuarine. In the deepest cores there were four separate estuarine units, separated by non-estuarine units.

The Alameda Formation, as described by Trask and Rolston (1951), is sand, sandy clay, and fine gravel of alluvial and estuarine deposits. It contains a volcanic ash layer similar to one in the Merced Formation on the southwest side of the San Francisco Peninsula, which was interpreted by Louderback (1951) to indicate coeval deposition of the two units (see Figure 3). The ash was found in bore hole 42, near the west end of the "southern crossing" of Trask and Rolston (1951), at a depth of 280 ft (85 m, see Figure 3). What was apparently the same ash layer ("tuff"), although labeled "borehole 2," was indicated by Atwater and others (1977) to have a probable age of 1 Ma (early Pleistocene). However, Sarna-Wojcicki (1976, 1985) identified the ash, in these and other locations, as the Rockland ash. As noted above, the most recent dating of this widespread ash, which was erupted near Lassen Peak in the southern Cascades, is 0.57 to 0.60 Ma (Lanphere and others 2004). The upper surface of the Alameda Formation was eroded subaerially, with the main course of streams from the southern bay area lying east of Yerba Buena Island.

On land (as indicated by Trask and Rolston [1951], but not shown on the geologic map of Graymer [2000]) the estuarine San Antonio Formation overlies the Alameda Formation and underlies the Merritt sand, whereas under the bay the alluvial and eolian Posey Formation lies between the San Antonio Formation and the alluvial and eolian Merritt sand, with unconformities separating the various units. The San Antonio and Posey formations are sand and clay. The San Antonio Formation correlates with late Pleistocene estuarine deposits of Atwater and others (1977) and McGann and others (2002), which are interpreted to have been deposited in the latest (prior to the present) interglacial stage, the Sangamon (indicated by McGann and others [2002], as substage 5e, ~ 125 – 120 ka). After deposition of the Posey Formation, the area near the Bay Bridge was again eroded subaerially, this time with the main course of streams from the southern bay area lying west of Yerba Buena Island.

The Merritt sand, composed of well sorted sand and silt, was deposited over the eroded San Antonio and Posey formations, then was in turn eroded subaerially, again with the main course of streams from the southern bay area lying west of Yerba Buena Island. The Bay mud was deposited above the Merritt sand, in the marine condition of the present sea level. On the bay shore of San Francisco, Schlocker (1974) identified Colma Formation in the subsurface beneath the Ferry Building as being the age equivalent of the Merritt sand, with its base at a depth of 143 ft (44 m), with older sediment below to the depth of Franciscan Complex bedrock at 270 ft (82 m) below sea level. This location is close to the west end of the "parallel crossing" (Bay Bridge) of Trask and Rolston (1951), in which a combined unit of "Merritt sand, Posey, and San Antonio Formations" is shown as overlying the Alameda Formation and underlying Bay mud.

As noted, elsewhere than the bridge crossings, there is much less direct information about subsurface sediments. Rogers (1997) presented a map based on wells that shows the depth to bedrock of the

Franciscan Complex as approximately 500 ft (150 m) near Oakland and beneath the eastern Bay Bridge span, but greater than 1100 ft (335 m) farther south. Hart and others (2002) presented a seismic reflection profile a few kilometers farther south, in San Leandro Basin, with approximately 1 km of sedimentary deposits. Jachens and others (2002) indicated that a sediment depth of approximately 1 km is also present within the San Francisco Bay block in the Merced Formation along the San Andreas Fault and in a fault sliver north of San Pablo Bay. Both of the latter two locations are along the margins of the block. The site of the deep Merced Formation is interpreted as a pull-apart basin between two fault strands. In contrast, the San Leandro Basin is within the block.

Goldman (1969) presented cross sections for two locations near Richmond and two south of the Bay Bridge, in addition to that of the Bay Bridge. The Richmond and Bay Bridge cross sections were labeled as Older Bay Mud and Younger Bay Mud, rather than the formation names of Trask and Rolston (1951). The maximum thickness of sediment overlying Franciscan Complex bedrock in the Richmond cross sections was approximately 200 ft (60 m). The sections south of the Bay Bridge were labeled with textural terms and the greatest total thickness of sediment was not shown, apparently deeper than 200 ft (60 m).

In the northern part of Central Bay, the channel of the Sacramento River is interpreted to have passed through Raccoon Strait, north of Angel Island, rather than down the main valley east of Angel Island (Trask 1956). Carlson and McCulloch (1970) show depth to bedrock in Central Bay based on seismic reflection profiles, with the channel of Raccoon Strait having slightly deeper bedrock than areas south of Angel Island. The greatest depths of bedrock in Raccoon Strait are more than 300 ft (~ 90 m), but these are closed depressions, with a sill shallower than 200 ft (~ 60 m) between them, so this shallower sill depth may have been the depth of the river channel. The bedrock depths were calculated using the sound velocity in water for the sedimentary fill, which would underestimate the actual depth (the velocity of sound in water is 1.5 m sec^{-1}). The underestimation would be most pronounced in the areas of thickest sediment.

The greatest depths to bedrock in the area of Central Bay and the Golden Gate are greater than 400 ft (120 m). There are three areas with this depth and all are closed depressions, so they may be tectonic rather than erosional features. The bedrock depths of Carlson and McCulloch (1970) were combined with bathymetric depths to produce a sediment thickness map (Chin and others 2004). The greatest thickness is over 90 m, again slightly underestimated due to the seismic velocity. The areas of greatest sediment thickness correspond to the deepest closed depressions of the bedrock depths. These sediments have not been characterized as to formations or depositional environments. There are five areas of no sediment, having instead exposed bedrock on the bay floor, Anita Rock, Harding Rock, Shag Rock, Arch Rock, and Blossom Rock. All except Anita Rock have been deepened by blasting to decrease hazards to navigation (Chin and others 2004).

The original reflection profiles used by Carlson and McCulloch (1970) are no longer available (J. Chin, personal communication). However an example of a reflection profile on Point Knox Shoal is shown in ADEC (2000) and several profiles near the above mentioned rocks are shown in SeaSurveyor (2002). These show some apparent unconformities within the Central Bay sediment, where identifiable beds pinch out, but otherwise do not show many clearly identifiable reflectors such as would be seen the bedded marine sedimentary rocks typical of petroleum exploration reflection profiles.

