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Geology Of Palo Alto 30 X 60 Minute Quadrangle, California: A Digital Database

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Geologic Explanation

Introduction

This map database represents the integration of previously published and unpublished maps by several workers (see Sources of Data index map on Sheet 2 and the corresponding table below) and new geologic mapping and field checking by the authors with the previously published geologic map of San Mateo County (Brabb and Pampeyan, 1983) and Santa Cruz County (Brabb, 1989, Brabb and others, 1997), and various sources in a small part of Santa Clara County. These new data are released in digital form to provide an opportunity for regional planners, local, state, and federal agencies, teachers, consultants, and others interested in geologic data to have the new data long before a traditional paper map is published. The new data include a new depiction of Quaternary units in the San Francisco Bay plain emphasizing depositional environment, important new observations between the San Andreas and Pilarcitos faults, and a new interpretation of structural and stratigraphic relationships of rock packages (Assemblages).

Scope and Purpose of this report

The purpose of this new map is to compile the best available data on the identity and distribution of bedrock units, surficial deposits, and geologic structures at a regional scale, and to integrate those data into a digital spatial database. The digital nature of the product is important because it allows the geologic data to be easily combined with other data to produce derivative products (some of which are discussed below), allows new information to be readily integrated into the map database, makes transfer of data to users easy via the Internet, and facilitates production of a high-quality paper maps. Some of the benefits that can be derived from these geologic data are discussed below.

1. **Materials properties and geologic maps.** The character of the materials beneath the ground surface affect engineering use of the land. For example, expansivity of the materials may affect the stability of foundations, permeability determines the success of water wells and suitability of the ground for septic systems, and ease of excavation is related to hardness of the material and fracture spacing. Such material properties can be delineated in a regional way based on lithologic units shown on geologic maps. The characterization of several materials properties of geologic map units has been done in the San Francisco Bay region by Ellen and Wentworth (1995) for hillside materials, and Helley and others (1979) for flatland (Quaternary) materials. Our geologic map can be used in combination with the reports mentioned above to give the most up-to-date depiction of the distribution of materials properties that affect land use engineering.

2. **Earthquake shaking and geologic maps**. The intensity of earthquake shaking has been shown to depend strongly on the distribution of geologic units, the intensity increasing with decreasing firmness of ground materials. In the San Francisco Bay region, the relationship between intensity and geologic units was first calculated by Borcherdt and others (1975). More recently, earthquake shaking maps have been prepared for the region for a number of hypothetical earthquakes (Perkins and Boatwright, 1995), that integrate the effect of the geologic units on the calculated intensity. These intensity maps are based on the most detailed geologic maps that were available during their study, but could be improved by integration of the most up-to-date geologic mapping available, such as this report.

3. **Liquefaction potential and geologic maps**. Liquefaction during earthquakes happens in areas underlain by loose sand and silt that is saturated with water. The distribution of these areas can be delineated by geologic and hydrologic mapping. This mapping was first done for the San Francisco Bay region by Youd and others (1973), and later by Dupre and Tinsley (1980), and Tinsley and Holtzer (1990). Most recently, Sowers and others (1992) have developed a technique that combines geologic mapping of surficial deposits with other mapped factors to produce a map of liquefaction potential. The method of that report is entirely compatible with the new mapping of surficial units in this report, and therefore this report could be used in combination with other factors to produce a liquefaction susceptibility map for the map area.

4. **Ground water pollution and geologic maps**. In urban areas, such as the San Francisco Bay region, the contamination of ground water by introduction of pollution from the surface is a major problem (Howard, 1997). Because the flow of groundwater pollutants is governed by the porosity and permeability of materials shown on geologic maps, areas that are vulnerable to rapid contamination of groundwater can be identified. In the southern San Francisco Bay region, for example, Helley (1986) showed that pollutants tended to follow high-porosity Holocene stream channel and levee deposits, like those shown on our map.

5. **Relating landslides to geologic maps**. Although the distribution of mapped landslides is a good first order indicator of future landslide activity in the San Francisco Bay region (Nilsen and Turner, 1975), a better analysis of the landslide hazard is provided by a statistical approach that involves more than a single factor, and yields a quantitative prediction of landslide potential. Work by Brabb and others (1972) in San Mateo County provided the first such study using two factors, lithologic distribution, taken from a geologic map, and slope, in addition to landslide distribution. GIS capabilities now allow a much more sophisticated analysis, using many factors and a variety of statistical methods (see Soeters and van Westin, 1996, for a discussion of statistical methods). At least one of the factors required for any such analysis, lithologic distribution, is provided solely by a geologic map. In addition, some, but not all, of the additional factors, such as distance from an active fault or orientation of strata, may be derived from a geologic map. Clearly, accurate geologic maps are a prerequisite to sophisticated studies of landslides.

6. **Location of mineral hazards and geologic maps**. Certain naturally occurring minerals can pose a hazard to human health or to the environment when disturbed by human development. An example is the naturally occurring mercury deposits in the San Francisco Bay region (J. Rytuba, USGS, written comm., 1997). Because hazardous minerals are in many places associated with a specific geologic unit, such as mercury with silica-carbonate rock in serpentinite (Crittenden, 1951), geologic maps that show the distribution of those units can be used to regionally delineate the potential hazard.

7. **Seismic velocity.** Accurate seismic velocity models are required to precisely locate earthquake epicenters, which can be used to map fault location, geometry, and activity. Seismic velocity is proportional to the density of the rock in the crust, which in turn is dependent on the rock type. However, most seismic velocity models are constructed by calculation based on travel times of seismic waves from various sources. Construction of a superior model may be possible by combining the regional distribution of geologic materials at the surface provided by a geologic map with data from well logs, and aeromagnetic, gravity, and seismic data..

8. **Earthquake faults and geologic maps**. Although regional geologic maps cannot take the place of large-scale fault-rupture hazard maps (Hart, 1988), they do show faults in their geologic context. Recent work by the authors along the Hayward fault in the east San Francisco Bay area has shown that studying active faults in their geologic context reveals a much more complex history of faulting and a wider zone of Holocene active faults than previously thought (Graymer, Jones, and Brabb, 1995). In addition, other recent work based on the geologic context of faults in the San Francisco Bay region (Jones and others, 1995, Jayko and Lewis, 1996) has shown that a component of stress in the area is perpendicular to known active faults, suggesting the possibility of active thrust and blind-thrust faults. The 1989 Loma Prieta earthquake may have occurred on such a fault. Blind-thrusts, in areas without intensive seismic reflection/refraction studies, such as most urban areas, must be mapped by studying the regional structure, as there is no surface rupture.

