Geology of the Cape Mendocino, Eureka, Garberville, and Southwestern part of the Hayfork 30 x 60 Minute Quadrangles and Adjacent Offshore Area, Northern California

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U.S. GEOLOGICAL SURVEY

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INTRODUCTION

PURPOSE

These geologic maps and accompanying structure sections depict the geology and structure of much of northwestern California and the adjacent continental margin. The map area includes the Mendocino triple junction, which is the juncture of the North American continental plate with two plates of the Pacific ocean basin. The map area also encompasses major geographic and geologic provinces of northwestern California. The maps incorporate much previously unpublished geologic mapping done between 1980 and 1995, as well as published mapping done between about 1950 and 1978. To construct structure sections to mid-crustal depths, we integrate the surface geology with interpretations of crustal structure based on seismicity (McPherson and Dengler, 1992; Oppenheimer and others, 1993; Magee and others, 1994), gravity and aeromagnetic data (Jachens and Griscom, 1983; Griscom and Jachens, 1989; Griscom, 1973, 1980a,b), offshore structure (McCulloch, 1987; Clarke, 1992 and this report), and seismic reflection and refraction data (Wentworth and others, 1984; Wentworth and Zoback, 1990; Ramirez, 1993; Godfrey and Clarke, 1995; Levander and others, 1995; Meltzer, 1995; Beaudoin and others, 1996; Godfrey and others, 1998; Henstock and others, 1997; Godfrey, 1997; Hole and others, 1998).

In addition to describing major geologic and structural features of northwestern California, the geologic maps have the potential to address a number of societally relevant issues, including hazards from earthquakes, landslides, and floods and problems related to timber harvest, wildlife habitat, and changing land use. All of these topics will continue to be of interest in the region, as changing land uses and population density interact with natural conditions. In these interactions, it is critical that the policies and practices affecting man and the environment integrate an adequate understanding of the geology.

FUNDING BACKGROUND

Field investigations in the map area have been supported by several programs of the U.S. Geological Survey. Much of the geologic mapping on federal lands was funded in the late 1970's and 1980's by the U.S. Geological Survey Wilderness Program's mineral resource investigations. These investigations were carried out in cooperation with the U.S. Forest Service, U.S. Bureau of Land Management, and the U.S. Bureau of Mines. Subsequently, in 1982, the mapping investigations were expanded to cover regional geologic mapping, at a scale of 1:100,000, of a transect extending from the northern California offshore margin eastward to the Klamath and Sierra Nevada Mountains. This project continued until about 1987, under funding from the Geologic Framework Studies and National Geologic Mapping programs of the U.S. Geological Survey. Subsequent preparation of these maps as a digital map product was partially supported by the National Earthquake Hazards Reduction and Deep Crustal Studies programs of the U. S. Geological Survey, but support for publication of the maps was lost in 1995, after reorganization of the U.S. Geological Survey. Funding for publication as a digital database was restored in October, 1999, upon recognition that the maps have immediate value for addressing hydrologic, slope stability, timber harvest, and wildlife habitat issues in this region.

ACKNOWLEDGEMENTS

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PREVIOUS WORK

Studies of the onshore and offshore geology of the area cited here include geophysical studies based on aeromagnetics, gravity, and seismic reflection and refraction. Other topical studies have concerned seafloor plate reconstructions and the seismology and geodetics of the region.

Previous work in the offshore area, from south of the Mendocino fracture zone northward, includes the work of Silver, 1971a,b; McCulloch, 1987; Curray and Nason, 1967; Clarke, 1990, 1992; Clarke and Field, 1989; Crouch and Bachman, 1987; and Horan and Hopps, 1987. Geologic mapping in the onshore Eel River basin region has focused predominantly on the stratigraphy and deformation of Neogene basin fill, on oil resource potential (Ogle, 1953; Carver, 1985), or on seismic hazards, especially those associated with the now-decommissioned Humboldt Nuclear Reactor (Woodward-Clyde Consultants, 1980). Geologic mapping studies in the western on-land half of the report area since the 1980's have emphasized the structure and subdivision of the accretionary Coastal belt of the Franciscan Complex, and the delineation of fault-bounded non-accretionary outliers of the Eel River basin section that overlie or are imbricated into the Franciscan Complex. These studies include the work of Beutner and others, 1980; McLaughlin and others, 1982; Underwood, 1983; Bachman and others, 1984; Menack, 1986; Blake and others, 1988; McLaughlin and others, 1994; and Aalto and others, 1995. Many recent studies have focused on the mapping and dating of marine and nonmarine terraces as a means of delineating the parts of this region that are undergoing rapid tectonic uplift (Lajoie and others, 1982; McLaughlin and others, 1983; Bickner, 1985; Hagemann, 1985; Lajoie, 1986; and Merritts and Bull, 1989).

Most geologic mapping investigations in the central and eastern Coast Ranges and Klamath Mountains Provinces have emphasized delineating the timing of metamorphism and the juxtaposition and structural significance of fundamental accretionary boundaries, including the boundary separating the Klamath Mountains from the Coast Ranges. A few topical studies have focused on late Cenozoic deformation. Significant published work includes: Irwin (1960); Suppe and Armstrong (1972); Irwin and others (1974); Worrall (1981); Wright (1981); Blake and Jayko (1983); McDowell and others (1984); Irwin (1985); Irwin and others (1985); Blake and others (1988); and Wright and Fahan (1988). Publications that have focused on late Cenozoic strike-slip fault deformation in the Coast Ranges province include Herd (1978); Kelsey and Hagans (1982); and Kelsey and Carver (1989).

METHODS

Geologic mapping used in this report was compiled at scales ranging from 1:250,000 in the offshore region to scales of 1:100,000 to 1:24,000 onshore. Map users may refer to figure 1 to determine sources of geologic data used for specific areas of the geologic map. The resolution of this mapping is variable, depending on its original scale. The more detailed mapping was done along the boundaries of major accretionary terranes. Where exposure was good and access available, critical contacts and structures were mapped at scales of 1:24,000 to 1:62,500. Large tracts of land between the areas of detailed mapping, however, were mapped largely from aerial photographs, particularly in areas of private land in the Coast Ranges Province where permission to enter could not be obtained. Photointerpretation of the geology is based on black-and-white and color aerial photographs at approximate scales of 1:12,000 (BLM, 1973; Humboldt County Assessor, 1974); 1:20,000 (Cartwright Aerial Surveys, Inc., Sacramento, 1981); 1:80,000 (USGS, 1976); 1:143,000 (source unknown, 1969); and false-color IR photos at a scale of 1:130,000 (NASA, 1978).

Landslides shown on the maps are those that we noted during field and photo mapping of the regional geology. They do not provide a complete portrayal of landsliding in the map area. More complete portrayal of the various landslides and landslide processes in the map area can be found elsewhere (California Department of Conservation, Division of Mines and Geology, 1999).

PHOTOINTERPRETIVE MAPPING

In addition to routine use of aerial photographs during field mapping, systematic mapping of topographic form, as expressed in stereoscopic pairs of high-altitude aerial photographs, was used to complement the field mapping. This mapping was used in two principal ways. First, it was used to draw contacts between major geologic units. Many Quaternary map units such as landslides and alluvial deposits are recognized principally by their topographic form. Other young deposits, such as the late Cenozoic overlap deposits of the Wildcat Group (Ogle, 1953) and related rocks, in many places also exhibit a distinctive topographic form that enabled delineation of contacts and extrapolation between field exposures. Similar photointerpretive clues aided in mapping many of the major geologic units west of South Fork Mountain.

The second use of systematic photointerpretation involved subdivision of major geologic units by topographic form. Many of the major units have been disrupted tectonically and as a result contain heterogeneities that are reflected as contrasts in topographic form (fig. 2). In the San Francisco Bay region, similar topographic contrasts within the Franciscan Complex correspond systematically to contrasts in lithology and structural condition of the rock mass (Reid, 1978; Peterson, 1979; Ellen and others, 1979; Savina, 1982), apparently because different processes of erosion and landsliding operate in the different rock masses and associated soil materials (Ellen and others, 1982). There, systematic mapping of topographic form was used to help subdivide the Franciscan Complex in Marin County for incorporation into a regional map of engineering character of earth materials (Ellen and Wentworth, 1995). We applied the methods developed in the San Francisco Bay area to Franciscan rocks of north coastal California.

In the soil-mantled landscape of coastal California, rock masses larger than a few hundred meters in diameter tend to develop topographic forms related to the erosional and slope-stability properties of the constituent materials. These properties may be controlled by many factors, such as structural state of the rock mass and orientation of layering. Rates of tectonic uplift (Merritts and Bull, 1989) may also play a role in the development of topographic form, but geodetic work (Stein and others, 1993) indicates that these rates tend to vary gradually and over areas much broader than many of the subunits of abruptly contrasting topographic expression delineated on the map. Other possible factors, such as rainfall, also tend to vary at broad scale.

Rock masses of the map area consist dominantly of sandstone and clayey rock (argillite) that are sheared or otherwise disrupted to varying degrees. Sandstone rock masses weather to granular (sandy and silty) soil that is stable enough to form steep slopes. The stability and homogeneity of such soils and rock masses tend to result in steep, sharp-crested topography dissected by a regularly spaced array of straight, well-incised sidehill drainages (hard topography of Ellen and others, 1982). Clayey rock masses, especially where sheared, weather to clayey soil materials. These clayey soils and bedrock are so weak that they can support only gentle hillslopes and poorly incised sidehill drainages, and crests tend to be rounded (soft topography of Ellen and others, 1982). Where rock masses are heterogeneous, such as where sandstone is interrupted by clayey sheared rock or where clayey sheared rock includes masses of sandstone or other lithologies, the mixed hillslope processes result in topography that is irregular in form, intermediate in steepness, or that otherwise reflects the mix of materials. In such cases, sidehill drainages, which in homogeneous materials tend to run directly downhill, tend to be crooked or irregular in spacing, and the landscape takes on an erratic, irregular aspect when viewed from the high altitudes used in this analysis.

Most major units of the map area west of the Grogan-Red Mountain fault zone are divided by topographic expression into three or four subunits. These subunits describe a gradation in topographic expression that reflects the general changes in lithology and structural condition described above (fig. 2).

Subunits co1 and cm1 have rounded, irregular, generally lumpy, and largely gently sloping topography that lacks a well-incised system of sidehill drainages. These units correspond to melange or other sheared rock that contains abundant clayey, penetratively sheared argillite.

Subunits krk1, y1, co2, and cm2 generally have irregular, gently to moderately sloping topography that lacks a well-incised system of sidehill drainages. These units correspond to melange having subequal amounts of sandstone and argillite or to highly folded and variably sheared, predominantly argillitic sequences.

Subunits krk2, y2, co3, and cb1 have steep topography with generally sharp crests and well-incised but irregular sidehill drainages. These units generally correspond to highly folded broken formation that includes zones of clayey sheared argillitic rock.

Subunits krk3, y3, co4, and cb2 consist of sharp-crested, steep topography that has a regular, well-incised system of sidehill drainages. These subunits generally correspond to the least disrupted rock masses of their respective terranes and lack significant zones of clayey sheared argillitic rock.

To produce the final map, the systematic mapping of topographic form was incorporated into the lithologic and structural framework provided by field mapping. Where the boundaries of topographic units coincided with contacts mapped in the field, or where field observations were sparse, the subunits were incorporated directly and the final map shows the topographic units as originally mapped. Where the topographic units diverged from units mapped in the field, the field mapping took precedence. In places where the topographic units were combined with similar interpretive units from previous mapping, as in much of the mapping in the Hayfork quadrangle, a reasonable compromise between the interpretations was determined by the senior author. In cases where unique lithologic identity had been determined for rock masses (for example, unit cwr, White rock sandstone of the Central belt), the lithologic identity alone is indicated, without topographic subunit assignment. As a result of this general procedure for combining the topographic units with the field mapping, the systematically mapped topographic forms are retained more consistently in the several terranes of the Coastal belt than in the Central belt.

GEOLOGIC AND STRUCTURAL OVERVIEW

The area of this report straddles two major onshore geographic provinces, the Klamath Mountains and the Coast Ranges, and extends offshore to the inner continental margin. The region is further subdivided into a number of geologic provinces. From east to west, these geologic provinces reflect the long-term accretionary history of the continental margin. The region also exhibits the more recent transition from a subduction margin on the north, to a northwardly-propagating right-lateral transform margin to the south that is superposed on the older accretionary margin. The discussion first moves from east to west, focusing on the long-term accretionary history of the region. It then moves from north to south, focusing on the geologic events associated with the ongoing transition from a convergent to a transform margin.

The timing of accretion ranges from Paleozoic in the eastern part of the area to Pliocene or Pleistocene along the coast north of Cape Mendocino. This sequential east-to-west accretionary history is recorded in a number of penetratively deformed, fault-bounded bodies of rock that are here referred to as structural "terranes". These terranes are overlain locally by younger strata that depositionally overlap the terrane boundaries and thus are informally referred to as "overlap deposits" (fig. 3). The present transform margin occupies the offshore map area south of the Mendocino fracture zone and a wide swath of the onshore Coast Ranges southwest of the latitudes of Petrolia, Honeydew, and Garberville (fig. 3).

The deformational history of the area is here viewed from the perspective of movement of the various faults bounding the structural terranes and by the fault kinematics associated with the recently developed San Andreas transform margin. Accretion and subduction are ongoing beneath the continental margin north of the Mendocino fracture zone, contemporaneously with dextral slip that is associated with propagation of the San Andreas fault system from the south. Ongoing deformation (figs. 3, 6a, and 6b) is driven by interactions among the Gorda, Pacific, and North American plates. Collective deformation resulting from this simultaneous three-plate interaction characterizes the Mendocino triple junction.

KLAMATH MOUNTAINS PROVINCE

The northeast quarter of the Garberville quadrangle is occupied mainly by terranes of the Klamath Mountains province (fig. 3). The Klamath Mountains consist of eight or more allochthonous terranes that were sequentially accreted to an early Paleozoic continental margin. The oldest terranes of the Klamath Mountains are exposed northeast of the Garberville quadrangle. Only the younger terranes, which include, from east to west, the Eastern Hayfork, Western Hayfork, Rattlesnake Creek, and Western Klamath (also known as Smith River) terranes, are exposed in the Garberville quadrangle. These younger terranes were accreted during a series of Middle and Late Jurassic episodes and have rotated clockwise as much as about 80 degrees (Irwin and Mankinen, 1998). The accretionary episodes are named after the accreted terrane. Pre-accretionary plutons are present in some of the accreted terranes. Plutons that intrude previously amalgamated terranes as the result of the generation of magma during a later accretionary episode are referred to as accretionary plutons. At several places in the Garberville quadrangle, the accreted terranes are overlain by sedimentary outliers of Cretaceous strata of the Great Valley sequence. These outliers of Great Valley sequence are considered part of an overlap assemblage containing Early Cretaceous (Valanginian) fossils and exhibit an upward transition from nonmarine to marine strata. The overlap assemblages and accretionary plutons constrain the accretion of Klamath Mountains terranes to predate the Valanginian stage of the Early Cretaceous. The western geologic boundary of the Klamath Mountains in the southern part of the province is generally considered to be the South Fork fault that commonly separates the Western Klamath terrane from the Pickett Peak terrane of the California Coast Ranges (fig. 3).

