Geologic Map and Map Database of Western Sonoma, Northernmost Marin, and Southernmost Mendocino Counties, California

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Contents

Geologic Explanation and Acknowledgements

Introduction

This report contains a new geologic map at 1:100,000 scale and an associated set of geologic map databases (Arc-Info coverages) containing information at a resolution associated with 1:62,500 scale. The map and map database, along with this interpretive text, are based on the integration of previous work with new geologic mapping and field checking by the authors (see Sources of Data index map on the map sheet or the Arc-Info coverage wso-so and the textfile wso-so.txt). The descriptive text (below) contains new ideas about the geologic structures in the area, including the active Hayward-Rodgers Creek-Healdsburg Fault system and other active faults in the area, as well as the geologic units and their relations, including the origin of the Franciscan Complex mélange and the Coast Range ophiolite.

Together, the map (or map database) and unit descriptions in this report describe the composition and distribution of geologic materials and the orientation and distribution of geologic structures within the study area at regional scale. Such regional geologic information is important for analysis of earthquake shaking, landslide susceptibility, engineering materials properties, mineral resources and hazards, and groundwater resources and hazards. It is also vital for answering questions about the geologic history and development of the California Coast Ranges.

The information, however, is not sufficiently detailed for site-specific evaluations. Those seeking detailed information of that kind should consult the more detailed earthquake-hazards maps produced by the California Division of Mines and Geology or contact a licensed geologist or engineering geologist.

The map area includes about two-thirds of Sonoma County and a small part of Marin County west of longitude 122°45'W and north of latitude 38°15'N, plus a tiny part of southern Mendocino County along the north edge of the map. This area includes the Pacific coastline in the western part, low rolling hills in the southern part, rugged mountainous terrain in the northern and central parts, and the broad flatlands of Santa Rosa and Alexander Valleys in the eastern part. The northern and central mountains are largely uninhabited, but the eastern valleys are undergoing rapid development.

The map in this report is modified from and supercedes USGS Open-File Report 71-44 (Blake and others, 1971). Two factors led to the decision to remap the area. First, there has been almost 30 years of new geologic information accumulated for the map area. Two areas within the map, in particular, have received much attention since the earlier work: Cazadero/Ward Creek in the central part of the map, where the medium- to high-grade blueschist rocks and minerals have been studied in detail (Liou and Maruyama, 1987; Maruyama and Liou, 1988, 1989; Erickson, 1995; Wakabayashi, 1992a), and the Geysers geothermal field in the northeast corner of the map, which was carefully studied in relation to the production of geothermal steam for generating electricity (McLaughlin, 1978, 1981; McLaughlin and Ohlin, 1984; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Dalrymple, 1992; Hulen and Nielson, 1993; Stanley and others, 1998). Second, tectonic theories for the California Coast Ranges have changed since the publication of the earlier map, and the new tectonic models have a strong influence on the depiction of through-going active faults, volcanic fields, folds, and other mapped features.

The digital nature of the geologic map information available in this publication is important for three reasons. First, the geologic map data can be digitally combined with other map datasets (topography, groundwater information, landslide distribution) for rapid and complex regional analysis of geologic resources and hazards. Second, digital maps are much more easily updated than traditional printed maps. Third, digital publication provides an opportunity for regional planners, local, state, and federal agencies, teachers, consultants, and others who are interested in geologic data to have the new information long before a traditional paper map could be published.

Stratigraphy

Mesozoic and Tertiary terrane complexes

The bedrock units in the San Francisco Bay region are made up of two components: amalgamated, highly deformed tectonostratigraphic terranes that are displaced, at least in part, hundreds to thousands of kilometers from their position of origin (allocthonous or parautochthonous); and generally younger, less deformed rocks that overlie the amalgamated terranes and are roughly in their original location (except for transport along the San Andreas fault system). In most of the region, the older set of rocks is Mesozoic and the younger is Tertiary, but in the map area the amalgamated terranes include some rocks as young as Miocene. The young age of rocks within these displaced terranes reflects additional complexity in the geologic and structural history of the map area that is not found in any other part of the region.

The amalgamated terranes can be grouped into three related rock complexes. One of these, the Great Valley complex, is made up of the Jurassic Coast Range ophiolite, which in the map area consists mostly of serpentinite, gabbro, diabase, basalt, and keratophyre (altered silicic volcanic rocks), and the Jurassic and Cretaceous Great Valley sequence, composed of sandstone, conglomerate, and shale. Although the sedimentary rocks and ophiolite have been tectonically separated almost everywhere in the map area, the Great Valley sequence was originally deposited on the ophiolite. This depositional relationship is extrapolated from contacts exposed outside the map area: in the Berkeley Hills (Jones and Curtis, 1991; Graymer and others, 1996) and Solano County in the San Francisco Bay region, and elsewhere in California. This complex represents the accreted and deformed remnants of arc-related Jurassic oceanic crust with a thick sequence of overlying turbidites, at least in part related to the North American forearc (parautochthonous).

The second set of amalgamated terranes is the Franciscan Complex. These terranes are composed of weakly to strongly metamorphosed graywacke, argillite, basalt, chert, limestone, and other rocks. The rocks of the Franciscan Complex in the map area are mostly derived from Jurassic to Cretaceous oceanic crust and pelagic deposits overlain by Upper Jurassic to lower Tertiary turbidites. Although most Franciscan Complex rocks are little metamorphosed, high-pressure, low-temperature metamorphic minerals are common in rocks that crop out as mélange blocks (Bailey and others, 1964) and in several fault-bounded lenses within the map area. High-grade metamorphic blocks in sheared but relatively unmetamorphosed argillite matrix (Blake and Jones, 1974) reflect the multi-stage history of the Franciscan Complex. The eastern and central parts of the complex were subducted beneath the Coast Range ophiolite, a process that continued until after the deposition of the Franciscan Complex sandstone exposed south of the map area that contains Campanian (Late Cretaceous) fossils (Blake and others, 2000). The youngest parts of the Franciscan Complex, including Tertiary sedimentary rocks, must have accreted in late Eocene or younger time, after deposition of the Tertiary strata. Their original relationship to the older Fransiscan complex rocks and the Great Valley complex is not well understood. Because much of the Franciscan Complex was accreted beneath the Great Valley complex, the contact between the two Mesozoic complexes is everywhere faulted (Bailey and others, 1964), and the Franciscan Complex presumably underlies the entire San Francisco Bay area east of the San Andreas Fault. Subsequent deformation, described below, has obliterated the original subduction contact almost everywhere.

A third complex crops out in the map area only west of the San Andreas Fault Zone at Bodega Head, which is composed of granitic rocks of the Salinian complex. This is the northernmost outcrop of the Salinian complex, which extends southwards between the San Andreas and Sur-Nacimiento Fault Zones about 500 km to the Big Pine Fault east of Santa Barbara (Ross, 1972). The complex in the San Francisco Bay region is made up of Late Cretaceous (81.6-91.6 Ma, Curtis and others, 1958; 80-117 Ma, Kistler and Champion, 1991) granitic rocks intruded into high-grade metamorphic rocks, Late Jurassic (161 Ma, James and others, 1993) gabbroic rocks, and Late Cretaceous (Campanian to Maastrictian) sedimentary rocks (Branner and others, 1909; Hall and others, 1959; Clark, 1981; Brabb and others, 2000).

Both the Franciscan and the Great Valley complexes have been further divided into a number of fault-bounded tectonostratigraphic terranes (Blake and others, 1982, 1984). When the terranes were first defined, the prevailing methodology was to identify separate terranes if there was any doubt about stratigraphic linkage between structurally separated entities. As a result of further research, many additional data, in particular new fossil localities, are known and the distribution and nature of the original terranes have been greatly modified in this report (see below). The distribution of terranes in the map area is shown in map of terranes on the map sheet as well as in the Arc-Info coverage wso-terr.

Description of Terranes

GREAT VALLEY COMPLEX

Healdsburg terrane (gvh)
KJgvc, KJgvs, Jv, Jd, sp

Rocks assigned to the Healdsburg terrane crop out in four fault-bounded lenses. The type area is near Healdsburg, where as much as 3,000 m of Lower Cretaceous conglomerate depositionally overlie Upper Jurassic shale over keratophyre, basalt, gabbro, and peridotite of the Coast Range ophiolite. No depositional contact between the basal shale and the underlying ophiolitic rocks has been observed in the map area, but west of Dry Creek orientation of thin shale and sandstone beds are concordant with the approximate trend of the basal contact, suggesting that the original depositional contact may be preserved there.

The Healdsburg terrane is distinguished from coeval Great Valley sequence rocks by its abundant conglomerate containing clasts mostly of light-colored (often pink) rhyolite porphyry and rhyolitic welded ash-flow tuff, plus minor quartzite (quartz arenite) pebbles (Blake and others, 1984; Jayko and Blake, 1993). Biotite from two cobbles near Black Point south of the map area in Marin County yielded a K-Ar age of about 145 Ma (Berkland, 1969). The source for this Late Jurassic rhyolite remains unknown but, based on sedimentologic and petrologic analyses, appears to be somewhere south of the present Sierra Nevada magmatic arc where a source for the quartzite (quartz arenite) is available in the Peninsula Range of southern California (Jayko and Blake, 1993).

Restoration of Miocene and younger offset on the Hayward-Petaluma Valley /Rodgers Creek fault system proposed by Graymer (1999) juxtaposes the rocks of the Healdsburg terrane north of San Francisco Bay with rocks of similar composition and age east of San Jose (the Berryessa Formation, Wentworth and others, 1998a). The latter rocks were included in the Healdsburg terrane by Jayko and Blake (1993) based on similarity of age and clast composition. Further restoration across the Calaveras Fault Zone brings the combined Healdsburg/Berryessa rocks into proximity with unnamed rocks of similar composition but unknown age in the Quien Sabe area south of Gilroy (Leith, 1949). Because this offset between Black Point and Gilroy would account for all faults of the San Andreas system that cut the Healdsburg terrane, the separation between Gilroy and the Peninsula Range must have taken place on pre-San Andreas faults.

Del Puerto terrane (gvd)

Jk, Jv, sp

The main body of Great Valley complex rocks that have been assigned to the Del Puerto terrane (Blake and others, 1984) lies some 100 km southeast of the map area in the eastern Diablo Range. There, the basal part of the stratigraphic sequence in the terrane is composed of dismembered ophiolite and a thick accumulation of silicic volcanic rocks (keratophyre and quartz keratophyre), overlain by silicic tuff and tuffaceous sandstone of the Upper Jurassic Lotta Creek Formation and Upper Jurassic to Lower Cretaceous turbidites. These rocks are overlain by Upper Cretaceous and Paleocene strata that overlap unconformably eastward onto Sierran basement, which requires the Del Puerto terrane there to be, at least partly, in place (autochthonous).

In the map area, a single small body of Late Jurassic rock in the Camp Meeker quadrangle is herein assigned to the Del Puerto terrane. Although the rock body is small, fault bounded, and isolated from other Del Puerto terrane bodies, this assignment is made because of 1) the presence of a sliver of silicic tuff similar to the Lotta Creek Formation and 2) the absence of much silicic volcanic detritus in the Upper Jurassic and Lower Cretaceous strata (which would be suggestive of Healdsburg rather than Del Puerto terrane).

These Del Puerto terrane rocks are stucturally interleaved with rocks of the Franciscan Complex and Healdsburg terrane and are more than 100 km from the main body of Del Puerto terrane. Restoration of San Andreas fault system offsets described for the Healdsburg terrane, however, brings the Del Puerto terrane rocks of the map area into proximity with the equivalent rocks in the Diablo Range.

Elder Creek terrane (gve)

KJgv, Jv, sp

Great Valley complex rocks east of the Maacama Fault at Black Mountain (Jimtown and The Geysers quadrangles) belong to the Elder Creek terrane, which is marked by the absence of much silicic volcanic rock and the presence of ophiolite breccia at the base of the sedimentary sequence. The Great Valley complex rocks there are composed of serpentinite, sheeted diabase, and pillow basalt overlain by ophiolite breccia, basaltic sandstone, and shale (McLaughlin and Ohlin, 1984).

The Great Valley complex rocks at Black Mountain are interleaved with Franciscan Complex rocks, and so have undergone considerable fault offset. However, Black Mountain is in the same general area as the rest of the Elder Creek terrane north and east of the map area, the easternmost part of which is coextensive with Great Valley rocks that overlap Sierran rocks. Therefore, the Black Mountain rocks must be considered largely in place with respect to North America (parautochthonous).

The ophiolitic rocks that form the base of the Black Mountain section are chemically distinct from the bulk of the Coast Range ophiolite. Giaramita and others (1998) showed that the geochemical signature of the Black Mountain rocks is more akin to mid-ocean ridge basalts than most Coast Range ophiolite rocks (which have a forearc signature, see below), although the high Th/Ta ratio still suggested to them that the Black Mountain rocks formed in a (rifted) forearc.

Point Arena terrane (gvp)

KJsb, Ka, Ks, TKu, Tg

The rocks west of the San Andreas Fault Zone, from Fort Ross northward, are assigned to the Point Arena terrane. This terrane is composed of a basal mafic volcanic section derived from the upper part of ophiolite crust (Phillips and others, 1998) structurally overlain by Upper Cretaceous and lower Tertiary turbidites. These rocks have been assigned to the Great Valley complex (Wentworth and others, 1998b) based on the presence of sheeted sills in the ophiolitic rocks, the absence of blueschist facies metamorphism, and the structural relationship between the ophiolitic rocks and the overlying strata.

However, there are major differences between the rocks of the Point Arena terrane and other Great Valley complex terranes, including the lack of Jurassic and Lower Cretaceous strata, the presence of tropical mollusks (Elder and others, 1998), and the presence of mafic-clast conglomerate. Furthermore, chemical analysis of the ophiolitic rocks in the Point Arena terrane suggest that they were formed in a back-arc environment (Phillips and others, 1998) rather than the forearc environment suggested by the chemistry of most Coast Range ophiolite rocks (see below).

Coast Range ophiolite (cro)

The ophiolitic rocks that make up the basal part of all the Great Valley complex terranes in the map area include most of the rock types that make up a typical ophiolite suite, including serpentinite, pyroxenite, gabbro, diabase, and massive and pillowed basalt. The ophiolite formed between about 164 and 173 Ma (Blake and others, 1992; Hagstrum, 1997; Hopson and others, 1997), but its origin is a matter of debate. As summarized recently by Dickinson and others (1996), three models of ophiolite generation have been suggested for the Coast Range ophiolite: mid-ocean ridge volcanism at equatorial latitudes associated with seafloor spreading, back-arc spreading related to west-directed subduction under an ocean-island arc west of North America, and fore-arc spreading related to east-directed subduction under North America. Geochemical evidence suggests that most Coast Range ophiolite rocks formed in a fore-arc setting (Shervais, 1992; Shervais and Kimbrough, 1985; Dickinson and others, 1996; but see also MacPherson and others, 1985; Giaramita and others, 1998). Paleomagnetic inclinations show that they formed in roughly the same latitude relative to North America that they now occupy, which seems to rule out large northward transport. In addition, there are two belts of ocean-island arc volcanics in the Sierra Nevada Foothills that are roughly the same age as the Coast Range ophiolite [including the Logtown Ridge Formation, Copper Hill volcanics of Clark (1964), and Gopher Ridge Volcanics (Lindgren and Turner, 1894; Imlay, 1961; Behrman, 1978; Graymer and Jones, 1991)] and two similar belts in the Klamath Mountains (the Hayfork and Western Klamath terranes, Murchey and Blake, 1993). These ocean-island arc rocks lie between the Coast Range ophiolite and preexisting North American crust. An additional coeval belt of arc volcanic rocks is preserved as roof pendants within the Sierra Nevada (the Goddard terrane of Nockelberg, 1983). The presence of ocean-island arc rocks between Coast Range ophiolite and North American rocks suggests that there was at least one ocean-island arc between the ophiolite and North America when the ophiolite formed, which would preclude its formation in the forearc related to east-directed subduction beneath North America.

We thus propose a fourth model that satisfies all these geochemical, paleomagnetic, and geologic constraints (fig. 1). In this model, the Coast Range ophiolite formed in the fore-arc of an ocean-island arc related to east-dipping, ocean-ocean subduction some distance west of North America. The Gopher Ridge Volcanics are the remnant of an island arc related to the Coast Range ophiolite, whereas the Goddard terrane represents the remnant of the continental arc related to east-directed, ocean-continent subduction beneath North America. Ophiolite and island-arc rocks were transported more or less directly eastward and accreted to the continental margin after deposition of Kimmeridgian strata that overlie the arc rocks in the Sierra Foothills. During this accretion, arc volcanic rocks and overlying sedimentary rocks underwent penetrative deformation and greenschist-facies metamorphism, prior to intrusion of latest Jurassic (Tithonian) unfoliated plutonic rocks (Saleeby and others, 1989; Graymer and Jones, 1994; Nockelberg, 1983). The accretion probably coincides with early deformation of the Coast Range ophiolite section and deposition of locally overlying ophiolite breccia (Robertson, 1989). The deformed ophiolite and the ophiolite breccia are overlain by unmetamorphosed Tithonian strata (Knoxville Formation), marking the close of the deformational period. This Late Jurassic (late Kimmeridgian to early Tithonian) period of accretion and deformation has been called the Nevadan orogeny (Hinds, 1934).