9. **Education and scientific inquiry**. In addition to applications related to engineering and geologic hazards, regional geology can be a subject of intellectual curiosity and academic inquiry. This map represents the state of knowledge of the geology of the area at the time of publication, and can be used by the academic community and by the public to understand the geology of the area at a regional scale.

NOTE

Uses of this map database are limited by compilation scale and content. The map is not intended for site specific studies of any sort The fault maps of the California Division of Mines and Geology (see Hart, 1988 for an index) should be used for site specific studies of fault activity, whereas the work of Wentworth and others, 1997, provide a regional depiction of landslides and Pike, 1997, provides an index of more detailed work.

Stratigraphy

Lithologic associations in the Palo Alto 30 X 60 minute quadrangle are divided into ten assemblages (see Index Map on Sheet 2). As defined in Graymer, Jones, and Brabb (1994), assemblages are large, fault - bounded blocks that contain a unique stratigraphic sequence. The stratigraphic sequence differs from that of neighboring assemblages by containing different rock units, or by different stratigraphic relationship among similar rock units. These stratigraphic differences represent changes in depositional conditions in one or more large depositional basins. The current adjacent location of the different assemblages reflects the juxtaposition of different basins or parts of basins by large offsets along the faults that bound the assemblages.

In general, the Tertiary strata in the map area rest with angular unconformity on three complexly deformed Mesozoic rock complexes. One of these Mesozoic complexes is made up of the Coast Range ophiolite, which includes serpentinite, gabbro, diabase, and basalt; keratophyre which is closely associated with the ophiolite; and overlying Great Valley sequence of Jurassic and Cretaceous age. This complex represents the accreted and deformed remnants of Jurassic oceanic crust, overlying arc volcanic rocks, and a thick sequence of turbidites. In the map area rocks of this complex are only definitely present in small, fault-bounded slivers at the base of the Portola Valley Assemblage, although the large unit of diabase and gabbro (db) along the San Andreas fault in the Woodside Assemblage may also be part of the complex.

The second Mesozoic complex is the Franciscan complex, which is composed of weakly to strongly metamorphosed graywacke, argillite, limestone, basalt, serpentinite, chert, and other rocks. The rocks of the Franciscan complex in the area were probably Jurassic oceanic crust and pelagic deposits overlain by Upper Jurassic to Upper Cretaceous turbidites. Although Franciscan rocks are dominantly little metamorphosed, high-pressure, low-temperature metamorphic minerals are common within the complex (Bailey, Irwin, and Jones, 1964). High-grade metamorphic blocks in sheared but relatively unmetamorphosed argillite matrix (Blake and Jones, 1974) reflects the complicated history of the Franciscan. The complex was subducted beneath the Coast Range ophiolite, at least in part, during Late Cretaceous or early Tertiary time, after the deposition of the Franciscan sandstone containing Campanian (Late Cretaceous) fossils that crops out in Marin County. Because the Franciscan was subducted under the complex containing the Coast Range Ophiolite, the contact between the two Mesozoic complexes is everywhere faulted (Bailey, Irwin, and Jones, 1964), and the Franciscan complex presumably underlies the entire area east of the Pilarcitos fault.

The third Mesozoic complex is the Salinian complex, which is composed of granitic plutonic rocks, and inferred gabbroic plutonic rocks at depth, overlain in places by Cretaceous strata. It is separated from the combined Franciscan, Coast Range ophiolite, Great Valley sequence Mesozoic basement on the east by the Pilarcitos fault in the north part of the map area, and the San Andreas fault in the south part of the map area where the Pilarcitos and San Andreas faults join. In places, small outcrops of pre-plutonic (Paleozoic?) rocks are also preserved, such as KJv in the Pigeon Point Assemblage, marble and hornfels (m) in the Montara Mountain Assemblage, and schist (sch) in the Santa Cruz Assemblage. The plutonic rocks are part of a batholith that has been displaced northward by offset on the San Andreas fault system. Estimates of total offset vary, but all are more than a few hundred kilometers.

An angular unconformity at the base of the Tertiary strata has been preserved in all of the assemblages. The exception is the Portola Valley Assemblage, where the base of the Tertiary strata is everywhere faulted.

Paleontology

Hundreds of fossil collections from the Palo Alto 30 X 60 minute quadrangle are described in the references provided in this report, as well as in Brabb (1983).

Radiometric Ages

A compilation of the radiometric ages of rocks in the Palo Alto 30 X 60 minute quadrangle and other areas south of latitude 38 degrees is provided by Lindquist and Morganthaler (1991). Additional data are provided by Sarna-Wojcicki (1976, and written comm., 1990), Sarna-Wojcicki and others (1979), Turner (1970), Brabb and Hanna (1981), and Curtis (1989).

Structure

The faults of the map area are characterized by both strike-slip and dip-slip components of displacement. Three major fault systems display large late Tertiary right-lateral offsets-- the San Andreas, the Pilarcitos, and the San Gregorio fault zones. These fault systems trend roughly N30W, and most of them have many fault strands in a broad zone as much as 10 km wide. Offset is distributed on the various faults in the zones, and the locus of fault movement associated with a fault zone has changed through geologic time (see Graymer, Jones, and Brabb, 1995, and Montgomery and Jones, 1992, for a description of fault zone evolution and distribution of offset on similar active faults in the East Bay region). Both the San Andreas and San Gregorio fault zones have strands which display Holocene offset. The land on either side of the San Andreas fault zone was displaced up to several meters in the map area during the 1906 earthquake.

Current estimates of total offset since 8 Ma are about 35 km for the San Andreas fault zone in the map area, 120 km for the Pilarcitos fault zone, and 155 km for the San Gregorio fault zone (Clark and others, 1984, McLaughlin and others, 1996, Dickinson, 1997). However, ongoing work by the authors and others has correlated the Coast Range ophiolite (Jgb, Jsv, sp) and Great Valley Sequence (Ka, Ks) rocks at the base of the Portola Valley Assemblage with rocks in the Gualala area more than 150 km north of the map area, which might indicate even more offset on the Pilarcitos fault.