The nucleus of the Klamath Mountains is northeast of the map area and formed in Silurian-Devonian time as part of a volcanic island arc (Irwin and Wooden, 1999; see Wallin and Metcalf, 1998, for an alternative explanation). The roots of the arc are represented by gabbroic plutons and complexes that intrude the large peridotite slab of the Trinity subterrane, also northeast of the map area. The volcanic rocks of the arc and cogenetic intrusive stocks are about 400 Ma (Albers and others, 1981). Arc magmatism probably occurred during the Central Metamorphic episode, when oceanic volcanic and sedimentary protoliths of the Central Metamorphic terrane were subducted beneath the Trinity subterrane along the Bully Choop thrust fault (Irwin and Wooden, 1999). The Central Metamorphic accretionary episode was followed by the Fort Jones (also known as Stuart Fork) episode.

The Fort Jones terrane (northeast of the map area) is a metamorphosed subduction complex of mafic metavolcanics, argillite, chert, and local blocks of blueschist. The time of its accretion to the Central Metamorphic terrane is not precisely known. The blueschist blocks yield Late Triassic ages (about 220 Ma; Hotz and others, 1977), but plutonism and volcanism in the Redding subterrane that may be related to the Fort Jones accretionary episode suggest a Permian-Triassic accretion (Irwin and Wooden, 1999). Triassic rocks of the Redding subterrane have rotated clockwise about 110 degrees (Irwin and Mankinen, 1998).

The North Fork terrane to the northeast of the map area consists of dismembered ophiolite, mafic volcanic and sedimentary rocks, radiolarian chert, and limestone. The rocks range in age from late Paleozoic to Jurassic. The youngest strata are Early Jurassic (Pliensbachian) chert (Blome and Irwin, 1983), which establishes an earliest possible accretion time for the North Fork terrane.

The Eastern Hayfork subterrane is the oldest accretionary unit exposed in the Garberville quadrangle, lying in fault contact above the Western Hayfork subterrane along the Wilson Point thrust at the northeast corner of the quadrangle. This melange of oceanic rocks includes shreds of ophiolite, mafic metavolcanic rocks, argillite, scattered blocks of schist, chert, and blocks of exotic limestone. Some of the chert and limestone contain Late Permian and Triassic fossils. The Late Permian limestone is locally notable for Tethyan faunas that are unknown in most of North America. Based on the early Jurassic (Pliensbachian) age of chert in the North Fork terrane, the Eastern Hayfork subterrane probably accreted to the North Fork terrane no earlier than early(?) Middle Jurassic (approximately Bajocian time) (Irwin and Wooden, 1999).

The Western Hayfork subterrane was a late Middle Jurassic volcanic arc consisting mainly of Hayfork Bally Meta-andesite and cogenetic plutons such as the Ironside Mountain batholith and, in the Garberville quadrangle, the Wildwood pluton. These pre-accretionary rocks range in age from 168 to 177 Ma (Fahan, 1982; Lanphere and others, 1968; Wright, 1981). Based on the isotopic ages of the pre-accretionary arc volcanics and plutons and the intrusive relations of younger plutons and fault relations, the timing of Western Hayfork subterrane accretion to the Eastern Hayfork subterrane along the Wilson Point and correlative faults, is assumed to be at 168 Ma.

The Rattlesnake Creek terrane is a melange consisting of ophiolite, broken volcanic and sedimentary formations, limestone, chert, blocks of amphibolite, and preaccretionary (about 200 Ma) plutons. Fossils from the limestone and chert range from late Paleozoic to Middle Jurassic (possibly as young as Bathonian). The Rattlesnake Creek terrane accreted to the Western Hayfork subterrane along the Salt Creek and correlative faults. The time of the accretionary episode is constrained to Callovian-Oxfordian (about 164 Ma) by the Middle Jurassic fossils and by the approximately 160 Ma accretionary plutons that cut the suture between the Rattlesnake Creek terrane and Western Hayfork subterrane north of the Garberville quadrangle (Irwin and Wooden, 1999).

The Smith River subterrane, which is one of several divisions of the Western Klamath terrane, forms the most westerly part of the Klamath Mountains in the Garberville quadrangle. It consists mainly of Late Jurassic Galice? Formation of mildly slaty graywacke and argillite, locally with andesitic pyroclastic beds. In the 1:62,500 scale Pickett Peak quadrangle, the Galice? Formation is semischistose near some major tectonic boundaries. The subterrane also includes the Glen Creek Gabbro-Ultramafic Complex, as well as several slices of serpentinite and associated rocks along the South Fork fault, that may be correlative with the Josephine ophiolite (Wyld and Wright, 1988).

Ophiolitic rocks along the South Fork fault near the Devil's Elbow were described and dated by Wyld and Wright (1988), who considered them to be a slice of the Josephine ophiolite of the Klamath Mountains Province. One of the coauthors of this report (A.S. Jayko), however, has reinterpreted these rocks to be part of the Coast Range ophiolite, of about the same age (middle Jurassic; Lanphere, 1971), based on the presence of distinctive ophiolitic breccia which overlies the Coast Range ophiolite near Paskenta, to the southeast (part of the Elder Creek terrane; Blake and others, 1999). Unlike typical rocks of the structurally overlying Smith River subterrane, the ophiolitic slivers along the South Fork fault lack a penetrative cleavage. A similar conclusion as to the origin of the ophiolitic breccia along the South Fork fault was reached by A. Robertson (personal commun. with M.C. Blake, Jr., 1990). If this reinterpretation is correct, it suggests that the Klamath Mountains have entirely overridden the Coast Range ophiolite and the Great Valley Sequence north of Paskenta.

In the Garberville quadrangle, the South Fork fault separates the rocks of the Klamath Mountains from those of the Coast Ranges. The age of the fault is not precisely known, but must be as young or younger than the metamorphic age of the South Fork Mountain Schist, dated at about 115-120 Ma (Lanphere, 1978). More recent $^{39}Ar/^{40}Ar$ step heating ages on the South Fork Mountain Schist coupled with a fission track study of the thermal history of these rocks (J. Wakabayashi, in Tagami and Dumitru, 1996) suggests that the age of faulting is about 125 Ma.

COAST RANGES PROVINCE

The Coast Ranges comprise the onshore part of the map area west of the Klamath Mountains Province. The province is underlain in the upper crust predominantly by accreted Mesozoic and Cenozoic rocks of the Franciscan Complex and by structural remnants of a Mesozoic forearc, including the Coast Range ophiolite and Great Valley sequence. This accretionary assemblage, like the Klamath Mountains terranes, has accreted to North America sequentially from east to west and is continuing this accretion at present in the offshore area north of the Mendocino fracture zone. The Franciscan Complex is subdivided into three broad belts which become younger to the west, the Eastern, Central, and Coastal belts (Irwin, 1960), and each belt is further subdivided into a number of structural terranes (fig. 3). These Mesozoic and Cenozoic basement rocks locally are overlain depositionally and structurally by Miocene and younger forearc strata.

The province also encompasses the Mendocino triple junction. North of the triple junction the North American Plate is in low-angle thrust contact with the Gorda plate along the Cascadia subduction zone, and it joins the Pacific plate to the south along the steep dextral San Andreas transform. The Gorda and Pacific plates are in contact along the offshore Mendocino fracture zone, whose dextral offshore motion is caused by eastward underthrusting of the Gorda Plate in conjunction with northeastward motion of the Pacific plate along the San Andreas transform.

Outliers of Great Valley Sequence and Coast Range Ophiolite

In the Coast Range Province of the map area, composite structural outliers of Mesozoic sedimentary and ophiolitic rocks correlative with the Great Valley forearc basin and underlying Coast Range ophiolite are recognized in a few areas west of the Klamath Mountains. Numerous bodies of mafic rocks, including serpentinized peridotite, gabbro, basaltic flows, and intrusive rocks are widely dispersed along high- and low-angle faults in the Central belt of the Franciscan Complex. Many of these mafic to ultramafic fault slivers and blocks are probably derived from the Coast Range ophiolite (McLaughlin and others, 1988). This can be demonstrated with confidence, however, at only three localities: the Lassics area, southwest of the Mule Ridge and Grogan-Red Mountain fault zones; near Benbow southeast of Garberville; and at Bear Buttes north of Garberville.

The sedimentary and igneous assemblage at the Benbow locality is very different from that at the Lassics. The ophiolitic rocks at Benbow have affinities to a well-studied, thicker, more extensive Coast Range ophiolite section 300 km southeast of Benbow, in Del Puerto Canyon east of San Jose, California. The Benbow section, here correlated with the Del Puerto terrane of the Coast Range ophiolite (McLaughlin and others, 1988) includes igneous and sedimentary rocks with lithologies similar to those of oceanic arcs. The arc-like lithologies include radiolarian-bearing siliceous tuff, keratophyric tuff, and mafic to andesitic flow rocks intruded by quartz keratophyre dikes. At Benbow these rocks are overlain by a thin attenuated section of penetratively sheared tuffaceous mudstone containing carbonate concretions with radolaria of Late Jurassic (late Tithonian) age. The Bear Buttes area north of Garberville consists of a thick section of mafic dikes and sills that overlies a thin sliver of cumulate gabbro and a serpentinite-matrix melange containing blocks of peridotite, gabbro, diabase, and basalt. These rocks are inferred to represent a dismembered piece of the Benbow section of the Del Puerto terrane.

At the Lassics, northeast of Zenia, the Coast Range ophiolite section resembles that of the Coast Range ophiolite and overlying basal sedimentary section of the Great Valley sequence in Sacramento Valley. In particular the Lassics section includes an ophiolitic melange unit with blocks of sedimentary breccia identical to breccia overlying the Coast Range ophiolite of the western Sacramento Valley (Wagner, 1975; Robertson, 1989 and 1990). This breccia is composed of igneous clasts derived from the ophiolite section (Kelsey and Hagans, 1982; Hopson and others, 1981; McLaughlin and others, 1988; Robertson, 1989 and 1990). The Coast Range ophiolite section at the Lassics thus is correlated with the Sacramento Valley section of the Coast Range ophiolite and basal Great Valley sequence, named the Elder Creek terrane for exposures in Elder Creek.

The attenuated Lassics section of the Elder Creek terrane overlies a large slab of the Franciscan Complex Eastern belt, which is surrounded by melange of the Central belt and displaced along the Mule Ridge and Grogan-Red Mountain fault zones (fig. 3 and structure sections). These Eastern belt rocks are correlated with the Little Indian Valley argillite subunit of the Yolla Bolly terrane, originally described near Wilbur Springs about 160 km southeast of the Lassics area (McLaughlin and Ohlin, 1984; McLaughlin and others, 1990) and northeast of the southeastward projected Grogan-Red Mountain and Mule Ridge fault zones (McLaughlin and others, 1988; Blake and others, 1984, 1988).

Franciscan Complex

Eastern belt

The Eastern belt of the Franciscan Complex is composed of rocks that are generally less disrupted by penetrative shear than structurally lower rocks in Franciscan belts and terranes to the west. The Eastern belt rocks, however, have also generally undergone a more uniform regional metamorphism to higher-pressure mineral assemblages than Franciscan belts and terranes to the west. The Eastern belt is subdivided into two structural terranes, the Pickett Peak and Yolla Bolly, separated by low-angle faults. The terranes are subdivided into several subunits that also are separated along low-angle faults and are characterized by different but overlapping compositions and degrees of textural reconstitution. The metamorphic ages of the two terranes differ, with metamorphism of the Pickett Peak terrane being significantly older than that of the Yolla Bolly terrane. Textural reconstitution and development of blueschist facies mineral assemblages in the rocks of each terrane generally increases gradationally eastward and structurally upward; however, these gradations are truncated along the low-angle faults that bound the terranes. In the Yolla Bolly terrane, metamorphic textures and mineral assemblages may also be truncated at the fault boundaries of subunits within the terrane. Metasandstones in Eastern belt terranes generally contain less than 1 percent K-feldspar, due largely to replacement by sodic plagioclase or white mica during high pressure metamorphism. Exceptions to this generalization exist, however; and stained slabs of Eastern belt metasandstones occasionally exhibit as much as a few percent K-feldspar (fig. 5).

Pickett Peak terrane

The Pickett Peak terrane is the structurally highest terrane in the Eastern belt and consists of schistose and semischistose quartz-mica-lawsonite-bearing metasedimentary and blue and green amphibole-bearing metavolcanic rocks. The terrane includes the South Fork Mountain Schist (Irwin and others, 1974), including the Chinquapin Metabasalt Member, and the Valentine Springs Formation (Worrall, 1981). The Valentine Springs Formation consists predominantly of metagraywacke (textural zones 2B to 3A of Blake and others, 1967) with minor fine-grained mafic metavolcanic rocks and rare metachert. The depositional and igneous ages of the protoliths of the Pickett Peak terrane are unknown. The rocks have undergone regional blueschist metamorphism, exhibiting progressively higher textural reconstitution in conjunction with development of higher-pressure blueschist mineral facies assemblages toward the South Fork fault (Blake and others, 1967).

The most highly reconstituted, structurally highest, and easternmost unit of the Pickett Peak terrane is the South Fork Mountain Schist. Lanphere and others (1978) radiometrically dated the South Fork Mountain Schist by whole-rock K-Ar methods and concluded that the metamorphism occurred about 115-120 Ma. Other whole-rock K-Ar dating (McDowell and others, 1984; Suppe, 1973) yielded ages in the range of about 110-158 Ma for both the South Fork Mountain Schist and Valentine Spring Formation. The K-Ar ages cluster around 124-125 Ma, which was regarded as the most likely age of Pickett Peak terrane metamorphism (Blake and others, 1984). More recently, J. Wakabayashi (cited in Tagami and Dumitru, 1996) obtained step-heating $^{39}Ar/^{40}Ar$ ages of 121-124 Ma on white micas from the South Fork Mountain Schist near Tomhead Mountain, east of the map area.