Serpentinite that is structurally interleaved with Franciscan Complex mélange or that contains high-grade metamorphic blocks has previously been mapped as part of the Franciscan Complex (for example, Coleman, 1996). Therefore, it is important to point out that we consider all serpentinite in the map area part of, or derived from, the Coast Range ophiolite. We base this conclusion primarily on 1) the structural position of the Coast Range ophiolite in the upper plate of the subduction zone associated with accretion of the Franciscan Complex, which would have brought the basal (serpentinite generating) part of the Coast Range ophiolite into proximity with Franciscan Complex rocks, but would not have brought the base of Franciscan Complex ophiolite to higher structural levels and 2) on the absence of intermediate parts of Franciscan Complex ophiolitic crust (static and cumulate gabbro) in the Coast Ranges (see Blake and others, 2000, for a more complete discussion of the serpentinite).

FRANCISCAN COMPLEX

In the northern Coast Ranges, the Franciscan Complex is made up of three structural belts: an Eastern Belt composed of coherent medium- to low-grade blueschist metamorphic rocks (lawsonite-albite and lawsonite-jadeite-quartz sub-facies); a Central Belt composed of slabs of coherent Jurassic and Cretaceous low-grade metavolcanics and metasediments (prehnite-pumpellyite facies) interleaved within mélange; and a Coastal Belt composed mostly of Late Cretaceous and early Tertiary, low-grade metasediments (laumontite facies). The position of these belts probably reflects the order of accretion of Franciscan Complex terranes from easternmost to westernmost. The first-accreted Eastern Belt rocks were also farthest subducted and most metamorphosed, whereas Coastal Belt rocks, which are generally farthest west, are least metamorphosed. The distribution of Franciscan Complex rocks in the map area is not nearly as simple as it is farther north, but we have retained the belt nomenclature as general categories in which to group the Franciscan terranes. Disruption of the simple belt pattern that is observed farther north is probably due to post-accretion faulting, including, but not limited to, offset on faults of the San Andreas Fault system.

Eastern Belt

Cazadero terrane (fcz)
KJfm, KJfmgs

The easternmost Franciscan Complex rocks in the northern Coast Ranges make up the Pickett Peak terrane, which is composed of coherent (not mélange), glaucophane-schist facies, textural zone 2B and 3 metagraywacke, metachert, and metabasalt. K/Ar, Rb/Sr, and Ar/Ar whole-rock and single-mineral ages range from about 135-110 Ma (Lanphere and others, 1978; McDowell and others, 1984; Wakabayashi, 1999a), whereas white-mica Ar-Ar ages range from about 121-125 Ma (Wakabayashi, 1999a).

In the map area, medium-grade blueschist makes up the newly-named Cazadero terrane. These rocks form a more than 50-km-long, northwest-trending slab of textural zone 2B-3A (Jayko and others, 1986) glaucophane- and jadeite-bearing metagraywacke (the Skaggs Springs schist of Wakabayashi, 1992b) that runs from the Healdsburg quadrangle to the Gube Mountain quadrangle. They also form a set of smaller (less than 15 km long) lenses of low- to medium-grade (type II and III of Coleman and Lee, 1963) metabasalt and metasediments (the Ward Creek Schist of Coleman and Lee, 1963) interleaved with mélange and Great Valley complex rocks in the Cazadero and Fort Ross quadrangles. K/Ar radiometric dates from the Ward Creek schist range from 135±7 to 150±7.5 Ma (Lee and others, 1964; Coleman and Lanphere, 1971) in addition to an Ar/Ar age of 142.6±0.5 Ma (Wakabayashi and Deino, 1989), and the Skaggs Springs schist has yielded an Ar/Ar age of about 141 Ma (Wakabayashi, 1999a). These rocks were previously correlated with the Pickett Peak terrane of the northern Coast Ranges (Blake and others, 1984), but they differ from those rocks in that they are largely metagraywacke rather than metapelite, are higher grade (higher P/T), and are older than most Pickett Peak terrane rocks.

Yolla Bolly terrane (fyb)
KJfm, KJfmgs

Although not extensive in the map area, one of the most widespread and distinctive Franciscan Complex units in the San Francisco Bay region is the Yolla Bolly terrane. This terrane consists of metagraywacke, metachert, and metabasalt, all containing abundant blueschist-facies minerals such as lawsonite, jadeitic pyroxene, and metamorphic aragonite. In addition, the metagraywacke is characterized by a weak to pronounced foliation (textural zone 2 of Blake and others, 1967).

No fossils are known from the Yolla Bolly rocks of the study area, but similar metachert from the Diablo Range and northern Coast Ranges (Sliter and others, 1993; Isozaki and Blake, 1994) yielded ages that range from Early(?) to Late Jurassic, and the overlying metagraywacke in the Diablo Range is latest Jurassic (Tithonian; Crawford, 1976). The blueschist metamorphism shows that these rocks have been subducted, with the age of the graywacke, derived from arc volcanics associated with a subduction zone, presumably marking the time when the oceanic rocks approached and entered the trench (Wentworth and others, 1998a). The radiometric age of metamorphic minerals in Yolla Bolly terrane rocks is 92-100 Ma (Maruyama and others, 1992; Mattinson and Echevarria, 1980), marking the peak of subduction zone metamorphism. Thus, Yolla Bolly terrane rocks were resident in the subduction zone for at least 50 million years after the Late Jurassic time of their approach and entry into the trench.

The outcrops of Yolla Bolly terrane rocks in the Two Rock quadrangle comprise the northern tip of a north-northwest-trending slab of jadeite-bearing metagraywacke with a pronounced foliation (textural zone 2B of Jayko and others, 1986). These rocks have been correlated with the type Yolla Bolly terrane of northern California (Blake and others, 1984) based on similarities in lithology, sandstone composition, and metamorphic state. In addition, a complex set of northwest-trending slabs of type I and II basalt and metabasalt with minor metagraywacke (textural zone 2A) in the Duncans Mills, Cazadero, and Fort Ross quadrangles are tentatively assigned to the Yolla Bolly terrane, even though they were previously thought to be a lower-grade equivalent of the Ward Creek schist (Coleman and Lee, 1963).

Central Belt

Novato Quarry terrane (fnq)

Kfss

The Novato Quarry terrane forms a relatively narrow and discontinuous, northwest-trending belt between the Hayward Fault, southeast of the map area, and the San Andreas Fault. Though mostly southeast of the map area, Novato Quarry terrane rocks form a small thrust wedge interleaved with mélange in the Bodega Head quadrangle.

This terrane consists largely of thin-bedded turbidites with local channel deposits of massive sandstone (see Blake and others, 1984, for discussion of depositional environments as well as photographs of typical outcrops). Although the strata are in many places folded and locally disrupted (broken formation), they are nearly everywhere well bedded.

The Novato Quarry terrane sandstone contains metamorphic prehnite and pumpellyite and is arkosic with abundant K-feldspar, indicating derivation from a granitic or rhyolitic source area. Several specimens of *Inoceramus schmidti* of Late Cretaceous (Campanian) age have been found in this terrane (Bailey and others, 1964). Novato Quarry terrane sandstone composition is similar to the arkosic part of the Coastal belt, but Coastal belt strata are generally more poorly bedded and more disrupted and Novato Quarry terrane rocks are older.

The age of the Novato Quarry terrane rocks constrains Central Belt Franciscan Complex sandstone deposition to have continued at least into Campanian time, with subsequent accretion at the subducting plate margin.

Devils Den Canyon terrane (fdd)

Kfss

Three slabs of coherent graywacke northeast of Alexander Valley (Jimtown, Geyserville, Asti, and The Geysers quadrangles) are herein assigned to the Devils Den Canyon terrane. These rocks include those designated Devils Den Canyon terrane by McLaughlin and Ohlin (1984), rocks outside their study area, and rocks they correlated with the Geysers terrane (which is considered herein part of the Marin Headlands terrane). These rocks were also previously considered part of the Rio Nido terrane (Jayko and Blake, 1984) and both Rio Nido and Central terranes (Blake and others, 1984).

The graywacke of the Devils Den Canyon terrane is feldspathic-lithic, locally displays a very slight incipient foliation (textural zone 2A of Jayko and others, 1986), and contains abundant, large (more than 1 mm) grains of detrital white mica. Microscopic pumpellyite is abundant, but lawsonite and prehnite are not. McLaughlin and Ohlin (1984) noted that some Devils Den Canyon terrane graywacke is rich in chert detritus, but point counts by Jayko and Blake (1984) showed no such distinction relative to other Central Belt terranes. No fossils are known from the Devils Den Canyon terrane, so its age relative to other Franciscan Complex terranes is not constrained.

The Devils Den Canyon terrane rocks are grouped together because of their geographic proximity and their lithologic similarity. They are distinguished from other, similar graywacke of the Lake Sonoma terrane and the Coastal Belt terranes because of their structural position and incipient foliation. They contain less lithic detritus than the graywacke of the Marin Headlands terrane and Central “terrane”. We have discarded the Rio Nido terrane designation, and other rocks previously assigned to that terrane are now considered part of the newly named Lake Sonoma terrane and the Coastal Belt terranes (see Undivided Central and Coastal Belt below for discussion).

Lake Sonoma terrane (fls)

Kfss, gs

The positively identified extent of the newly named Lake Sonoma terrane is one body of coherent graywacke and minor chert and greenstone southwest of Lake Sonoma (Warm Springs Dam, Tombs Creek, and Bigfoot Mountain quadrangles). The graywacke is moderately lithic and unfoliated (textural zone 1 of Jayko and others, 1986). Small to large lenses of intercalated chert and greenstone are common in parts of the terrane and are also unfoliated.

Lake Sonoma terrane graywacke has previously been considered part of the Coastal Belt (Bailey and others, 1964) and the Rio Nido terrane (Blake and others, 1984; Jayko and Blake, 1984). The lithology of the graywacke in this terrane is indistinguishable from that of the lithic facies of the Coastal Belt (Jayko and Blake, 1984). However, these rocks have yielded a fossil of Late Cretaceous (Turonian) age (Bailey and others, 1964). That age is too old to permit the Lake Sonoma terrane rocks to be part of the Coastal Belt, because graywacke from the latter is underlain by younger pelagic deposits of Late Cretaceous (Campanian-Maastrichtian) to middle Eocene age (Sliter, 1984 and written commun., 1990). The Lake Sonoma terrane graywacke is also similar to that of the Devils Den Canyon terrane, but is provisionally distinguished herein based on lower structural position, lack of foliation, and presence of greenstone and chert. As noted above, we have discarded the Rio Nido terrane designation (see Undivided Central and Coastal Belt below for discussion).

Marin Headlands terrane (fmh)
Kfgwy, KJfch, KJfgcs, KJfgc, Jfgs

Marin Headlands terrane is the most widely dispersed Central Belt terrane in the San Francisco Bay area, cropping out at Mount Diablo in Contra Costa County, in San Mateo County, in San Francisco, in several areas of Marin County, and as two large bodies in the map area: a complexly faulted slab more than 25 km long in the northeast corner of the map area (Asti and The Geysers quadrangles) and a narrow, tightly folded and faulted body west of Healdsburg (Guerneville, Geyserville, and Warm Springs Dam quadrangles).

Rocks of this terrane have been previously mapped as Geysers terrane (McLaughlin and Ohlin, 1984), Central terrane (Blake and others, 1984), and Central and Nicasio Reservoir terranes (Jayko and Blake, 1984). However, Murchey and Jones (1984) showed that chert bodies from the rocks in the map area contain radiolarians that match almost all the radiolarian assemblages known from the Marin Headlands type area. Furthermore, like the type area, the rocks assigned to this terrane are distinguished by coherent stacked sequences of pillowed greenstone, ribbon chert, and lithic graywacke.

The age and tectonic history of the Marin Headlands terrane is also well constrained. The chert layers range in age from late Early Jurassic (Toarcian to Pleinsbachian) to late Early or early Late Cretaceous (late Albian to Cenomanian), although the oldest cherts are missing in the map area (the basal chert here is early Middle Jurassic, Bajocian; Murchey and Jones, 1984). Graywacke that overlies chert south of the mapped area has yielded ammonites of Albian to Cenomanian age (Bailey and others, 1964). Geochemical and paleomagnetic analysis of the pillow basalt and chert (Karl, 1984; Gromme, 1984; Shervais, 1989; Murray and others, 1990; Hagstrum and Murchey, 1993) has revealed a history of Early Jurassic oceanic crust being progressively overlain by pelagic deposits (chert), while being together brought closer to North America by plate motion until close approach to the subduction margin in Albian or Cenomanian time, when arc-related detrital sediments overwhelmed pelagic deposition. Soon after, the upper oceanic crust and overlying sediments were accreted to the continental margin at about 10°-15° north latitude and have been transported north to their current position (about 37°-39° north latitude) by transform offset along the continental margin.

The history of the Marin Headlands terrane provides an attractive model for the tectonic history of all Franciscan Complex terranes: oceanic rocks (including MORB and seamounts), overlain by pelagic and detrital sediments, brought into proximity with North America by convergent plate motion, more or less subducted, accreted, and moved northward to their current position on the continent by transform offset along the continental margin.

Central “terrane” (mélange, fm)
fsr, KJfs

All of the previously described Franciscan Complex terranes in the map area are tectonically enclosed in an argillite matrix mélange that has been called the Central terrane (Blake and others, 1982, 1984). Most of the matrix consists of sheared mudstone (argillite) and lithic sandstone, within which are mixed numerous blocks and slabs of coherent graywacke, greenstone, chert, metamorphic rocks, limestone, serpentinite, and other rocks. Although treated as a single terrane, the mélange is actually the result of the tectonic and (or) sedimentary mixing of rocks derived from several terranes: the rocks that would form the sheared matrix from one or more terranes, the chert, greenstone and metamorphic rocks from other Franciscan Complex terranes, and the serpentinite and scarce gabbro from the Coast Range ophiolite. In particular, most of the chert blocks that crop out in the mélange in Marin County, south of the mapped area, can be assigned with confidence to the Marin Headlands terrane based on similarity of radiolarian faunas (Murchey and Jones, 1984).

In a few places in the map area, such as the sea cliffs south of Goat Rock in the Arched Rock quadrangle, the southwestern part of Pine Flat Road in the Jimtown quadrangle, and along King Ridge Road in the Cazadero quadrangle, coherent bodies of lithic graywacke and conglomerate crop out. These rocks are identical in composition to the graywacke that forms part of the mélange matrix (Jayko and Blake, 1984). The graywackes have yielded several Late Jurassic fossils (Bailey and others, 1964). Rocks of similar age and composition are well exposed at the abandoned quarry at Greenbrae in Marin County south of the study area (Blake and others, 2000). There, it is possible to see preserved slabs of interbedded graywacke, mudstone, chert, and tuffaceous greenstone that have yielded both megafossils and microfossils (radiolaria and dinoflagellates) of Late Jurassic and Early Cretaceous age (Blake and Jones, 1974; Murchey and Jones, 1984). In Greenbrae, the strata are progressively more disrupted by normal faulting outward toward the edge of the coherent body.

Despite their similar ages, the radiolarian fauna found in the Marin Headlands chert blocks in the mélange is different from that found in chert interbedded in the matrix source rock. This difference in chert faunas has led to the concept that the mélange matrix is derived from a deep-water, continental-margin deposit into which the accreting terranes were introduced by tectonic or sedimentary processes. The idea that the matrix material is derived from sediments related to the continent is supported by the observation that chert pebbles from conglomerate associated with matrix graywacke have yielded Late Triassic to Early Jurassic radiolaria (Seiders and Blome, 1984), older than those known from any Franciscan chert, but equivalent to many chert bodies in the Sierra Foothills (for example, see Graymer and Jones, 1994). Deformation during accretion resulted in the interleaving of the rocks that would become mélange matrix and the accreted terranes. Deformation during subsequent uplift has led to both the almost complete disruption of the original sedimentary character of the matrix and the inmixing of exotic blocks derived from the accreted terranes, such as the chert blocks from Marin Headlands terrane (Blake and Wentworth, 1999). Only in a few locations, like the seacliffs south of the mouth of the Russian River, is the sedimentary layering of the mélange matrix source rock preserved.

During the period of deformation and inmixing of accreted terrane rocks, graywacke from accreted terranes was probably also sheared into the mélange matrix at the boundary of coherent graywacke slabs. For example, the boundary between Marin Headlands terrane graywacke and adjacent mélange is gradational in the sea-cliff exposures at Rodeo Cove south of the mapped area (see Blake and others, 2000). Such inmixing of other Franciscan Complex graywacke into the mélange matrix is limited, however, as indicated by a matrix composition that is generally more lithic than graywacke found in coherent slabs of other terranes (Jayko and Blake, 1984).