The source of the sediment in the units near the Bay Bridge is not extensively discussed in the works cited. The alluvial deposits would have been deposited during low sea level stands, so are presumably derived from erosion of local uplands, including areas now below sea level, in the southern bay area. Eolian deposits could have had a local source, or have been derived from the Pacific coast (Atwater and others 1977), similar to the modern eolian deposits that covered the San Francisco Peninsula prior to cultural development (Schlocker 1974). The estuarine deposits, particularly the fine grained clays derived from suspended sediment, could have had a mixture of sources. However it is clear that there have been repeated cycles of the configuration of the bay as a river canyon and a body of marine water, with the present time representing the latest interglacial high sea level stand. During low sea level stands, the previously deposited units have been eroded, so they are in themselves a sediment source for later units.

Louderback (1951) interpreted the present bathymetrically deepest part of the strait of the Golden Gate, 381 ft (116 m) to be the bottom of the channel of the Sacramento River during glacial low sea level stands. Atwater and others (1977) interpreted the lowest channel elevation to be somewhat higher, 70 m below present sea level, on the basis of the depth of bedrock shown by seismic reflection data of Carlson and McCulloch (1970). Atwater and others (1977) cite bedrock sills located about 5 km east and northeast of the Golden Gate, whereas Carlson and McCulloch (1970) also show shallower bedrock to the west, with depth 250 – 300 ft (75 – 90 m), between Mile Rock and Point Bonita, which could be interpreted as the greatest depth of the paleo river channel.

The geologic reason why an east-west canyon should exist at Golden Gate, between the high ridges of the San Francisco Peninsula and Marin Headlands, is not completely clear. In apparent accordance with Louderback's (1951) interpretation that the main topographic depression of the bay is due to tectonics and not to erosion, Schlocker (1974) suggested that a major fault might exist in the Golden Gate channel, because the rock types and structural trends within the Franciscan formation on the north and south sides are quite different, but stated that supporting evidence for a fault was limited. The rock types are predominantly chert and basalt on the north, as compared with abundant serpentinite on the south. If the canyon is not caused by some structural mechanism, it appears similar to the type of canyon cut by an antecedent stream, which would mean that the Sacramento River already flowed through this location prior to uplift of the ridges and was able to erode downward fast enough to maintain the location. The antecedent stream interpretation is presented for the Golden Gate canyon by Louderback (1951), who also interprets a similar development of Carquinez canyon (now Strait). In the latter case, as noted above, the location of the canyon is attributed to structural control.

As discussed further below, the maximum depth of the Golden Gate channel is approximately the elevation of the low sea level stand at the last glacial maximum (LGM, this elevation had not been accurately quantified when Louderback wrote his 1951 paper), at approximately 17 Ka. This elevation (bathymetric depth) on the present continental shelf is located west of the Farallon Islands, so there must have been a channel leading westward from the Golden Gate. As noted by Howard (1951), the location of this channel, and the possibility that the river once discharged south of Santa Clara Valley rather than through the Golden Gate, is a matter of speculation. Trask (1956) shows a map with the channel heading directly west, passing south of the Farallon Islands, but this must be regarded as speculation. This speculative situation persists today, in spite of the existence of high resolution marine seismic reflection data (Bruns and others 2002; Barnard and others 2007a). One feature that is resolved in the reflection data is a 50 – 100 m deep graben in the northern half of the offshore San Andreas Fault zone, so the river channel could possibly have occupied the graben.

The question of the paleo river channel off the Golden Gate may be pertinent to sediment transport in San Francisco Bay, because the channel is presumably filled and covered with sediment that may have been transported through the location of the bay. Therefore, the configuration of the offshore paleo channel may have impacted the degree to which sediment was either stored or passed through within the bay.

The presumed location of the paleo river channel includes an arcuate bathymetric feature called the San Francisco bar ("Bar" is often capitalized, e.g. Battalio and Trivedi [1996]; ADEC [2000], whereas Gilbert [1917] used the term "Golden Gate bar," Moore [1965] used the term "Bay Bar," Barnard and others [2007a] used the term "ebb-tidal delta," and NOAA chart 18649, "Entrance To San Francisco Bay," labels the northern part "Fourfathom Bank"), which covers the southern part of the graben, and a field of underwater dunes (called "giant sand waves" by Barnard [2006a, 2006b]) between the deepest part of the Golden Gate and the San Francisco Bar.

As a result of this very young sediment cover (the sediment has not been dated, but was interpreted as “Holocene” in Bruns and others [2002], and as “recent,” presumably meaning the same as Holocene, in Barnard and others [2007a]), no geomorphic expression exists of the San Andreas Fault zone in this area, which is in distinct contrast to most of the rest of the fault zone.

SEDIMENT SOURCES

As noted above, possible sediment source areas, or provenance, of the unconsolidated sediment in the San Francisco Bay estuarine system may be geographically divided into: the local Coast Range geologic materials, the Franciscan Complex and younger volcanic and sedimentary rocks; and the geologic materials carried into the estuary by the Sacramento River, comprehensively termed “Sierran.” Geologic materials that are similar to the Sierran source area, including Mesozoic intrusive rocks and metamorphic roof pendants, are also located west of the San Andreas Fault system, in the Salinian Block. In the study area, this block is presently all submarine, but to the north and south, at Point Reyes and Montara Mountain, respectively, Mesozoic intrusive rock is exposed on the coast and is a source of local beach sediment. To the west, the Farallon Islands are Mesozoic intrusive rock. At lower sea level stands, there may have been subaerial erosion of Salinian Block basement rock west of the study area.

Sediment from both Franciscan and Sierran source areas are transported into the bay area at present, and this was also the case during the later part of the Pleistocene, when some relict or paleo deposits were laid down, especially in the offshore area.

Franciscan Source Types

At a macroscopic level, sediment derived from the Franciscan Complex is characterized by distinctive lithologic types, including notably chert and serpentine. Louderback (1951) described rock fragments dredged from the deepest part of Golden Gate in 1912-1913 as gabbro, Franciscan sandstone, chert and serpentine, interpreted to have been derived from the immediate vicinity of Golden Gate. Wahrhaftig (1984) noted that the Franciscan Complex in Marin Headlands is practically devoid of serpentine, except for one small outcrop near Point Bonita, so the serpentine in the dredged sediment of the Golden Gate, also found in Central Bay mined sand, is apparently derived from the south side of the Golden Gate, where it outcrops widely.