Yolla Bolly terrane

The Yolla Bolly terrane consists predominantly of quartzofeldspathic metagraywacke with minor intercalated metachert and metavolcanic rocks. These rocks are reconstituted to textures ranging from semi-schist to rocks exhibiting very weak or no cataclasis (textural zones 2A to 2B of Blake and others, 1967). The rocks generally contain incipiently developed blueschist facies minerals, including lawsonite and blue amphibole, and very rarely, jadeitic pyroxene. In places these rocks are intruded by rare alkalic mafic intrusives. The terrane is divided into several subunits that are separated generally along low-angle thrust faults: the Taliaferro Metamorphic Complex of Suppe and Armstrong (1972), Chicago Rock melange, Graywacke of Hammerhorn Ridge, Devils Hole Ridge Broken Formation (Blake and Jayko, 1983), and Little Indian Valley argillite (McLaughlin and Ohlin, 1984). Many of these units were originally mapped and named in areas southeast of the Garberville quadrangle. Refer to Blake and others (1999), McLaughlin and others (1990), Jayko and others (1989), Blake and others (1988), Blake and others (1984), McLaughlin and Ohlin (1984), Blake and Jayko (1983), Worrall (1981), Irwin and others (1974), and Suppe (1973), for further information on these terrane subunits. Metamorphism and poor radiolarian preservation in most metachert of the Yolla Bolly terrane permit only a broad age assignment of Middle Jurassic to middle Cretaceous. Radiolarian assemblages from a few carefully studied metachert sections (Baumgartner, 1987; Isozaki and Blake, 1994; B. Murchey, personal commun., 1999), however, indicate a much narrower age range of early Middle Jurassic (Aalenian) to Late Jurassic (Tithonian) for the metacherts. Late Jurassic (Tithonian) to Early Cretaceous (Valanginian) macrofossils are found in depositionally overlying metagraywacke of the terrane.

The Yolla Bolly terrane apparently accreted to the Pickett Peak terrane along the northwestward extension of the Sulphur Creek thrust of Worrall (1981), which separates the two terranes southwest of Pickett Peak. The accretion probably corresponded to the timing of prominent duplexing of basal radiolarian chert with the overlying clastic rocks (metagraywacke) of the section. Presumably during the subduction process, oceanic basalt was almost entirely removed from the base of the Yolla Bolly section, although a few scraps are preserved locally below the metachert (see Isozaki and Blake, 1994, for further discussion).

The timing of subduction and accretion of the Yolla Bolly terrane is poorly dated. Whole-rock metamorphic ages range from about 90 to 115 Ma (Suppe, 1973; Lanphere, 1978; McDowell and others, 1984). U-Pb radiometric ages from zircon and sphene in gabbroic intrusive rocks outside of the map area (Mattinson and Echeverria, 1980) suggest that clastic sediments of the terrane were intruded in the early Late Cretaceous (about 95 Ma), followed shortly after by subduction and blueschist metamorphism about 90 Ma. Accretion of the terrane pre-dates its juxtaposition with the Central belt and the northward translation of Yolla Bolly rocks along the Mule Ridge and Grogan-Red Mountain fault zones that probably continued through the Eocene (fig. 3). Yolla Bolly terrane accretion also probably pre-dated the approximately 58 to 42 Ma unroofing and recycling of rocks in the terrane. This timing is based on clasts of Yolla Bolly-derived lawsonitic and jadeitic metasandstone and metachert found with other Franciscan-derived clasts in Paleocene conglomerate. The conglomerates are found overlying outliers of the Coast Range ophiolite and Great Valley Sequence that are imbricated with the Central belt (Berkland, 1973; Blake and others, 1984) and also in late Eocene conglomerate in the Franciscan Coastal belt (McLaughlin and others, 1994).

Central belt

The Central belt of the Franciscan Complex extends over a considerable part of the Garberville and Hayfork quadrangles as well as small areas of the Eureka and Cape Mendocino sheets. The Central belt consists predominantly of a melange with interleaved slabs and blocks of more coherent broken and folded sequences of sandstone and shale turbidites. Locally, large blocks and slabs of metabasalt with intercalated chert or limestone are included in the melange. Other lithologies within the melange of the Central belt include glaucophane- and jadeite-bearing meta-igneous rocks, eclogite, garnet-bearing amphibolite, lawsonite-chlorite- and white mica-bearing quartz-schist and phyllite, serpentinite, and other minor ophiolitic constituents. Commonly, the matrix of the melange is composed of penetratively sheared argillite with partings of chloritic, actinolitic metatuff. Locally, the argillite may display relict bedding and include calcareous or cherty concretions, or impure thin-bedded chert. Radiolaria and dinoflagellates from these hemipelagic sequences range in age from Late Jurassic (Tithonian) to Middle Cretaceous (Albian) (fig. 4; table1).

Several named subunits of metasandstone and argillite were mapped in the Central belt, based on distinctive compositions, particularly K-feldspar content (fig. 5), their associations with other rock types, or their degree of metamorphism. Two of these sandstone subunits are the laumontized, K-feldspar- and biotite-rich White Rock sandstone (Jayko and others, 1989) and the low (0-trace percent) K-feldspar- and pumpellyite-laumontite-bearing Haman Ridge graywacke (Jayko and others, 1989). These subunits are named for their occurences in the adjacent Covelo 1:100,000 quadrangle (Jayko and others, 1989; Blake and others, 1984; Blake and others, 1988). The White rock sandstone subunit is thought to be Late Cretaceous and possibly Paleocene in age based on dinoflagellate ages and on lithologic similarity to rocks in the Coastal belt (Jayko and others, 1989). It should be pointed out, however, that nearly all clastic rocks of the Coastal belt are Paleocene or younger (McLaughlin and others, 1994). The Haman Ridge graywacke unit may be Cretaceous in age based on its lithologic similarity to the English Ridge graywacke unit of the Covelo area that contains Middle Cretaceous (Cenomanian to Albian) fossils (Jayko and others, 1989). The undated, non-laumontized, K-feldspar- and biotite-rich Fort Seward sandstone (this report) is not recognized beyond the Fort Seward area, but could be related to the White Rock subunit.

Other units of metasandstone and meta-argillite are unnamed but are subdivided on the basis of their topographic expression into two melange units and two units of broken formation. These units generally exhibit weak to no cataclasis and typically contain less than 0.5 percent, but locally, from several percent to more than 10 percent detrital K-feldspar (fig. 5); they contain pumpellyite, and rarely, incipient lawsonite.

Fossils in the unnamed metasandstone and meta-argillite subunits of the Central belt, including the melange matrix, range from Late Jurassic (Tithonian) to Middle Cretaceous (Aptian or Albian). Most of the fossils are radiolaria or dinoflagellates from carbonate concretions or chert nodules in the map area and the Covelo quadrangle (Jayko and others, 1989) and *Buchias* from numerous localities elsewhere in the northern Coast Ranges.

Metasandstone blocks and slabs of texturally reconstituted metasandstone, with incipiently developed blueschist facies minerals, have been correlated with the Yolla Bolly or Pickett Peak terranes of the Eastern belt (Blake and others, 1988; McLaughlin and others, 1988).

The matrix of the melange units is predominantly of pumpellyite metamorphic grade, and according to some work (Cloos, 1983), reaches incipient lawsonite conditions. We find no petrographically identifiable lawsonite in the matrix of the Central belt in the map area and therefore interpret the lawsonite-bearing Eastern belt blocks to have been tectonically interspersed with the lower-grade metasandstone subunits and matrix rocks since 88 Ma (youngest paleontologic age from pelagic foraminiferal limestone blocks). Radiometric ages of 160-162 Ma for blocks of glaucophane-bearing high blueschist-grade rocks (knockers) enclosed in the melange matrix indicate that these high-grade metamorphic rocks are derived from an older terrane subjected to much higher pressure metamorphic conditions (Blake and others, 1988).

Blocks of bedded radiolarian chert in melange of the Central belt (Murchey, 1984; Murchey and Jones, 1984), some of which is depositional on basalt, have radiolarian faunas indicating continuous deposition from the Early Jurassic (about 190 Ma) to the early Late Cretaceous (about 93 Ma). Melange blocks of bedded pelagic limestone (Sliter, 1984), also with basaltic substrates, locally have foraminifer faunas indicating continuous pelagic deposition from the Aptian (about 120 Ma) to the Coniacian (about 88 Ma). These siliceous and calcareous pelagic rocks apparently represent at least 100 m.y. of oceanic deposition, away from the continental margin, because there is no indication of a terrigenous clastic contribution to these sections or of tectonic disruption during deposition. Radiolarian data from cherts that depositionally overlie basalt indicate an Early Jurassic or older age for the underlying basalt; foraminifers in pelagic limestone lenses that depositionally overlie basalt, in contrast, are Aptian, indicating that basalt underlying the limestone is Aptian or older. No chert younger than Early Jurassic or pelagic limestone younger than Aptian has been found in depositional contact with basalt in the Central belt. Nor has pelagic Aptian limestone anywhere been found to depositionally overlie a section of Early Cretaceous and older radiolarian chert on basalt. This suggests that basaltic basements associated with the cherts and pelagic limestones are of distinctly different ages. The data could be interpreted to suggest that pelagic sediments were deposited on static oceanic crust at a time of very slow or inactive spreading, although alternative interpretations are possible. The data all suggest that fragments of Jurassic to Cretaceous oceanic crust and overlying pelagic deposits were disrupted at the continental margin and were tectonically assembled as the Central belt melange, largely after 88 Ma.

The Central belt was accreted to the Eastern belt of the Franciscan Complex along the Grogan-Red Mountain fault zone, which exhibits evidence of oblique dextral translation consistent with the evidence for northward translation of scraps of pelagic sediment and oceanic crust of the Central belt from equatorial latitudes. Accretion of the Central belt therefore involved 88 Ma and older pelagic deposition on oceanic crust at equatorial paleolatitudes, then oblique northeastward translation, interaction with terrigenous sediment and older accreted materials along the continental margin, followed by partial subduction and probable tectonic wedge emplacement of these rocks between 88 Ma and the early Tertiary. Uplift and unroofing of the Central and eastern belts in the Paleocene to early Eocene possibly was in response to wedge emplacement of the Central belt. Oblique convergence and accretion along the eastern side of the Central belt probably continued at least until the late Eocene (about 40 Ma) when the Coastal belt began its accretion beneath the western margin of the Central belt (McLaughlin and others, 1994) along the Coastal belt thrust.

Coastal belt

The onshore, western half of the map area is underlain by rocks belonging to the Coastal belt. The Coastal belt is further divided into several structural terranes that overlap in age and are separated along low to moderately dipping, warped fault zones. These terranes have undergone zeolite-grade metamorphism and locally contain abundant laumontite. One of these terranes, the False Cape, has only recently been recognized (Aalto and others, 1995).

Yager terrane

The Yager terrane originally was named the Yager Formation by Ogle (1953), who considered these rocks to be Late Cretaceous. The terrane is considered to be a tectonostratigraphic terrane of the Coastal belt because (1) it is faulted at the base and depositionally overlapped only by Neogene or younger strata; (2) the rocks of the Yager terrane are complexly disrupted by folding, faulting, and penetrative shearing; and (3) the Yager terrane rocks have been subjected to the same laumontite-grade of metamorphism and partly overlap the ages of other rocks of the Coastal belt.

The Yager terrane is composed predominantly of argillite, sandstone, and conglomerate. The predominant lithology is thin-bedded turbiditic argillite and interbedded sandstone. These rocks may be well bedded, broken, or sheared. Locally, thick, nested, channelized sandstone intervals occur within the thin-bedded argillaceous sections. Near Cummings, sandstone channels are up to 167 m thick. Nested, channeled sections commonly display up-section thickening or thinning of beds. Fine-scale, ripple-drift cross-laminations, convolutions, and traction and load features are also locally common.

Sandstones of the Yager terrane are predominantly arkosic to feldspathic and lithic with abundant chert detritus, felsite, and volcanic rock fragments, mudstone rip-up clasts, chloritized biotite, and pink to white muscovite. Sandstone compositions suggest mixed provenances including granitic and metamorphic sources from the area of the Idaho batholith, a quartz-rich Sierran plutonic source, and a Paleogene magmatic arc volcanic source (Underwood and Bachman, 1986; Bachman and others, 1984; Underwood, 1983).

Conglomerates are locally present in the Yager terrane, notably near the western edge of the terrane near Panther gap in the Cape Mendocino 1:100,000 quadrangle. These conglomerates are composed chiefly of polymict resistant pebble- to boulder-size clast populations, including dark chert and hornfels, red felsite, multicolored porphyritic to tuffaceous volcanic and hypabyssal intrusive rocks of silicic to intermediate composition, and quartzite. Most of these clasts have volcanic, metavolcanic, and metasedimentary provenances. Many of the clasts have been recycled from older conglomeratic sequences of the continental margin, including the Great Valley sequence and Franciscan Complex.

Direct evidence of detritus from older terranes of the Franciscan Complex (such as detritus composed of glaucophane- or lawsonite-bearing metamorphic rocks) is rare or lacking in Yager terrane conglomerates of the map area. Conglomerates of the Yager terrane in the adjacent Covelo quadrangle to the southeast, however, locally include clasts derived from older terranes of the Franciscan Complex. For example, west of Laytonville a monomict chert-clast conglomerate occurs in the Yager terrane near its faulted eastern contact with the Central belt. This conglomerate consists of angular green radiolarian chert clasts that contain radiolarian faunas of Early Cretaceous (zone MH-5 of Murchey, 1984; Berriasian to Valanginian stage range) age. The fauna is restricted to bedded radiolarian cherts of the same age in the adjacent Central belt of the Franciscan Complex (McLaughlin and others, 1994).

The Yager terrane is interpreted to represent strata deposited in a tectonically disrupted channelled-slope, or slope basin setting (Underwood, 1983; Bachman and others, 1984). The terrane was deposited coevally above and up-slope from rocks of the Coastal terrane (Underwood and Bachman, 1986) and may have depositionally overlapped the Central belt (McLaughlin and others, 1994). Original contact relations are obscured by subsequent thrusting of the Central belt westward over the eastern side of the Yager terrane and imbrication of the Yager terrane along its western boundary with more outboard rocks of the Coastal terrane. Structurally isolated rocks identical to those of the Yager terrane, which are imbricated with the Coastal terrane at Devils Gate and north of the mouth of the Mattole River (Miller and others, 1983), are included with the Coastal terrane here, although they may represent western outliers of the Yager terrane.

The age of rocks in the Yager terrane, based largely on spores, pollen, and dinoflagellates from carbonate concretions and carbonate interbeds in the argillaceous lithofacies, is Paleocene(?) to late Eocene (fig. 4 and table 1). Most of the Yager could have been deposited in the middle to late Eocene (McLaughlin and others, 1994; Evitt and Pierce, 1975).

