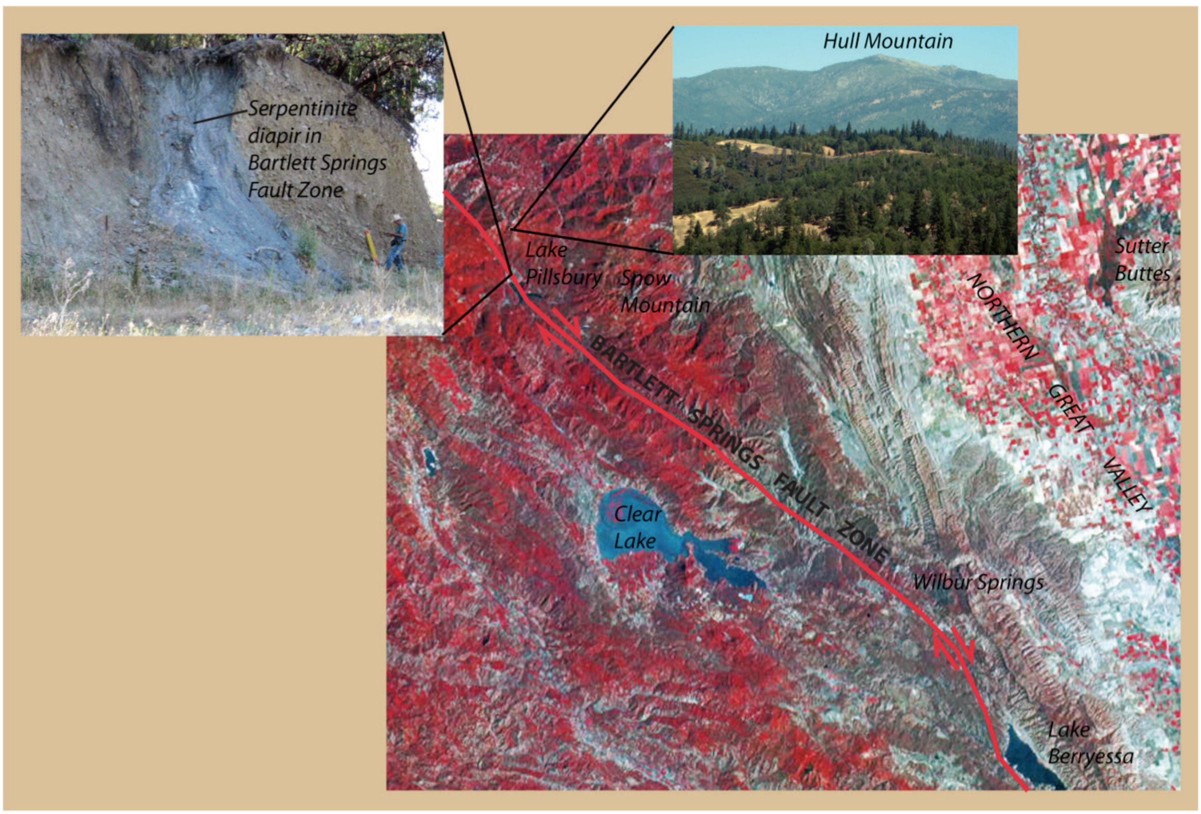
Geologic Map of the Bartlett Springs Fault Zone in the Vicinity of Lake Pillsbury and Adjacent Areas of Mendocino, Lake, and Glenn Counties, California

By Henry N. Ohlin, Robert J. McLaughlin, Barry C. Moring, and Thomas L. Sawyer



View of Bartlett Springs Fault Zone between Lake Berryessa to southeast and Lake Pillsbury, to northwest, from false color 1976 vintage NASA-USGS EROS Data Center landsat image. Clear Lake is in central southwest part of air photo image. Inset photograph in upper right is view to northeast, at rocks of Eastern belt of Franciscan Complex that underlie Hull Mountain. Wooded foreground underlain largely by mélange. Photo taken near Logan Spring by R.J. McLaughlin, 2010. Inset photograph in upper left is of serpentinite diapir along Bartlett Springs Fault Zone that intrudes Pleistocene gravels near Gravelly Valley northwest of Lake Pillsbury (location on geologic map sheet). Photo by J.J. Lienkaemper, 2009.