As observed in the drainages that discharge directly to the estuary, the main area of present day erosion and transport of pebble size and larger Franciscan Complex material is at the Golden Gate itself. Additionally, some material may occasionally come from erosional events from Angel Island and Tiburon Peninsula. Although similar material exists in various locations upstream in the Coast Ranges drainage area of the estuary, the rivers and creeks that discharge to the estuary have very flat gradients and do not presently appear to transport coarse material such as found near Golden Gate.

Gilbert (1917) noted the presence of chert in the sand of the San Francisco Bar. Moore (1965) interpreted the sediment of the ocean floor from the Golden Gate to the San Francisco Bar (ebb-tidal delta), including the beaches of the San Francisco Peninsula and Marin Headlands, to be of sediment originating in the “Franciscan Province” on the basis of its content of the heavy minerals karinthine (similar to hornblende and glaucophane), epidote, glaucophane and actinolite. Similarly, Hall (1966) interpreted a hornblende, epidote, and tremolite-actinolite as being of Franciscan origin in the lower Merced Formation. Yancey and Lee (1972) identified a similar Franciscan heavy mineral assemblage of glaucophane and jadeite in southern San Francisco Bay. However, they also identified a hornblende-augite-hypersthene sediment assemblage derived from mixing of sediments from volcanic, metamorphic, and sedimentary rocks of the Central Valley that is widespread within the San Francisco Bay system and on the continental shelf to the west. The latter assemblage may be considered as “Sierran” (see below).

On both the north and south sides of the Golden Gate (Marin Headlands and the Point Lobos to Fort Point part of the San Francisco Peninsula, respectively) are slow moving landslides that are presently active. These contribute detritus directly to the beaches and may continue below sea level. Schlocker (1974) shows twelve landslides between Point Lobos and Fort Point, several of which involve serpentine. On Marin Headlands the material in the landslides is mainly chert and metabasalt. There are no known quantitative measurements of the rates of movement of these landslides, but they may be visually estimated to be on the order of tens of cubic meters per year. Sloan (2006) observed that “Many feet of rock may tumble into the sea during a single heavy winter storm” at Marin Headlands. This anecdotal account was not described in more detail, but presumably represents cliff erosion.

There are two Quaternary sedimentary formations, the Merced Formation (mixed with Sierran material near the top) and the Colma Formation (mixed with Sierran material), which are composed mainly of fine sand and are exposed above sea level in the study area. The older of these is the Merced Formation which is exposed at the south end of Ocean Beach (Schlocker 1974) and is interpreted to underlie the ocean floor offshore of the entire study area (Bruns and others 2002). The Merced Formation is folded along the San Andreas Fault south of Ocean Beach and is locally overlain by flat-lying Colma Formation (see Figure 3). These units form high cliffs that are actively eroding directly onto the beach. One landslide in 2003 deposited approximately 500,000 cubic yards of material into the ocean (Sloan 2006).

The area of very active cliff erosion is south of Ocean Beach, at Fort Funston and Daly City. In this area, longshore transport is generally to the south (Kamel 1962; Moore 1965; Barnard 2005) and thus it does not appear at present that sediment is transported from the eroding cliffs to the area of north Ocean Beach to Central Bay (south Ocean Beach is the site of active coastal erosion, Barnard and others 2007a). However, Schlocker (1974) interpreted the modern Ocean Beach sand to be derived from the Merced Formation and Colma Formation on the basis of hornblende and pyroxene grains, that are not typical of Franciscan Complex sandstone. The pyroxene grains are etched like those of the Merced Formation. Following the description of Hall (1966), the non-Franciscan hornblende and pyroxene grains would be Sierran. This suggests that either longshore transport patterns were different in the past, or that the Ocean Beach sand is at least in part derived from the offshore part of the Merced Formation.

The Colma Formation is younger than the Merced Formation and, as defined and mapped by Schlocker (1974), is nearly horizontal, with similar, time equivalent, dipping beds mapped as “slope debris and ravine fill.” Schlocker (1974) interprets its main source to be the Merced Formation, with possibly some input from the ancestral Sacramento River (i.e., Sierran). It is exposed locally on the San Francisco Peninsula landward of Ocean Beach, near Point Lobos (also called Lands End, at the north end of Ocean Beach) and at the Presidio, in the subsurface in the northeast Peninsula, and on Angel Island (see Figure 2). Most of the Colma deposits on the Peninsula do not appear to be actively eroding, although the deposit at the Presidio may have been eroding prior to construction and landscape planting there (prior to approximately 1900). Beds of the “slope debris and ravine fill” are eroding by rainfall erosion and minor block slumping at the north end of Baker Beach. On Angel Island there appears to be cliff erosion of the Colma Formation, and Schlocker (1974) showed local landslides there. This is a source of sand at beaches on the southwest and southeast part of the island, and may contribute to the sediment on the nearby bay floor. No quantitative erosion rates are known.

Much of the San Francisco Peninsula was covered by sand dunes prior to urbanization, derived mainly by eolian transport from Ocean Beach. Presently, at Ocean Beach this type of sand is removed from nearby streets and redeposited on the beach, especially in the area of active erosion.

Schlocker (1974) mentions black sands at Ocean Beach, and his Plate 2, Table F “Composition of Sand Grains” shows the presence of magnetite in all samples with grains larger than +200 mesh (one beach sample was finer) from the Colma Formation, Ocean Beach, and dunes. These black sands may be seen on south Ocean Beach in the area of active coastal erosion.

Sierran Source Types

Sediment entering the upper part of the San Francisco Bay estuary from the Delta, at Suisun Bay, may be derived from all parts of the Central Valley, Sierra Nevada, and other mountains drained by the Sacramento and San Joaquin rivers. However, the dominant source area is the Sierra Nevada, composed mainly of Mesozoic intrusive rocks, with older roof pendants and younger volcanic rocks.