Strata of the Yager terrane are essentially devoid of preserved foraminifers or radiolarians in contrast to similar but more disrupted hemipelagic lithofacies within the more westwardly located Coastal terrane. This general lack of calcareous and siliceous micro-organisms in the Yager terrane, compared to a relative abundance of spores, pollen, and dinoflagellates, may be related to availability of sediment derived from the continental margin (McLaughlin and others, 1994). A rapid influx of land-derived, plant-rich organic and fine-grained siliciclastic material, perhaps down-slope from a major deltaic setting, could have greatly diluted the marine micro-organic component of the sediment. This model is consistent with a slope basin origin (Underwood and Bachman, 1986) and perhaps suggests that the Yager terrane was deposited generally higher on the slope, or closer to the continental margin, than the bulk of the Coastal terrane.

The Yager terrane is internally disrupted by both penetrative deformation and complex folding (McLaughlin and others, 1994). At least three major fold sets are recognized: (1) a set of north-northeast-vergent recumbent folds, followed by (2) upright to asymmetrical folds indicative of northeast-southwest-oriented compression, followed by (3) broad open folds that post-date the early Miocene to Pliocene deposition of overlap deposits. Shear surfaces, boudinage, and brittle fracturing in the Yager terrane apparently crosscut the two early fold sets and predate early Miocene overlap deposits.

Coastal terrane

The Coastal terrane is the most aerially extensive terrane of the Coastal belt. Like the Yager terrane, the Coastal terrane consists predominantly of deep-water marine sandstone, argillite and scaly argillite, and subordinate, interbedded, dark-gray carbonate beds, lenses, and concretions. However, the Coastal terrane is typically more penetratively disrupted than the Yager terrane. These disrupted rocks include scattered but significant amounts of sheared-in rocks of lithologies not found in the Yager. Some of these lithologies are considered exotic to the Coastal terrane. The exotic rock types include sheared blocks and slabs of Cretaceous alkali basalt flows, flow breccias, and intrusive rocks having geochemical affinities to off-ridge oceanic plateaus and seamounts (McLaughlin and others, 1994); pink to gray limestones that locally overlie the basaltic rocks and contain foraminiferal faunas indicating deposition at northern equatorial latitudes (Sliter and others, 1986; McLaughlin and others, 1994); and rare blocks of glaucophane schist present locally along the sheared boundary separating the Coastal terrane from the King Range terrane.

Sandstones of the Coastal terrane have a range in framework grain composition that completely overlaps the more restricted compositional range of the Yager terrane (Underwood and Bachman, 1986). The compositional overlap is considered to be evidence that the Yager and Coastal terranes partly shared the same provenances (Underwood and Bachman, 1986). A model was suggested (Underwood and Bachman, 1986) in which sandstones of the Yager terrane were deposited in submarine fan channels and (or) canyons that traversed the Coastal terrane. These channelized deposits are subsequently thought to have been tectonically imbricated with clastic rocks of the Coastal terrane. Evidence of common provenances of some clastic rocks of the Coastal and Yager terranes, including unroofed older Franciscan rocks, is found in conglomerate in the Coastal terrane at Devils Gate, along the coast north of Petrolia. This conglomerate contains clasts clearly derived from the Central and Eastern belts of the Franciscan Complex (such as lawsonitic and jadeitic metasandstone, serpentinite, high-grade blueschist, and red radiolarian chert). A similar Franciscan provenance was found for some conglomerate in the Yager terrane (see section on Yager terrane).

The basaltic rocks and their associated pelagic limestones are interpreted to be fragments of the Farallon Plate, which have been scraped off and incorporated into the lower slope and trench slope region of the early Cenozoic accretionary margin during subduction. Oceanic rocks of similar composition are also found as a minor component of the distal lithofacies of the King Range and False Cape terranes, but they are of different ages and are even less abundant than those in the Coastal terrane. On the basis of the rare presence of Late Cretaceous (Campanian to Maastrichtian) arkosic sandstone interbedded with basalt and limestone of equatorial affinity (McLaughlin and others, 1994), some sandstone in the Coastal terrane is also considered translated from lower latitudes.

Scattered blocks of glaucophane schist in the Coastal terrane adjacent to the thrust boundary with the King Range terrane are enclosed in highly sheared hemipelagic rocks. The blueschist blocks probably were transported from a setting low in an accretionary complex and mixed with the more shallowly subducted hemipelagic strata (such as the depositional settings of Type III melanges of Cowan, 1985). One model to explain the present distribution of the rare blueschist blocks would be to directly uplift these rocks from the subduction zone that was beneath the northern California margin in the early to late Tertiary. High-grade blueschist blocks are, however, absent in the Coastal belt, except for the rare blocks described here in the melange of the Coastal terrane and one other block mapped in the King Range terrane at Pt. Delgada. We speculate that these blueschist blocks could have been exhumed along the King Range thrust zone from structurally underlying rocks of the Central belt of the Franciscan Complex. Locally abundant high-grade blueschist blocks are known from surface exposures of the Central belt to the east (see map sheets and structure sections A-A" and A-B"). A model is suggested in which rocks of the King Range terrane were originally deposited on older rocks of the Central belt in a trench-slope setting. In the model, the King Range terrane and Central belt were subsequently obducted onto the Coastal terrane in the Pliocene-Pleistocene (see structure sections).

The Coastal terrane is composed of rocks of two widely different age spans and formational settings. Thin dark gray carbonate interbeds and concretions in commonly sheared hemipelagic sequences locally contain dinoflagellates, spore and pollen flora, planktic foraminifers, and admixed fine-grained terrigenous sediment, indicative of deposition along the continental margin. The fossils collectively indicate a predominantly middle to late Eocene age (table 1). Somewhat older (early Eocene and Paleocene) strata are present in the Coastal terrane of the Covelo sheet (McLaughlin and others, 1994; Jayko and others, 1989; Evitt and Pierce, 1975). The paleolatitudinal affinities of the early Tertiary flora and fauna from the hemipelagic and terrigenous rocks suggest their derivation from middle latitudes, north of about 30°N (McLaughlin and others, 1994).

The other component of the Coastal terrane includes blocks of pelagic limestone associated with allochthonous basaltic oceanic rocks. These pelagic limestones contain planktic and benthic foraminifers of Late Cretaceous (Campanian to Maastrichtian) age, having morphologic characteristics indicating that they lived at latitudes between 20°S and 20°N (McLaughlin and others, 1994).

Paleomagnetic data (Harbert and others, 1984; McLaughlin and others, 1994) also suggest a low-latitude origin between about 20°N and 28°N for the pelagic limestones and basalts. Hagstrum (1990) suggested that the remnant signature of early magnetization of these limestones was acquired at the time that the Farallon plate (on which the limestones were deposited) encountered the North American plate subduction margin (probably in the Eocene). This interpretation implies that these rocks encountered the North American plate margin at about 28°N, and then were translated northward parallel to the margin, between about 49 and 24 Ma (early Eocene to early Miocene time).

Within the Cape Mendocino and Eureka 1:100,000 quadrangles, the Coastal terrane characteristically is disrupted by penetrative shearing, which may occur in discrete zones tens of meters to kilometers in width. The rare blocks of blueschist, limestone, and basalt described above occur in these zones, where penetrative deformation has been most intense. These areas of the Coastal terrane are best characterized as melange, after the definition of Hsu (1968). However, in the inland part of the map area, deformation of the Coastal terrane is less penetrative and the terrane is typically a broken formation with large areas of intact folded strata interrupted by closely to widely-spaced fractures and faults.

In the Cape Mendocino and Eureka 1:100,000 quadrangles, intact areas of broken formation are typically more sandstone rich than the penetratively deformed, argillaceous part of the section, regarded as the early Tertiary matrix of the Coastal terrane melange. Map patterns and field relations of the more intact strata of the Coastal terrane indicate that these rocks are large boudins, phacoids, and slabs. As discussed above, some of these boudined bodies of well-bedded to massive sandstone and argillite are compositionally identical to and were probably derived from the same provenance as sandstone in the Yager terrane.

Fractures and faults in the Coastal terrane are typically filled with laumontite and calcite. Laumontite is ubiquitous in the Coastal terrane but is concentrated in the sandstones and in fracture fillings, suggesting deposition from fluids that circulated within the accretionary margin prior to and following lithification of the sandstones. Permeability was a major parameter affecting laumontite distribution.

The youngest rocks of the Coastal terrane involved in penetrative deformation are exposed along the coast between Cape Mendocino and Bear River. These rocks consist of rare, boudined blocks of silty sandstone and mudstone that contain Pliocene or younger deep and shallow marine foraminifers and mollusks enclosed within older melange (Aalto and others, 1995). Considerable if not most deformation in the on-land Coastal terrane was later than about 41 Ma. Some deformation of the volumetrically small Cretaceous sedimentary and volcanic components of the Coastal terrane may have begun earlier, between the latest Cretaceous and late Paleocene, during tectonic transport and juxtaposition of the Cretaceous rocks with the younger continent-derived sedimentary rocks of the terrane.

King Range terrane

The King Range terrane is divided into two structural units, the King Peak and Point Delgada units, based on lithologic and age differences. Both units have undergone penetrative deformation (shearing and boudinage), and both have also been extensively folded during or following this deformation. Complex folding is, perhaps, the most characteristic structural feature of the terrane.

The sandstone and argillite of King Peak is the younger structural unit of the King Range terrane. It is composed of a thin-bedded sequence of highly folded and sheared calcareous argillite, interbedded fine-grained sandstone, and local thick-bedded intervals of sandstone. Sporadic zones of argillite-matrix melange enclosing lenses and blocks of sandstone, pebbly to bouldery conglomerate, and minor mafic igneous rocks (mostly basaltic, locally pillowed volcanic rocks) are associated with the King Peak unit. The volcanic rocks locally are overlain by radiolarian and diatom-bearing ribbon chert, or more rarely by red to gray pelagic limestone. Radiolaria and foraminifers from the pelagic and hemipelagic rocks indicate a middle Miocene depositional age, with local reworking of Early Tertiary foraminifers (McLaughlin and others, 1982 and 1985). A whole-rock K-Ar age of 16.2 ± 0.5 Ma on a block of relatively unweathered basalt in lower Cooskie Creek is consistent with the middle Miocene age assignment for the unit (McLaughlin and others, 1982, 1985). Alkalic geochemical affinities (high TiO_2) of the volcanic rocks from this unit suggest their formation in an off-ridge oceanic seamount or plateau setting.

The older unit of the King Range terrane consists of the igneous and sedimentary rocks of Point Delgada. These rocks are recognized only at Point Delgada in the intertidal zone beneath Quaternary marine and nonmarine deposits. The unit includes a lower sequence of basaltic pillow flows, intrusive sills, flow breccias, tuffs, and basaltic sandstones. Locally, minor red and gray calcareous argillite and calcite-veined limestone are intercalated with the basalt flows and tuffs. The volcanic rocks are overlain by a thin argillite-matrix melange that encloses rounded boulder-size clasts of porphyritic mafic to siliceous volcanic rocks, quartzite, greenschist, black to green chert, and rare blocks of glaucophane schist. The melange, in turn, is structurally overlain by turbiditic arkosic metasandstone and argillite. The metasandstone includes the metamorphic mineral assemblage quartz, albite, chlorite, white mica, and pumpellyite. A later hydrothermal alteration vein system that cuts the sandstone and volcanic rocks includes the mineral assemblage quartz, calcite, epidote, and adularia, locally with pyrite, chalcopyrite, and Ag-bearing sphalerite and galena (McLaughlin and others, 1985). Radiolaria from red interpillow argillites of this unit are Late Cretaceous (Campanian or Coniacian) in age.

The King Range terrane, which was assembled during the middle Miocene in a lower slope to trench-slope setting, is the youngest accretion-related terrane assigned to the Franciscan Complex. It may be partly equivalent to the newly recognized False Cape terrane (Aalto and others, 1995), although present data indicate the False Cape rocks to be somewhat older (early Miocene). The King Range terrane rocks have been thrust northeastward onto the continental margin along a system of thrusts that juxtapose Pliocene and Miocene non-accretionary marine strata near Petrolia, north of the King Range.

The Point Delgada subunit of the King Range terrane is juxtaposed with the King Peak subunit along a steep northwest-trending fault that parallels and partly coincides with a fault that ruptured during the San Francisco earthquake of 1906. Adularia in northeast-trending hydrothermal vein sets that cross this boundary at Pt. Delgada, however, yield K-Ar dates of 13.8 ± 0.4 Ma (McLaughlin and others, 1985), and paleothermal isograds from vitrinite reflectance data indicate minimal long-term offset on this active fault (Underwood and others, 1999; Underwood, 1989). Apparently, no significant lateral offset has occurred between the Point Delgada and King Peak subterranes of the King Range terrane since the middle Miocene. Recent fission track studies (Dumitru, 1991) indicate that the King Peak subterrane has been uplifted 3 to 5 km since about 1.2 Ma. The northeast-vergent thrust system that bounds the north and east sides of the King Range terrane possibly has accommodated some of this uplift. It has also been proposed (McLaughlin and others, 1994, 1982) that the King Range terrane may have undergone significant Miocene and younger northward translation with the Pacific Plate within the San Andreas fault system. Recent identification near False Cape, however, of rocks similar in age, lithology, and formational setting to the King Range terrane (Aalto and others, 1995), suggests that large-scale northward translation of the King Range terrane with the Pacific plate may not be required.

False Cape terrane

Rocks exposed at False Cape and along the coast between the mouths of Oil Creek and Bear River are assigned to the False Cape terrane of the Coastal belt (Aalto and others, 1995; and Map Sheets 1 and 2). These rocks are bounded on the north and south by major, steep-dipping, wide zones of shear similar in character to the zone of suturing along the north and east sides of the King Range terrane. The general east-west structural grain of this terrane indicates that it extends for some distance inland along the south-facing slopes of Bear River ridge north of Bear River. The inland boundaries of the terrane are highly conjectural, however, and need further study. The faulted southern contact of the terrane is aligned with the Bear River fault zone, which juxtaposes the False Cape terrane rocks with entrained Miocene and Pliocene slope and shelf facies strata of the Bear River beds of Haller (1980). The False Cape terrane has not been recognized in the subsurface of the Neogene Eel River basin to the north. In this area, the Neogene basin deposits are considered to overlie rocks of the Yager and (or) Coastal terranes (Ogle, 1953; Hoskins and Griffiths, 1971). Recognition of False Cape terrane rocks in the subsurface beneath Eel River basin would be difficult, however, because their general lithology and degree of structural disruption is similar to the other terranes of the Coastal belt. Without accurate age data, False Cape terrane rocks could easily have been erroneously assigned to the Yager or Coastal terranes.