Pamphlet to accompany

Open-File Report 2010–1301

2010

U.S. Department of the Interior
U.S. Geological Survey

Contents

Figures

Tables

Introduction

The Lake Pillsbury area lies in the eastern part of the northern California Coast Ranges, along the east side of the transform boundary between the Pacific and North American plates (fig. 1). The Bartlett Springs Fault Zone is a northwest-trending zone of faulting associated with this eastern part of the transform boundary. It is presently active, based on surface creep (Svarc and others, 2008), geomorphic expression, offset of Holocene units (Lienkaemper and Brown, 2009), and microseismicity (Bolt and Oakeshott, 1982; Dehlinger and Bolt, 1984; DePolo and Ohlin, 1984). Faults associated with the Bartlett Springs Fault Zone at Lake Pillsbury are steeply dipping and offset older low to steeply dipping faults separating folded and imbricated Mesozoic terranes of the Franciscan Complex and interleaved rocks of the Coast Range Ophiolite and Great Valley Sequence. Parts of this area were mapped in the late 1970s and 1980s by several investigators who were focused on structural relations in the Franciscan Complex (Lehman, 1978; Jordan, 1975; Layman, 1977; Etter, 1979). In the 1980s the U.S. Geological Survey (USGS) mapped a large part of the area as part of a mineral resource appraisal of two U.S. Forest Service Roadless areas. For eval uating mineral resource potential, the USGS mapping was published at a scale of 1:62,500 as a generalized geologic summary map without a topographic base (Ohlin and others, 1983; Ohlin and Spear, 1984). The previously unpublished mapping with topographic base is presented here at a scale of 1:30,000, compiled with other mapping in the vicinity of Lake Pillsbury. The mapping provides a geologic framework for ongoing investigations to evaluate potential earthquake hazards and structure of the Bartlett Springs Fault Zone.

This geologic map includes part of Mendocino National Forest (the Elk Creek Roadless Area) in Mendocino, Glenn, and Lake Counties and is traversed by several U.S. Forest Service Routes, including M1 and M6 (fig. 2). The study area is characterized by northwest-trending ridges separated by steep-sided valleys. Elevations in this part of the Coast Ranges vary from 1,500 ft (457 m) to 6,600 ft (2,012 m), commonly with gradients of 1,000 ft per mile (90 m per km). The steep slopes are covered by brush, grass, oak, and conifer forests. Access to most of the area is by county roads and Forest Service Route M6 from Potter Valley to Lake Pillsbury and by county road and Forest Service Route M6 and M1 from Upper Lake and State Highway 20. From the north, State Highway 261 provides access from Covelo. Forest Service Route M1 trends roughly north from its intersection with Route M6 south of Hull Mountain and through the Elk Creek and Black Butte Roadless areas to State Highway 261. Side roads used for logging and jeep trails provide additional access in parts of the area.

Present and Previous Studies

This geologic mapping study was conducted as a reconnaissance study during the summers of 1980 and 1981 for the purpose of evaluating the mineral resource potential of U.S. Forest Service lands. The investigation consisted of geologic mapping in conjunction with sampling of stream sediment and bedrock for geochemical analysis. Samples suspected to contain radiolaria (mostly cherts) were also collected from the Mesozoic bedrock and submitted to C.D. Blome (USGS) for paleontologic dating. The geologic map in this report consists in part of original mapping and in part of mapping that is modified from previous studies. Landslides were mapped from color 1:24,000 air photos and generally only the larger slides are shown, though numerous small debris flows are present.

Irwin (1960) provided an early description of the regional geologic setting for this area and a summary of the mineral resources. Publications by the California Division of Mines and Geology describe mineral deposits and past mineral production for the region (Eric, 1948; Trask and others, 1943; Trask, 1950). Unpublished reports by J.V. Vantine, M. Dwyer, and F. Kilmer of the California Department of Water Resources (CDWR, 1966, 1968, 1969) and student theses (Lehman, 1974; Jordan, 1975; Layman, 1977; Etter, 1979) greatly aided in the preparation of this geologic map. The CDWR studies included aeromagnetic and gravity surveys over most of the study area. Exploration drill holes made by the CDWR during their water tunnel investigations were later used for heat flow measurements (Lachenbruch and Sass, 1980).

In an unpublished report for Pacific Gas and Electric Company, Bolt and Oakeshott (1982) evaluated the seismicity along the Bartlett Springs Fault Zone in the vicinity of Lake Pillsbury. Later, DePolo and Ohlin (1984) published a brief description of Quaternary fault geomorphology and seismicity associated with the Bartlett Springs Fault Zone at Lake Pillsbury and proposed that it was an important member of the boundary between the Pacific and North American plates. At about the same time, seismic parameters for the Bartlett Springs Fault Zone were investigated by Dehlinger and Bolt (1984). These studies were followed by a geotechnical investigation of Scott Dam at Lake Pillsbury for Pacific Gas and Electric Company (Geomatrix Consultants, 1986). More recently, investigations of the Bartlett Springs Fault Zone and adjacent areas have been conducted by the U.S. Geological Survey under a Cooperative Research and Development Agreement (CRADA) with Pacific Gas and Electric Company (Langenheim and others, 2007; McLaren and others, 2007; Svarc and others, 2008; Lienkaemper and Brown, 2009; this study).