The mechanism by which the mélange blocks (knockers) were originally incorporated into the matrix rock is still an issue of some debate. The two contrasting models can be briefly described as follows:

1. The sedimentary model suggests that blocks (olistoliths) were transported into the depositional environment of the matrix material by gravity driven debris slides. The trench associated with the subduction zone provides an area of suitably steep slope for this theory and the converging plates bring the displaced terranes into proximity of the continental margin mélange matrix. The resulting olistostrome then underwent the deformation described above, disrupting the original depositional character of the matrix/block relationships.
2. The tectonic model suggests that primary incorporation of blocks into mélange was by tectonic processes. During and after accretion, lenses of rock derived from incoming exotic terranes were interleaved with continental margin deposits by faulting. Subsequent deformation during uplift further broke up the lenses of exotic rocks, forming the mélange blocks observed today.

We prefer the tectonic model for the Franciscan Complex mélange for the following reasons:

1. No original depositional relationship between block and matrix has been observed, although areas of relatively undisrupted matrix graywacke are known. Several workers have documented contacts reported as depositional within the mélange, but those contacts are either between different lithologies within a single mélange block or coherent parts of the mélange matrix strata (such as the graywacke on chert contact reported by Erickson, 1995). Presumed contacts are the result of progressively increasing shearing at the transition from a coherent block to mélange (such as that reported by Gucwa (1975) and found at Rodeo Cove and Greenbrae).
2. Radiolarians in the blocks are of similar age to or younger than those in the matrix. If the blocks were deposited as olistoliths, they would have had to be lithified prior to redeposition. This implies that they should be appreciably older than the matrix, like those cherts found in the pebbles within matrix conglomerates. Likewise, mélange blocks of limestone are known to contain Late Cretaceous (Cenomanian and Turonian) fossils (Bailey and others, 1964; Sliter, 1984), much too young to be redeposited as olistoliths in Late Jurassic-Early Cretaceous time.
3. High-grade metamorphic blocks are incorporated into low-grade mélange matrix. The tectonic model provides the mechanism (fault offset) to transport material from the deeper part of the subduction zone back into the upper part of the accretionary prism, intermixing high-grade material with lower grade rock. The sedimentary model requires that blueschist metamorphism was complete before formation of olistoliths, suggesting a tectonic history of deep subduction, uplift to the surface, erosion and deposition, shallow subduction and accretion, and a second period of uplift to the surface. The complex series of events required by the sedimentary model would have had to take place quickly, because, although the age of the high-grade blocks is about 160 Ma, metamorphic minerals in veins in the blocks are as young as 135 Ma (Kelley, 1982; McDowell and others, 1984; Wakabayashi and Deino, 1989; Nelson, 1991; Wakabayashi, 1992a, 1999a) which overlaps with, and in some cases is younger than, the Late Jurassic (Tithonian, 141-146 Ma, van Eysinga, 1978) age of the matrix sediments.

Explanations for the origin of the mélange blocks that are more complex can be proposed in order to retain the sedimentary model. For example, some authors have proposed distinguishing several distinct mélange terranes within the Central Belt. Perhaps the younger chert and limestone blocks are limited to mélange derived from a younger olistostrome. No young fossils have been found in lithic graywacke associated with the mélange, however, and no coherent graywacke of appropriate age (younger than Turonian limestone blocks) and composition to be part of a younger olistostrome is known in the Franciscan Complex (Marin Headlands terrane graywacke is similar in composition, but is too old). Furthermore, young mélange blocks are not concentrated in specific zones in the map area, making the idea of multiple mélanges less likely. The model of a single mélange derived from a young olistostrome with Late Jurassic graywacke included as detritus explains the presence of old fossils and the generally similar distribution of mélange blocks throughout the area but does not explain the lack of known young lithic graywacke or the compositional similarity between the Late Jurassic lithic graywacke and mélange matrix.

The presence of serpentinite blocks in the mélange also suggests that blocks of the Coast Range ophiolite may have been incorporated into the mélange during uplift and disruption, although the correlation of the serpentinite blocks with the Coast Range ophiolite is unproven (see Blake and others, 2000). Macpherson and others (1990) argued that many of the volcanic blocks in the mélange may also come from the Coast Range ophiolite.

Undivided Central and Coastal Belt (fcl)
TKfs

As noted above, graywacke of the Lake Sonoma terrane is lithologically indistinguishable from that of the Coastal Belt lithic facies, but the age of the Lake Sonoma terrane graywacke is Late Cretaceous (Turonian) whereas the Coastal Belt graywacke is Late Cretaceous (Maastrichtian) and Tertiary. Blake and others (1984) noted the age distinction, and divided the similar graywacke in the map area into Coastal terrane (younger) and Rio Nido terrane (older) based on differing K-feldspar content. However, reexamination of the K-feldspar distribution (Bailey and others, 1964; Blake, unpub. data) reveals no distinction between rocks previously mapped as Coastal terrane and Rio Nido terrane. In addition, laumontite, which indicates the very low grade metamorphism associated with the Coastal Belt, has been found by the authors in rocks previously mapped as Rio Nido terrane. Therefore, at this time, among rocks previously mapped as Rio Nido or Coastal terrane, it is possible to categorize only those graywacke bodies that are stratigraphically well controlled by fossils to specific terranes or belts with any confidence.

As a result, we have designated all those bodies of graywacke similar to Lake Sonoma terrane and Coastal Belt lithic facies graywackes that lack known fossils as undivided Central and Coastal Belt. Because the Rio Nido area is underlain by rocks thus designated as undivided, we have abandoned the name Rio Nido terrane for those rocks known to be older and renamed them Lake Sonoma terrane after the large reservoir in the area of the critical Turonian fossil locality. More detailed studies of laumontite distribution or more fossil data would probably make separation of the presently undivided rocks possible, but that is beyond the scope of this work.

Coastal Belt (fco)
TKfss

The Coastal Belt has been subdivided into terranes in areas north of the map area, but although Coastal Belt rocks in the map area were previously designated part of the Coastal terrane (Blake and others, 1984), we found insufficient evidence to extend those terrane distinctions into the map area. The Coastal Belt rocks in the map area are very low grade (laumontite facies) and consist of moderately lithic to quartz-feldspathic wacke, underlain locally by minor greenstone, chert, and limestone. Bailey and others (1964) reported a Late Cretaceous (Turonian) age from one of the limestones, but that locality (Annapolis quadrangle) is now thought by us to be a block in an infaulted lens of Central Belt mélange. Pelagic limestone interbedded with chert and basalt at the base of the section on Wheatfield Fork of the Gualala River (Tombs Creek quadrangle) has yielded fossils of middle Eocene age (W. Sliter, written commun., 1990).

In the same structural block north of the map area, the sandstone contains fossils of Late Cretaceous to late Eocene (possibly Oligocene) age (Evitt and Pierce, 1975; Bachman, 1978). There, sandstone overlies basalt and pelagic deposits of Late Cretaceous (Campanian to Maastrichtian) age (Bachman, 1978; Sliter, 1984) along a sheared contact. Farther north, where the Coastal Belt is divided into three terranes, McLaughlin and others (1980) reported Coastal Belt rocks as young as middle Miocene overlying ophiolitic rocks of Late Cretaceous (Coniacian to Campanian) age from one terrane (King Range terrane).

The Coastal Belt sandstones within the map area are mostly massive, but where fine-grained interbeds are present, the bedding is almost everywhere moderately to completely disrupted by extensional deformation, creating lenses (boudins) of competent sandstone in a sheared mudstone and siltstone matrix.

The Coastal Belt rocks are probably derived from Late Cretaceous and early Tertiary seafloor and overlying Cretaceous and Tertiary pelagic and detrital sediments that were accreted in late Eocene to Miocene time. Systematic variation in sandstone composition suggest that Coastal Belt detritus was derived from a number of different sources, including two different batholithic sources as well as an arc-volcanic source and Central Belt Franciscan

Complex sources (Kramer, 1976; Underwood and Bachman, 1986; McLaughlin and others, 1994). Detailed geochemical studies reveal that the source of the coeval Tyee Formation in Oregon was the Idaho Batholith (Heller and others, 1985), so Underwood and Bachman (1986) proposed that Coastal Belt detritus was derived from the Idaho Batholith, Sierra Nevada batholith, and eastern Oregon/Washington volcanic arc rocks.

Paleontologic (Sliter, 1984) and paleomagnetic (Harbert and others, 1984) data suggest that deposition of the Late Cretaceous limestone took place at about 20° N latitude and that these Coastal Belt rocks were transported to their accretion to North America by relative motion of the Farallon plate. Accretion, extensional deformation, and erosional unroofing of the Coastal Belt was completed before the deposition of the largely undeformed, unconformably overlying Pliocene Ohlson Ranch strata.

Tertiary Stratigraphy

Franciscan Complex detritus in the Paleocene strata overlying Great Valley complex rocks in Rice Valley (Berkland, 1973) and the eastern Diablo Range (Bartow, 1985), as well as the presence of unmetamorphosed early Eocene quartzofeldspathic strata overlying Franciscan Complex metamorphic rocks in San Mateo County (Pampeyan, 1993), indicate that much of the tectonic activity that brought the two Mesozoic complexes together in the San Francisco Bay area was complete by early Tertiary time. In the map area, however, early Tertiary overlapping strata are missing, and the oldest overlapping strata are the late Miocene Burdell Mountain volcanics (Tb) of Blake and others (2000).

Early Tertiary strata in the map area are instead parts of the Coastal Belt (Franciscan Complex) and the Point Arena terrane (Great Valley complex). The Paleogene strata do not overlap bounding faults, and are unrelated to the juxtaposed rocks in that their age and lithology are incompatible with being part of the same depositional system. For example, Campanian graywacke of the Novato Quarry terrane was probably deposited in an arc-trench environment, whereas coeval pelagic limestones in the Coastal Belt were deposited far offshore. The Coastal Belt terranes didn't experience arc-trench deposition until post-Maastrichtian time, and there are no coeval Novato Quarry terrane rocks (the Novato Quarry terrane had probably been accreted by that time). The incompatible stratigraphies show that the Mesozoic and Tertiary terranes have experienced a history distinct from adjoining rocks and, therefore, were formed apart from them and have been juxtaposed with the other Mesozoic terranes in the area by post-Eocene accretion and transform offset. The Salinian complex rocks at Bodega Head lack any Tertiary strata whatsoever, but stratigraphic relations at Point Reyes south of the map area show that the Salinian complex terranes have also undergone similar post-Eocene offset.

The lack of pre-late Miocene strata overlapping the Central and Eastern Belt terranes of the Franciscan Complex and Healdsburg and Del Puerto terranes of the Great Valley complex in the map area is puzzling. The age of the graywacke in the Franciscan Complex suggests that Central Belt terrane accretion was complete by Late Cretaceous (Campanian or Maastrichtian) time, because graywacke deposition is thought to reflect approach to the subduction zone. Furthermore, Tertiary stratigraphic relations south of the map area indicate that Franciscan and Great Valley complex rocks were exposed at the surface as early as Paleocene time (for example, see Graymer and others, 1994; Wentworth and others, 1998a; Brabb and others, 2000). The Mesozoic rocks in the map area must either have become unroofed later than similar rocks farther south, have been uniformly uplifted until late Miocene time so that earlier Tertiary deposition never took place, or have undergone pervasive uplift and total erosion of previously overlying pre-late Miocene strata in Miocene time. After restoration of post-late Miocene right-lateral fault offset related to the San Andreas Fault System (see below), Mesozoic rocks in the map area are adjacent to middle Miocene and older strata in the Berkeley Hills. Those strata do not contain recognizable Franciscan Complex detritus, however, suggesting that the map area was either not undergoing extensive erosion that would produce a large amount of detritus or that at that time sediment was transported westward and not recorded in the onshore stratigraphic record.

Whatever the reason for the lack of pre-late Miocene strata in the map area, by late Miocene time the Mesozoic rocks were at the surface. In the southeastern part of the map area, Mesozoic rocks are overlain by ~12 Ma Burdell Mountain volcanics of Blake and others (2000). Rocks in the northern part of the map area were being eroded and the sediment transported eastward to form alluvial deposits that now make up the Orinda Formation in the Berkeley Hills (Wakabayashi, 1999b). Most of the map area continued to be free of sedimentary accumulation until the present, except for four areas.

The southeastern part of the area was covered by a latest Miocene to Pliocene marine embayment to produce the Wilson Grove Formation. Coeval estuarine deposits (sand and gravel of Cotati) and alluvial deposits (Petaluma Formation) adjoining the Wilson Grove Formation on the east suggest a transitional marine-nonmarine depositional environment. The Petaluma Formation at the surface is presently separated from the marine and estuarine rocks by the Petaluma Valley Fault, and restoration of the southern margin of these formations suggests about 35 km of right offset since deposition. These marine and nonmarine rocks extend under the Quaternary deposits of Santa Rosa Valley, as revealed by well logs (D. Zigler, Chevron Petroleum, retired, written commun.). Basalt flow rock is interlayered with the basal part of the sequence in the southeasternmost part of the Wilson Grove Formation and the sand and gravel of Cotati (Two Rock quadrangle), suggesting that onset of deposition was accompanied by volcanism. The basalts have yielded radiometric ages of about 6-8 Ma (Fox and others, 1985b), so they are coeval with and probably associated with the development of the Sonoma Volcanic field farther east. It remains undetermined whether there exists a causal relationship between the development of the Sonoma Volcanic field and the initiation of deposition.

The eastern part of the map area (east of the Rodgers Creek-Healdsburg Fault) was overlain in latest Miocene to Pliocene time by Sonoma Volcanics and interleaved volcaniclastic strata of the Glen Ellen Formation. Volcanic centers and detrital sources were all east of the map area, as shown by clast imbrication, clast source, and other flow-direction indicators within both the Sonoma volcanics and Glen Ellen Formation (McLaughlin and others, 1999).

The northeastern part of the map area developed a small basin probably related to a right-step asperity in the right-lateral Maacama Fault Zone. The timing of the development of this basin is poorly constrained, because the infilling sedimentary deposits (unit Tls) lack diagnostic fossils.

The northwestern part of the map area east of the San Andreas Fault Zone was overlapped by shallow marine deposits in Pliocene time in a narrow embayment to form the Ohlson Ranch Formation.

The overall environment of the map area in late Tertiary time, then, was probably one of low-lying coastal hills and shallow marine embayments flanked on the east by an active volcanic center with related west-facing alluvial fans. Most of the uplift that formed the steep topography seen today postdates Pliocene time, except perhaps in the north-central part of the map area where Tertiary strata are not present.

The Tertiary stratigraphic relationships in the mapped area also reveal significant late Tertiary and Quaternary fault offset. The Glen Ellen and the younger part of the Petaluma-Cotati-Wilson Grove deposystems were roughly coeval, but were distinct in their detritus and depositional environment. The boundary between the two deposystems is the Rodgers Creek-Healdsburg Fault Zone. The juxtaposition of these fault-separated rock bodies with significantly different stratigraphies suggests that they originally formed in separate depositional basins or widely separated parts of a large basin and have since been juxtaposed by large offsets on the separating faults.

Quaternary Surficial Deposits

Quaternary surficial deposits in the map area are mostly undivided. The exceptions are beach sand and marine terraces along the Pacific coast, river terraces along the Russian River and other major drainages, and older alluvial fan deposits in Santa Rosa Valley (Healdsburg and Sebastapol quadrangles). The older alluvial fan deposits were previously mapped as Glen Ellen Formation (Blake and others, 1971; Knudsen and others, 2000), but we have reclassified them based on three factors: 1) they are much less deformed than Glen Ellen Formation, 2) they are not as lithified, and 3) they lack the interbedded tuff that is widespread in much of the Glen Ellen Formation. For a more detailed map of the Quaternary deposits, especially the late Pleistocene and Holocene deposits, see the recent regional Quaternary map of Knudsen and others (2000).

Paleontology

Many different kinds of fossils have proved invaluable in understanding the geology of the map area: *Buchia* in the Franciscan and lower Great Valley complex rocks, *Inoceramus* in the Franciscan Complex, ammonites and mollusks in the Point Arena terrane, radiolarians in the Franciscan Complex chert and Great Valley complex tuff, foraminifers in the Great Valley complex shales and Franciscan Complex limestones, palynomorphs in the Coast Belt, and mollusks, marine and nonmarine vertebrates, and diatoms in the Tertiary rocks.

A partial list of references to paleontological reports in the map area and surrounding areas includes White (1885), Stirton (1939), Weaver (1944), Gealey (1951), Travis (1952), Matsumoto (1960), Bailey and others (1964), Wentworth (1967), McNitt (1968), Christensen (1973), Blake and Jones (1974), Bachman (1978), McLaughlin (1978), McLaughlin and others (1980), Murchey and Jones (1984), Elder and others (1998), McFadden (1998), and Naidu (1999). Preparation of a digital database of fossil localities and associated paleontologic information is being prepared by workers at the U.S. Geological Survey and University of California, Berkeley.