The three major right-lateral fault systems also form many of the boundaries of the assemblages. The juxtaposition of rocks with different stratigraphic histories across these faults probably resulted from the large offsets on the faults. The other assemblage-bounding faults probably had total offsets of tens of kilometers as well, as they also juxtapose rocks with different stratigraphic histories, although the offset is undoubtedly less than the three major systems, as the stratigraphic differences are less.

In addition to strike-slip faults, some faults in the map area have a major component of reverse or thrust offset. These structures run generally subparallel to the strike-slip faults, and reflect a component of stress perpendicular to the trend of the faults. This fault-normal compression has generated faults that typically have juxtaposed older rocks above younger. Part of the offset on some of these reverse and thrust faults has taken place during Quaternary time, as shown by faulting of QTsc west of Crystal Springs Reservoir.

Apparent offset on the large, assemblage-bounding faults in the west-central part of the map area becomes progressively younger to the northeast. The Zayante fault completed most of its offset by late Miocene time, because the base of the Santa Margarita Sandstone (Tsm) unconformably overlaps the fault. The Butano fault appears to have completed the bulk of the offset along it by Pliocene or latest Miocene time, because it is overlapped by the Purisima Formation (Tp, Tpt), but truncates Tsm and Tsc. The La Honda fault cuts the Tp, and so was active at least into the Pliocene, whereas the Pilarcitos fault cuts the QTsc so was active into the Pleistocene, but both show little or no evidence for Holocene offset. The San Andreas fault zone is the locus of Holocene activity, as shown by the large offset in 1906. The significance of this northeastward younging trend is not at present understood.

Folds in the map area can be divided into two categories based on axial trend and style of deformation. The first category includes tight folds and overturned folds with inclined axial planes whose axes trend obliquely to the major strike-slip fault zones (about N60W). These folds were probably caused by the same component of regional stress that formed the strike-slip faults and the thrust and reverse faults of the second category discussed above.

The second category of fold is tight, upright folds whose axes strike roughly parallel to the major strike-slip faults (about N30W). These folds must have been formed by a component of regional compression perpendicular to the strike-slip faults (Jones and others, 1995).

Preserved folds in the maps area for the most part formed in Pliocene or later time, because Pliocene strata (Tp), where present, are involved in the folds. In the Portola Valley Assemblage, major pre-Pliocene Tertiary folding is not indicated, because Pliocene rocks are folded as much as pre-Pliocene Tertiary strata. However, in the Butano Ridge and Santa Cruz Assemblages, the major angular unconformity at the base of the late Miocene strata indicates a significant period of pre-late-Miocene folding. In addition, whereas all pre-late Miocene strata in the Butano Ridge Assemblage appear to have undergone the same amount of deformation, an additional major angular unconformity is present within the pre-late Miocene strata of the Santa Cruz Assemblage at the base of the middle Miocene Lompico Sandstone (Tlo). In the Montara Mountain Assemblage a nonconformity at the base of the middle Miocene strata and an angular unconformity at the base of the Pliocene strata indicate two periods of pre-Pliocene Tertiary uplift and folding. In the Pigeon Point Assemblage, a similar angular unconformity at the base of the Pliocene is present, and Tuv rests unconformably on Kpp. In the Mindego Hill Assemblage, the base of the Pliocene unconformity is again present, but the middle Miocene strata there are folded as much as the pre-Miocene strata, indicating that only one period of pre-Pliocene Tertiary deformation occurred in that Assemblage. In the Woodside Assemblage, Pliocene rocks of the Merced Formation are folded as much as earlier Tertiary strata, indicating that Tertiary deformation in that Assemblage must be Pliocene or younger. The Tertiary deformation of the strata in the map area is, therefore, a complex amalgamation of independently deformed blocks that have been brought into proximity only in late Tertiary time. Pre-Tertiary folding undoubtedly occurred, associated with subduction of the Franciscan complex beneath the Coast Range ophiolite and subsequent deformation associated with the unconformity at the base of the Tertiary sequence, as well as offset on strike-slip faults. These folds have for the most part been totally disrupted. The youngest folding must postdate the Pliocene and Pleistocene deposition of QTsc and QTm, as those strata are folded in at least one area, and are steeply inclined throughout the county. Pleistocene strata and marine terraces have not been observed to be folded, but are tilted and uplifted in several places, and locally faulted. Late Pleistocene and Holocene surficial deposits retain most of their original depositional shape and orientation, so are not tilted or folded, but late Pleistocene alluvium and marine terrace deposits have been uplifted as much as several meters in places throughout the county.

Description Of Map Units

af **Artificial fill (Historic)**--Loose to very well consolidated gravel, sand, silt, clay, rock fragments, organic matter, and man-made debris in various combinations. Thickness is variable and may exceed 30 m in places. Some is compacted and quite firm, but fill made before 1965 is nearly everywhere not compacted and consists simply of dumped materials

alf **Artificial levee fill (Historic)**--Man-made deposit of various materials and ages, forming artificial levees as much as 6.5 m high. Some are compacted and quite firm, but fills made before 1965 are almost everywhere not compacted and consist simply of dumped materials. The distribution of levee fill conforms to levees shown on the most recent U.S. Geological Survey 7.5-minute quadrangle maps

Qhasc **Artificial stream channels (Historic)**--Modified stream channels, in most places where streams have been straightened and realigned

Qhsc **Stream channel deposits (Holocene)**--Poorly to well-sorted sand, silt, silty sand, or sandy gravel with minor cobbles. Cobbles are more common in the mountainous valleys. Many stream channels are presently lined with concrete or rip rap. Engineering works such as diversion dams, drop structures, energy dissipaters and percolation ponds also modify the original channel. Many stream channels have been straightened, and these are labeled Qhasc. This straightening is especially prevalent in the lower reaches of streams entering the estuary. The mapped distribution of stream channel deposits is controlled by the depiction of major creeks on the most recent U.S. Geological Survey 7.5-minute quadrangles. Only those deposits related to major creeks are mapped. In some places these deposits are under shallow water for some or all of the year, as a result of reservoir release and annual variation in rainfall.