As a macroscopic characteristic, sand that is carried into the upper part of the San Francisco Bay estuarine system by the Sacramento River has a notable mica content. Mica is a mineral with a thin, platy form, so that is it easily suspended and transported. The input of sediment into the upper part of the estuary during Holocene time is described in Goman and Wells (2000), who noted the presence of mica in a silty-sandy lamina in the upper part of a core whose basal age is dated at 6310 years, so mica transport by the Scaramento River is apparently a long-lived characteristic. Some mica was noted by ADEC (2000) in the descriptions of cores from Point Knox Shoal, Presidio Shoal, and the San Francisco Bar, possibly indicative of Sierran input. Mica is found locally in some Central Bay mined samples, particularly from Presidio Shoal, but not in all. It is not found in most Point Knox Shoal samples. It is found in all Suisun Bay mined sand samples.

Heavy and/or dark minerals have been used to distinguish Sierran from Coast Range sediment sources. As noted above, Yancey and Lee (1972) identified a hornblende-augite-hypersthene assemblage derived from mixing of sediments from volcanic, metamorphic, and sedimentary rocks of the Central Valley, i.e., Sierran. Similarly (and also noted above), Hall (1966) interpreted a hornblende, hyspersthene, and augite suite in the Merced Formation as Sierran, derived from Miocene andesites in the Sierra Nevada and Cascades.

A great deal of study has been devoted to measuring suspended load transport into and through the Suisun Bay area (e.g., Buchanan and Lionberger 2007), with recent estimates in the order of 1.2 million metric tons per year (McKee and others 2006, measurement methods discussed in Ganju and Schoellhamer 2006), reduced from earlier estimates of 4 million metric tons per year (Shvidchenko and others 2004). However, most of this is high in the water column, and is presumably silt-sized material. Porterfield (1980) estimated bedload transport of approximately 44,000 tons per year in the Sacramento River at Sacramento, so this may be considered as an approximate value for sand inflow to Suisun Bay.

A volumetrically significant quantity of Sierran sediment, mainly fine grained, entered the San Francisco Bay estuary in the late 1800s as a result of hydraulic gold mining. This was initially deposited in the upper part of the estuary, Suisun Bay and San Pablo Bay, and has been eroding more recently, possibly being redeposited in lower parts of the estuary as well as transported to the ocean as suspended sediment (Jaffe and others 1998; Cappiella and others 1999). In Central Bay, Fregoso and others (2008) show mainly erosion in the period 1855 – 1895, deposition (accretion) in the period 1895 – 1947, and erosion in the period 1947 – 1979, with some variation between smaller sub-regions.

Sediments on the sea floor that appear to have been deposited in an earlier transport regime than the present, but have not been accurately dated, may be termed “paleo deposits.” Moore (1965) concluded that sediments in the area offshore of the San Francisco Bar (ebb-tidal delta), in water deeper than 90 to 120 ft (30 to 40 m), are paleo deposits, but that the area closer to Golden Gate has sediments that are deposited by present day processes and have the same mineralogy as in Central Bay. Similarly, Cherry (1966) concluded, for the area north of Bolinas Bay, that sediments in water deeper than approximately 90 ft (30 m) are paleo deposits, but material closer to shore is eroded from the local coast.

GLACIAL AND INTERGLACIAL PERIODS

As noted above, estuarine conditions existed in San Francisco Bay during the Sangamon interglacial stage (Atwater and others 1977; McGann and others 2002) at 120 – 125 Ka, as well as at present (Holocene).

Atwater and others (1977) presented a chart of these and earlier glacial and interglacial intervals extending back to 1 Ma (early to mid Pleistocene), and indicates the deposition of terrestrial and estuarine deposits during the earlier period, but without correlating these estuarine deposits to specific earlier interglacial periods. However, Atwater and others (1997) used a date of 1 Ma for the Rockland ash, which is now dated as 0.57 – 0.6 Ma (Lanphere and others 2004), so the sequence of glaciations may have covered a smaller time span than indicated. Clifton and others (1998) interpreted changes of depositional environment within the Merced Formation as representing Pleistocene eustatic sea level changes.

Since the last glacial maximum (LGM, Wisconsin glaciation) at 17 to 18 Ka, sea level has risen from approximately 120 m below the present sea level. This has been documented in a number of locations, notably in the Barbados Islands using corals (Fairbanks 1989; Peltier and Fairbanks 2006). As noted in Edwards (2006), there are slight variations in the record of sea level rise between different locations that may be associated with variations in land elevation rather than simply sea level. However, the Barbados record is adequately descriptive of conditions that prevailed in the world oceans in general, and may be used for the San Francisco Bay area, showing that sea level rose fairly continuously from 18 Ka to 7 Ka, when it reached approximately the present level.

As noted above, the term Holocene refers to the time since 11.5 Ka. The 11.5 Ka date is actually the end of a thousand year cold spell called the Younger Dryas that occurred during the general post-LGM warming. The Younger Dryas record is very pronounced in temperature records of ice cores and deep sea sediment cores (e.g., Oldfield 2005), but not very notable in the sea level rise record. As noted by Malamud-Roam and others (2007), during Holocene time temperature in the local area and bay water has varied, with a cool period at about 3.5 Ka corresponding to low salinity in the estuary water and increased sediment load from the Sacramento River.

TIDAL AND FLUVIAL INFLUENCES

Water elevation changes due to ocean tides in the San Francisco Bay estuarine system extend inland as far as Sacramento and Stockton. Because the area affected is so large, a large volume of water, called the "tidal prism," moves in and out of the Golden Gate during the diurnal tidal cycles. This volume has decreased in historic time due to filing and diking of the bay (and was presumably decreasing naturally due to deposition prior to historic time, albeit more slowly). Gilbert (1917) cited a tidal prism of 1.63 x 10^9 m^3, Conomos (1979) cited a 1931 value of 1.59 x 10^9 m^3, and a presumably current value from US Army Corps of Engineers (USACE or ACOE) is 1.48 x 10^9 m^3. Barnard and others (2007a) cite a present value of 2 x 10^9 m^3, but it is not clear why this value is larger than the others. In any case, the historic reduction of the tidal prism has correspondingly reduced the maximum current velocities, which for present conditions are cited by Barnard and others (2007a) as having a maximum of more than 2.5 m sec^{-1} (5.6 mi hr^{-1}) at the Golden Gate.