Radiometric Ages

Several different types of rock bodies in the study area have yielded radiometric ages. The volcanic rocks at and near the base of the Wilson Grove Formation and the sand and gravel of Cotati (Tb) have been studied: the most recent report of ages is Fox and others (1985b). Several silicic tuffs that crop out in the map area have been studied by Sarna-Wojcicki (1976) and Sarna-Wojcicki and others (1979). The granitic rocks at Bodega Head have been dated by Kistler and Champion (1991). Dates from the metamorphic rocks in the Eastern Belt as well as metamorphic blocks in the Central Belt mélange have been published by several workers (including Wakabayashi, 1992a; Coleman and Lanphere; 1971, Lee and others, 1964). An overview of radiometric ages in the map area is provided by Kelley (1982), and an overview of Franciscan Complex ages is found in Wakabayashi (1999a).

Structure

The mapped structures fall into two general categories. The older structures are faults that trend generally about N 60° W and are associated with terrane boundaries. Most of these faults dip steeply to the east. The sense of offset on these faults is difficult to determine because the stratigraphies on either side are at least in part unrelated. Parallel faults within coherent terrane slabs are mostly reverse faults that duplicate the internal stratigraphy.

The older structures are truncated by a second set of structures that trend about N30°W. These folds and faults are associated with the faults of the San Andreas Fault system, including the San Andreas, Tolay, Rodgers Creek-Healdsburg, and Maacama fault zones. The sense of offset on these faults is dominantly right lateral, but also includes a significant fault-normal compressional component. The compression is shown by folding and uplift of young strata (QTge, QTor, Qt) adjacent to the fault zones, especially in the eastern part of the map area.

An exception to the overall sense of transpression in the younger system is present at right steps in the fault zones, such as at Little Sulphur Creek (Maacama Fault Zone) and Santa Rosa Valley (Tolay/Petaluma River Fault Zone). In those areas, small fault basins have been formed due to localized transtension. In the Santa Rosa Valley area, these basins have been overlapped and covered by Quaternary alluvial fan deposits, but are known from gravitational anomalies (Chapman and Bishop, 1988). This overlap of basins suggests that right-stepping, right-lateral offset on this fault zone must have died out before Pleistocene time.

Note also that near the younger fault zones, the older (terrane bounding) structures are deflected to be parallel to the younger structural trend. Because of this reorientation, older structures may have been reactivated by younger deformation.

Also present in the map area are many structures that are not depicted in this report because of their small size and complexity. These structures include folded foliation within coherent Eastern Belt terrane slabs; tight folds, shear zones, and extensional fabric in coherent Central and Coastal Belt terrane slabs; disruption and shear fabric in mélange matrix; orientation of bedding or foliation in mélange blocks; and small folds in Great Valley complex strata.

Structural History

The structures in the map area result from a complicated structural history that includes late Mesozoic to early Cenozoic subduction and accretion, at least two periods of subsequent uplift and detachment faulting, followed by oblique strike-slip and reverse faulting that continues today.

The earliest structural relationships in the map area are those that juxtapose the multiple terranes of the Franciscan Complex and the Great Valley complex. Franciscan Complex terranes were transported by oceanic plate motion and accreted to North America at a subduction zone margin. The Great Valley complex formed on the hanging wall of the subduction zone. Because the structurally highest Franciscan Complex rocks are blueschists, Franciscan Complex accretion must have been accomplished by subduction and underplating of incoming terranes to the continental margin, rather than obduction and overthrusting. Therefore the subduction zone hanging wall rocks (Great Valley complex) were originally structurally highest throughout the Coast Ranges.

The metamorphic age of the Cazadero terrane is approximately 130-160 Ma, about the same as the depositional age of the Yolla Bolly and mélange matrix graywackes and the oldest part of the Great Valley complex sediments, and is older than other Franciscan Complex graywackes in the Central and Coastal Belts. Therefore, the Cazadero terrane entered the subduction zone before other Franciscan Complex terranes, prior to 160 Ma.

Structural relationships in the northern Coast Ranges (Wentworth and others, 1984; Blake and others, 1967) suggest that the Cazadero terrane was once the structurally highest and innermost Franciscan Complex terrane in the map area, although the metamorphic grade of Cazadero terrane rocks shows that it was subducted deeper than any other Franciscan Complex terrane, as much as 20 km (P=9.5-12 kb, T=360-380°C; Maruyama and Liou, 1988; Moore and Blake, 1989; Oh, 1990; Oh and others, 1991). Its current structural position, interleaved with terranes of the Central Belt and the Healdsburg terrane of the Great Valley complex, along with the lack of Cazadero terrane rocks along the eastern margin of the Coast Ranges, suggest that it was originally accreted south of the Great Valley, and has since been transported north, along with the Healdsburg terrane.

The model for the history of Franciscan Complex terranes suggested by the Marin Headlands terrane implies that the age of the graywacke sediments in any terrane marks the time of approach of that terrane to the subduction zone and the associated volcanic arc detrital source. The graywacke age of the Yolla Bolly terrane suggests that it approached the continent in Late Jurassic

(Tithonian, 141-146 Ma) time, coeval with deposition of mélange matrix and early Great Valley complex sediments, the latter and possibly the former in the hanging wall of the subduction zone. The Yolla Bolly terrane's subduction resulted in metamorphic ages of about 90-110 Ma and metamorphism less than that of the Cazadero terrane, but greater than that of any Central Belt terrane.

The order of accretion of the structurally lower Central Belt terranes is more problematical because of lack of age control in the Devils Den Canyon terrane and other terranes outside the map area. However, known graywacke ages suggest that Marin Headlands terrane approached the subduction zone first, in late Early to early Late Cretaceous time (Albian to Cenomanian, 106-97 Ma), followed by the Lake Sonoma terrane in middle Late Cretaceous time (Turonian, 94-88 Ma) and the Novato Quarry terrane in late Late Cretaceous time (Campanian, 76-68 Ma). All of these terranes lack the blueschist facies metamorphism characteristic of the Eastern Belt terranes, so they were never subducted as deeply as the higher-grade rocks.

The structural stacking of the oldest, most subducted terranes over the youngest and least subducted suggests that compressional forces at the convergent subduction margin thrust deeply subducted rocks progressively upward to the top of the accretionary prism. Tagami and Dumitru (1996) used zircon fission-track data to show that Yolla Bolly terrane rocks cooled from 300°C to 100°C between 100-70 Ma while Central Belt terranes were being accreted. Wakabayashi and Unruh (1995) proposed that Central Belt terrane subduction at that time was accompanied by thrusting of Eastern Belt terranes to higher structural levels together with detachment and attenuation of the overlying Great Valley complex rocks (first described by Jayko and others, 1987).

Presumably, the rocks that would become the matrix for the mélange were formed between the subduction zone and North America, overlying oceanic crust related to the Coast Range ophiolite in the hanging wall. One of the many unique features of the mélange is that it is interleaved with elongate slabs of coherent Great Valley and Franciscan complex rocks. These relationships extend north of the Mendocino Triple Junction into southwest Oregon and, thus, predate the San Andreas fault system. The interleaving of slabs of mélange matrix sediments with the accreted terranes of the Central Belt probably occurred, at least in part, as the terranes entered the oblique subduction zone, dragging slabs of the hanging wall down. Blueschist facies metamorphism of a small percentage of mélange matrix (Cloos, 1983) supports the idea that matrix was dragged into the subduction zone, though only a small percentage reached blueschist depths. Serpentinite and other ophiolitic rocks that crop out as blocks in the mélange may have been dragged into the subduction zone at this time as well. Transpressive deformation in the accretionary prism above the trench probably further intercalated the mélange with ophiolite and accreted terranes at this time.

As noted above, the period of accretion and crustal thickening was accompanied by detachment and attenuation. The previously stacked terranes were significantly thinned, and previously buried ophiolite and Franciscan Complex rocks were brought to the surface. This thinning resulted in the almost complete attenuation of the Coast Range ophiolite in the map area, leaving only the dismembered fragments of the ophiolite present. Attenuation also took place between the Franciscan Complex terranes, as evidenced by the lateral discontinuity of some terranes in the region (for example, the Novato Quarry terrane is found structurally below the Healdsburg terrane in the map area, separated only by mélange, but in Marin County, south of the map area, coherent slabs of several terranes are present between the Novato Quarry and Healdsburg terranes).

The timing of detachment and attenuation varied throughout the Coast Ranges. Cowan and Page (1975) showed that blueschist facies Franciscan Complex rocks were unroofed by late Late Cretaceous time (Campanian, 76-68 Ma) in the southern Coast Ranges, whereas Krueger and Jones (1989) and Harms and others (1992) showed that the first period of regional attenuation probably initiated 60-70 Ma in the Diablo Range and the northern Coast Ranges. They suggested that extension was complete by late Oligocene time based on the age of strata that overlapped extensional faults (Page, 1970), but in some parts of the San Francisco Bay area, erosional and possibly structural unroofing persisted into the middle Miocene, as suggested by the unconformable contact of middle Miocene strata on Franciscan Complex rocks in the Diablo Range (Osuch, 1970; Graymer and others, 1996) and on Great Valley complex strata in Marin (Blake and others, 2000). Before attenuation was completed, regional uplift of buried layers to the surface had been accomplished by the early Eocene throughout most of the San Francisco Bay region, as indicated by the presence of ophiolite and Franciscan Complex detritus in sedimentary strata of that period both south and east of the mapped area (for example, the Domengene Sandstone in the Cordelia area contains detritus derived from the Coast Range ophiolite; Graymer and others, 1999) and by Eocene sediments that lie unmetamorphosed on Franciscan Complex basement (for example, the Whiskey Hill Formation in San Mateo County; Pampeyan, 1993). Tagami and Dumitru (1996) used apatite fission-track data to show that Yolla Bolly rocks were lifted through the 90°C level about 40 Ma. The overall picture, then, is one of uplift and attenuation that started as early as 100 Ma (as suggested by zircon fission-track data), had unroofed Franciscan Complex rocks regionally by Eocene time (37-

57 Ma), and may have continued locally as late as middle Miocene time (20 Ma).

The attenuation of this period probably obliterated most of the subduction-related thrust faults in the mapped rocks. For example, the original subduction related thrust fault between the Franciscan Complex and Coast Range ophiolite was reactivated as a detachment fault throughout most of its extent (Krueger and Jones, 1989), and many of the other rock units in the map area are also bounded by normal faults. However, the timing of offset on most of the faults is poorly constrained, so some early faults may remain unrecognized. The tectonic model of incorporation of blocks into the Franciscan Complex mélange suggests that much of the tectonic mixing associated with mélange was accomplished during attenuation, and disruption of coherent parts of the mélange matrix in the map area by normal faulting supports this idea (Blake and others, 2000).

The entire period of extensional faulting in the accretionary prism was accompanied by continued east-directed oblique subduction. By Eocene time, the Coastal Belt terranes were in position to begin receiving arc-derived detritus near the subduction zone. Coastal Belt rocks were accreted from late Eocene to middle Miocene time (40-20 Ma), perhaps associated with the end of attenuation and detachment in the accretionary prism.

The accretion of the Coastal Belt rocks was also coeval with the initiation of tectonic wedging that followed attenuation in the Central Belt. First described by Wentworth and others (1984), tectonic wedging describes east-dipping reverse faulting in the upper crust that soles into a basal decollement in the mid-crust that rooted into the subduction zone. The result is wedge-shaped blocks of upper crust being driven eastward. This process probably produced much of the repetition of structural levels seen in the map area, as originally gently east-dipping bodies of Franciscan and Great Valley complex rocks have been compressed, steepened, and stacked onto originally higher structural levels. The best example of this repetition is the stacking of Franciscan Complex rocks structurally over Great Valley complex rocks that originally formed the highest structural level in the Coast Ranges, first described in Napa County east of the map area (Weaver, 1949). In the map area, Franciscan Complex rocks wedged over Great Valley complex rocks have previously been documented in the Geysers area (Jimtown and The Geysers quadrangles; McLaughlin, 1978) and the Camp Meeker quadrangle (Christensen, 1973). Our work suggests that all of the slabs of Great Valley complex rocks in the map area have a similar structural position.

By late Miocene time, the regional tectonic stress again changed to transpression associated with the development of the San Andreas fault system, although upper crustal tectonic wedging continued. Jones and others (1994) described a significant component of compression normal to the San Andreas fault system and suggested that the pervasive tight folding and imbricate faulting of the Miocene and Pliocene strata in the San Francisco Bay area is due to this compression (see also Graymer, 2000). In the map area, this type of compressive deformation is present in the Glen Ellen Formation and Sonoma Volcanics at the eastern edge of the map and is probably responsible for uplift of the shallow marine Ohlson Ranch Formation to its present position more than 300 m above sea level. It is important to note that compressive deformation is not uniformly distributed throughout the map area, as shown by the relatively undeformed and only modestly uplifted (less than 150 m) the shallow marine Wilson Grove Formation.

In addition to compressive deformation, there is strong evidence of large amounts of right-lateral offset in late Miocene and later time. The San Andreas Fault Zone in central California has undergone about 290-315 km of total right-lateral strike slip (Wentworth and others, 1998b; Dickinson, 1997). In the San Francisco Bay region, this amount is distributed onto several splays of the San Andreas Fault system. About 115-140 km of the offset passed west of San Francisco Bay and feeds into the San Andreas Fault Zone in the map area, and about 175 km of offset passed east of San Francisco Bay (Fox and others, 1985b; McLaughlin and others, 1996; Jachens and others, 1998). Of that eastern offset, 75 km feeds into faults east of the map area and 100 km feeds into the Tolay/Petaluma River Fault Zone (35 km) and the Rodgers Creek/Healdsburg/Maacama Fault Zone (65 km) via the Hayward Fault Zone (modified from Graymer, 1999; Blake and others, 2000; see the index map of faults on the map sheet or the Arc/Info coverage wso-flt for fault names). Additional offset feeds into the San Andreas Fault Zone in the map area from the San Gregorio Fault Zone that joins the San Andreas Fault Zone in southern Marin County. The San Gregorio Fault Zone has undergone about 155-175 km of right offset (Clark and others, 1984; Jachens and others, 1998), so the San Andreas Fault Zone in Marin County south of the map area has undergone about 270-315 km of right-lateral slip. As much as 105 km of that offset may splay from the San Andreas Fault Zone and pass west of the Point Arena terrane on a submarine fault zone (Wentworth and others, 1998b), although Jachens and others (1998) used aeromagnetic evidence to argue that the proposed offshore location of that fault conflicts with the distribution of magnetic rocks at depth. The problem may be resolved by correlation of the granitic rocks at Bodega Head with similar rocks at Montara Mountain in San Mateo County (Kistler and Champion, 1991). The Bodega Head/Montara Mountain correlation requires a major fault between Point Reyes and Bodega Head with 105 km of right offset.

Because this fault would splay from the San Andreas Fault Zone farther south than the splay proposed by Wentworth and others (1998b), it can pass west of the large unfaulted magnetic body described by Jachens and others (1998). In the map area, then, the San Andreas Fault Zone may have only accumulated 165-210 km of right slip.

As a result of the large amounts of right-lateral slip along the continental margin related to the San Andreas Fault system (including the San Gregorio Fault Zone) since late Miocene time (less than 22 Ma), Salinian complex granitic rocks have been brought north as much as 490 km, although granitic rocks at Bodega Head, as well as Great Valley complex Point Arena terrane rocks, may have only traveled 340-385 km. Salinian rocks are thought to be offset from correlative rocks in the Mojave Desert in southern California based on similar age and chemistry (especially Sr isotope ratios which are sensitive to crustal contamination and are therefore good indicators of intrusive environment; Kistler and others, 1973).

The restoration of San Andreas Fault system offset is not enough, however, to account for the presence of tropical mollusks in the Late Cretaceous (late Campanian-early Maastrichtian, about 70-67 Ma) rocks in the Point Arena terrane. If those mollusks were restricted to tropical latitudes, the Point Arena terrane Cretaceous rocks must have been transported hundreds of kilometers from the south prior to the development of the San Andreas Fault system (Wentworth and others, 1998b; Elder and others, 1998). A similar Late Cretaceous to early Tertiary, south to north transport history is recorded in the Coastal Belt of the Franciscan Complex (Sliter, 1984; Harbert and others, 1984).

The Tolay/Petaluma River Fault Zone has probably been inactive at least since Pleistocene time as indicated by overlap of Pleistocene alluvial deposits in Santa Rosa Valley. Principal active faulting in the map area is thought to be focused on the San Andreas, Healdsburg, and Maacama fault zones (Hart and Bryant, 1999). The San Andreas Fault in the map area experienced 4.5 to 5 m of right-lateral surface fault rupture during the 1906 earthquake (Galloway, 1966; Lawson, 1908). The Healdsburg/Rodgers Creek Fault is thought to be the northern extension of the Hayward Fault, which generated a large earthquake in 1868, although no fault rupture occurred in the map area during that event. The more modest 1969 Santa Rosa earthquakes (M 5.6 and M 5.7) were generated by the Rodgers Creek Fault (Budding and others, 1991). For more about active faults in the region, see Working Group on California Earthquake Probabilities (1999).