Qbs **Beach sand (Holocene)** -- Unconsolidated, well-sorted sand. Local layers of pebbles and cobbles. Thin discontinuous lenses of silt relatively common in back-beach areas. Thickness variable, in part due to seasonal changes in wave energy: commonly less than 10 m thick. May interfinger with either well-sorted dune sand or, where adjacent to coastal cliff, poorly-sorted colluvial deposits. Iron- and magnesium-rich heavy minerals locally form placers as much as 0.7 m thick.

Qhbm **Bay mud (Holocene)**-- Water-saturated estuarine mud, predominantly gray, green and blue clay and silty clay underlying marshlands and tidal mud flats of San Francisco Bay, Pescadero, and Pacifica. The upper surface is covered with cordgrass (*Spartina* sp.) and pickleweed (*Salicornia* sp.). The mud also contains a few lenses of well-sorted, fine sand and silt, a few shelly layers (oysters), and peat. The mud interfingers with and grades into fine-grained deposits at the distal edge of Holocene fans, and was deposited during the post-Wisconsin rise in sea-level, about 12 ka to present (Imbrie and others, 1984). Mud varies in thickness from zero, at landward edge, to as much as 40 m near north County line

Qhb **Basin deposits (Holocene)**--Very fine silty clay to clay deposits occupying flat-floored basins at the distal edge of alluvial fans adjacent to the bay mud (Qhbm). Also contains unconsolidated, locally organic, plastic silt and silty clay deposited in very flat valley floors

Qhbs **Basin deposits, salt-affected (Holocene)** -- Clay to very fine silty-clay deposits similar to Qhb deposits except that they contain carbonate nodules and iron-stained mottles (U.S. Soil Conservation Service, 1958). These deposits may have been formed by the interaction of bicarbonate-rich upland water and saline water of the San Francisco Bay estuary. With minor exceptions, salt-affected basin deposits are in contact with estuary deposits.

Qhfp **Floodplain deposits (Holocene)**--Medium to dark gray, dense, sandy to silty clay. Lenses of coarser material (silt, sand, and pebbles) may be locally present. Flood plain deposits usually occur between levee deposits (Qhl) and basin deposits (Qhb)

Qhl **Natural levee deposits (Holocene)**--Loose, moderately to well-sorted sandy or clayey silt grading to sandy or silty clay. These deposits are porous and permeable and provide conduits for transport of ground water. Levee deposits border stream channels, usually both banks, and slope away to flatter floodplains and basins. Abandoned levee systems, no longer bordering stream channels, have also been mapped

Qhaf1 **Younger alluvial fan deposits (Holocene)** -- Brown, poorly-sorted, dense, sandy or gravelly clay. May represent the modern loci of deposition for Qhaf, although small fans at mountain fronts may have a debris-flow origin.

Qhaf **Alluvial fan and fluvial deposits (Holocene)**--Alluvial fan deposits are brown or tan, medium dense to dense, gravely sand or sandy gravel that generally grades upward to sandy or silty clay. Near the distal fan edges, the fluvial deposits are typically brown, never reddish, medium dense sand that fines upward to sandy or silty clay

Qyf **Younger (inner) alluvial fan deposits (Holocene)**--Unconsolidated fine- to coarse-grained sand, silt, and gravel, coarser grained at heads of fans and in narrow canyons

Qyfo **Younger (outer) alluvial fan deposits (Holocene)**--Unconsolidated fine sand, silt, and clayey silt

Qcl **Colluvium (Holocene)**--Loose to firm, friable, unsorted sand, silt, clay, gravel, rock debris, and organic material in varying proportions

Qs **Sand dune and beach deposits (Holocene)**--Predominantly loose, medium- to coarse-grained, well-sorted sand but also includes pebbles, cobbles, and silt. Thickness less than 6 m in most places, but in other places may exceed 30 m

Qal **Alluvium (Holocene)**--Unconsolidated gravel, sand, silt, and clay along streams. Less than a few meters thick in most places

Qls **Landslide deposits (Pleistocene and/or Holocene) --** Poorly sorted clay, silt, sand, and gravel. Only a few very large landslides have been mapped. For a more complete map of landslide deposits, see Nilsen and others (1979).

Qpaf **Alluvial fan and fluvial deposits (Pleistocene)**--Brown dense gravely and clayey sand or clayey gravel that fines upward to sandy clay. These deposits display variable sorting and are located along most stream channels in the county. All Qpaf deposits can be related to modern stream courses. They are distinguished from younger alluvial fans and fluvial deposits by higher topographic position, greater degree of dissection, and stronger soil profile development. They are less permeable than Holocene deposits, and locally contain fresh water mollusks and extinct late Pleistocene vertebrate fossils. They are overlain by Holocene deposits on lower parts of the alluvial plain, and incised by channels that are partly filled with Holocene alluvium on higher parts of the alluvial plain. Maximum thickness is unknown but at least 50 m.

Qpaf1 **Alluvial terrace deposits (Pleistocene)**--Deposits consist of crudely - bedded, clast-supported, gravels, cobbles, and boulders with a sandy matrix. Clasts are as much as 35 cm in intermediate diameter. Coarse sand lenses may be locally present. Pleistocene terrace deposits are cut into Pleistocene alluvial fan deposits (Qpaf) a few meters and lie up to several meters above Holocene deposits

Qpoaf **Older alluvial fan deposits (Pleistocene)**--Brown dense gravely and clayey sand or clayey gravel that fines upward to sandy clay. These deposits display various sorting qualities. All Qpoaf deposits can be related to modern stream courses. They are distinguished from younger alluvial fans and fluvial deposits by higher topographic position, greater degree of dissection, and stronger profile development. They are less permeable than younger deposits, and locally contain fresh- water mollusks and extinct Pleistocene vertebrate fossils.