The tidal currents are strong enough to transport sediment as bed load, as well as suspended load. There are areas of ebb tide dominated transport and flood tide dominated transport (Rubin and McCulloch 1979, 1980), with a flood tide dominated area in much of Central Bay, interpreted to be a flood tidal delta. Sediment as coarse as pebbles larger than 5 cm is apparently transported as bed load by flood tide dominated tidal currents to Point Knox Shoal.

Within the estuarine system, the vertical tidal range, and therefore the volume of water that moves during tidal cycles, varies. In the south bay, the tidal range is larger than at Golden Gate due to a forced oscillation caused by the basin shape. In the Sacramento and San Joaquin rivers, the tidal range is smaller than at Golden Gate.

Where the river flows enter the estuarine system, at the east end of Suisun Bay, tidal flows are normally much larger than river flows. As shown in the California Department of Water Resources Delta Atlas (see http://baydeltaoffice.water.ca.gov/DeltaAtlas/03-Waterways.pdf), average river outflow at Chipps Island (the nominal boundary between the delta and San Francisco Bay) is 940 m^3 sec^{-1} (32,000 cfs) in winter and 18 m^3 sec^{-1} (6,000 cfs) in summer, whereas average tidal flow is 5,000 m^3 sec^{-1} (170,000 cfs). As indicated by the California Department of Water Resources DAYFLOW model (see http:/www.iep.ca.gov/dayflow), "typical summer tidal cycle maximum flow" is approximately 9,000 m^3 sec^{-1} (330,000 cfs). Most of the time the river flow is approximately an order of magnitude smaller than the tidal flow, so currents and sediment transport are due to the ebb and flood tides. However, occasionally very large storm flows in the rivers are larger than the tidal flows, having reached approximately 16,000 m^3 sec^{-1} (550,000 cfs) in the winter of 1996-97. Thus, the maximum currents would occur during ebb tidal flow combined with such large storm flows, presumably resulting in maximum transport of bedload sediment downstream into the estuarine system.

GRAIN SIZE

A variety of grain size classification schemes are used by engineers, agronomists, and geologists. In one that is commonly used by American geologists (Modified Wentworth, Walker and Cohen 2006), material with diameter less than 63 µm is called silt and clay, material with diameter from 63 µm to 2 mm is called sand (with five sub-classifications), material with diameter from 2 mm to 4 mm is called gravel, material with diameter from 4 mm to 256 mm is called pebble, and larger is called boulder. The data for classification using this system is typically obtained by mechanically measuring the weight of different size fractions in a sample, separated by sieves or an equivalent device. In reporting, various size fractions are listed and plotted. As seen below, the names of the sub-classifications of sediment size, particularly sand, in various studies are frequently different from those mentioned here. In other evaluations, only the mean grain diameter is given. USGS has recently used a digital camera to record and measure mean grain diameter on the sea floor, without necessarily collecting a sample (Barnard and others 2007b).

A somewhat different approach involves visual identification of the sediment texture, rather than measurements. One commonly used is the Unified Soil Classification System (abbreviated USCS, Walker and Cohen 2006), with terms such as "SM Silty sands, sand-silt mixtures" and "SP Poorly graded sands, gravelly sands, little/no fines."

Variations of these classification schemes, or similar ones, have been used in the historical literature, making exact direct comparison between individual studies difficult, but general trends are hopefully clear.

The majority of the floor of the San Francisco Bay estuarine system is fine material, mainly silt and clay, sometimes with a minor component of fine sand (Figure 4). As a geologic unit this is called Bay Mud. It is capable of being transported as suspended load and may be deposited by flocculation processes produced by fresh / salt water interactions (Ganju and others 2007). Monitoring to determine the concentration of suspended load in the bay water using optical devices is done continuously from instruments of bridge supports and other structures and on periodic cruises by USGS (e.g., Buchanan and Lionberger 2007).

A map of parts of the bay which have sand bottom was presented by Goldman (1969). This shows sand in the channel though Suisun and San Pablo bays, in an irregular pattern in Central Bay, and on San Bruno Shoal. The Central Bay sand area of Goldman (1969) does not include some parts of Point Knox Shoal where sand is commercially mined, so the map may not be entirely accurate. A somewhat different map was presented by Trask (1956) for Central Bay and the area off Golden Gate. This shows rock bottom at the deep part of the strait of the Golden Gate. Bayward there is a progression through "coarse sand and fine gravel," "medium sand," and "fine sand and silty sand" reaching east of Angel Island, with finer material east, south, and north. Seaward of the rock bottom at Golden Gate there is an area of "fine sand and silty sand," including San Francisco Bar, with a concentric area of "coarse sand and fine gravel" and "medium sand" located off Point Lobos. These terms apparently represent visual descriptions of samples using a scheme similar to USCS.