Description of Map Units

SURFICIAL DEPOSITS

af **Artificial fill (Holocene (Historic))**—Man-made deposit of various materials. Some are compacted and quite firm, especially in earthen dams, but other fills made before 1965 are nearly everywhere not compacted and consist simply of dumped materials. Only two bodies of this unit are shown on the map, one in the Warm Springs Dam and one in the Arched Rock quadrangle. The many other bodies of this unit are too small to be shown at map scale

Qal **Alluvial fan and fluvial deposits (Quaternary)**—Alluvial fan deposits are brown or tan, medium dense to dense, gravelly sand or sandy gravel that generally grade 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. This unit also includes floodplain deposits: medium to dark gray, dense, sandy to silty clay. Lenses of coarser material (silt, sand, and pebbles) may be locally present. In addition, this unit includes natural levee deposits: loose, moderately sorted 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. This unit also includes stream channel deposits: poorly sorted to well-sorted sand, silt, silty sand, or sandy gravel with minor cobbles. Cobbles are more common in the mountain valleys. At the mouth of the Russian and Gualala Rivers and the two esteros in the Valley Ford quadrangle, this unit also includes bay mud (Qm)

Qm **Bay mud (Quaternary)**—Water saturated estuarine mud, predominantly gray, green, and blue clay and silty clay underlying marshlands and tidal mud flats. The mud also contains a few lenses of well-sorted, fine sand and silt, a few shelly layers (oysters), and peat. This unit is mapped separately only in the Bodega Head quadrangle

Qs **Beach and dune sand (Quaternary)**—Fine-grained, very well sorted, well-drained, eolian deposits. They occur mainly in large sheets, as well as many small hills, most displaying Barchan morphology. Dunes display as much as 30 m of erosional relief and are presently being buried by bay mud (Qm). They probably began accumulating after the last interglacial high stand of sea level began to recede about 71 ka, continued to form when sea level dropped to its Wisconsin minimum about 20-15 ka, and probably ceased to accumulate after sea level reached its present elevation (about 6 ka)

Qls **Landslide deposits (Quaternary)**—Poorly sorted clay, silt, sand, gravel, boulders, and rock masses. Only a few large landslides are shown. For a more complete map of landslide deposits, see Nilsen and others (1979)

Qt **Alluvial and marine terrace deposits (Pleistocene)**—Deposits consist of crudely bedded, clast-supported gravels, cobbles, and boulders with a sandy matrix. Clasts as much as 35 cm intermediate diameter are present. Coarse sand lenses may be locally present. Alluvial terrace deposits lie on flat surfaces cut into bedrock a few meters that are up to several tens of meters above Qal deposits. Marine terrace deposits lie on one or more flights of flat surfaces that are cut into bedrock and lie up to 275 m above present sea level. These terrace deposits are the remnants of an older alluvial system that have been lifted above present depositional levels by tectonic uplift associated with regional transpression

Qpoaf **Older alluvial fan deposits (Pleistocene)**—Roughly horizontal beds of buff siltstone and claystone, buff to gray, fine- to coarse-grained lithic sandstone, pebbly sandstone, pebbly mudstone, and pebble to cobble conglomerate. Clasts include silicic to intermediate volcanics, obsidian, varicolored chert, graywacke and metagraywacke, quartzite, metachert, hornfels, quartz, charcoal, and petrified wood. Previously mapped (Blake and others, 1971; Fox, 1983) as Glen Ellen Formation based on similar clast composition (especially obsidian), we differentiate Qpoaf from QTge based on the lack of deformation and volcanics interbedded in Qpoaf and because Qpoaf is softer and less resistant than QTge. Qpoaf deposits probably formed as a large alluvial fan system at the west edge of hills and ridges underlain by Glen Ellen Formation and Sonoma Volcanics during uplift and transpression related to the Rodgers Creek/Healdsburg Fault Zone. Much Qpoaf detritus is probably reworked from the Glen Ellen Formation. This unit is at least 65 m thick. It is incised and overlain by Qal. This unit may be coeval in part with Qt and related in part to the same older alluvial system

ROCKS EAST OF AND WITHIN THE SAN ANDREAS FAULT ZONE

Clear Lake Volcanics—In the northeast corner of the map area (The Geysers quadrangle) are a few small outliers of the large Clear Lake volcanic complex that crops out mostly in Lake County to the northeast. This very young volcanic center (Pliocene to Holocene) is the northernmost manifestation of northward younging volcanism thought to be related to the initiation of the San Andreas Fault system (Fox and others, 1985b). The near-surface magma and remnant heat from plutonic rocks related to the volcanic center is probably driving the hydrothermal activity at The Geysers. For a more complete description of the Clear Lake Volcanics, see Hearn and others (1995). In the map area, the Clear Lake volcanics include:

Qr **Rhyolite and rhyodacite (Pleistocene)**—Porphyritic biotite rhyolite and rhyodacite flows. Contains parts of the rhyolite of Alder Creek and rhyodacite of Cobb Mountain of Hearn and others (1995). Rhyolite has yielded radiometric ages of 1.11±0.02 to 1.15±0.02 Ma, and rhyodacite has yielded ages of 1.05±0.02 to 1.06±0.02 Ma (Hearn and others, 1995)

Qob **Olivine basalt (Pleistocene)**—Olivine-rich basalt flows, dikes, and diatreme breccia. Equivalent to the olivine basalt of Caldwell Pines of Hearn and others (1995). The basalt has yielded a radiometric age of 1.66±0.12 Ma (Hearn and others, 1995)

QTge **Glen Ellen Formation (Pleistocene(?) and Pliocene)**—Brown- to buff-weathering, interbedded siltstone, fine- to coarse-grained sandstone, pebbly and cobbly sandstone, conglomerate, and tuff. Sandstone is tuffaceous or feldspathic arenite. Coarse clasts include mafic to silicic volcanics, obsidian, pumice, varicolored chert, and graywacke. The eastern part of the Glen Ellen Formation (mapped as QTget) contains more interbeds of tuff. Radiometric ages from interbedded tuff show that the Glen Ellen Formation is 3.1 Ma or younger (McLaughlin and others, 1999). The basal part of the Glen Ellen Formation is coeval with and interfingers with the upper part of the Sonoma Volcanics

Tor **Ohlson Ranch Formation (Pliocene)**—Mostly horizontal, thick beds of buff weathering, white to light-gray, well-consolidated, soft, quartz-lithic arenite. Also includes buff-weathering gray siltstone, pebbly to cobbly sandstone and conglomerate, red lithic sandstone, and white tuff. A tuff bed near the base of the unit in the Plantation quadrangle has been correlated (Sarna-Wojcicki, 1976) with the Nomlaki Tuff, which has yielded a radiometric age of 3.3 ± 0.4 Ma (Evernden and others, 1964). Locally concentrated Pliocene marine molluscan fossils have also been identified from this unit (Peck, 1960). This formation lies in angular unconformity over Franciscan Complex rocks and in at least one location (Soda Springs Road in the Annapolis quadrangle) includes slabs as much as 10 m long of the underlying rock. For a more complete description of the formation, see Higgins (1960). The unit has been locally subdivided into:

Tors **Sandstone**

Torc **Conglomerate**

Tls **Sedimentary rocks of Little Sulphur Creek (Pliocene and (or) Miocene)**—Confined to a narrow band in the northeast part of the map area (Asti, The Geysers, and Jimtown quadrangles), this unit is composed of massive to distinctly bedded boulder to pebble conglomerate and breccia, lithic sandstone, siltstone, and mudstone. Coarse clasts in places exceed 3 m in length and include varicolored chert, blueschist, graywacke, gabbro, serpentinite, diabase, and basalt, probably derived from surrounding Mesozoic rocks. One clast of middle Miocene fossiliferous arkose has also been found (McLaughlin and Nilsen, 1982), but no similar rock is known from the surrounding area. Freshwater ostracod and gastropod fossils have been reported from this unit, as have brackish or marine foraminifers, but none of these fossils provide good age control (Gealey, 1951; McNitt, 1968; McLaughlin and Nilsen, 1982). A Miocene or younger whale vertebra has also been reported (McNitt, 1968), but given the partly nonmarine nature of the unit, it is possible that this fossil was reworked from an older unit, perhaps the same as the fossiliferous arkose clast. McLaughlin and Nilsen (1982) interpreted this unit to have formed in a fault basin associated with a right step in the Maacama Fault Zone and suggested the unit was 3 Ma or younger based on the timing of initiation of San Andreas Fault system activity at this latitude. However, it is possible that the fault basin was related to a pre-San Andreas structure. Therefore, the age of the unit can only be constrained with confidence to post-date the middle Miocene age of the included arkose clast

Sonoma Volcanics (Pliocene and Miocene)—In the eastern part of the map area are a few outliers of the large, young Sonoma Volcanic complex, the bulk of which lies farther east. The complex includes rhyolite, dacite, andesite, and basalt tuff; glass; flow rock; pyroclasitic breccia; and intrusives that were probably derived from several eruptive centers; along with interbedded volcaniclastic sedimentary rocks. Radiometric ages from the Sonoma Volcanics range from 2.9±0.2 Ma to 6.95±0.2 Ma (Fox , 1983; Fox and others, 1985a). The Sonoma Volcanics, together with the Clear Lake Volcanics, Donnell Ranch volcanics of Youngman (1989), and Burdell Mountain volcanics of Blake and others (2000), are thought to have formed as part of the northward younging series of volcanic centers related to initiation of the San Andreas Fault system (Fox and others, 1985b). For more about the Sonoma Volcanics, see Fox (1983) and Sarna-Wojcicki (1976). In the map area, the Sonoma Volcanics are divided into:

Tsa **Andesite**—Plagioclase and plagioclase-hornblende porphyry andesite flow rock. Also includes minor plagioclase-quartz porphyry dacite flow rock

Tsb **Basalt**—Plagioclase porphyry basalt flow rock. Also includes minor vesicular andesite flow rock and volcanoclastic conglomerate

Twg **Wilson Grove Formation (late Pliocene to late Miocene)**—Mostly massive or thick-bedded, buff-weathering, light-gray, fine-grained quartz-lithic arenite. Also locally includes beds of mollusk- and gastropod-shell hash, pebble to boulder conglomerate, and tuff. Fossils from the Wilson Grove Formation range in age from late Miocene to late Pliocene (C. Powell, oral commun.; Travis, 1952; Naidu, 1999). The lower part of the unit overlies and is interbedded with late Miocene and early Pliocene basalt flow rock (Tb). At least part of the Wilson Grove Formation is probably the marine equivalent of the estuarine sand and gravel of Cotati and the alluvial Petaluma Formation. A distinctive tuff marker is distinguished locally:

Twgt **Tuff (late Miocene)**—White, water-lain tuff and pumice breccia. Informally named Roblar tuff by Sarna-Wojcicki (1992), this tuff has yielded K/Ar ages ranging from 5.68±0.68 to 6.26±0.1 (Bartow and others, 1973; Sarna-Wojcicki, 1976; Fox and others, 1985a)

Tc **Sand and gravel of Cotati (Pliocene and late Miocene)**—Thick-bedded to massive, white quartz arenite, buff-weathering siltstone, and pebble conglomerate. Coarse clasts include varicolored chert; gray or brown laminated chert; red, gray, and white quartz- and plagioclase-porphyry volcanics; black basalt; blueschist; graywacke; greenstone; quartz; and black hornfels. Locally present within the sandstone beds are estuarine mollusk, crustacean, and gastropod fossils. The laminated chert clasts may be derived from middle Miocene Monterey or Claremont Formation cherts (Fox, 1983), although the nearest outcrop of these units is several tens of kilometers to the southeast. However, offset on the Hayward-Rodgers Creek/Healdsburg and the Hayward-Tolay/Petaluma River Faults have probably moved the sand and gravel of Cotati and Wilson Grove Formation about 60 km from the southeast since deposition of the sand and gravel of Cotati. The sand and gravel of Cotati overlies and is interbedded with late Miocene and early Pliocene basalt flow rock (Tb), overlies the rhyolite intrusive breccia of the Donnell Ranch volcanics of Youngman (1989; Tdb), and interfingers on the west with the marine Wilson Grove Formation. The age of the sand and gravel of Cotati is not as well constrained as that of the Wilson Grove Formation, but must postdate the underlying Donnell Ranch volcanics (Tdb, about 9.3 Ma) and include the age of interlayered basalt (Tb, 4.26±0.27 Ma). Because it interfingers with the Wilson Grove Formation, we consider the sand and gravel of Cotati to be the estuarine equivalent of at least part of the Wilson Grove Formation. The sand and gravel of Cotati is probably also the estuarine equivalent of at least part of the alluvial Petaluma Formation. The sand and gravel of Cotati is in places indistinguishable from the Petaluma Formation, although some beds may be distinguished by having estuarine fossils or by having small, very spherical pebbles in conglomerate. Because the sand and gravel of Cotati is so similar in places to the Petaluma Formation, we have mapped the boundary between the two units at the Petaluma Valley Fault, which separates verifiable sand and gravel of Cotati outcrops from the main extent of Petaluma Formation. However, the two formations probably interfingered during deposition, and therefore some of what is mapped herein as sand and gravel of Cotati might actually be Petaluma Formation

Tp **Petaluma Formation (Pliocene and late Miocene)**—Only the northwesternmost part of the outcrop area of this formation is within the map area (Two Rock quadrangle), although oil-well data show that it extends under Santa Rosa Valley (D. Zigler, written commun.). Gray weathering, brown and green pebble- and cobble-conglomerate, gritstone, lithic and quartz-lithic arenite, and mudstone. Coarse clasts include varicolored chert, quartz- and plagioclase-porphyry rhyolite and andesite, vesicular andesite, laminated rhyolite, white tuff, basalt, quartz, graywacke, greenstone, and laminated chert. Locally present within the sandstone and conglomerate are land-mammal fossils, and lacustrine and estuarine ostracods (Liniecki-Laporte and Anderson, 1988) have been found in the mudstone. Mammalian fossils originally described as late Pliocene (Stirton, 1939) are now known to be late Miocene (late Hemphilian, McFadden, 1998). However, early Pliocene mammalian fossils have been found elsewhere within the unit (early Blancan; Bartow and others, 1973; Davies, 1986). East of the map area, the Petaluma Formation also includes a tuff bed correlated with Twgt (Sarna-Wojckici, 1976) and a layer of basalt flow rock dated at 8.52±0.18 Ma (Fox and others, 1985a). The Petaluma Formation overlies and interfingers with the Donnell Ranch volcanics of Youngman (1989) at its base (Fox, 1983; Youngman, 1989) and is coeval with (and may interfinger with) the lower part of the Sonoma Volcanics at its top. It is probably the nonmarine equivalent of the estuarine sand and gravel of Cotati and marine Wilson Grove Formation. As described above, the sand and gravel of Cotati and the Petaluma Formation are in part indistinguishable, and strata that include estuarine ostracods that were previously mapped as Petaluma Formation would be considered by us to be interfingered sand and gravel of Cotati. The Petaluma Formation lies mostly east of the Petaluma River Fault and has been offset about 35 km from the Wilson Grove and sand and gravel of Cotati west of the fault. It has also been offset about 25 km by movement on the Rodgers Creek-Healdsburg Fault from its original depositional position

Tb **Undivided basalt (Pliocene and Miocene)**—Black basalt, plagioclase porphyry basalt and andesite, and vesicular basalt and andesite flow rock. In the map area, outcrops of Tb have yielded radiometric ages ranging from 4.26±0.27 Ma to 7.83±0.29 Ma (Fox and others, 1985a). However, Tb also includes older basalt which is intruded by Tdb. We correlate this older basalt with either an older part of the Donnell Ranch volcanics of Youngman (1989) or the about 12 Ma Burdell Mountain volcanics of Blake and others (2000; the nearest verified outcrop of Burdell Mountain volcanics is at Meecham Hill, Cotati quadrangle, just southeast of the map area)

Tdb **Donnell Ranch volcanics of Youngman, 1989 (Miocene)**—Plagioclase-porphyry rhyolite pumice-tuff vent breccia. This unit has yielded a K/Ar age of 9.36±0.38 Ma (A. Sarna-Wojcicki, written commun., 2000) and is correlated with the Donnell Ranch volcanics of Youngman (1989) and the volcanics of Berkeley Hills, southeast of the map area, based on similar age and composition. It has been offset from these correlated volcanics by movement on the Hayward-Petaluma River and Hayward-Rodgers Creek-Healdsburg Faults