Qof **Coarse-grained older alluvial fan and stream terrace deposits (Pleistocene)**--Poorly consolidated gravel, sand, and silt, coarser grained at heads of old fans and in narrow canyons

Qmt **Marine terrace deposits (Pleistocene)**--Poorly consolidated and poorly indurated well- to poorly-sorted sand and gravel. Thickness variable but probably less than 30 m

QTsc **Santa Clara Formation (lower Pleistocene and upper Pliocene)**--Gray to red-brown poorly indurated conglomerate, sandstone, and mudstone in irregular and lenticular beds. Conglomerate consists mainly of subangular to subrounded cobbles in a sandy matrix but locally includes pebbles and boulders. Cobbles and pebbles are mainly chert, greenstone, and graywacke with some schist, serpentinite, and limestone. On Coal Mine Ridge, south of Portola Valley, conglomerate contains boulders of an older conglomerate as long as one meter. Gray to buff claystone and siltstone beds on Coal Mine Ridge contain carbonized wood fragments as large as 60 cm in diameter. Included in Santa Clara Formation are similar coarse-grained clastic deposits near Burlingame. Sarna-Wojcicki (1976) found a tuff bed in Santa Clara Formation near Woodside, and correlated it with a similar tuff in the Merced Formation. Later work indicated that the tuff correlates with the 435 ka Rockland ash (Sarna-Wojcicki, oral comm., 1997). Thickness of Santa Clara Formation is variable but reaches a maximum of about 500 m along Coal Mine Ridge

QTsl **Lake beds (upper Pliocene)** -- Fine-grained sandstone, calcareous mudstone, and marl. Locally contains vertebrate fossils of late Pliocene (Blancan) age. Fossiliferous marl is best exposed near Stevens Creek Reservoir, where it is about 30 m thick.

QTm **Merced Formation (lower Pleistocene and upper Pliocene)**--Medium-gray to yellowish gray and yellowish orange, medium- to very fine-grained, poorly indurated to friable sandstone, siltstone, and claystone, with some conglomerate lenses and a few friable beds of white volcanic ash. In many places sandstone is silty, clayey, or conglomeratic. Some of the conglomerate, especially where fossiliferous, is well cemented. Volcanic ash is in beds as much as 2 m thick and consists largely of glass shards. In type section of Merced Formation north of the map area, the ash was originally reported by Sarna-Wojcicki (1976) to be 1.5 ± 0.8 m.y. old, but more recent work by Sarna-Wojcicki and others (1991) indicates that the formation contains both the 738 ± 3 ka Bishop ash and the 435 ka Rockland ash (Sarna-Wojcicki, oral comm., 1997). Merced Formation is about 1525 m thick in the sea cliffs north of Mussel Rock

Tp **Purisima Formation (Pliocene and upper Miocene)**--Predominantly gray and greenish-gray to buff fine-grained sandstone, siltstone, and mudstone, but also includes some porcelaneous shale and mudstone, chert, silty mudstone, and volcanic ash. West of Portola Valley, this unit consists of fine- to medium-grained silty sandstone. Locally divided into:

Tptu **Tunitas Sandstone Member (Pliocene)**--Greenish-gray to light-gray, pale-orange, or greenish-brown, very fine- to medium-grained sandstone with clay matrix. Concretions generally less than 30 cm across are present locally. Tunitas ranges in thickness from 76 m at type section to 122 m elsewhere

Tpl **Lobitos Mudstone Member (Pliocene)**--Dark-gray to light-gray and shades of brown, unbedded, silty mudstone. Lobitos has a maximum thickness of 140 m.

Tpsg **San Gregorio Sandstone Member (Pliocene)**--Greenish-gray to light-brown fine- to coarse-grained sandstone containing calcareous concretions less than 30 cm across. San Gregorio Member ranges in thickness from 45 m at type section to about 140 m elsewhere

Tpp **Pomponio Mudstone Member (Pliocene)**--Gray to white porcelaneous shale and mudstone, in places rhythmically bedded with alternating layers of nonsiliceous mudstone. This unit resembles Monterey Shale, Santa Cruz Mudstone, and Lambert Shale. At its type section in Pomponio Creek the member is 700 m thick

Tpt **Tahana Member (Pliocene and upper Miocene)**--Greenish-gray to white or buff, medium- to very fine-grained sandstone and siltstone, with some silty mudstone. Locally, such as at San Gregorio State Beach, sandstone is tuffaceous and weathers white. Near Memorial Park, this member includes dark-gray porcelaneous mudstone. Pebble conglomerate occurs near base from Memorial Park eastward. Maximum thickness is 655 m. A tuff bed in this member west of the San Gregorio fault has been tentatively correlated with the 2.6 Ma Ishi Tuff (Sarna-Wojcicki and others, 1991)

Tsc **Santa Cruz Mudstone (upper Miocene)**--Brown and gray to light-gray, buff, and light-yellow siliceous mudstone with nonsiliceous mudstone and siltstone and minor amounts of sandstone. Santa Cruz Mudstone is more than 1000 m thick

Tsm **Santa Margarita Sandstone (upper Miocene)**--Light-gray to grayish-orange to white, friable, very fine- to very coarse-grained arkosic sandstone. Fine-grained sandstone commonly contains glauconite. A quartz and feldspar pebble conglomerate crops out locally at the base of section. Santa Margarita Sandstone is as thick as 60 m

Tms **Unnamed marine sandstone and shale (upper Miocene)** -- Light-gray, grayish-orange, and white, soft, friable, very fine- to medium-grained, well-sorted, poorly cemented quartzose sandstone with minor interbeds of siliceous mudstone and semi-siliceous shale. Contains late Miocene, shallow water marine fossils (Sorg and McLaughlin, 1975).