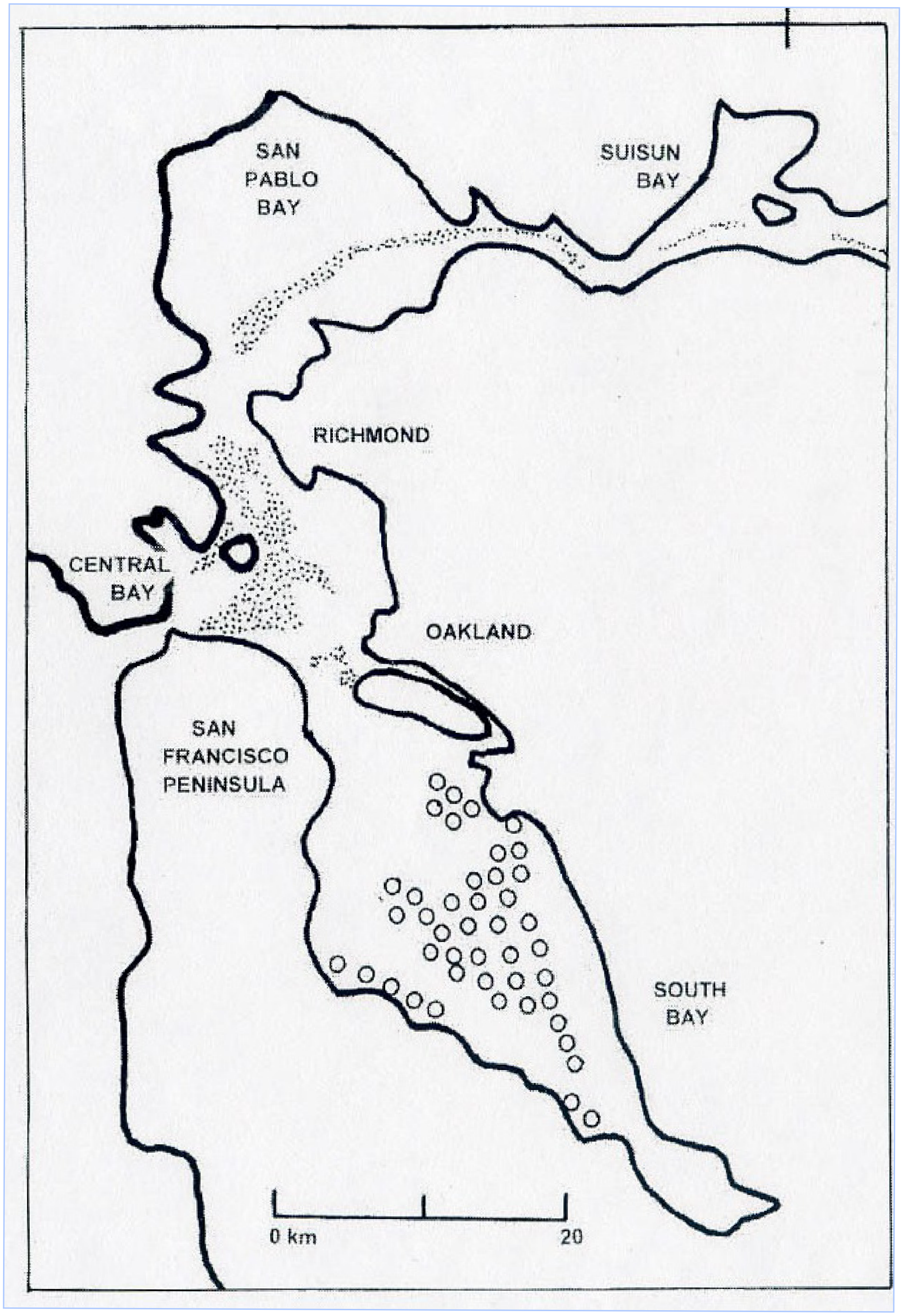

Figure 4 Distribution of sand (dots) and shell (circles) in the San Francisco Bay estuarine system, after Goldman (1969). In Suisun Bay and San Pablo Bay, sand is restricted to the deep channel, which is partly maintenance dredged, with other area having finer grained material. Sand is mined in Suisun Bay. In western Central Bay, the bottom material is not accurately depicted (see Figure 5).

A different sort of "habitat" interpretation for Central Bay was presented by Greene and others (2007), based on various multibeam and side scan sonar data sets (Figure 5). This includes anthropogenic features, areas of rock bottom and sediment waves. The interpretation is based on a textural categorization scheme with ninety categories, much more complex than USCS, including larger scale features such as waves and hummocks.

Schlocker (1974) presented grain size plots for Ocean Beach, for a raised beach near Baker Beach, for dune sand samples, and for two samples of the Colma formation. The Ocean Beach sample was mainly medium sand (0.28 mm to 0.5 mm) with some coarse (0.5 to 1.0 mm) and very coarse (1.0 to 2.0 mm). The other samples were all finer, mostly fine sand (0.13 mm to 0.28 mm), with some finer material, including 5% to 10% silt in the Colma formation. He also noted the presence of "gravel" (1 to 6 inches, or 2.5 to 15 cm) at the northwest end of Raccoon Strait, with the pieces being coated by bryozoa, which were interpreted to indicate a marine origin, i.e., having been submerged in the bay, rather than derived directly from on land. This would suggest that they had been transported by the marine currents.

An investigation of possible borrow areas for expansion of San Francisco International Airport (ADEC 2000) presented grain size plots for Point Knox Shoal, Presidio Shoal, and San Francisco Bar (as well as some data from the vicinity of San Francisco International Airport). The data, from cores and grab samples, are presented as both grain size plots (using a terminology for sand sizes slightly different from the Modified Wentworth system mentioned above) and USCS textural names (cone penetrometer data are also presented). The grain size plots for San Francisco Bar show fine sand (defined as 63 μm to 0.4 mm diameter) and medium sand (defined as 0.4 mm to 2 mm) with minor silt and these same grain size terms were used in the USCS descriptions. The plots for Presidio Shoal show slightly smaller grain size, mainly fine sand, and some clay in the USCS descriptions. The plots for Point Knox Shoal show some samples with fine to medium sand, but also some with material in the range of gravel (5 mm to more than 20 mm in the coarsest samples), so this area has some sediment that is significantly coarser than in the others. This is consistent with the presence of a significant amount of pebble sized material in mined sand from Point Knox Shoal.

Barnard and others (2007a) presented grain size data for the area outside the Golden Gate, including both the area of "giant sand waves" (as these authors termed the submerged dunes), the San Francisco Bar, and off Ocean Beach. These included grab sample data, some presumably evaluated using sieve analyses, and digital bottom camera data. The results (see their Figure 8.5) show the giant sand wave area and off Baker Beach to have isolated patches of coarse sand (defined as greater than 0.5 mm) within a larger area of medium sand (0.25 to 0.5 mm), surrounded by a larger area of fine sand (0.125 mm to 0.25 mm) that includes the San Francisco Bar, and very fine sand (0.625 mm to 0.125 mm) farther offshore. This is a similar area to part of the map of Trask (1956), which, however, showed a larger area of "Coarse sand and fine gravel" west of Point Lobos and an area of "Rock" immediately offshore there. Some additional samples were added to the Trask (1956) data set by Moore (1965), who showed a plot of mean grain sizes with areas similar to Trask's (1956) map. The differences may represent physical changes within the period between these studies, or a difference in the sampling methods.

In spite of the difficulties in comparing grain size data that are presented in a variety of formats, it is clear that most of the estuarine system is floored by silt or smaller material. Near the Golden Gate there is apparently a fining of grain sizes both inward and outward from the deep, rock-floored channel.