Franciscan Complex

Coastal Belt

TKfss **Sandstone (late Eocene to Late Cretaceous, Maastrichtian)**—Mostly massive, brown-weathering, dark-green or gray, feldspathic and feldspathic-lithic wacke. Sandstone in places contains detrital biotite and (or) large slate chips. This unit also locally includes disrupted, thin-bedded sandstone and blue-gray weathering, greenish-gray or dark-gray shale or slate. Structural disruption ranges from shearing evident in the fine-grained beds to dismemberment into lenses of sandstone (boudins) in a sheared shale matrix. The zeolite mineral laumontite is visible in veins and shear zones throughout the unit. This unit has yielded Paleocene and Eocene palynomorphs north of the map area (Bachman, 1978) and overlies middle Eocene to Late Cretaceous basalt and pelagic limestone (Bachman, 1978; Sliter, 1984). The feldspathic-lithic part of the unit (not mapped separately) is lithologically indistinguishable from TKfs and parts of Kfss

TKfgs **Greenstone (middle Eocene to Late Cretaceous)**—Orange-red weathering greenstone derived from pillow and massive basalt and basalt breccia. Original rock texture (pillows, bedding) well preserved. Includes middle Eocene to Late Cretaceous (Campanian to Maastrichtian) pelagic limestone locally. Depositionally underlies TKfss

Coastal or Central Belt

TKfs **Sandstone (late Eocene to Late Cretaceous, Turonian)**—Mostly massive, brown- and orange-weathering, green to gray feldpathic-lithic wacke. Contains detrital biotite and muscovite in places. Locally includes disrupted thin beds of sandstone and dark-gray shale and slate. Laumontite is visible in veins and shear zones in places. This unit lacks known fossils and other stratigraphic control and is lithologically indistinguishable from TKfss and parts of Kfss

Central Belt

Kfss **Sandstone (Late Cretaceous, Turonian to Campanian)**—Massive to distinctly bedded, brown-weathering, green, gray, or white, feldspathic and feldspathic-lithic wacke. In the Bodega Head quadrangle, this unit consists of distinctly bedded white and gray, K-feldspar- and biotite-bearing feldspathic wacke and dark-gray shale. Similar rocks south of the map area contain Late Cretaceous (Campanian) fossils (Bailey and others, 1964). In the Lake Sonoma area (Warm Springs, Tombs Creek, and Bigfoot Mountain quadrangles), the unit consists of massive to distinctly bedded, buff-weathering, gray, K-feldspar- and biotite-bearing feldspathic-lithic wacke, pebbly wacke, and conglomerate, and dark-gray concretionary shale. Coarse clasts include graywacke, shale, limestone (concretions, some fossiliferous), greenstone, and chert. The unit in this area overlies chert and greenstone and has yielded a Late Cretaceous (Turonian) *Inoceramus labiatus* (Bailey and others, 1964). Other than this fossil and the presence of chert, this unit is indistinguishable from TKfs and the feldspathic-lithic part of TKfss. In the northeasternmost part of the area (Jimtown, Geyserville, Asti, The Geysers, and Highland Springs quadrangles), this unit is composed of distinctly bedded, brown-weathering, greenish-gray, muscovite- and K-feldspar-bearing feldspathic-lithic wacke and dark-gray, mica-bearing siltstone and slate. The sandstone in this area has locally an incipient foliation (textural zone 2A of Jayko and others, 1986), bears muscovite instead of biotite, and has not yielded age-diagnostic fossils but is otherwise similar to the wacke near Lake Sonoma as well as TKfs and the feldspathic-lithic part of TKfss. These rocks are mapped as Kfss because of their structural position east of Lake Sonoma

Kfg **Greenstone (Late(?) Cretaceous)**—Massive and pillowed greenstone, lacking evidence of metamorphism in hand sample, and minor chert. This unit crops out in small lenses at the base of Late Cretaceous (Turonian) sandstone in the Lake Sonoma area

Kfgwy **Sandstone (Late and Early Cretaceous, Cenomanian and (or) late Albian)**—Thick-bedded, buff-weathering, gray lithic wacke and dark-gray shale. The unit locally includes lenses of pebble and cobble conglomerate and pebbly sandstone and mudstone. Coarse clasts include basalt, diabase, gabbro, andesite, varicolored chert, blueschist, and serpentinite. This unit overlies Cenomanian or late Albian chert (KJfc), and similar sandstones in Marin and San Francisco Counties (south of the map area) have yielded both Cenomanian and Albian fossils. This unit is distinguished from other Cretaceous Franciscan Complex sandstones by the large amount of lithic detritus and small amount of K-feldspar (0-6%). It is similar in composition to coherent parts of KJfs, but differs by age and preserved depositional contact with chert

KJfgcs **Greenstone, chert, and sandstone (Cretaceous and Jurassic)**—Disrupted and interleaved graywacke (Kfgwy), chert (KJfc), and greenstone (Jfgs). Individual rock bodies too small to show at map scale

KJfc **Chert (Cretaceous and Jurassic)**—Thin-bedded red chert with buff-weathering, dark-gray shale and slate partings. Radiolarians from this unit range from Late or Early Cretaceous (Cenomanian or late Albian) to Middle Jurassic (Bajocian; Murchey and Jones, 1984)

KJfgc **Greenstone and chert (Cretaceous and Jurassic)**—Disrupted and interleaved chert (KJfc) and greenstone (Jfgs). Individual rock bodies too small and complicated to show at map scale. Minor amounts of graywacke (Kfgwy) also present locally

KJfs **Graywacke and mélange (Cretaceous and Jurassic)**—Massive to distinctly bedded, brown-, orange-, and white-weathering, green to gray, lithic wacke and dark-gray or black siltstone, shale, and slate, grading into mélange consisting of sheared argillite and graywacke matrix enclosing blocks and lenses of sedimentary, metamorphic, and volcanic rocks (see fsr below for a more complete description of mélange). Because contacts between coherent graywacke and mélange are gradational (derived from different amounts of shearing) and because of the size and amount of cover in the map area, it was not possible in this study to differentiate everywhere between coherent graywacke and mélange. Where observed, coherent graywacke masses within the unit are indicated by a green hachure, while large observed blocks that are too small to map at 1:100,000 scale are indicated by diamonds (high-grade) and triangles (low-grade), and structural bodies known to be comprised primarily of mélange are mapped separately (fsr). Coherent graywacke bodies also locally include conglomerate, pebbly sandstone, and rare thin beds of red and white chert. Coarse clasts include black chert, quartzite, hornfels, granite, rhyolite, lithic wacke, blueschist, greenstone, green chert, marble, amphibolite, and quartz-mica schist. In many places, the graywacke contains conspicuous large chips of black and green shale. Coherent sedimentary rocks range from completely unfoliated to moderately foliated (Textural Zones 1-2A of Jayko and others, 1986). Late Jurassic (Tithonian) fossils have been found in both the coherent graywacke and the mélange matrix (Bailey and others, 1964; D.L. Jones, written commun.). Interbedded chert from the Asti quadrangle has been sampled, but not yet processed for microfossils. Interbedded chert in similar coherent graywacke in Marin County has yielded Late Jurassic to Early Cretaceous microfossils (Murchey and Jones, 1984). Chert pebbles from conglomerate have yielded Late Triassic to Early Jurassic microfossils (Seiders and Blome, 1984). Graywacke in this unit is distinguished from most other Franciscan Complex graywacke by its high lithic content. It is similar in composition to Kfgwy but is significantly older, is in places more foliated, and lacks the depositionally underlying sequence of chert (KJfc) and greenstone (Jfgs)

fsr **Mélange**—Sheared argillite, graywacke, and minor green tuff matrix enclosing blocks and lenses of graywacke, chert, metachert, greenstone, serpentinite, silica-carbonate rock, blueschist (metasediment and metabasalt), eclogite, amphibolite, limestone, and quartz-mica schist. Enclosed blocks and lenses range in size from pebbles to several hundred meters. The matrix graywacke has yielded Late Jurassic (Tithonian) fossils. It is identical in age and composition to coherent graywacke in unit KJfs, and is probably derived from tectonic dismemberment of that unit. High-grade blocks in the map area have yielded metamorphic ages of about 138-150 Ma (K/Ar; Kelley, 1982; Lee and others, 1964), similar to the age of Cazadero terrane blueschists. Chert blocks from the map area have been sampled but not yet analyzed for microfossils. Chert blocks in Marin County south of the map area are almost all similar to coherent chert of the Marin Headlands terrane (Murchey and Jones, 1984). Mélange blocks are probably derived from tectonic detachment of pieces of surrounding coherent Franciscan and Great Valley complex terranes. Blocks about 5-50 m. in size are shown where recognized by diamonds (high-grade metamorphic rocks) and triangles (low-grade and unmetamorphosed rocks), whereas the largest mélange blocks are mapped as separate units:

gs **Greenstone block**—Includes massive and pillowed greenstone and basalt. Also locally includes greenstone and basalt breccia and diabase

ch **Chert block**—Includes massive and thinly bedded red, green, and white chert and metachert

gwy **Graywacke block**

m **High-grade metamorphic rock block**—Includes blueschist metabasalt and metasediment, amphibolite, eclogite, and quartz-mica schist

sp **Serpentinite block**

Jfgs **Greenstone (Jurassic)**—Massive and pillowed basalt metamorphosed to greenstone. Amygdaloidal in places. Geochemical analysis suggests that these rocks originated as MORB, and paleomagnetic analysis suggests a near equatorial origin (Hagstrum and Murchey, 1993). This unit depositionally underlies chert (KJfc), and therefore predates Middle Jurassic chert deposition.

Eastern Belt

KJfm **Metagraywacke (Cretaceous and Jurassic)**—Blueschist facies metagraywacke. In the map area, this unit mostly consists of brown-weathering, blue, schistose (textural zone 2B-3A of Jayko and others, 1986), white-mica- and glaucophane-bearing metagraywacke. These rocks crop out both as a large coherent belt in the central part of the map area (the Skaggs Springs schist of Wakabayashi [1992b]), a much smaller coherent body in the Cazadero and Fort Ross quadrangles, and small slabs and lenses within mélange (fsr) in the Healdsburg, Jimtown, and Geyserville quadrangles. The Skaggs Springs schist has yielded an Ar/Ar metamorphic age of about 141 Ma (Wakabayashi, 1999a). This unit also includes the northernmost tip of a belt of brown-weathering, gray, foliated (textural zone 2A of Jayko and others, 1986), jadeite-bearing metagraywacke in the Two Rock quadrangle. Similar jadeite-bearing metagraywacke elsewhere in the Coast Ranges has yielded radiometric metamorphic ages of 90-110 Ma (Wakabayashi, 1999a; Mattinson and Echevarria, 1980) and has yielded Late Jurassic (Tithonian) fossils

KJfmg **Metabasalt (Cretaceous and Jurassic)**—Blueschist facies metabasalt. In the map area, this unit consists of medium-grade (Type III), blue and green, glaucophane-epidote-garnet-sphene-bearing, foliated metabasalt (the Ward Creek schist of Coleman and Lee, 1963) and lower grade (Type II), green, glaucophane-muscovite-lawsonite-sphene-bearing, nonfoliated metabasalt. Type III metabasalt is interlayered with pink, green, brown, or blue metachert, dark-brown or bluish-black metashale and metaironstone, and white, aragonite-bearing metacarbonate. The original textures (pillows, vesicles, amygdules) are generally preserved in Type II metabasalt, but are mostly obliterated in Type III. The contact between Type II and III metabasalts is gradational. In some structural blocks, Type II metabasalt grades into Type I greenstone, which lacks blueschist-facies metamorphic minerals, but Type III metabasalt does not crop out in those areas. Structural blocks containing Type II and III metabasalt are indicated on the map by a black hachured pattern, whereas those blocks containing only Type I and II metabasalt are unhachured. Geochemical analysis of the higher grade part of the unit suggests it was derived from a seamount (Coleman and Lee, 1963) that was subducted to a maximum depth of about 20 km (P=9.5-12 kb, T=360-380°C; Maruyama and Liou, 1988; Moore and Blake, 1989; Oh, 1990; Oh and others, 1991). Type III metashale has yielded K/Ar metamorphic ages of 130-135 Ma (Lee and others, 1964), and Ward Creek metabasalt (presumably Type III) has yielded an Ar/Ar metamorphic age of 142.6±0.5 Ma (Wakabayashi and Deino, 1989). Other reported metamorphic ages for higher grade (type not specified) rocks of this unit are 135±7 Ma to 150±7.5 Ma (K/Ar; Coleman and Lanphere, 1971), 130-140 Ma (Ar/Ar, K/Ar; Wakabayashi, 1999a), and 133.1±6.7 to 153.6±7.7 Ma (K/Ar, Rb/Sr; Kelley, 1982)

Great Valley complex

KJgv **Sandstone, shale, and conglomerate (Early Cretaceous and Late Jurassic)**—Distinctly bedded, brown-weathering, dark-gray to white, biotite- and muscovite-lithic wacke and siltstone, dark-gray siltstone and shale, and pebble to boulder conglomerate. Coarse clasts include quartz- and plagioclase-porphyry volcanics, granitic rocks, gray rhyolite tuff, and chert. Sparse Late Jurassic (Tithonian) and Early Cretaceous (Valanginian) molluscan fossils have been found throughout the unit west of the Maacama Fault (Bailey and others, 1964;

Travis, 1952; Christensen, 1973; Gealey, 1951), whereas east of the Maacama Fault the strata have yielded Early Cretaceous (Hauterivian-Barremian) fossils (McLaughlin and Ohlin, 1984; D.L Jones, written commun.). Largely subdivided into:

KJgvs **Sandstone, siltstone, and shale**

KJgvc **Conglomerate**

Jk **Knoxville Formation (Late Jurassic)**—Distinctly-bedded black shale and thin beds of biotite-lithic wacke that contain only Late Jurassic fossils. Mapped only in the Camp Meeker quadrangle

Jsv **Keratophyre and quartz keratophyre tuff (Late Jurassic)**—This unit is only mapped in one small area in Camp Meeker quadrangle. Highly altered, distinctly bedded, red, green, and white intermediate and silicic tuff. Feldspars are almost all replaced by albite. Contains Late Jurassic (Tithonian) radiolarians and bright green celadonite crystals. Probably correlative with tuff of the Lotta Creek Formation of the western San Joaquin Valley hundreds of kilometers southeast of the map area. This unit also includes minor amounts of augite-porphyry breccia. These rocks are probably the altered remnants of tuff and volcanic detritus derived from a volcanic arc and deposited on the Coast Range ophiolite. The presence of Lotta Creek Formation tuff here is indicative of the large amounts of fault offset experienced by the California Coast Ranges

Coast Range ophiolite (Late and Middle Jurassic)—Consists of:

Jv **Mafic and intermediate volcanic rocks**—Mostly massive basalt, also includes amygduloidal and plagioclase-porphyry basalt, pillow basalt, diabase, keratophyre, and amygduloidal and plagioclase-hornblende-porphyry andesite. Coast Range ophiolite volcanic rocks are distinguished from Franciscan Complex volcanic rocks by lack of metamorphism and alteration, by association with intrusive rocks, and by lack of associated ribbon chert.