Tlad **Ladera Sandstone (upper(?) and middle Miocene)**--Medium- to light-gray to yellowish-gray and buff, fine-grained, poorly cemented sandstone and siltstone, with minor amounts of coarse-grained sandstone, yellow-brown dolomitic claystone, and white to light-gray porcelaneous shale and porcelanite. Fine-grained sandstone and siltstone comprise more than 90 percent of formation. Coarse-grained sandstone crops out in beds less than a few meters thick in lower half of section; dolomitic claystone and porcelaneous shale beds are less than a meter thick and outcrop scattered through the upper half of the section; porcelanite crops out in thin-bedded lenses less than a few meters thick in the lower part of the section. At and near base of Ladera Sandstone are medium to thick lenticular beds of well-cemented fossiliferous, chert-granule sandstone which interfingers with fine-grained sandstone. About 450 m thick

Tm **Monterey Formation (middle Miocene)**--Grayish-brown and brownish-black to very pale orange and white, porcelaneous shale with chert, porcelaneous mudstone, impure diatomite, calcareous claystone, and with small amounts of siltstone and sandstone near base. Monterey is generally thinner-bedded than the Santa Cruz Mudstone but closely resembles parts of Purisima Formation, especially Pomponio Mudstone Member. Thickness ranges from 120 to more than 600 m

Tlo **Lompico Sandstone (middle Miocene)**--Very pale orange, fine to coarse-grained, mostly well-cemented and hard arkosic sandstone. Maximum thickness about 300 m

Tpm **Page Mill Basalt (middle Miocene)**--Interlayered, columnar-jointed basaltic flows and agglomerate. Flows are dark greenish gray to light gray, dense to vesicular, and finely crystalline; agglomerate is light gray to reddish brown. Volcanic rocks are pyritiferous in part. Ranges in thickness from 0 to 15 m. The Page Mill Basalt has yielded a K/Ar age of 14.8 ± 2.4 Ma (Turner, 1970, recalculated by Fox and others, 1985).

Tuv **Unnamed Sedimentary and Volcanic Rocks (Miocene and Oligocene)**--Mainly dark-gray, hard mudstone in Año Nuevo area and massive, coarse-grained and pebbly, crossbedded, hard sandstone in Pescadero Point area. Mapped as Vaqueros(?) Formation by Hall and others (1959), but rocks do not resemble those of Vaqueros Sandstone in Santa Cruz Mountains. Includes andesite breccia. Intrusive rocks associated with the andesite have yielded a K/Ar age of 22.0 ± 0.7 Ma (Taylor, 1990). Contains foraminifers and mollusks of Zemorrian (Oligocene) and Saucesian (Miocene) age according to Clark and Brabb (1978). About 135 m thick near Pescadero Point and at least 85 m thick near Año Nuevo

Tls **Lambert Shale and San Lorenzo Formation, Undivided (lower Miocene, Oligocene, and middle and upper Eocene)**--Brown and dark-gray to gray, brown, and red mudstone, siltstone, and shale. Includes some beds of fine- to coarse-grained sandstone. Lambert Shale is generally more siliceous than San Lorenzo Formation, but the two units cannot be distinguished where out of stratigraphic sequence and without fossils

Tla **Lambert Shale (Oligocene and lower Miocene)**--Dark-gray to pinkish-brown, moderately well-cemented mudstone, siltstone, and claystone. Chert crops out in a few places in upper part of section, and sandstone bodies up to 30 m thick, glauconitic sandstone beds, and microcrystalline dolomite are present in places. Lambert Shale is generally more siliceous than San Lorenzo Formation and less siliceous than the Monterey Shale. It resembles Santa Cruz Mudstone and parts of Purisima Formation. Lambert Shale is about 1460 m thick

Tmb **Mindego Basalt and related volcanic rocks (Miocene and/or Oligocene)**--Basaltic volcanic rocks, both extrusive and intrusive. Extrusive rock is primarily dark-gray to orange-brown to greenish-gray flow breccia, but includes lesser amounts of tuffs, pillow lavas, and flows. Extrusive rocks have a maximum thickness of 120 m. Intrusive rock is dark greenish gray to orange brown and medium to coarsely crystalline. It commonly weathers spheroidally, and crops out as roughly tabular bodies up to 180 m thick intruding older sedimentary rocks. Minor amounts of sandstone and mudstone are locally included. The Mindego Basalt has yielded a K/Ar minimum age of 20.2$\pm$1.2 Ma (Turner, 1970, recalculated by Fox and others, 1985).

Tvq **Vaqueros Sandstone (lower Miocene and Oligocene)**--Light-gray to buff, fine- to medium-grained, locally coarse-grained, arkosic sandstone interbedded with olive- and dark-gray to red and brown mudstone and shale. Sandstone beds are commonly 0.3 to 3 m thick and mudstone and shale beds are as much as 3 m thick. Vaqueros varies from a few meters to as much as 700 m in thickness

Tz **Zayante Sandstone (Oligocene)** -- Thick- to very thick-bedded, yellowish-orange arkosic non-marine sandstone containing thin interbeds of greenish and reddish siltstone and lenses and thick interbeds of pebble and cobble conglomerate. Thickness 550 m along Lompico Creek.

Tsl **San Lorenzo Formation (Oligocene and upper and middle Eocene)**--Dark-gray to red and brown shale, mudstone, and siltstone with local interbeds of sandstone. About 550 m thick. Locally divided into:

Tsr **Rices Mudstone Member (Oligocene and upper Eocene)**--Olive-gray to red and brown unbedded mudstone and siltstone with some laminated shale. Spheroidal weathering is common, as are elongate carbonate concretions. About 300 m thick

Tst **Twobar Shale Member (middle and upper Eocene)**--Olive-gray to red and brown laminated shale with some mudstone. Includes a few thin interbeds of very fine-grained sandstone which thicken to as much as 30 m near Big Basin. About 240 m thick

Tb **Butano Sandstone (middle and lower Eocene)**--Light-gray to buff, very fine- to very coarse-grained arkosic sandstone in thin to very thick beds interbedded with dark-gray to brown mudstone and shale. Conglomerate, containing boulders of granitic and metamorphic rocks and well-rounded cobbles and pebbles of quartzite and porphyry, is present locally in lower part of section. Amount of mudstone and shale varies from 10 to 40 percent of volume of formation. About 3000 m thick

Tbu **Upper sandstone member** -- Thin-bedded to very-thick-bedded medium- gray, fine- to medium-grained arkosic sandstone containing thin interbeds of medium-gray siltstone. Thickness about 215 m.

Tbm **Middle siltstone member** -- Thin- to medium-bedded, nodular, olive-gray pyritic siltstone. Thickness about 215 m.

Tbl **Lower conglomerate and sandstone member** -- Thick to very thick interbeds of sandy pebble conglomerate and very-thick-bedded to massive, yellowish-gray, granular, medium- to coarse-grained arkosic sandstone. Thickness as much as 1500 m.