The False Cape terrane is composed predominantly of penetratively deformed, thinly and rhythmically interbedded, scaly argillite and less abundant arkosic wacke turbidites. These terrigenous strata include abundant intercalated thin beds and lenses of hemipelagic limestone, diatomaceous and radiolarian-bearing cherty limestone, and diatomaceous chert, suggesting deposition close to the carbonate compensation depth (CCD). Locally, the False Cape terrane includes a thin zone up to about 3 m thick of thin-bedded, chloritic, cherty tuff. The tuff is overlain by 2 to 3 m of thin-bedded, red, ferruginous, scaly argillite and dark gray, diatomaceous, limestone and chert. Although laumontite has not been identified in the False Cape terrane rocks, along the north side of the terrane, north of Oil Creek, large shear-bounded phacoids of thick-bedded to massive, laumontized, lithic arkosic wacke, basaltic flow breccia, tachylitic breccia, and red cherty limestone are enclosed in sheared argillite. Those rocks resemble, and may be part of the Coastal terrane. Along both its northern and southern margins, boudined outcrop- to map-scale blocks of weakly lithified strata derived from the Wildcat Group and Bear River beds (Haller, 1980) are sheared into the False Cape terrane (see sections on Wildcat Group and Bear River beds below).

Diatoms in the hemipelagic cherts, cherty argillites, and limestones of the False Cape terrane are indicative of a late Oligocene to early Miocene (> 20.6 Ma) age (Aalto and others, 1995; J. Barron, written commun., 1993). The ferruginous limestone unit that locally overlies red chert and chloritic tuff just south of False Cape contains a deep water planktonic foraminifer fauna indicative of an early Miocene age (about 18 - 22 Ma) (Aalto and others, 1995; W.V. Sliter, written commun., 1993).

Oil seeps issue from rocks of the False Cape terrane at numerous localities. Areas of hydrocarbon leakage are indicated by a strong kerosene odor and hydrocarbon seeps (smell muds) which are particularly prevalent in intensely sheared rocks along the margins of the False Cape terrane and within the core areas of folds. Hemipelagic to pelagic, calcareous, and siliceous rocks appear to be most petroliferous. It is doubtful that any major stratigraphically controlled hydrocarbon reservoir could be present in the False Cape terrane, however, due to its inherent impermeable argillitic character and the widespread calcite veining. Viable hydrocarbon reservoirs or source rocks, speculatively, could be associated with thrust-fault-bounded slabs of the Wildcat Group or the Bear River beds (Haller, 1980) that are imbricated with or buried beneath the False Cape terrane (McLaughlin and others, 1999).

Like other terranes of the Coastal belt, the False Cape terrane has undergone complex penetrative deformation. This deformation is characterized by an early pervasive flattening that produced classic pinching and swelling, necking, boudinage, scaly argillite, and related extensional deformation. The deformation is typical of rocks deformed in an accretionary complex and may be related to sediment compaction, fluid expulsion, and low-angle detachment slippage in the lower region (lower slope or trench-slope) of an accretionary prism (Aalto and others, 1995).

Early flattening produced a pervasive fabric and shear parting nearly parallel to bedding. This fabric was subsequently folded into complex outcrop-scale folds that are refolded into a recumbent map-scale, south-vergent anticline-syncline set. East-west oriented recumbent folds are truncated to the north and south against the False Cape and Bear River fault zones (see map sheets and fig. 3).

The False Cape terrane lies in the hanging wall of the Bear River fault zone, a thrust fault zone that emplaces the False Cape terrane rocks southward over Miocene to Pliocene slope and shelf facies strata of the Bear River beds. One interpretation of this relationship is that the False Cape terrane was underthrust eastward as much as 40 - 60 km (by analogy to the width of the present Cascadian continental margin) beneath the slope and shelf in Miocene to Pliocene time and later thrust back to the surface over the Bear River Neogene section in the late Pliocene to Pleistocene. Alternatively, following deposition of False Cape pelagic and hemipelagic strata along the late Oligocene to early Miocene trench-slope, the Cascadian subduction margin and associated accretionary prism abruptly migrated 40 - 60 km seaward. The shelf and slope facies strata of the Bear River beds were then deposited on the former Oligo-Miocene accretionary prism in the middle and late Miocene. This in turn was followed by late Pliocene to Pleistocene emplacement of the False Cape terrane over the Bear River beds along the Bear River fault zone.

Structural relations along the upper fault boundary of the False Cape terrane show that these rocks are structurally beneath older Yager and Coastal terrane rocks (see map sheets and structure section A-A"). Initially, the False Cape rocks must have been thrust beneath the older terranes in the Miocene and younger accretionary prism. This out-of-sequence thrust relationship between the False Cape terrane and older Franciscan rocks may reflect increased coupling between the Gorda and North American plates in the late Neogene during encroachment of the Pacific Plate into the Cape Mendocino region.

Oligocene intrusive rocks

The Central belt is intruded by trachytic volcanic rocks of unusually high alkalic composition at two localities northeast of Arcata: one locality is at Granite Butte, along Fickle Hill Ridge; the other locality is in a road cut along Highway 299 to the north of Granite Butte. The fission track ages of these rocks are 35.3 ± 2.0 Ma and 36.0 ± 0.9 Ma, respectively (Meyer and Naeser, 1970). The intrusives are compositionally similar to a suite of alkalic intrusives and volcanic rocks that occur for some distance northward into western Oregon (Wells and others, 1984) and include the Coyote Peak diatreme (Morgan and others, 1985), which intrudes the Central belt in northern Humboldt County north of the map area.

Late Cenozoic post-accretionary Overlap Assemblage

Late Cenozoic deposits formed in a variety of marine to nonmarine depositional settings in the Cascadian forearc region overlie the late Cenozoic to late Mesozoic accreted terranes of the Franciscan Complex. Fossils and structural data onshore indicate that the age of these deposits overlaps that of the youngest (Miocene) rocks of the structurally underlying accretionary complex. Since their deposition, the overlap rocks were juxtaposed and imbricated with rocks of the accretionary prism by Pliocene to Pleistocene thrust faulting. Paleobathymetric data from benthic foraminifers in the on-land exposures of these deposits (table 1) show a general southwestward deepening in depositional settings of the marine Miocene and Pliocene strata to depths greater than 2,000 m from the southern edge of Eel River basin to the vicinity of Petrolia. Although the non-accretionary overlap deposits are partly similar in their ages and bathymetry to rocks of the Franciscan Complex, they are considerably less deformed and lack penetrative flattening, boudinage, scaly argillite, and block-in-matrix texture, except locally along faults. The overlap assemblage is also less lithified and is unmetamorphosed, with no laumontite- or higher-grade metamorphic mineral assemblages present.

Wildcat Group

The Eel River basin occupies most of the onshore Eel River Valley in the Eureka and northern part of Cape Mendocino 1:100,000 quadrangles. The Eel River basin is filled with sedimentary deposits of the Wildcat Group of Ogle (1953), which is divided into several formations that occur at the surface and in the subsurface of the Eel River basin. Here, we include the Falor Formation of Manning and Ogle (1950), several outliers of marine and nonmarine Miocene to Pliocene strata in the Garberville and Phillipsville areas, a faulted remnant of Pliocene nearshore marine strata near Bridgeville, and a few isolated remnants of shallow marine to nonmarine deposits that occur in the map area near Zenia and Lake Mountain. Strata of the Wildcat Group also extend for some distance into the offshore (Hoskins and Griffiths, 1971). These deposits have been interpreted as the southernmost part of the Cascadian forearc. The reader is referred to Ogle (1953) for detailed descriptions of the various formations of the Wildcat Group. For more recent studies of these rocks see Clarke (1992), McCrory (1989), McCrory (1995), Woodward Clyde and Associates (1980), and Ingle (1976).

In general, the Wildcat Group consists predominantly of weakly to moderately well lithified sandstone, siltstone, mudstone, and minor conglomerate. These rocks range in age from late Miocene (Mohnian) at the base of the Pullen Formation to Pleistocene in the upper beds of the Carlotta and Hookton Formations (Ogle, 1953). Along the coast, between Guthrie and Oil Creeks, basal beds of the Pullen Formation overlie the Oil Creek breccia unit of Bachman and others (1984) reported to contain a late Oligocene to early Miocene lower bathyal microfauna . The Oil Creek breccia unit may be part of the Bear River beds of Haller (1980) or the False Cape terrane (Aalto and others, 1995), because all three units reportedly include deep-water strata of similar age. Contacts above and below the breccia are faulted (Aalto and others, 1995), obscuring any original depositional relations and making its formational assignment problematic.

In the subsurface of Eel River basin, the Wildcat Group unconformably overlies middle Miocene rocks that have been assigned to the Bear River beds (Hoskins and Griffiths, 1971; Haller, 1980). This correlation is also problematic, as indicated in the following section on the Bear River beds of Haller (1980). The reported subsurface unconformity between the Wildcat Group and middle Miocene strata has been related to a pre-late Miocene change in geometry of the southern part of the Pacific-Farallon ridge system (McCrory, 1989; Clarke, 1992; Harbert and Cox, 1989).

Chetelat and Ingle (1987) have reported foraminifera of early Miocene (Saucesian) age from deep marine (> 2,000 m) basal strata of the Wildcat Group south of Centerville Beach. From their description and location of the early Miocene unit (Chetelat and

Ingle, 1987), it is likely that it corresponds to the Oil Creek breccia of Bachman and others (1984). It is older than, and therefore not part of, the Wildcat Group as originally defined (Ogle, 1953).

At the south side of the Eel River basin near the coast, the lower beds of the Wildcat Group and the Oil Creek breccia unit (Aalto and others, 1995; Bachman and others, 1984) are faulted against the Coastal belt along the Russ fault. However, at Scotia, about 40 km inland, the basal Pullen Formation rests unconformably on highly folded beds of the Yager terrane. The Wildcat Group is folded into open to tightly appressed, upright to asymmetrical folds that trend W-NW and plunge either to the east or west. Fold amplitudes diminish up-section, and subsurface data offshore (Clarke, 1990) and onshore (Clarke and Carver, 1992) indicate that some folds are floored by flat, W-SW-vergent thrusts that root in the Cascadia subduction complex. These folded rocks of the Wildcat Group are overlain by mildly warped to undeformed nonmarine Pleistocene strata of the Hydesville and Rohnerville Formations (Ogle, 1953) and by younger Quaternary deposits.

Bear River beds of Haller (1980)

The name Bear River beds (Haller, 1980; Klienpell, 1938) was informally applied to strata of Miocene and Pliocene age that are exposed along the coast north and south of Bear River within the Bear River fault zone (map sheets and fig. 3). We herein adopt this usage. The Bear River beds are thrust beneath rocks of the False Cape terrane on the north; they are imbricated with the Coastal terrane along a branch of the Bear River fault zone to the south and entrained along west-northwest-oriented strands of the Bear River fault zone to the east (map sheets and fig. 3).

Kleinpell (1938) described foraminifers from the Bear River beds, based largely on collections by Cushman and others (1930), and assigned these rocks to the Relizian and Luisian stages of the middle Miocene. In a more recent review and with additional collections, Haller (1980) noted that some of the foraminiferal data suggest the presence of late Miocene and Pliocene strata in addition to the middle Miocene rocks.

Our data from the Bear River section (table 1 and fig. 4) include age assignments and paleobathymetry from benthic foraminifers, nannofossils, and diatoms. In addition, an age is assigned to a volcanic ash bed on the basis of petrographic characteristics, major and minor element content of the volcanic glass shards, and correlated K-Ar ages (A. Sarna-Wojcicki, written and oral commun., 1993; Aalto and others, 1995). Collectively, these data indicate the presence of middle Miocene (Luisian to Relizian), late Miocene (Mohnian), and Pliocene strata in the Bear River section (see Cape Mendocino 1:100,000 quadrangle, table 1 and fig. 4). Most of the coastal section containing middle Miocene diatoms, nannofossils, and benthic foraminifers, however, also includes Pliocene or younger benthic foraminifers with upper bathyal to abyssal depth ranges between 500 and 2,000 m (J. Barron, K. McDougall, and D. Bukry, written commun., 1994). Sandstone dikelets are intruded along joints and other soft sediment deformation features also occur locally (see also Aalto and others, 1995). These data suggest that the middle Miocene diatoms and nannofossils from the coastal section are largely reworked. The Bear River beds, therefore, are largely coeval with the basal Pullen Formation (upper Miocene to Pliocene) of the Wildcat Group of Ogle (1953). The lower part of the Bear River section appears to include some older Miocene strata along the upper Bear River southeast of Capetown, but this part of the section needs to be more closely examined for un-reworked middle Miocene microfossils before any such age assignment can be made.

Exposures of the Bear River beds north of the mouth of Bear River consist of brown, diatomaceous, silty mudstone interbedded with fine-grained silty sandstone turbidites and sporadic interbeds of buff-weathering, dolomitic, diatomaceous limestone. Up-section, thin-bedded sandstones become somewhat more abundant, and the mudstones are more diatomaceous. The lowermost exposures of the Bear River section are imbricated with and faulted against the False Cape terrane. South of the faulted contact with False Cape terrane rocks, the Bear River beds are upright and dip steeply to moderately southward.

South of the mouth of Bear River, the Bear River beds are warped into a westward-plunging, open synclinal fold whose axial region is unconformably overlain by less appressed, weakly lithified, massive to thick-bedded siltstone and fine-grained sandstone. These stratigraphically higher Pliocene strata contain molluscan fossils indicating deposition in an inner slope or shelf setting. The contrast in depositional setting of these beds with those of the underlying deeper water section suggests uplift, downslope transport of the younger shallower marine facies, and (or) possibly a marine regression in the early Pliocene.

Strata in the south flank of the synclinal fold include diatomaceous to porcellaneous mudstone, porcellanite, and dolomitic carbonate lenses. Locally, a thick glauconitic sandstone horizon is present that may mark a late Miocene to Pliocene unconformity. The Bear River beds are sheared and disrupted increasingly toward the faulted southern boundary of the section. A benthic foraminiferal fauna from sheared scaly mudstone near the base of the beach exposures of the section south of Bear River is early Pliocene in age. The paleobathymetry of this microfauna indicates deposition at 1,500-2,000 m (lower bathyal to abyssal depths) with considerable downslope transport of some species from shallower water.

Near the base of the Bear River beds south of the mouth of Bear River, a thin gray volcanic ash bed overlies bathyal to abyssal strata of early Pliocene age. This tephra layer is correlated on the basis of trace and minor elements with tephra layers of latest Miocene or early Pliocene age in the basal beds of the Wildcat Group along the Van Duzen River (A. Sarna-Wojcicki, written commun., 1993; table 1 and fig. 4). The basal Wildcat Group tephra horizons along the Van Duzen River have yielded K-Ar ages of about 9.3 Ma (biotite) and 9.6 Ma (plagioclase), respectively, and a fission track age of 5.9 Ma (A. Sarna-Wojcicki, written commun., 1993). The late Miocene age indicated by radiometric data from the Van Duzen River ash beds, together with the Pliocene benthic foraminifers in strata immediately beneath the correlative ash in the Bear River section, suggests that there is possible contamination of the Van Duzen River ash by older biotite and plagioclase, that the Bear River ash occurs in overturned beds, or that the section is repeated by thrusting.