Jd **Mafic and intermediate intrusive rocks**—Diabase, gabbro, and diorite. Also includes minor intrusive keratophyre. The Franciscan Complex terranes contain very few outcrops of intrusive rocks, especially plutonic rocks like gabbro and diorite, so presence of this unit is indicative of Coast Range ophiolite affinity

Ju **Ultramafic rocks**—Peridotite and pyroxenite. More or less serpentinized, but rocks of this unit generally maintain relic plutonic fabric (bastite).

sp **Serpentinite**—Mainly sheared serpentinite, but also includes massive serpentinized harzburgite. In places, pervasively altered to:

sc **Silica carbonate rock**

spm **Serpentinite matrix mélange**—Sheared meta-serpentinite containing large blocks and lenses (as much as 10 m. or more in diameter) of high-grade metamorphic rocks, graywacke, and greenstone. Only large lenses are mapped. In the eastern part of the Warm Springs Dam quadrangle, serpentinite, greenstone, and blueschist are tightly interleaved at outcrop scale

ROCKS WEST OF AND WITHIN THE SAN ANDREAS FAULT ZONE

Tsm **Sandstone and mudstone of the Fort Ross area (early Miocene)**—Gray-white, K-feldspar-bearing arkose overlain by black, somewhat fissile clayey siltstone. The sandstone is interbedded with black mudstone. The siltstone contains thin beds and laminae of fine-grained sandstone and has yielded fish scales and early Miocene (Saucesian) foraminifers (Wentworth, 1967)

Great Valley(?) complex

Tg **German Rancho Formation of Wentworth and others (1998b) (Eocene and Paleocene)**—Distinctly bedded, fine- to medium-grained, K-feldspar-bearing feldspathic arenite, mudstone, and conglomerate. Coarse clasts consist mostly of granitic rocks, amphibolite, schist, gneiss, quartzite, and porphyry volcanics. Eocene and Paleocene fossils have been collected from many places in the unit (for a recent discussion, see Wentworth and others, 1998b; Elder and others, 1998; McDougall, 1998), although the Paleocene section occurs only south of Black Point. North of Black Point, the base of the unit is marked by red and green mudstone yielding early Eocene microfossils (Wentworth and others, 1998b; McDougall, 1998) and the Paleocene section is missing. This absence is attributed by Wentworth and others (1998b) to attenuation faulting

TKu **Undifferentiated German Rancho and Gualala Formations (Eocene to Late Cretaceous)**—Because of poor exposure, fault offset, lack of fossil age control, and similarity of lithologies, it has not been possible to differentiate between these two formations in a fault bounded sliver just west of the San Andreas Fault Zone (Stewarts Point, Annapolis, and Plantation quadrangles). Outcrops of this unit are primarily deeply weathered arkose

Gualala Formation of Wentworth and others (1998b) (Late Cretaceous and Paleocene?)—In the map area, everywhere divided into:

Ka **Anchor Bay member**—Greenish-gray, fine- to medium-grained, plagioclase-bearing feldspathic arenite and mafic-clast pebble to boulder conglomerate. Laumontite veins are found throughout the sandstone. Coarse clasts include mostly basalt, diabase, gabbro, diorite, quartz diorite, and andesite, although pyroxenite is locally present in boulder conglomerate. Molluscan fossils of Late Cretaceous age have been found throughout the member (Elder and others, 1998), but foraminifers of Late Cretaceous to late Paleocene age have been found in the same section, interleaved both with each other and with Late Cretaceous molluscan fossils (Wentworth and others, 1998b; McDougall, 1998). This apparent conflict is still unresolved

Ks **Stewarts Point member**—Gray, fine- to medium-grained, K-feldspar and plagioclase-bearing feldspathic arenite and conglomerate. Coarse clasts include porphyry volcanics and granitic rocks. This unit has yielded Late Cretaceous (late Campanian or younger) molluscan fossils and foraminifers (Wentworth and others, 1998b; McDougall, 1998; Elder and others, 1998)

KJsb **Spilite near Black Point of Wentworth and others (1998b) (Cretaceous? or Jurassic?)**—Massive to pillowed basalt flows and sheeted diabase sills, metamorphosed to low-grade greenschist facies (albite-chlorite-clinozoisite; Phillips and others, 1998). Wentworth and others (1998b) correlate this unit with the Coast Range ophiolite, but the geochemical studies of Phillips and others (1998) suggest a back-arc magmatic affinity, which differs from the Coast Range ophiolite (fore-arc affinity). Jachens and others (1998) correlate the positive magnetic anomaly related to this unit with that related to the Logan gabbro in San Mateo County to the south (offset by the San Andreas/San Gregorio Fault Zone), but there is no unequivocal match between any strata in the area underlain by Logan gabbro and strata underlain by this unit. This unit was originally assigned to the Cretaceous (Wentworth, 1967), but no direct evidence is available and both correlated mafic bodies are Jurassic (James and others, 1993; Blake and others, 1992; Hagstrum, 1997; Hopson and others, 1997)

Salinian complex

Kgr **Quartz diorite of Bodega Head (Cretaceous)**—White or gray, hornblende-biotite quartz diorite. Includes intermediate and felsic, fine-grained to pegmatitic dikes and pods. Plagioclase- and K-feldspar-porphyry quartz diorite present locally. This unit has yielded a Rb/Sr age of 80-92 Ma (Kistler and Champion, 1991)

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Digital Publication and Database Description

Introduction

This publication includes, in addition to cartographic and text products, geospatial (GIS) databases and other digital files. These files are published on the Internet through the U.S. Geological Survey (USGS) web sites. The database files are particularly useful because they can be combined with any type of other geospatial data for purposes of display and analysis. The other files include digital files that support the databases, and digital plot files that can be used to display and print the cartographic and text products included in this publication.

Following is the digital publication and database description. It contains information about the content and format of the digital geospatial databases used to create this digital geologic map publication. **This information is not necessary to use or understand the geologic information in the map and preceding geologic description.** The digital publication and database description contains information primarily useful for those who intend to use the geospatial databases. However, it also contains information about how to get digital plot files of the map and geologic pamphlet via the Internet, as well as information about how the map sheet and pamphlet were created, and information about getting copies of the map sheet and text from the USGS.

In addition, in 1999, the USGS adopted policies regarding revision of publications, introducing the concept of version numbers similar to those used in the computer industry. See the section called “Revisions and version numbers” for information about the version system and about how to access a revision list explaining changes from version 1.0, if any have been made.

The digital map database, compiled from previously published and unpublished data and new mapping by the authors, represents the general distribution and orientation of bedrock and surficial deposits in the mapped area. Together with the accompanying text (available as digital files wsomf.txt, wsomf.pdf, or wsomf.ps), it provides current information on the geologic structure and stratigraphy of the map area. The database delineates map units that are identified by general age and lithology following the stratigraphic nomenclature of the USGS. The scale of the source maps limits the spatial resolution (scale) of the database to 1:62,500 or smaller. The content and character of the database, as well as two methods of obtaining the database, are described below.

For those who don't use digital geologic map databases

For those interested in the geology of the mapped area who do not use an ARC/INFO compatible Geographic Information System (GIS), we have provided two sets of plotfiles containing images of much of the information in the database. Each set contains an image of a 1:100,000 scale geologic map sheet and explanation and an explanatory pamphlet. There is a set of images in PostScript format and another in Adobe Acrobat PDF format (see the sections “PostScript plot files” and “PDF plot files” below).

Those interested who have computer capability can access the plot file packages in either of the two ways described below (see the section “Obtaining the digital database and plotfile packages”). However, it should be noted the plot file packages do require gzip and TAR utilities to access the plot files. Therefore additional software, available free on the Internet, may be required to use the plot files (see section “Tar files”).

Those without computer capability can obtain plots of the map files through USGS plot-on-demand service for digital geologic maps (see section “Obtaining plots from USGS Map On Demand Services”) or from a commercial vendor (see section “Obtaining plots from a commercial vendor”).

MF-2402 Digital Contents

This report includes three digital packages. The first is the PostScript Plotfile Package, which consists of PostScript plot files of a map sheet containing a geologic map and explanation and a pamphlet containing a geologic description. The second is the PDF Plotfile Package, which contains the same plotfiles as the first package but in Portable Document Format (PDF). The third is the Digital Database Package, which contains the geologic map database itself and the supporting data, including base maps, map explanation, geologic description, and references.

Postscript plotfile package

This package contains the images described here in PostScript format (see below for more information on PostScript plot files):

wsomap.ps	A PostScript plotfile containing an image of the geologic map and base maps at a scale of 1:100,000 along with a map explanation including terrane map, index maps, and correlation chart
wsomf.ps	A PostScript plotfile that contains an image of the pamphlet containing detailed unit descriptions and geological information, a description of the digital files associated with the publication, plus references cited

PDF plotfile package

This package contains the images described here in PDF format (see below for more information on PDF plot files):

wsomap.pdf	A PDF file containing an image of the geologic map and base maps at a scale of 1:100,000, along with a map explanation including terrane map, index maps, and correlation chart
wsomf.pdf	A PDF file that contains an image of the pamphlet containing detailed unit descriptions and geological information, a description of the digital files associated with the publication, plus references cited

Digital database package

The database package includes geologic map database files for the map area. The digital maps, or coverages, along with their associated INFO directory have been converted to uncompressed ARC/INFO export files. ARC export files promote ease of data handling, and are usable by some Geographic Information Systems in addition to ARC/INFO (see below for a discussion of working with export files). The ARC export files and the associated ARC/INFO coverages and directories, as well as the additional digital material included in the database, are described below:

ARC/INFO export file	Resultant Coverage	Description of Coverage
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wso-geol.e00	wso-geol/	Polygon and line coverage showing faults, depositional contacts, and rock units in the map area
wso-strc.e00	wso-strc/	Point and annotation coverage showing strike and dip information
wso-blks.e00	wso-blks/	Point and annotation coverage showing location of high- and low-grade blocks in Franciscan rock units
wso-grst.e00	wso-grst/	Polygon coverage showing areas of medium- to high-grade blueschist facies metamorphism within unit KJfmg
wso-ss.e00	wso-ss/	Polygon coverage showing areas of coherent greywacke in unit KJfs (graywacke and mélange)

The database package also includes the following ARC coverages and files:

ARC Coverages, which have been converted to uncompressed ARC/INFO export files

ARC/INFO export file	Resultant Coverage	Description of Coverage
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wso-quad.e00	wso-quad/	Polygon, line, and annotation coverage showing index map of quadrangles in the map area
wso-corr.e00	wso-corr/	Polygon, line, and annotation coverage of the correlation table for the units in this map database. This database is not geospatial
wso-so.e00	wso-so/	Polygon, line, and annotation coverage showing sources of data index map for this map database
wso-terr.e00	wso-terr/	Polygon and line coverage of the index map of tectonostratigraphic terranes in the map area (terranes are described above)
wso-xsl.e00	wso-xsl/	Line and annotation coverage of the cross-section line A-A'
wso-xsa.e00	wso-xsa/	Polygon, line, and annotation coverage of SW- to NE-trending cross section. Note: This coverage is NOT georeferenced

ASCII text files, including explanatory text, ARC/INFO key files, PostScript plot files, and an ARC Macro Language file for conversion of ARC export files into ARC coverages

wsomf.ps	A PostScript plotfile that contains an image of the pamphlet containing detailed unit descriptions and geological information, a description of the digital files associated with the publication, plus references cited
wsomf.pdf	A PDF version of wsomf.ps
wsomf.txt	A text-only file containing an unformatted version of wsomf.ps without figures
wsofig1.tif	A TIFF file of figure 1 from wsomf.ps
wsoso.txt	ASCII text-only file containing sources of data related to coverage wso-so
import.aml	ASCII text file in ARC Macro Language to convert ARC export files to ARC coverages in ARC/INFO
mf2402d.met	A parsable text-only file of publication level FGDC metadata for this report
mf2402e.rev	A text-only file describing revisions, if any, to this publication

The following supporting directory is not included in the database package but is produced in the process of reconverting the export files into ARC coverages:

info/	INFO directory containing files supporting the databases

Tar files

The three data packages described above are stored in TAR (UNIX tape archive) files. A TAR utility is required to extract the database from the TAR file. This utility is included in most UNIX systems and can be obtained free of charge over the Internet from Internet Literacy's Common Internet File Formats Webpage (http://www.matisse.net/files/formats.html). All TAR files have been compressed and may be uncompressed with **gzip**, which is available free of charge over the Internet via links from the USGS Public Domain Software page (http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/public.html). In addition, several common proprietary freeware programs such as Stuffit Expander (http://www.aladdinsys.com/expander/index.html) and shareware programs such as WinZip (http://www.winzip.com) can handle both TAR file extraction and gzip uncompression. When the TAR file is uncompressed and the data is extracted from the TAR file, a directory is produced that contains the data in the package as described above. The specifics of the TAR files are listed below:

Name of compressed TAR file	Size of compressed TAR file (uncompressed)	Directory produced when extracted from TAR file	Data package contained
mf2402a.tgz	5.9 MB (27.4 MB)	wsops	PostScript Plotfile Package
mf2402b.tgz	6.4 MB (6.5 MB)	wsopdf	PDF Plotfile Package
mf2402c.tgz	3.4 MB (33.7 MB)	wsogeo	Digital Database Package

PostScript plot files

For those interested in the geology of the map area who don't use an ARC/INFO compatible GIS system, and for those who want a copy of the USGS format cartographic product, we have included a separate data package with two PostScript plot files. One contains a color plot of the geologic map at 1:100,000 scale, along with a terrane map, index maps, correlation chart, and map explanation (wsomap.ps). A second PostScript file (wsomf.ps) contains the geologic and digital publication description and discussion (this pamphlet).

The PostScript images of the geologic maps and map explanation are 50 inches high by 34.5 inches wide, so it requires a large plotter to produce paper copies at the intended scale. In addition, some plotters, such as those with continual paper feed from a roll, are oriented with the long axis in the horizontal direction, so the PostScript image will have to be rotated 90 degrees to fit entirely onto the page. Some plotters and plotter drivers, as well as many graphics software packages, can perform this rotation. The geologic description is on 8.5- by 11-inch pages.

The PostScript plotfiles for maps were produced by the ‘postscript’ command with compression set to zero in ARC/INFO version 7.1.1. The PostScript plotfiles for pamphlets were produced in Microsoft Word 6.0 using the Destination PostScript File option from the Print command.

PDF plot files

We have also included a second digital package containing PDF versions of the PostScript map sheet and pamphlet described above. Adobe Acrobat PDF (Portable Document Format) files are similar to PostScript plot files in that they contain all the information needed to produce a paper copy of a map or pamphlet and they are platform independent. Their principal advantage is that they require less memory to store and are therefore quicker to download from the Internet. In addition, PDF files allow for printing of portions of a map image on a printer smaller than that required to print the entire map without the purchase of expensive additional software. All PDF files in this report have been created from PostScript plot files using Adobe Acrobat Distiller. In test plots we have found that paper maps created with PDF files contain almost all the detail of maps created with PostScript plot files. We would, however, recommend that those users with the capability to print the large PostScript plot files use them in preference to the PDF files.

To use PDF files, the user must get and install a copy of Adobe Acrobat Reader. This software is available **free** from the Adobe website (http://www.adobe.com). Please follow the instructions given at the website to download and install this software. Once installed, the Acrobat Reader software contains an on-line manual and tutorial.

There are two ways to use Acrobat Reader in conjunction with the Internet. One is to use the PDF reader plug-in with your Internet browser. This allows for interactive viewing of PDF file images within your browser. This is an easy way to quickly look at PDF files without downloading them to your hard disk. The second way is to download the PDF file to your local hard disk and then view the file with Acrobat Reader. **We strongly recommend that large map images be handled by downloading to your hard disk**, because viewing them within an Internet browser tends to be very slow.

To print a smaller portion of a PDF map image using Acrobat Reader, it is necessary to cut out the portion desired using Acrobat Reader and the standard cut and paste tools for your platform and then to paste the portion of the image into a file generated by another software program that can handle images. Most word processors (such as Microsoft Word) will suffice. The new file can then be printed. Image conversion in the cut and paste process, as well as changes in the scale of the map image, may result in loss of image quality.

However, test plots have proven adequate. Superior quality can be obtained by using image processing software that can open PDF files (like Adobe Photoshop Elements) to crop and print a portion of the map.

Obtaining the Digital Database and Plotfile Packages

The digital data can be obtained in either of two ways listed below:

a. Western Region Geologic Publication Web Page
b. Anonymous ftp over the Internet

To obtain TAR files of database or plotfile packages from the USGS web pages

The USGS now supports a set of graphical pages on the World Wide Web. Digital publications (including this one) can be accessed via these pages. The location of the main Web page for the entire USGS follows:

http://www.usgs.gov

The Web server for digital publications from the Western Region is:

http://geopubs.wr.usgs.gov

To access this publication directly, go to the following:

http://geopubs.wr.usgs.gov/map-mf/mf2402

Besides providing easy access to the entire digital database, the Western Region Web page also affords easy access to the PostScript and PDF plot files for those who do not use digital databases (see below).

To obtain TAR files of database or plotfile packages by ftp

The files in this report are stored on the USGS Western Region FTP server. The Internet ftp address of this server is:

ftp://geopubs.wr.usgs.gov

The user should log in with the user name ‘anonymous’ and then input an e-mail address as the password. This will give the user access to all the publications available via ftp from this server.

The files in this report are stored in the subdirectory:

pub/map-mf/mf2402

Obtaining plots from a commercial vendor

Those interested in the geologic map, but who use neither a computer nor the Internet, can still obtain the information. Many vendors can download the plotfiles via the Internet. Important information regarding file formats is included in the sections “Tar files,” "PostScript plot files," and “PDF plot files” above, so be certain to provide a copy of this document to your vendor.

Obtaining plots from USGS Map On Demand Services

The USGS provides a plot-on-demand service for map files, such as those described in this report, through Map On Demand Services. In order to obtain plots, contact Map On Demand Services:

U.S. Geological Survey
Information Services
Box 25286
Federal Center
Denver, CO 80225-0046

(303) 202-4200
1-800-ASK-USGS

FAX: (303) 202-4695

e-mail: infoservices@usgs.gov

Be sure to include with your request the MF report number.

Revisions and version numbers

From time to time, new information and mapping, or other improvements, will be integrated into this publication. Rather than releasing an entirely new publication, the USGS has adopted a policy of using version numbers similar to those used in the computer industry. The original version will be labeled Version 1.0. Subsequent small revisions will be denoted by the increase of the numeral after the decimal, while large changes will be denoted by increasing the numeral before the decimal. Information about the changes, if any, that have been made since the release of Version 1.0 will be listed in the publication revision file. This file will be available at the publication web site (see above) and also will be included in the digital database package. A simplified version of the revision list will be included in the publication metadata.