Tblc **Conglomerate** -- Thick to very thick interbeds of sandy pebble conglomerate mapped locally in the lower member.

Tbs **Shale in Butano Sandstone (lower Eocene)**--Greenish-gray, light gray, red, and reddish brown clay shale, mudstone, siltstone, and a few thin interbeds of light gray sandstone. Exposed near the head of Corte Madera Creek. Total thickness is unknown, but at least 200 m of this material is exposed

Tw **Whiskey Hill Formation (middle and lower Eocene)**--Light-gray to buff coarse-grained arkosic sandstone, with light-gray to buff silty claystone, glauconitic sandstone, and tuffaceous siltstone. Sandstone beds constitute about 30 percent of map unit. Tuffaceous and silty claystone beds are expansive. Locally, sandstone beds are well cemented with calcite. At apparent base of section on north side of Jasper Ridge, just east of Searsville Lake, a thin greenstone-pebble conglomerate is present. In places within this map unit, sandstone and claystone beds are chaotically disturbed. This formation is as much as 900 m thick

Tws **Shale in Whiskey Hill Formation (lower Eocene)**--Brown and reddish brown claystone, mudstone, siltstone and shale. Locally contains lenses of sandstone up to 50 m thick. Exposed along Highway 84, and along Highway 92, east of Half Moon Bay, where a small patch of red mudstone can be seen in a drainage ditch. Total thickness is unknown, but at least 200 m of this material is exposed along Highway 84.

Tu **Unnamed sedimentary rocks (Eocene?)** -- Mudstone, shale, and argillite with minor sandstone.

Tl **Locatelli Formation (Paleocene)** -- Nodular, olive-gray to pale-yellowish-brown micaceous siltstone. Thickness 245-275 m. Locally near base includes:

Tlss **Sandstone** -- Massive, medium-gray, fine- to medium-grained arkosic sandstone. Maximum thickness 25 m.

Kpp **Pigeon Point Formation (Upper Cretaceous)**--Sandstone and conglomerate, interbedded with siltstone and mudstone and pebbly mudstone. Sandstone is fine- to coarse-grained, arkosic, and gray to greenish gray; mudstone and siltstone are gray or black to buff. Conglomerate contains well-rounded pebbles, cobbles, and boulders of red and gray fine-grained and porphyritic felsic volcanic rocks, granitic rocks, chert, quartzite, dark-colored metamorphic rock, limestone, and clastic sedimentary rocks. Pigeon Point Formation is estimated to be more than 2600 m thick

Ksh **Unnamed shale (Upper Cretaceous)**--Dark-gray, thin-bedded, nodular shale and silty shale. Unit is exposed only in the bed of San Francisquito Creek, in Menlo Park, where about 15 m of section is visible

Ka **Conglomerate of strata of Anchor Bay (Wentworth, 1968) (Cretaceous)**--Massive sandstone and conglomerate with pebbles and cobbles of diabase, gabbro, and minor granitic rocks; contains abundant shell fragments of a rudistid bivalve similar to *Coraliochama orcutti* of Late Cretaceous (Campanian) age.

Ks **Unnamed sandstone and shale (Cretaceous(?))**-- Rhythmically interbedded, indurated micaceous sandstone and greenish-gray argillite; age uncertain, but probably Cretaceous based on lithologic similarity to other Cretaceous strata in the Santa Cruz Mountains

Kgr **Granitic rocks of Montara Mountain (Cretaceous)**--Very light gray to light brown, light brown, medium- to coarsely-crystalline foliated granitic rock, largely quartz diorite with some granite. These rocks are highly fractured and deeply weathered. Foliation is marked by an alignment of dark minerals and dark dioritic inclusions. Tabular bodies of aplite and pegmatite generally parallel foliation. Rocks from this unit have yielded K/Ar ages of 91.6 Ma (Curtis, Everndon, and Lipson, 1958) and 86.2±3.4 Ma (Calif. Div. Mines and Geol., 1965), fission track ages of 84.1±7.8 Ma and 81.7±6.3 Ma (Naeser and Ross, 1976), and most recently Rb/Sr and Ar/Ar ages of 93±2.5 Ma (Kistler and Champion, 1997).

Kqd **Granitic rocks of Ben Lomond Mountain (Cretaceous)** -- Predominantly dark-weathering, white to light-gray, fine- to coarse-grained hornblende-biotite quartz diorite. Also includes stocks and plugs of medium- to coarse-grained, light-gray alaskite and granite, and dark, fine- to coarse-grained, hornblende-cummingtonite gabbro. Alaskite dikes similar to the larger alaskite body, locally intrude the quartz diorite. The gabbro body appears in map view to intrude the quartz diorite as well, but contact relations have not been observed because of poor exposure of the gabbro. The quartz diorite is very similar to that of Montara Mountain, but is distinguished by having fewer dark minerals and virtually lacking metallic opaque minerals (Ross, 1972), as well as by association with other types of plutonic rocks. Rocks from this unit have yielded fission track ages of 86.9±6.6 Ma (Naeser and Ross, 1976) and K/Ar ages of 71.0±0.9 Ma (Calif. Division of Mines and Geology, 1965) and 86.9±6.6 Ma (Leo, 1967). This unit includes, mapped locally:

ga **Granite and alaskite**

hcg **Hornblende-cummingtonite gabbro**

KJv **Unnamed volcanic rocks (Cretaceous or older)**--Dark-gray, dense, finely-crystalline felsic volcanic rock, with quartz and albite phenocrysts. Exposed only west of Pescadero. Thickness unknown