BEDFORMS

Morphological shapes that develop on the sediment of the floor of the bay and ocean in response to currents are called bedforms. These were investigated in the 1970s using sidescan sonar and more recently using multibeam swath bathymetry, a variety of sidescan sonar (see Chin and others 2004, for a description of the method), which provides very graphic images of the sea floor.

Figure 5 Western Central San Francisco Bay. Within the dashed line, areas of varying bottom material, modified from Greene and others (2007) and Chin and others (2004), are: vertical stripes – dump sites; horizontal stripes – rock; circles – disrupted areas ("borrow pits"); wavy dashed lines – sediment waves (mostly sand); no pattern – mostly sand. There is some "gravel" bottom (pebble size material) on western Point Knox Shoal. Bathymetric contours of 30 m, 60 m, and 90 m from Chin and others (2004) are shown. Areas deeper than 30 m are in Raccoon Strait, southeast of Angel Island, and at Golden Gate. The steep isolated rock shallower than 30 m east of Golden Gate is herein named Cavallo Spire. Sand mined is mined on all three shoals.

Rubin and McCulloch (1979) used sidescan sonar data to describe bedforms including sand waves (alternatively called submarine dunes), flat beds associated with both high and low current velocities, and bedrock and boulders. They showed a significant area in Central Bay, including an area southwest of Angel Island and an area north of Alcatraz Island, that is dominated by flood tide currents, with ebb tide dominated currents closer to the shore of Sausalito and the north shore of San Francisco. Seaward of the Golden Gate the dominant current is ebb tidal, except for an eddy of flood tidal dominance off Baker Beach. Rubin and McCulloch (1980) presented similar information, along with laboratory flume studies to understand the mechanisms of the bedforms.

An area of Central Bay generally west of Angel Island is dominated by flood tide currents (Rubin and McCulloch 1979, 1980). Therefore, deposition of sediment is likely to also be dominantly by flood tide, with material being transported eastward from the Golden Gate. Such eastward transport was estimated by Battalio and Trivedi (1996) to be in the range of 0 to 100,000 m^3 yr^{-1} and was qualitatively noted by Barnard and others (2007). Keller (2006) estimated eastward sand transport at the San Francisco Marina in the period following lengthening of its jetty, 1963 to 2004, to be on the order of 6,000 to 30,000 yd^3 yr^{-1} (5,000 to 25,000 m^3 yr^{-1}) on the basis of historic bathymetric charts, with the transport mechanism being wave-suspension longshore drift.

A much more detailed view of the bedforms in Central Bay, using multibeam sonar data collected in 1997, was provided in Chin and others (2004), including a 3D image. Areas of sand waves and flat beds are clearly visible. The same multibeam data, along with some from outside the Golden Gate, is shown in various perspective views in Dartnell and others (2006). As noted above, this and other sonar data was used by Greene and others (2007) to develop a “habitat” description of the bay floor (see Figure 5).

In addition to the bedform features described by Rubin and McCulloch (1979), Chin and others (2004) show a topographic (bathymetric) depression on Point Knox Shoal southwest of Angel Island that coincides with the western part of the borrow area for construction of Treasure Island in the 1930s. Further southwest is a chaotic disrupted area, with closely spaced circular, semicircular, and elongate depressions. The disrupted area was tentatively ascribed to sand mining activity, as was a similar disturbed area on Presidio Shoal (see Figure 5), although these do not closely coincide with the actual areas of present sand mining (see Hanson and others 2004). A reexamination of the original Rubin and McCulloch (1979) records showed that some of the depressions existed in the 1970s.

An area of large sand waves on the outside of the Golden Gate, as shown by multibeam data collected in the early 2000s, was reported by Barnard and others (2006a, 2006b) and Barnard and others (2007a). Transport directions in this area interpreted from bedforms are similar to those shown by Rubin and McCulloch (1979), but more detailed. They show dominant ebb tide transport in the central area of the sand waves, with some flood tide dominated transport off Baker Beach and west of Point Bonita. Thus, on both the inside and outside of the narrow, deep channel of the Golden Gate are central areas of dominant transport away from the narrow channel, flanked by areas with the opposite dominant transport direction. These form an ebb-tidal delta on the outside and a flood-tidal delta on the inside, using the terminology of Dyer (1994).

The San Francisco Bar may be considered to be a large bedform. It has an arcuate shape with a radius of approximately 5 km, stretching from off Point Bonita on the north to off Ocean Beach on the south, but separated from the shore by channels at both ends. Its depth is in the range of 7 to 15 m (20 to 40 ft), shallowest at the northeast end (Potato Patch Shoal), rising approximately 10 to 15 m (25 to 40 ft) above the adjacent sea floor. Large surf waves break on the bar, particularly on Potato Patch Shoal, so the sand on the bottom is at least episodically transported by wave energy.

Gilbert (1917) interpreted the shape of the bar to be caused by tidal currents and stated that “But for the tidal currents the bar would extend in a direct line from Point Lobos to Point Bonita, and its crest, a continuation of Ocean Beach, would be above the level of high tide.” While the tidal currents are undoubtedly the dominant factor in creating the bar, there also appears to be southward transport of material. Kamel (1962) interpreted the concentration of thorium and heavy minerals on the top of the bar to indicate migration of material from the north to the south along the top of the bar. Consistent with this interpretation, Best and Griggs (1991) noted that the north side of the dredged shipping channel through the Bar rapidly fills with sediment, while the south side does not.

Gilbert (1917) found that the volume of the bar increased between 1855 and 1873, but decreased between 1873 and 1900, with the crest moving toward land during both periods. A similar shrinking of the bar between 1900 and 1956 was indicated by Battalio and Trivedi (1996), and Barnard and others (2007a) cited large scale erosion of the ebb-tidal delta from 1956 to 2006. Causes for these changes may include reduction of the tidal prism (volume of water moving through the Golden Gate during tidal cycles, see below), reduced amount of hydraulic mining debris, and other changes to the shape of the bottom inside and outside the bay, such as channel maintenance dredging and sand mining. Recently, dredge spoils from the navigation channel of the bar itself have been placed offshore of south Ocean Beach in an attempt to combat beach erosion, with some success (Barnard and others 2007a).

CULTURAL INFLUENCES

A variety of cultural influences have changed the shape of the basin of the San Francisco Bay estuarine system. These include hydraulic mining, navigation hazards removal, channel dredging, and sand mining. Most of these activities have reduced the water volume, and therefore the tidal prism for those changes within the range of tides, but some have locally slightly increased the volume.