South of the lower contact of the Bear River beds, boudined outcrop-scale masses of weakly lithified silty sandstone and scaly mudstone containing early Pliocene upper bathyal (150-200 m) benthic foraminifers are sheared into the structurally underlying rocks of the Coastal terrane over a distance of some 2 km. To the east, the Bear River beds are attenuated along the Bear River fault zone and yield both Pliocene (this study) and Miocene (Haller, 1980) foraminiferal faunas (table 1 and fig. 4). The north flank of the Bear River syncline is obliquely truncated by thrusting along the Bear River fault zone.

Post-accretionary Neogene strata in the Cape Mendocino to Petrolia area

South of Cape Mendocino, several fault-bounded slivers of late Cenozoic marine strata have been recognized within the Coastal terrane of the Coastal belt. These Neogene (late Miocene and early Pliocene) rocks were deposited in lower bathyal to abyssal (2,000-4,000 m) settings and imbricated with the Franciscan Complex. However, in contrast to the slivers north of Cape Mendocino, the thrust fault-bounded slivers to the south dip to the S-SW, subparallel to the N-NE-vergent thrust boundary between the King Range and Coastal terranes. The most prominent of these imbricated slivers of Wildcat Group-equivalent rocks are mapped in the vicinity of Petrolia. There, tectonically buried slivers and blocks of these weakly lithified rocks may have contributed both to the source rocks for petroleum generation and to the small, local hydrocarbon reservoirs within the Coastal terrane.

Unnamed upper Pleistocene and Holocene deposits

In the Mendocino triple junction region, marine and fluvial terrace deposits record high rates of tectonic uplift in the late Quaternary (Lajoie and others, 1982; McLaughlin and others, 1983; Hagemann, 1985; Bickner, 1985; Merritts and Bull, 1989). The terraces provide a record of tectonism in response to the evolution from a subduction to a transform margin with northward passage of the Mendocino triple junction. About 1.4 m of coseismic uplift of the wave-cut platform occurred along the coast between Cape Mendocino and the mouth of the Mattole River during the April, 1992, Petrolia earthquake (Oppenheimer and others, 1993).

Marine terrace deposits include well-sorted, coarse granule-sized (pea) gravels, cobble berms, and dune sand deposits preserved on uplifted Holocene and Pleistocene marine platforms. In several areas significant deposits are missing, and only an uplifted surface, characteristically with pholad borings and sometimes overlain by a thin cobble or gravel lag, is preserved. Along much of the steep coastal area, marine platforms with thin lag deposits are directly overlain by fluvial sediments and rock-fall or talus deposits. In the coastal region between Pt. Delgada and Whale Gulch, a late Wisconsinan (about 45 ka) marine platform is overlain by thin marine lag deposits and by several meters of poorly sorted wood-bearing fluvial gravel and thin interbedded gray silt. These deposits probably represent levee overbank deposition within a large river delta system that flowed parallel to the present coastline prior to a Holocene rise in sea level. In Eel River basin near Eureka, coseismic subsidence is believed to have occurred (Clarke and Carver, 1992; Valentine and others, 1992; Vick and Carver, 1988). Late Quaternary sediments that indicate this subsidence consist of lagoonal and brackish water deposits abruptly overlain by beach and dune or intertidal deposits.

Flights of late Quaternary fluvial terraces are well developed along the major rivers of the map area (Carver, 1985, 1987; Carver and Burke, 1987). These rivers include the Mad, Eel, Van Duzen, and Mattole Rivers. Thorough studies have recently been done on the Mattole River terrace system and its response to uplift of the coastline near Cape Mendocino (Merritts and Bull, 1989; Merritts and Vincent, 1989; Merritts and others, 1994). Another study by Bickner (1985), focused on the dating of river terraces of the Eel River near Garberville, suggests uplift rates on the order of 1 mm/yr in that area.

STRUCTURAL RELATIONS

Faults bounding belts of the Franciscan Complex

South Fork fault

A major east-dipping thrust fault, the South Fork fault, separates the Eastern Franciscan belt from the Klamath Mountains. As discussed earlier, the South Fork fault was an active accretionary (and exhumation?) boundary during the Early Cretaceous or later, based on the clustering of K-Ar ages of blueschist metamorphism from the underthrust Pickett Peak terrane at about 125 Ma (Blake and others, 1984; Tagami and Dumitru, 1996). As pointed out below and in the discussion of Klamath terranes, the South Fork fault at this latitude is a major overthrust along which rocks of the Klamath Mountains Province have overridden Jurassic through Early Cretaceous rocks of the Great Valley sequence, the Coast Range ophiolite, and the Franciscan Complex for a distance of at least 90 km (Blake and others, 1993 and 1999).

Fault slivers of ophiolitic rocks along the South Fork fault are assigned both to the Josephine ophiolite (the oceanic basement of the Smith River subterrane of the Western Klamath terrane) and to the Coast Range ophiolite (the oceanic basement of the Great Valley forearc basin southeast of the map area). In the Red Bluff and Covelo 1:100,000-scale quadrangles, respectively to the east and south of the Garberville quadrangle (Blake and others, 1999; Jayko and others, 1989), the South Fork fault merges with the Coast Range fault along a series of oblique southwest-vergent sinistral transfer faults. The ophiolite remnants along the South Fork fault that we interpret to be part of the Coast Range ophiolite presumably are all that remain of a thick section of Great Valley sequence and Coast Range ophiolite in the lower plate of the South Fork fault. These remnants, in turn, are part of the upper plate of the Coast Range fault, exposed southeast of the map area. This interpretation implies that Great Valley sequence strata could be present at depth to the east beneath the upper plate of the South Fork fault.

Coast Range fault

Southeast of the report area, the South Fork fault intersects the east-dipping Coast Range fault at the Yolla Bolly junction (Blake and others, 1984, 1988, 1999). South of this junction, the Coast Range fault separates the Franciscan Complex from the Jurassic and younger Coast Range ophiolite and depositionally overlying forearc strata of the Great Valley sequence. Small fault slivers of the Smith River terrane of the Klamath Mountains Province, furthermore, locally occur between the Coast Range ophiolite and the Franciscan Complex along the Coast Range fault south of the Yolla Bolly junction. This relationship suggests tectonic wedging of the Franciscan Complex into the basements of the Great Valley and Klamath Mountains Provinces and that the basements of the Klamaths and Great Valley must extend westward, beneath Franciscan rocks south of that junction (Jayko and Blake, 1986; Wentworth and others, 1984). South of the Yolla Bolly junction, rocks of the Great Valley sequence and the Coast Range ophiolite are everywhere in fault contact with the Franciscan Complex, either along the east-dipping Coast Range fault or along younger attenuation faults that have modified the original fault relations (Blake and others, 1984, 1988).

At the Yolla Bolly junction and to the north of it, the upper plate of the Coast Range fault is progressively cut out along a series of sinistral, west-vergent transfer faults that incrementally place the upper plate of South Fork fault over the Coast Range fault. The South Fork fault, in turn, thrusts the Smith River subterrane of the Western Klamath terrane westward at least 90 km over the Great Valley sequence, the Coast Range ophiolite, and the Eastern belt of the Franciscan Complex (see earlier discussion of the Smith River subterrane and South Fork fault and structure section A-B"; also refer to Blake and others, 1993 and 1999).

In three areas west of the Eastern belt of the Franciscan Complex, thin attenuated slices of the unmetamorphosed Great Valley sequence and Coast Range ophiolite overlie remnants of the Coast Range fault and are imbricated with the Franciscan Central belt. At the Lassics, along the east side of the Central belt, Eastern belt Franciscan rocks are imbricated into the Central belt with a remnant of the ophiolite and Great Valley sequence. In this composite remnant, rocks of the Coast Range ophiolite and minor Great Valley sequence strata overlie a larger outlier of the Eastern belt (see Garberville quadrangle and section A-B"). The composite outlier was translated northwestward within the Central belt along the Mule Ridge and Grogan-Red Mountain fault zones.

A second attenuated remnant of ophiolitic rocks that originally must have been in the upper plate of the Coast Range fault and is overlain by a scrap of radiolarian-bearing Great Valley sequence strata occurs above the Coastal belt thrust at Benbow southeast of Garberville. This latter remnant of strata from the upper plate of the Coast Range fault is imbricated at the base of the Central belt (McLaughlin and others, 1988). The occurrences of the Lassics and Benbow composite outliers of Coast Range ophiolite, Great Valley sequence, and Eastern belt rocks as slabs enclosed by the Central belt indicates that the Central belt accreted to the California margin only after the Eastern belt had earlier been juxtaposed with rocks of the Coast Range ophiolite and Great Valley sequence along the Coast Range fault (Garberville 1:100,000 quadrangle and fig. 3).

A third occurrence of Coast Range ophiolite remnants is found at Red Mountain, along the Red Mountain fault zone, at the boundary between the Central belt and western side of the Eastern belt (Garberville 1:100,000 quadrangle and fig. 3). Here, a slab of serpentinized peridotite (harzburgite and dunite) is imbricated with metagraywacke and metachert of the Yolla Bolly terrane and thrust over melange of the Central belt. Blocks of amphibolite and gabbro are present along this contact. The Coast Range fault, which may originally have separated the ophiolite from rocks of the Franciscan Complex, was completely obliterated here by the imbricate thrusts that juxtaposed the ophiolite with the Yolla Bolly terrane and Central belt. Alternatively, the Red Mountain ophiolite mass was peeled-up from the base of the Yolla Bolly terrane during wedge emplacement of the Central belt beneath the Eastern belt.

Grogan-Red Mountain fault zone

The Eastern and Central belts of the Franciscan Complex are separated along the steep northeast-dipping Grogan-Red Mountain fault zone, which also includes the Pine Butte fault east of the Lassics area. The distinctly straight northwest trend of the fault zone, its straight truncation of the Eastern belt, and the northwestward translation of Eastern belt blocks west of the zone suggest that the Grogan-Red Mountain fault has experienced dextral slip and dips steeply at the surface. Southeast of Red Mountain and in the Covelo 1:100,000 quadrangle (Jayko and others, 1989; Blake and Jayko, 1983), the fault zone bends southeastward, flattens, and dips to the northeast. In the offshore north of the map area, Clarke (1990) mapped a fault zone that is continuous with the Grogan-Red Mountain zone and is indicated from seismic reflection and refraction data (Clarke, 1990, 1992) to be an out-of-sequence northeast-dipping reverse fault.

The early history of the Grogan-Mule Ridge fault zone probably was as an oblique, subduction-accretion-related structure. After the locus of subduction stepped west of the Central belt to the Coastal belt thrust about 40 Ma (McLaughlin and others, 1994), the Grogan-Mule Ridge fault zone may have continued to accommodate dextral transpression until the end of the Eocene (McLaughlin and others, 1988). It is unclear when the latest movement on this fault occurred, however, since displaced deposits of Eocene age or younger have not been recognized along the fault zone in the map area. The oldest non-accretionary (forearc-related) strata in depositional contact with the Central belt in northern California and southern Oregon are Paleocene and Eocene in age. This relationship constrains latest accretion of the Central Belt and thus the timing of major slip on the Grogan-Red Mountain fault zone as an accretionary structure (Blake and others, 1984; McLaughlin and others, 1988). Others, however, have suggested that the fault zone has been active in the late Cenozoic (Kelsey and Hagans, 1982).

The Grogan-Red Mountain fault zone has probably been active since the early Late Cretaceous (about 90 Ma) based on the paleontologic and metamorphic ages of slabs of Eastern belt (Yolla Bolly terrane) rocks (Blake and others, 1984, 1988) displaced from the west side of the Eastern belt along the fault zone (fig. 3). Melange blocks of foraminiferal limestone of low paleo-latitudinal affinity in the Central belt near Harris are Coniacian in age, suggesting that northward translation of the Central belt, which presumably was at least partially accommodated along the Grogan-Red Mountain fault zone, postdates about 88 Ma.

Mule Ridge fault zone

The Mule Ridge fault, 4 to 8 km southwest of and subparallel to the Grogan-Red Mountain fault zone, is also nearly vertical to steeply northeast-dipping at the surface through most of the map area. The fault is well defined in the vicinity of the Lassics, but to the south it probably trends more southeastward (fig. 3) along the eastern boundary of the Haman Ridge graywacke unit of the Central belt (unit chr). Based on their parallelism and spacing, the timing and nature of displacements on the Mule Ridge and the Grogan-Red Mountain fault zones are probably similar.

Coastal belt thrust

The Coastal and Central belts of the Franciscan Complex are separated regionally along the Coastal belt thrust. In the Eureka 1:100,000 quadrangle, the Coastal belt thrust is obscured and possibly has been reactivated by younger thrust faults of the Mad River fault zone (Carver and others, 1984; Carver, 1985). In the offshore area, the Coastal belt thrust is traceable northward into Oregon on the basis of aeromagnetic anomalies associated with serpentinite bodies along the thrust zone (Clarke, 1992). In the Garberville quadrangle, the Coastal belt thrust is overlapped by Pliocene and Miocene strata equivalent to the Wildcat Group and Bear River beds. These overlap strata are broken by younger reverse and strike-slip faults. The depositional ages of Central belt and Yager terrane strata in the upper and lower plates of the Coastal belt thrust, together with the Miocene to Pliocene overlap assemblage, suggest that the thrust faulting occurred in the Oligocene (about 38 to 36 Ma). Alkalic trachyte intrusives of the Fickle Hill Ridge area, dated at 35 to 37 Ma (Meyer and Naeser, 1970), intrude through the Central belt in the upper plate of the thrust northeast of Arcata. The lack of shearing and deformation in these rocks suggest that they post-date major displacement on the Coastal belt thrust. The Coastal Belt thrust is broadly warped into a southeast-plunging antiform and synform pair in the Garberville region (fig. 3), indicating that contraction continued across the thrust for some time after juxtaposition of the Central and Coastal belts.

MENDOCINO TRIPLE JUNCTION AREA

The Cape Mendocino and Eureka 1:100,000 quadrangles are centered over the Mendocino triple junction. The fault boundaries that separate the North American, Pacific, and Gorda plates are depicted in fig. 5. The Pacific and North American plates are further divided by major faults into the subsidiary crustal blocks and terranes depicted on the geologic maps.