Digital database format

The databases in this report were compiled in ARC/INFO, a commercial Geographic Information System (Environmental Systems Research Institute [ESRI], Redlands, California), with version 3.0 of the menu interface ALACARTE (Fitzgibbon and Wentworth, 1991; Fitzgibbon, 1991; Wentworth and Fitzgibbon, 1991). The files are in either GRID (ARC/INFO raster data) format or COVERAGE (ARC/INFO vector data) format. Coverages are stored in uncompressed ARC export format (ARC/INFO version 7). ARC/INFO export files (files with the .e00 extension) can be converted into ARC/INFO coverages in ARC/INFO (see below) and can be read by some other Geographic Information Systems, such as MapInfo via ArcLink and ESRI's ArcView (version 1.0 for Windows 3.1 to 3.11 is available for free from ESRI's web site: http://www.esri.com). The digital compilation was done in version 7.1.2 of ARC/INFO with version 3.0 of the menu interface ALACARTE (Fitzgibbon and Wentworth, 1991; Fitzgibbon, 1991; Wentworth and Fitzgibbon, 1991).

Converting ARC export files

ARC export files are converted to ARC coverages using the ARC command IMPORT with the option COVER. To ease conversion and maintain naming conventions, we have included an ASCII text file in ARC Macro Language that will convert all of the export files in the database into coverages and create the associated INFO directory. From the ARC command line type:

```
Arc:  &run import.aml
```

ARC export files can also be read by some other Geographic Information Systems. Please consult your GIS documentation to see if you can use ARC export files and the procedure to import them.

Digital compilation

The geologic map information was digitized from stable originals of the geologic maps at 1:62,500 scale. The author manuscripts (pen on mylar) were scanned using an Altek monochrome scanner with a resolution of 800 dots per inch. The scanned images were vectorized and transformed from scanner coordinates to projection coordinates with digital tics placed by hand at quadrangle corners. The scanned lines were edited interactively by hand using ALACARTE, color boundaries were tagged as appropriate, and scanning artifacts visible at 1:24,000 were removed.

Base maps

Base map layers were derived from published digital maps (Aitken, 1997) obtained from the USGS Geologic Division Website for the Western Region (http://wrgis.wr.usgs.gov). Please see the website for more detailed information about the original databases. Because the base map digital files are already available at the website mentioned above, they are not included in the digital database package.

Faults and landslides

This map is intended to be of general use to engineers and land-use planners. However, its small scale does not provide sufficient detail for site development purposes. In addition, this map does not take the place of fault-rupture hazard zones designated by the California State Geologist (Hart and Bryant, 1999). Similarly, because only some of the landslides in the mapped area are shown, the database cannot be used to completely identify or delineate landslides in the region. For a more complete depiction of landslide distribution, see Nilsen and others (1979), Ellen and others (1997), and Wentworth and others (1997).

Spatial resolution

Uses of this digital geologic map should not violate the spatial resolution of the data. Although the digital form of the data removes the constraint imposed by the scale of a paper map, the detail and accuracy inherent in map scale are also present in the digital data. The fact that this database was edited at a scale of 1:62,500 means that higher resolution information is not present in the dataset. Plotting at scales larger than 1:62,500 will not yield greater real detail, although it may reveal fine-scale irregularities below the intended resolution of the database. Similarly, where this database is used in combination with other data of higher resolution, the resolution of the combined output will be limited by the lower resolution of these data.

Database specifics

What follows is a brief and simple description of the main databases included in this report and the data in them. For a comprehensive look at the database structure and content, please see the FGDC Metadata file, mf2402d.met, included in the database package and available separately at the publication web page.

The map databases consist of ARC coverages and supporting INFO files, which are stored in a Universal Transverse Mercator (UTM) projection (table 1). Digital tics define a 2.5 minute grid of latitude and longitude in the geologic coverages corresponding with quadrangle corners and internal tics. Note that coverage wso-xsa/ is not georeferenced.

Table 1. Map Projection File
The maps are stored in UTM projection. The following is an annotated projection file of the type used in Arc/Info.

```
PROJECTION UTM
UNITS METERS
ZONE 10
SPHEROID CLARKE1866
DATUM NAD27
PARAMETERS
END
```

The content of the geologic database can be described in terms of the lines, points, and areas that compose the map. Each line, point, or area in a map layer or index map database (coverage) is associated with a database entry stored in a feature attribute table. Each database entry contains both a number of items generated by Arc/Info to describe the geometry of the line, point, or area and one or more items defined by the authors to describe the geologic information associated with that entry. Each item is defined as to the amount and type of information that can be recorded. Descriptions of the database items use the terms explained in table 2.

Table 2. Field Definition Terms

ITEM NAME	name of the database field (item)
WIDTH	maximum number of digits or characters stored
OUTPUT	output width
TYPE	B-binary integer, F-binary floating point number, I-ASCII integer, C-ASCII character string
N. DEC.	number of decimal places maintained for floating point numbers

Because some of the database structure is similar for all coverages, some descriptions apply to all coverages in the publication. In that case, the notation <coverage> has been used to indicate the description is valid for any included coverage. The precise description for a particular coverage can be made by substituting the name of the coverage for <coverage>. For example, <coverage>-ID means that the description is the same for every coverage. The specific notation for a single coverage can be derived by replacing <coverage> with the coverage name (such as WSO-GEOL-ID for the coverage wso-geol).

Lines

The lines (arcs) are recorded as strings of vectors and are described in the arc attribute table (the format of the arc attribute table is shown in table 3). They define the boundaries of the map units, the boundaries of open bodies of water, and the map boundaries. These distinctions, including the geologic identities of the unit boundaries, are recorded in the LTYPE field according to the line types listed in table 4.

Table 3. Content of the Arc Attribute Tables

ITEM NAME	WIDTH	OUTPUT	TYPE	N. DEC	
FNODE#	4	5	B		starting node of arc (from node)
TNODE#	4	5	B		ending node of arc (to node)
LPOLY#	4	5	B		polygon to the left of the arc
RPOLY#	4	5	B		polygon to the right of the arc
LENGTH	4	12	F	3	length of arc in meters
<coverage>#	4	5	B		unique internal control number
<coverage>-ID	4	5	B		unique identification number
LTYPE	35	35	C		line type (see table 4)
FAULTNAME	35	35	C		name of fault, if any, only in WSO-GEOL

Table 4. Line Types Recorded in the LTYPE Field

wso-geol and wso-terr	wso-so and wso-quad
contact, approx. located	leader
contact, certain	map boundary
contact, concealed	quad boundary
contact, concealed, queried	water boundary
contact, inferred	source, boundary
contact, inferred, queried	
fault, active	
fault, approx. located	
fault, certain	
fault, concealed	
fault, concealed, queried	
fault, inferred	
fault, inferred, queried	
map boundary,	
reverse fault, approx. located	
reverse fault, certain	
reverse fault, concealed	
scratch boundary	
thrust fault, approx. located	
water boundary,	

Table 4a. Fault Names Recorded in the FAULTNAME Field

wso-geol ONLY

Bloomfield Fault
Healdsburg Fault Zone
Maacama Fault Zone
Petaluma Valley Fault
San Andreas Fault Zone
Tolay Fault

Note, not every line type listed is present in every coverage. For example, wso-terr only has some of the fault types listed.

The geologic linetypes are ALACARTE line types that correlate with the geologic line symbols in the ALACARTE line set GEOL.LIN according to the ALACARTE lines lookup table (GEOL.LUT). For more information on ALACARTE and its linesets, see Wentworth and Fitzgibbon (1991).

Areas

Map units (polygons) are described in the polygon attribute table (the format of the polygon attribute table is shown in table 5). In the geologic coverages (wso-geol) and the correlation coverage (wso-corr), the identities of the map units from compilation sources are recorded in the PTYPE field by map label (table 6). Map units are described more fully in the accompanying text file. In other coverages, various areal information is recorded in the PTYPE field (data source region number, assemblage number, terrane label, quadrangle name). Note that ARC/INFO coverages cannot contain both point and polygon information, so only coverages with polygon information will have a polygon attribute table, and these coverages will not have a point attribute table.

Table 5. Content of the Polygon Attribute Tables

ITEM NAME	WIDTH	OUTPUT	TYPE	N. DEC	
AREA	4	12	F	3	area of polygon in square meters
PERIMETER	4	12	F	3	length of perimeter in meters
<coverage>#	4	5	B		unique internal control number
<coverage>-ID	4	5	B		unique identification number
PTYPE	35	35	C		unit label

Table 6. Unit labels (see also Description of Map Units)

Jd
Jfgs
Jk
Jsv
Ju
Jv
KJfc
KJfgc
KJfgcs
KJfm
KJfmg
KJfs
KJgv
KJgvc
KJgvs
KJsb
Ka
Kfg
Kfgwy
Kfss
Kgr
Ks
QTge
QTget
Qal
Qls
Qm
Qob
Qpoaf
Qr
Qs
Qt
TKfgs
TKfs
TKfss
TKu
Tb
Tc
Tdb
Tg
Tls
Tor
Torc
Tors
Tp
Tp?
Tsa
Tsb
Tsm
Twg
Twgt
af
ch
fsr
fsr?
gs
gwy
m
sc
sp
spm
water

Note, not every unit label listed is present in every coverage. For example, queried units are not present in the Correlation of Map Units coverage (wso-corr).

Points

Data gathered at a single locality (points) are described in the point attribute table (the format of the point attribute table is shown in table 7). The identities of the points from compilation sources are recorded in the PTTYPE field by map label (tables 8, 9). Note that ARC/INFO coverages cannot contain both point and polygon information, so only coverages with point information will have a point attribute table, and these coverages will not have a polygon attribute table.

Table 7. Content of the Point Attribute Tables

ITEM NAME	WIDTH	OUTPUT	TYPE	N. DEC	
AREA	4	12	F	3	area of polygon in square meters
PERIMETER	4	12	F	3	length of perimeter in meters
<coverage>#	4	5	B		unique internal control number
<coverage>-ID	4	5	B		unique identification number
PTTYPE	35	35	C		unit label
DIP	3	3	I		dip of bedding or foliation (structure coverage only)
STRIKE	3	3	I		strike of bedding or foliation (structure coverage only)

Table 8. Point Types Recorded in the PTTYPE Field for structure coverage (wso-strc)

wso-strc
approx bedding
bedding
bedding w/tops
crumpled bedding
flat bedding
foliation
foliation and bedding
ot bedding
ot bedding estimated from afar
vert bedding
vert foliation and bedding
vert joint

The geologic point types in the structure coverage are ALACARTE point types that correlate with the geologic point symbols in the ALACARTE point set ALCGEOL.MRK according to the ALACARTE point lookup table. For more information on ALACARTE and its pointsets, see Wentworth and Fitzgibbon (1991). The point types in the block coverage (wso-blks) indicate specific rock types as listed in table 8a.

Table 8a. Block Types Recorded in the PTTYPE field and their corresponding metamorphic grade as shown by symbol on the map (wsomap.ps or wsomap.pdf)

wso-blks	high/low grade
bio qtz lith sandstone	Low
blsch metabasalt	High
blueschist	High
blueschist?	High
chert	Low
chert breccia	Low
eclgte + blscht + bio schst	High
eclogite	High
foliated green lithic wacke	High
gar omph eclog w/blsch ovrprnt	High
garnet blueschist	High
green chert w/rads	Low
green ribbon chert w/rads	Low
greenstone	Low
greenstone and metachert	Low
greenstone and metatuff	Low
greenstone breccia	Low
greenstone?	Low
greywacke	Low
high grade block	High
high grade block?	High
low grade block	Low
metachert	High
metagreenstone	High
metagreenstone and gneiss	High
metagreywacke	High
mica schist	High
mica-lithic wacke	Low
phyllite	High
pillow greenstone	Low
plag porph andesite	Low
pyrite blueschist	High
red chert	Low
red chert breccia w/rads	Low
red chert w/rads	Low
red limestone	Low
red ribbon chert	Low
red ribbon chert w/rads	Low
ribbon chert	Low
ribbon chert and chert breccia	Low
schist	High
schistose greenstone	High
serpentinite	Low
sheared greywacke	High
sheared arg w/sp + gs	High
yellow chert-tuff breccia	Low

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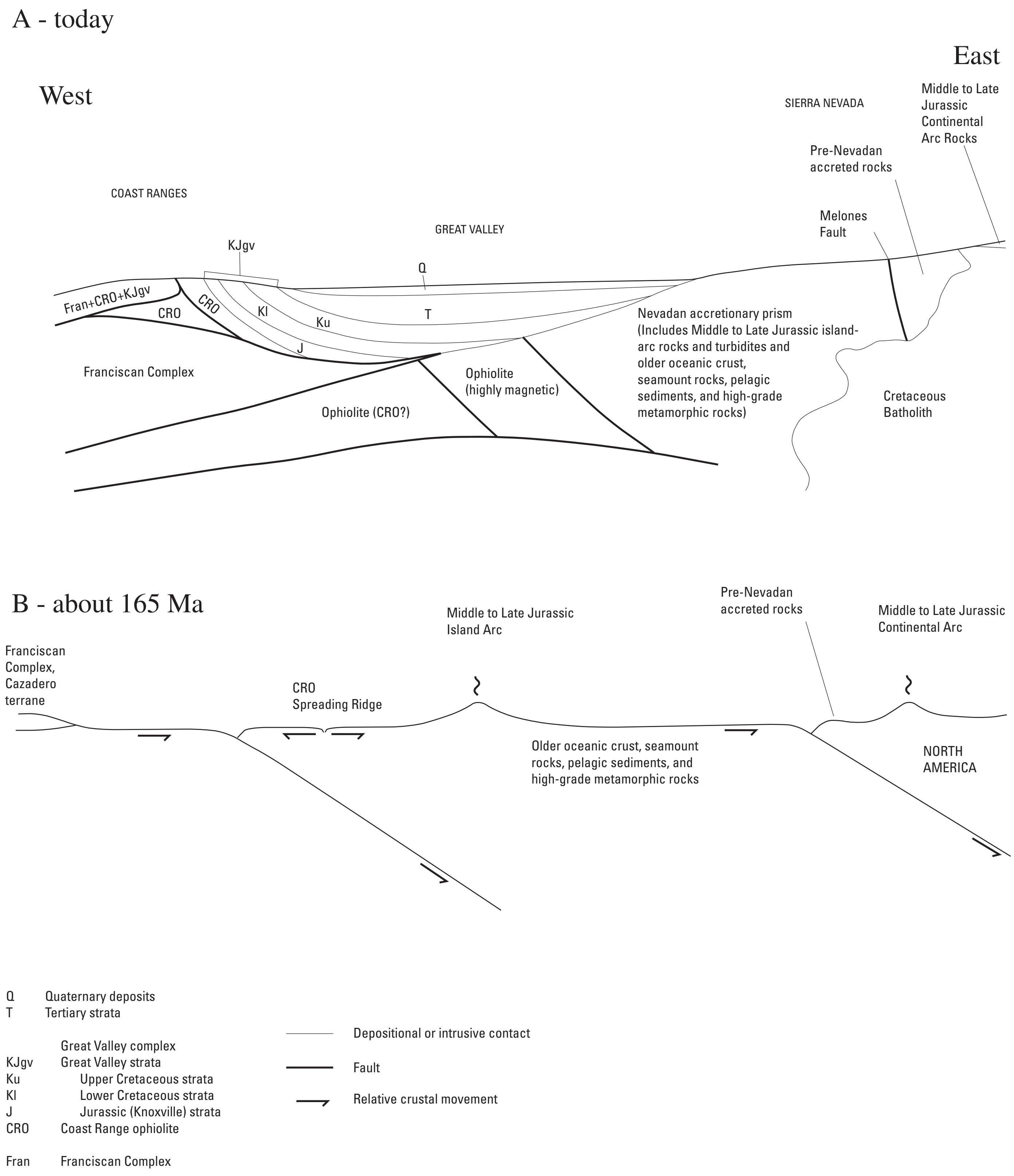

Figure 1. Schematic cross sections showing the observed and proposed original distribution of different major rock units that today underlie the California Coast Ranges, Great Valley, and Sierra Nevada Foothills. Cross section A shows distribution today, B shows relative distribution about 165 Ma. Note the position of the Coast Range ophiolite relative to the Middle to Late Jurassic island arc rocks (including the Logtown Ridge, Gopher Ridge, and Copper Hill volcanics) and the Middle to Late Jurassic continental arc rocks (including the Goddard terrane). The proposed model places the origin of the Coast Range ophiolite in the forearc of an oceanic island arc over an east-dipping, ocean-ocean subduction zone outboard of the North American subduction margin. The Coast Range ophiolite, island arc rocks, other older rocks, and overlying Late Jurassic turbidites were subsequently accreted to North America during the Nevadan Orogeny, about 150 Ma. The boundary between Nevadan and pre-Nevadan accretionary bodies is currently formed by the Melones Fault, a structure which remained active for several tens of millions of years after the Nevadan Orogeny. (Cross section A modified from Jachens and others, 1995)