KJf **Franciscan Complex, undivided (Cretaceous and Jurassic)**--Mostly graywacke and shale (fs). May be variably sheared. Partly coeval with Pigeon Point Formation (Kpp), granitic rocks of Montara Mountain (Kgr) and Ben Lomond Mountain (Kqd), unnamed shale (Ksh), and unnamed volcanic rocks (KJv). Locally divided into:

fs **Sandstone**--Greenish-gray to buff, fine- to coarse-grained sandstone (graywacke), with interbedded siltstone and shale. Siltstone and shale interbeds constitute less than 20 percent of unit, but in places form sequences as much as several tens of meters thick. In many places, shearing has obscured bedding relations; rock in which shale has been sheared to gouge constitutes about 10 percent of unit. Gouge is concentrated in zones that are commonly less than 30 m wide but in places may be as much as 150 m wide. Total thickness of unit is unknown but is probably at least many hundreds of meters

fg **Greenstone**--Dark-green to red altered basaltic rocks, including flows, pillow lavas, breccias, tuff breccias, tuffs, and minor related intrusive rocks, in unknown proportions. Unit includes some Franciscan chert and limestone bodies that are too small to show on map. Greenstone crops out in lenticular bodies varying in thickness from a few meters to many hundreds of meters

fc **Chert**--White, green, red, and orange chert, in places interbedded with reddish-brown shale. Chert and shale commonly are rhythmically banded in thin layers, but chert also crops out in very thick layers. In San Carlos, chert has been altered along faults to tan- to buff-colored clay. Chert and shale crop out in lenticular bodies as much as 75 m thick; chert bodies are commonly associated with Franciscan greenstone.

fl **Limestone**--Light-gray, finely- to coarsely-crystalline limestone. In places limestone is unbedded, in other places it is distinctly bedded between beds of black chert. Limestone crops out in lenticular bodies up to 120 m thick, in most places surrounded by Franciscan greenstone

fm **Metamorphic rocks**--Dusky-blue to brownish-gray blocks of metamorphic rock, commonly glaucophane schist, but some quartz-mica granulite. These rocks are finely to coarsely crystalline and commonly foliated. They almost always crop out as tectonic inclusions in sheared Franciscan rocks (fsr) and serpentinite (sp), and they reach maximum dimensions of several tens of meters though many are too small to show on map

fh **Argillite** -- Dark-gray to grayish-black argillite and shale with minor beds of sandstone.

fsr **Sheared rock (melange)**--Predominantly graywacke, siltstone, and shale, substantial portions of which have been sheared, but includes hard blocks of all other Franciscan rock types. Total thickness of unit is unknown, but is probably at least several tens of meters

sp **Serpentinite (Cretaceous and/or Jurassic)**--Greenish-gray to bluish-green sheared serpentinite, enclosing variably abundant blocks of unsheared rock. Blocks are commonly less than 3 m in diameter, but range in size from several centimeters to several meters; they consist of greenish-black serpentinite, schist, rodingite, ultramafic rock, and silica-carbonate rock, nearly all of which are too small to be shown on the map

Jsv **Siliceous volcanic rocks and keratophyre (Jurassic?)**-- Highly altered intermediate and silicic volcanic and hypabyssal rocks. Feldspars are almost all replaced by albite. Recent biostratigraphic and isotopic analyses yielded a Jurassic age for similar rocks in Alameda and Contra Costa Counties (Jones and Curtis, 1991)

Jgb **Gabbro (Jurassic?)**--Light green-gray, dark-gray weathering, mafic intrusive rock, mostly gabbro but also includes some diabase locally. The age of this unit is unknown, but the unit is probably part of the Jurassic Coast Range Ophiolite

db **Diabase and gabbro (Jurassic?)**

gd **Gneissic granodiorite (Mesozoic or Paleozoic)** -- Strongly foliated, black and white gneiss. Foliation due to alignment of lenses of dark minerals in a light-colored matrix.

sch **Metasedimentary rocks (Mesozoic or Paleozoic)** -- Mainly pelitic schist and quartzite.

m **Marble (Mesozoic or Paleozoic)**-- White to gray finely crystalline marble and graphitic marble, in places distinctly bedded, in places foliated. Near Montara Mountain, this unit also includes quartz-mica hornfels and crops out as rare isolated bodies as much as 75 m long in granitic rocks. Near Ben Lomond Mountain, the unit locally includes schist and calc-silicate rocks.

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Sources Of Data

Quaternary deposits in Santa Cruz County nearly entirely from Dupré (1975). Quaternary deposits in the west half of San Mateo County are mostly from Lajoie and others (1974), and in the east half are modified from Helley and Graymer (1997), Pampeyan (1994), Pampeyan (1993), and Lajoie and others (1974). Lines for San Andreas fault in San Mateo County are from Brown (1972)

1. Pampeyan (1993) and Helley and others (1994). See also Helley and Lajoie (1979), and Pampeyan (1970a). Faults inferred from geophysical investigations by Brabb and Hanna (1981) and Carle and others (1990).

2. Pampeyan (1993 and 1970a), some data from Dibblee (1966), Brown (1972), Dickinson (1970), Rodine (1973), and Fleck (1967). See also Brabb and others (1991), and Beaulieu (1970).

3. Dibblee (1966).

4 Cummings (1960) and Dibblee (1966). See also Cummings and others (1962).

5. McLaughlin (1969); some field checking by E.E. Brabb, 1969, and E.H. Pampeyan, 1971.

6. Rogers and Armstrong (1973), some data from Dibblee (1966).

7. Unpublished geologic mapping by S.A. Brooks, K.F. Oles, and Eugene Borax, Union Oil Company of California, 1956, scale 1:24,000; some data from Classen (1959). Additional field work by T.W. Dibblee, Jr.,1947-49, and by E.E. Brabb, 1968-69.

8. New mapping by authors.

9. Thomas (1951) and field reconnaissance by E.E. Brabb, 1969, and E.H. Pampeyan, 1963.

10. Schlocker and others (1965), and Brown (1972).

11. Esser (1958), and Mack (1959), modified by field checking by E.E. Brabb, 1968-69.

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15. Dibblee (1966), and Johnson and Ellen (1968).

16. Dibblee (1966). Some data from Cummings (1960) and Cummings and others (1962).

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18. Brabb (1960). See also Cummings and others (1962) and Brabb (1964).

19. Cummings (1960). See also Cummings and others (1962).

20. Clark (1970), Clark and Brabb (1978), and Brabb, Clark, and Throckmorton (1977). More recently Clark (1981).

21. Miller-Hoare (1980).

22. Sorg and McLaughlin (1975). Some data from Dibblee (1966), Cotton and Associates (1978), W. McCormick (written comm., 1991), Cotton and Associates (written comm., 1991), and Helley and others (1994).

23. Helley and others (1994). See also Helley and Lajoie (1979). Faults inferred from geophysical investigations by Brabb and Hanna (1981) and Carle and others (1990).

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