North of the Mendocino fracture zone, near longitude 125°W and latitude 40°30'N, the Gorda Plate is overlain by a Quaternary to Miocene pelagic, hemipelagic, and clastic sedimentary cover at least 3.5 km thick. These sediments are being partially underthrust eastward at the leading edge of the North American Plate margin and partially accreted in the hanging wall of the southern Cascadia subduction zone (Clarke, 1992, 1990; Clarke and Field, 1989; Silver, 1971a,b). East and up-slope of the megathrust, the accretionary prism of the North American Plate margin consists of pelagic, hemipelagic, and continent-derived, coarse- to fine-grained clastic deposits of Late Cretaceous and younger age. The rocks of the accretionary prism are imbricated along the numerous southwest-vergent thrusts of the prism. The south end of the accretionary prism in the hanging wall block of the Cascadia subduction zone is severely deformed in the Eureka and Cape Mendocino 1:100,000 quadrangles, probably due to increasingly stronger coupling between the North American and Gorda plates in this area since about 5 Ma (Wilson, 1989; Clarke, 1992; Clarke and Carver, 1992).

In this actively deforming area, imbricate thrusts and the axes of folds overlying blind thrusts in the accretionary prism offshore are oriented west-northwest and project southeastward to align with several moderately low- to steep-dipping faults onshore. In the onshore region, the rocks bounded by these faults correspond to increasingly more distal parts of the uplifted accretionary margin from northeast to southwest.

Between Cape Mendocino and the north side of the King Range terrane, the vergence of thrusting in the onshore area is toward the north-northeast. The offshore projection of these southwest-dipping thrusts is not presently recognized in seismic records due to a lack of coverage in critical areas. However, the north-northeast vergent thrust set that bounds the King Range terrane appears to link the onshore-projection of the Mendocino fracture zone to the north-northwest-trending transform boundary between the Pacific and North American plates (San Andreas fault). These northeast-vergent thrusts show evidence of Pliocene and younger movement contemporaneous with the activity of faults of the accretionary complex north of Cape Mendocino. We therefore interpret them to be rooted in the steep-dipping Pacific-North American plate boundary and to be related to ongoing northward propagation of the San Andreas transform (see Sheet 6, structure sections). Thus, the area south of Cape Mendocino is significantly overprinted by faulting associated with the Pacific-North American transform plate boundary.

The onshore region between about Cape Mendocino on the north and the northeastern boundary of the King Range terrane to the south may best be characterized as a narrow corridor of focused compressional deformation and high uplift rates in response to the oppositely verging blind thrusting that accommodates Gorda-North America and Pacific-North America plate motion. The locus of uplift within this corridor has been called the Mendocino Uplift (McLaughlin and others, 1992).

Faults of the Cascadia subduction margin

Cascadia Megathrust

In the offshore area, the currently active Cascadia megathrust (fig. 3) separates the western leading edge of the Coastal belt from the subducting Gorda oceanic plate and its associated overlying pelagic and land-derived sediment. The fault is also the presently active basal thrust of the modern offshore accretionary prism (Silver, 1971a,b; Clarke, 1992). The thrust apparently separates mafic igneous rocks of the underthrusting Gorda plate and its overlying Miocene and younger sedimentary cover from older uplifted rocks of the North American plate accretionary margin. The upper plate rocks include Late Cretaceous to Miocene rocks in the Yager, Coastal, and False Cape terranes of the Coastal belt, tectonically imbricated with more inboard, less deformed Miocene and younger strata deposited on the continental slope and in shallower marine settings. Older rocks of the Central belt may occur beneath the Coastal belt (structure sections A-A", A-B").

The Cascadia megathrust dips landward at about 10°-15° (Jachens and Griscom, 1983) and may be traced in seismic profiles southeastward in the offshore to a coordinate of about 124°43', 40°29' (Clarke, 1990). Southeast of this coordinate, the megathrust is not apparent from the seismic data and may not extend to the surface. The megathrust might intersect and be truncated against the offshore trace of the San Andreas fault, or the Cooskie fault segment of the King Range thrust zone. The megathrust extends eastward or southeastward at depth along the top of the Gorda Plate beneath the Petrolia area and intersects the northern and northeastern boundaries of the Pacific Plate along the Mendocino fracture zone and a northeastwardly verging thrust system that probably roots into the San Andreas fault beneath the King Range terrane (see Cape Mendocino quadrangle, sections A-A", A-B", and figs. 3, 6a, and 6b). These relations, together with the southwestwardly verging set of buried and exposed thrusts in the southern Cascadia subduction zone north of Petrolia, suggests that tectonic wedging may occur in the North American plate and Gorda plate rocks near their interface with this corner of the Pacific plate (structure section A-A" and fig. 6b).

Mad River fault zone

The Mad River fault zone (Carver and others, 1984; Carver, 1985) is a major zone of complexly imbricated and anastomosing, southwest-verging thrust faults that overprint the Coastal belt thrust (fig. 3). The faults of this zone have been shown to displace strata of late Pleistocene to Holocene age (Carver and others, 1984; Carver, 1985) and thus are probably active.

The Mad River fault zone extends northwestward into the offshore area north of Arcata, where seismic profiling indicates that the faults displace the youngest strata of the sea floor (Clarke, 1992; Clarke and Carver, 1992).

Little Salmon fault

The Little Salmon fault (fig. 3) is a steep to moderately low-dipping, southwest-vergent thrust fault zone present in the central Eel River basin south of Eureka (Ogle, 1953; Carver, 1987; Carver and Burke, 1987). The fault cuts and parallels the Coastal Belt thrust zone near Bridgeville, where faults of the Little Salmon fault zone displace shallow marine Pliocene strata of the Wildcat Group. The fault zone was examined in some detail during seismic hazards investigations at the Humboldt Bay nuclear reactor site south of Eureka, where it was found to displace strata of Holocene age and to cut the surface (Woodward-Clyde Consultants, 1980). In the offshore area, this fault aligns with thrust faults that displace the seafloor and dip shallowly to the northeast at depth. To the east of the Humboldt Bay reactor site, the Little Salmon fault is interpreted to dip northeastward and flatten with depth. Several subparallel faults in Eel River Valley, including the Yager fault (Ogle, 1953) and a northeast-dipping thrust that displaces Pleistocene strata near Anton, may root into the same zone of thrusting in which the Little Salmon fault is rooted. In addition, numerous northwest-trending folds in the Wildcat Group and the Hydesville and Rohnerville formations (Ogle, 1953) are considered to be folds in the hanging-wall blocks of this system of southwest-vergent blind thrusts (Carver, 1987).

Russ and False Cape fault zones

The Russ fault zone (Ogle, 1953) juxtaposes Miocene and younger strata of the Eel River forearc basin with coeval and older strata of the structurally underlying accretionary complex (Cape Mendocino and Garberville quadrangles and fig. 3). Onshore geology and seismicity (see geologic maps and figs. 5 and 6) suggest that the Russ fault is a steep southwest-dipping reverse fault. In the offshore, the fault appears to intersect or cuts off a seismically imaged southwest-vergent thrust (Clarke, 1992) that aligns with the False Cape fault onshore. Along the coast, between Guthrie and Oil Creeks, the Russ fault juxtaposes basal beds of the Wildcat Group and somewhat older Miocene strata to the north with the Coastal terrane of the Franciscan Complex to the south. South of the mouth of Oil Creek, the north-dipping False Cape fault displaces the Coastal terrane southward over the False Cape terrane (Aalto and others, 1995). Ogle (1953) considered all the rocks south of the Russ fault to compose a broad shear zone of Pliocene or younger age, which he named the False Cape shear zone. Ogle recognized blocks of what he considered to be Wildcat Group sandstone within the False Cape shear zone, but he did not recognize that south of the False Cape fault the shear zone itself consists of penetrativeley deformed hemipelagic to pelagic rocks of early Miocene age that we have separately mapped as the False Cape terrane (Aalto and others, 1995).

Inland, the Russ fault displaces strata of the Yager terrane to the south against the Pullen Formation to the north. Southeast of Scotia, in the Garberville 1:100,000 quadrangle, the Russ fault dies out within the Yager terrane, along the northeast flank of the broad southeast-plunging Garberville antiform (fig. 3) that has warped the Yager-Coastal terrane contact and the structurally higher Coastal belt thrust. The surface and subsurface distribution of earthquakes (figs. 5 and 6) strongly suggest that the Russ fault is active at shallow depths. The apparent southwest dip of the Russ fault (fig. 6b) suggests that it might be more closely associated with interaction between the Pacific and North American plates than with the Cascadia margin. Some of the deformation associated with the fault zone could be accommodated at the surface by the Garberville antiform and synform.

Bear River and Garberville fault zones

The term Bear River fault zone here refers to faults that bound the Bear River beds exposed along the coast north and south of the Bear River (fig. 3). North of the mouth of Bear River, the steep north-dipping branch of the Bear River fault zone thrusts rocks of the False Cape terrane over the Bear River beds. South of this fault, the Bear River beds are overturned or dip steeply and face to the south. Locally, False Cape terrane rocks are imbricated with the Bear River section along this northern branch of the fault zone (see Cape Mendocino and Eureka quadrangles; fig. 3; Aalto and others, 1995).

Along the coast south of the Bear River, the Miocene to Pliocene Bear River beds are warped into a west-plunging, open syncline (Cape Mendocino quadrangle and fig. 3). The south flank of this syncline is sheared along east-west trending, south-verging reverse faults. One east-west-trending branch of the Bear River fault zone truncates Pliocene strata at the south side of the Bear River section. This fault (Cape Mendocino quadrangle; fig. 3) merges with the northern branch of the fault zone east of Capetown along the Bear River and juxtaposes the Bear River beds to the north with rocks of the Coastal terrane to the south.

The north and south branches of the on-shore Bear River fault zone are aligned with southwest-vergent thrusts in the offshore accretionary prism. These thrusts also bound the offshore extension of the Bear River beds.

The inland extension of the Bear River fault zone is diffuse and not well defined except where the Neogene Bear River beds are present. The fault zone is aligned with a series of branching and stepping curvilinear physiographic lineaments and zones of shear that are on-trend with the northwestern extension of the Garberville fault zone.

South of the Bear River fault zone and north of Cape Mendocino, several outcrop-scale, phacoid-shaped blocks of friable arkosic siltstone are sheared into the Coastal terrane (Aalto and others, 1995). Some of these blocks contain molluskan shell fragments indicative of a Pliocene to Pleistocene age (Aalto and others, 1995). The local incorporation of Neogene clastic strata into the Coastal terrane as tectonic blocks along shear planes associated with the penetrative melange fabric indicates that this fabric formed very recently. Alternatively, the penetrative fabric formed prior to deposition of the Neogene strata but was reactivated to accommodate Neogene and younger shortening within the southern Cascadia accretionary complex. This wide zone of shearing might represent a zone of detachment into which the Bear River fault zone roots.

The Garberville fault zone consists of several widely spaced, steeply dipping reverse faults with components of dextral slip that bound elongate northwest-oriented slivers of marine and nonmarine overlap assemblage strata. Earthquake epicenters that plot along the Garberville fault have deep foci greater than 10-12 km and may be associated with the underthrust Gorda plate rather than the Garberville fault zone.

Faults of the Pacific-North American Plate boundary

Faults Between Cape Mendocino and the King Range terrane

Mattole Road lineament

Northwest of Petrolia, the Mattole Road crosses the north fork of the Mattole River and climbs westward onto the distal end of an uplifted Pleistocene fluvial surface associated with a former course of the Mattole River (see Cape Mendocino quadrangle). South of the Mattole Road, gravels of this fluvial unit are dissected and truncated along a prominent, straight, northwest-oriented zone of lineaments about 5 km long (fig. 3 and Cape Mendocino quadrangle). The lineaments are produced by straight, gulleyed swales aligned with the truncated south side of the fluvial surface. Southwest of this lineament the rocks consist of an upland of Coastal terrane rocks gulleyed by springs and water seeps vented along the lineament trend. Although the contact of the fluvial gravels with the Coastal terrane rocks is not exposed along the lineament, the anomalous physiography strongly suggests youthful fault control. The lineament also aligns approximately with the landward projections of both the Mendocino fault zone and the Cascadia megathrust. Further investigations are needed to determine to what extent the Mattole Road lineament is related to faulting and major offshore structures.

North Fork Road thrust and related faults near Petrolia

Another poorly exposed fault, present on the Chambers ranch west of the North Fork Road, thrusts sheared Eocene strata of the Coastal terrane northward over lower bathyal to abyssal Wildcat Group-related mudstones of early Pliocene age (Cape Mendocino quadrangle and fig. 3).

The North Fork Road thrust is part of a group of subparallel north-northeast-verging thrusts in the Petrolia area that display evidence of late Pliocene or younger displacement. Rocks involved in this thrusting are exposed at Larue Gulch and Peter B. Gulch along south-southeast-dipping shear zones (Cape Mendocino quadrangle and fig. 3). Shear fabric in these fault zones dips southward from 50° to vertical. At the mouth of Larue Gulch, a large boudined mass of friable quartzose sandstone is enclosed by sheared scaly argillite of the Coastal terrane. Although no fossil data is available, the poor lithification of this sandstone suggests that it may be derived from part of the Neogene section. Similar blocks of this coarse-grained, friable, quartzose sandstone are poorly exposed elsewhere within the south-dipping thrust zones of the Petrolia area (Cape Mendocino quadrangle).

Other curvilinear to straight faults of this thrust system include the Petrolia and Honeydew fault zones (Cape Mendocino quadrangle and fig. 3). These faults are traceable southeastward from the vicinity of Petrolia into parallel, N30°-40°W-trending faults that may merge at depth with the King Range thrust zone (Cape Mendocino quadrangle and fig. 3). The field relations of rocks exposed in these fault zones, including the King Range thrust zone, suggest that they are north-northeast vergent thrusts. We infer that these faults steepen southwestward and root into, or are cut off against, the steep-dipping Pacific-North American plate boundary (the San Andreas fault; see Cape Mendocino 1:100,000 quadrangle and structure sections).

King Range thrust zone

The King Range thrust zone (fig. 3 and Cape Mendocino quadrangle) is a composite of several steep- to shallow-dipping, north- to northeast-directed thrusts. The thrust zone appears to steepen southwestward, toward the San Andreas fault zone, and may root into the Pacific-North American plate transform boundary.