A major factor in filling parts of the estuarine system was debris from hydraulic gold mining in the Sierra Nevada (Gilbert 1917; Chin and others 2004). Approximately 1.1 x 10^9 m^3 (1.4 x 10^9 yd^3) was washed from the Sierra foothills in the late 1800s (1856 – 1887), causing filling of mud flats of as much as 0.75 to 1 m (2.5 to 3.3 ft) in Suisun and San Pablo bays and a smaller amount in Central Bay. This correspondingly decreased the tidal prism. Since the maximum of deposition in the late 1800s, this fine material has been eroding from the upper part of the estuary, changing tidal flats back into areas of open water (Cappiella and others 1999; Jaffe and others 1998; Fregoso and others 2008).

A great deal of intentional filling of wetlands has occurred on the shores of the bay, estimated by Chin and others (2004) as more than 90% of the wetlands that existed in 1800. Locally, as at Treasure Island, parts of what was previously shallow bay channel have been filled to create land. In that case, the material was dredged from Point Knox Shoal. This artificial transport of material changed the map of the shore of the bay, without changing the volume of water in the bay, but decreasing the tidal prism by moving the material from below the tidal range into the tidal range. In some cases, such as filling of the San Francisco Marina area following the 1906 earthquake, the fill material came from the land, so the volume of the bay as well as the tidal prism was decreased.

A number of rocks that were navigation hazards in Central Bay were blasted in the early 1900s (Chin and others 2004) to lower them sufficiently to reduce the hazard. The blasting debris is presumably still on the nearby bay floor. This blasting may have locally changed tidal current patterns, but would not have significantly changed the water volume of the bay. It would have slightly increased the tidal prism.

In Central Bay and Suisun Bay, sediment is mined for commercial construction sand, currently at a rate of approximately 1.2 million cubic yards per year. All of the mining activity is deeper than the tidal range, so it would increase the volume of the bay, but not change the tidal prism. Environmental aspects of this activity are described in Hanson and others (2004) and an Environmental Impact Report is currently being prepared for renewal of the leases for most of the mining areas, which leases are from the California State Lands Commission.

Channel maintenance dredging transports approximately half again as much sediment as sand mining (2.2 million cubic yards in 2007, DMMO 2008) of which approximately 80% is removed from the sedimentary environment of the estuarine system. Areas with significant amounts of channel maintenance dredging include Port of Oakland, Port of Richmond, and Suisun Bay. Most of the dredging is deeper than the tidal range, so it would increase the volume of the bay (except for the portion that is disposed within the bay), but not change the tidal prism.

SUMMARY

A review of the geologic literature regarding sedimentation in the San Francisco Bay estuarine system shows that:

- The main north-south part of the bay occupies a structural tectonic depression that developed in mid Pleistocene time. The depression is on the east side of a tectonic block between the San Andreas and Hayward faults, called the San Francisco Bay block. The depression may have been caused by eastward rotation of the tectonic block relative to a horizontal axis. However, this vertical subsidence caused by such rotation, a few hundred meters, is much smaller than horizontal strike slip fault motion that occurred during the same time period. The eastern parts of the estuarine system, including San Pablo Bay and Suisun Bay, are in locations that have had sedimentary deposition throughout late Mesozoic and Tertiary time.
- Superimposed on the tectonic structural patterns, the passages of Carquinez Strait and of the Golden Gate may represent antecedent stream erosion that was able to cut down rapidly enough to overcome the tectonic uplift of the Coast Ranges.
- Sedimentation within the main part of the bay has included estuarine (marine bay), alluvial (on-land river valley), and eolian (on-land wind blown) deposition. The ages of estuarine deposition includes the modern high sea level stand, the Sangamon interglacial period at approximately 120 Ka, and earlier interglacial periods since the bay's inception dating back perhaps 1 Ma.
- Sources of sediment can be generally divided into material eroded from the Coast Ranges, particularly from the Franciscan Complex with its distinctive rock types and mineralogy, and "Sierran," material transported into the estuary by the Sacramento River system, starting at about 0.6 Ma. The latter includes "paleo" deposits left from low sea level glacial stages when the Sacramento River drained through part of the present bay.
- Much of the estuarine system is floored by very fine sediment, silt size and smaller. Locally there are areas of sand floor, including the channels of San Pablo Bay and Suisun Bay, much of Central Bay and offshore of Golden Gate. In the vicinity of Golden Gate, sediment size decreases in both direction away from the deep channel located beneath the Golden Gate Bridge.
- Bedforms including sand waves, flat beds, and bedrock and boulders have been imaged by sonar studies and interpreted in terms of dominant transport directions. In the vicinity of Golden Gate this indicates the presence of an ebb-tidal delta on the outside (including San Francisco Bar) and a flood-tidal delta on the inside (parts of Central Bay).
- The history of alternating marine conditions during interglacial stages and river valley conditions during glacial conditions includes, as noted, high sea levels of the Sangamon interglacial stage (~ 120 Ka), earlier stages, and the present condition. The present high sea level condition is a result of sea level rise between the last glacial maximum (LGM), at approximately 18 Ka, and approximately 7 Ka. Sea level has been relatively stable since then, with the modern marine bay configuration.

- The large volume of water that moves in and out of the estuarine system each tidal cycle (the tidal prism) causes strong tidal currents, which are normally much stronger than currents associated with the flow of the Sacramento River, even in the upper part of the estuary. Occasionally, during large floods, river currents are dominant for periods of days or weeks in the upper part of the estuary.
- Cultural influences have altered conditions in the estuarine system. These include outwash of hydraulic mining debris from the late 1800s, blasting of rocks for reduction of navigation hazards, dredging of navigation channels and dumping of dredge spoils, filling of the bay to create salt ponds and land for construction, and commercial sand mining. Many of these have served to decrease the tidal prism, which correspondingly decreases the strength of tidal currents that transport sand and larger size sediment.

ACKNOWLEDGMENTS

This article was greatly improved by a number of anonymous reviewers and one named reviewer, H. Gary Greene. Andrei Sarna-Wojcicki was very helpful in clarifying the situation of the Rockland ash.

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