The thrust zone consists of several locally-named faults and wide zones of shearing around the north and east sides of the King Range terrane. Beginning at the coast south of Punta Gorda and moving east and then southeastward, the King Range thrust zone consists of the Cooskie fault zone, the Bear Creek fault zone, the Whale Gulch fault, and the Bear Harbor fault (fig. 3). The broad zone of shear associated with the Cooskie fault zone has apparently accommodated a significant component of the north-south shortening distributed among the northeast-vergent thrusts between the King Range and Petrolia. The Bear Creek fault zone on the east side of the King Range has also accommodated significant shortening and strike slip. The Whale Gulch fault is largely south of the map area but projects into the southwestern corner of the Cape Mendocino quadrangle along the eastern boundary of the King Range terrane (fig. 3 and Cape Mendocino quadrangle). This fault aligns with faults in the offshore part of the Covelo quadrangle to the south that are along the east side of the offshore San Andreas fault zone (McCulloch, 1987; McLaughlin and others, 1994). As such, the southeastern segment of the King Range thrust zone may correspond to a zone of dextral reverse slip.

Griscom (1980b) modeled shallow magnetic anomalies in the Coastal terrane adjacent to the northeast side of the King Range terrane and showed that the magnetic rocks associated with these anomalies extend southwestward beneath the northeast side of the King Range. These data suggest a shallow, southwestward dip of 35°-40° to the King Range thrust zone. The magnetic data also indicate that the King Range terrane structurally overlies the Coastal terrane along this thrust. Steepening of the thrust zone to the southwest, and its apparent merging with the San Andreas fault zone offshore, further leads us to interpret the King Range thrust to root into the Pacific-North American plate boundary.

Several lines of evidence discussed in a previous section on the geology of the King Range terrane suggest that significant displacement has occurred across the King Range thrust and that this fault could be a major part of the transform boundary. Although there is little question that the King Range terrane is allochthonous with respect to the adjacent Coastal terrane to the northeast, there is considerable doubt concerning the amount of dextral displacement that has occurred in conjunction with shortening and uplift across the King Range thrust since the Miocene. One model that has been proposed assumes that the King Range terrane accreted to the Pacific plate with part of the Farallon plate shortly after the middle Miocene (about 14 Ma) deposition of the King Peak subterrane. In this model, the terrane was translated as much as 460 km along the transform margin before its obduction along the King Range thrust at 1.2 Ma (McLaughlin and others, 1994). Alternatively, the Miocene rocks of the King Range terrane may have been deposited with those of the False Cape terrane in the Cascadia subduction complex near or at their present latitude but had lain farther to the west, in the lower region of the accretionary complex. In this latter model, the King Range thrust zone and other northeast-vergent thrusts between the King Range and Cape Mendocino have formed in response to northeast-southwest oriented compression only since arrival of the triple junction at this latitude about 1.2 Ma (Underwood and others, 1999).

San Andreas Fault zone

The San Andreas fault zone is poorly defined in the Cape Mendocino 1:100,000 quadrangle, and its geometry near the juncture with the Mendocino fracture zone is also controversial. This is largely because evidence for a well-defined, right-lateral active fault having an appropriately large displacement and an orientation and geometry consistent with that of the San Andreas fault is lacking in the onshore area. This has led to the general assumption that the main transform boundary is offshore north of Point Delgada but too close to the shoreline to be imaged in conventional shipboard seismic surveys. Detailed aeromagnetic data recently acquired by the U.S. Geological Survey support this interpretation (Jachens and Griscom, 1994) and suggest that the fault offshore dips nearly vertically to the northeast between Point Delgada and the Mendocino fracture zone.

The San Andreas fault zone is relatively well defined by seismic reflection lines and sparker profiling in the offshore north of Point Arena, California, to within 20 km of Point Delgada. This segment of the fault zone includes a fault that breaks the seafloor and is considered to be the 1906 earthquake trace of the San Andreas system (McCulloch, 1987). The offshore San Andreas fault zone south of Point Delgada is about 10 km wide (McCulloch,1987), and faults along the east side of the zone are aligned with the offshore projection of the Whale Gulch fault and a southeastern segment of the King Range thrust zone.

Onshore at Point Delgada, surface ruptures were documented in the April, 1906 earthquake on the San Andreas fault (Lawson, 1908; Brown and Wolfe, 1972). However, the 1906 earthquake surface rupture zone at Point Delgada was predominantly in a major landslide complex, and the sense of displacement was in large part consistent with rotational displacement within a reactivated landslide. Because of these relations, the interpretation of the 1906 deformation at Point Delgada as surface faulting was challenged (McLaughlin and others, 1982, 1985).

More recent evidence suggests the presence of a Holocene fault onshore at Point Delgada, which corresponds to the 1906 San Francisco earthquake rupture. Brown (1995) has argued on the basis of geomorphologic evidence and the reinterpretation of fission track data (Dumitru, 1991) in the vicinity of Point Delgada that a major active trace of the San Andreas fault does come onshore and that this feature corresponds to the 1906 earthquake trace of the San Andreas fault. In addition, new data from trenching investigations at Point Delgada confirm that a Holocene strike-slip fault does offset the Point Delgada landslide complex and continues northward onshore for at least 13 km in the King Range (Schill and others, 1995; Muller and others, 1995; Prentice and others, 1999). The bedrock geology, hydrothermal mineralization ages, and paleothermal data from vitrinite reflectance, isotopic compositions of carbonate and quartz veins, and fission track counts (Underwood and others, 1999) make it unlikely, however, that any major strike-slip displacement in excess of a few hundred meters can be accomodated on the newly recognized Holocene fault at Point Delgada or anywhere between the shoreline and the east side of the King Range terrane.

We interpret the San Andreas fault zone as bounded on the northeast by faults of the King Range thrust zone and on the southwest by a major fault that is offshore and west of Point Delgada. The offshore fault is interpreted here to extend northwestward close to the coastline, to dip steeply to the northeast beneath the King Range terrane, and to intersect the Cooskie fault zone in the offshore area at the north end of the King Range (Cape Mendocino quadrangle; also see McLaughlin and others, 1994). Northwest of the intersection of the hypothetical offshore San Andreas fault with the Cooskie shear zone (Cape Mendocino quadrangle and fig. 3), the San Andreas fault zone must extend along a series of submarine benches that are aligned with Mattole submarine canyon along the northeast flank of Mendocino Ridge. This northernmost segment of the San Andreas fault zone and its intersection with the Mendocino fracture zone are as yet poorly defined.

Mendocino fracture zone

At the latitude of Cape Mendocino, the Mendocino fracture zone defines the northern boundary of the Pacific Plate south of the Gorda-Juan de Fuca Ridge (Atwater, 1989). Motion of the Pacific Plate along the Mendocino fracture zone is right-lateral relative to the Gorda and North American plates and is driven predominantly by spreading at the Gorda Ridge. The juncture of the Mendocino fracture zone and San Andreas fault in the Mendocino triple junction area is characterized on land by northeast-vergent thrusting, crustal shortening, and high uplift rates. This focused deformation is apparently driven by a component of northeast-southwest-oriented compression between the Pacific and North American plates that is superposed on northwest-southeast-oriented convergence between the North American and Gorda plates.

The map area includes only that part of the Mendocino fracture zone that is east of 125° W longitude. The geometry of this segment of the fracture zone is atypical, due partly to proximity of the San Andreas fault zone. The fracture zone west of about 126°W is characterized by a prominent south-facing escarpment that juxtaposes young bouyant oceanic crust of the Gorda Plate on the north against Oligocene and older crust of the Pacific Plate to the south. The south-facing (up on the north) escarpment is present eastward to about longitude 126°, where the fault zone crosses the crest of Mendocino Ridge and the fault escarpment reverses its facing direction. East of this crossing, the Mendocino fracture zone is aligned along the base of the north-facing Gorda escarpment, on the north side of Mendocino Ridge. Here, the Pacific plate south of the fracture zone is composed of Oligocene and younger oceanic rocks and overlying rocks derived from a captured Miocene and older continental margin, referred to as the Vizcaino block (McCulloch, 1987; McLaughlin and others, 1994). These rocks are juxtaposed with the Miocene and younger oceanic to hemipelagic rocks of the Gorda Plate. The anomalously high, north-facing escarpment of the Mendocino fracture zone east of 126°W, therefore, may be attributed in large part to stacking of the Vizcaino block and its Mesozoic ophiolitic basement on top of the Pacific Plate.

Relationship of crustal structure to active deformation at the Mendocino Triple Junction

The coastal area between Cape Mendocino on the north and Bear Harbor, about 10 km south of Point Delgada, is characterized by anomalously high rates of uplift of the Quaternary marine terrace sequence. An uplifted mid-Wisconsinan marine platform exposed discontinuously between Point Delgada and Bear Harbor in this area is radiocarbon dated at about 45 ka (based on wood in fluvial silts and gravels overlying the marine platform), yielding an uplift rate on the order of 1 mm/yr (McLaughlin and others, 1983; Hagemann, 1985). The uplifted Holocene marine terrace, preserved at several localities along the coast north of Point Delgada, yields uplift rates on the order of 2 to 4 mm/yr, based on radiocarbon ages on pholad shells from burrows drilled into the marine platform (Lajoie and others, 1982). The uplift rates from the Holocene marine terrace define an area of high uplift between Cape Mendocino and Mussel Rock (1 to 3 mm/yr) and another area of high uplift south of the mouth of the Mattole River (1 to 5 mm/yr), separated by an area of pronounced rate drop (Lajoie and others, 1982; Merritts and Bull, 1989). Inland from the coast, studies of Pleistocene and Holocene fluvial terraces along the Mattole and Eel Rivers indicate that uplift rates of up to 1 mm/yr persist inland at least to Garberville (Bickner, 1985; Merritts and Bull, 1989; Merritts and Vincent, 1989; Merritts and others, 1994). Based on this information, and assuming that the focused uplift is driven by northeast-southwest-oriented compression, a region of uplift, elongated northwest-southeast, may be crudely delineated (fig. 3). This uplift region has been referred to as the Mendocino Uplift (McLaughlin and others, 1992). The origin and growth of the Mendocino Uplift may be directly related to several presently and recently active tectonic features of the Cape Mendocino area.

Deformation of the Gorda Plate at the south end of the Cascadia subduction complex may be significantly affected by several factors, including (a) northeast-southwest-oriented compression across the Pacific-North American plate boundary; (b) the close proximity to the Cascadia subduction front of young, hot lithosphere derived from the Gorda Ridge and Mendocino fracture zone; (c) a thickened clastic section above oceanic crust of the Gorda Plate in the triple junction region; and (d) high relief developed across the Mendocino fracture zone at its intersection with the North American Plate. Because the leading edge of the North American Plate bends southeastward at the south end of the Cascadia subduction zone, the subducting Gorda Plate must slide through a southeastwardly-pinching corridor between the leading edge of the North American Plate and the Pacific Plate. The combined resistance to subduction provided by bouyant Gorda Plate oceanic crust, a thickened overlying clastic cover, and the northeast-southwest-oriented component of compression between the Pacific and North American plates may thus contribute to increased coupling between the Gorda and North American Plates (Clarke and Carver, 1992) and to the accommodation of plate motion by focused vertical uplift in this area.

At depth, convergence between the North American and Gorda plates is accommodated by strong coupling above and below the megathrust of the Cascadia subduction complex. The coupling is manifested as west-southwest-vergent blind thrusting involving oceanic rocks of the Gorda Plate and clastic rocks in the accretionary complex of the overlying North American Plate.

Northeast-southwest-oriented compression across the Pacific-North American plate boundary is accomodated by northeastwardly vergent thrusts that root to the southwest in the steeply dipping Pacific-North American plate boundary. In the subducting Gorda Plate, this component of plate motion is partially accommodated by sinistral shear along northeast-southwest-oriented faults in the Gorda plate.

Thus, the Mendocino Uplift is driven by several components of plate motion. The northeastern flank of the uplift may be driven by thrusting rooted in the Gorda-North American plate boundary whereas uplift along the southwestern part of the uplift may reflect northeast-vergent thrusting rooted in the Pacific-North American plate boundary (fig. 3).

North of the Mendocino triple junction region, long-term Quaternary uplift rates based on marine terrace platforms and subsided coastal deposits (Mitchell and others, 1994; Kelsey and others, 1994) alternate from negative (subsidence) to positive (uplift, at rates of less than 1.0 mm/yr). Although shorter-term rates based on about 45 years of geodetic data suggest that there is a broad region of uplift in southern Cascadia extending from the latitude of Cape Mendocino northward to Cape Blanco, these high rates are apparently not permanently preserved in the long-term record. A principal reason for this disparity between the long- and short-term records is thought to result from tectonic subsidence and rebound in years following major seismic events along the subduction margin (Mitchell and others, 1994; Kelsey and others, 1994). Consequently, the Mendocino Uplift exhibits rates based on uplift of Quaternary marine and nonmarine terraces that are one to four orders of magnitude higher than rates based on the same criteria for the broader southern Cascadia uplift region between Cape Mendocino and Cape Blanco (Kelsey and others, 1994; Mitchell and others, 1994).

Recent earthquakes in the Cape Mendocino region seem to reflect these relations. The more recent of these, the M7.1 Petrolia earthquake of April, 1992, is the better studied of these seismic events, and coseismic uplift that accompanied the Petrolia earthquake is relatively well documented (Oppenheimer and others, 1993; Oppenheimer and Eaton, 1992). The distribution of the coseismic uplift appears to have been confined to the northwestern onshore region of the Mendocino Uplift. The favored focal mechanism for the M7.1 mainshock of the Petrolia earthquake (Oppenheimer and others, 1993) suggests that the event occurred on a N10°W-oriented blind thrust dipping northeastward at a very shallow angle (about 13°) at a depth of about 10 to 11 km (see structure section A-A" and fig. 6b, Sheet 6). These data (Oppenheimer and others, 1993) are entirely consistent with thrusting rooted in the zone of coupling between the Gorda and North American plates.

Another moderate earthquake that occurred onshore in the triple junction area in August, 1991 (the M6.2 Honeydew earthquake) also appears to have a thrust mechanism, but the earthquake location and mechanism are poorly constrained. An early study (McPherson and Dengler, 1992) located the earthquake focus beneath Cooskie Mountain southwest of Petrolia. The favored mechanism for the mainshock of the Honeydew earthquake was a 45° southwest-dipping fault plane that ruptured at a focal depth of 12 km. McPherson and Dengler (1992) favored this mechanism over a northeastwardly dipping fault plane because a linear, 4-km-long, northwest-trending zone of surface deformation occurred along the surface projection of the favored blind fault plane. The deformation zone was characterized by extensional cracking, liquefaction, and features indicative of vertical ground acceleration. These data were taken to indicate that seismic energy was focused over the hanging wall of the blind thrust on which slip occurred.

The Honeydew earthquake was later relocated 5 to 6 km northeast of its previous position near Cooskie Mountain and at a shallower depth of 8.7 km (M. Magee, personal commun., 1993). This new location places the focus of the Honeydew mainshock along the southwestward projection of the 1992 Petrolia mainshock, perhaps indicating that both earthquakes occurred on the same blind thrust.

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