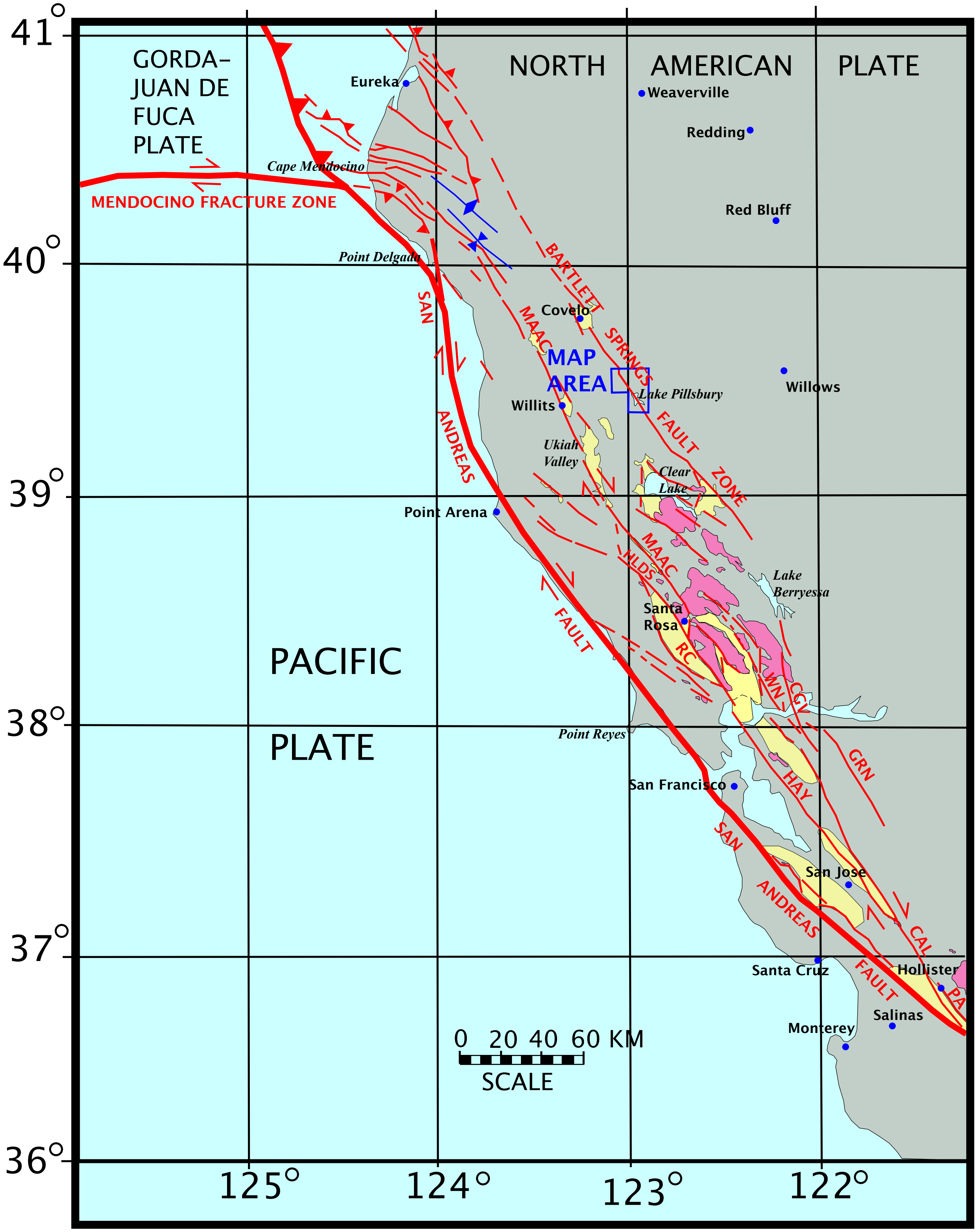


Figure 1. Map showing location of the map area, Bartlett Springs Fault Zone, Lake Pillsbury, and major faults (red) east of the San Andreas Fault in the Coast Ranges of northern California. Abbreviations for faults, delineated generally from north to south on map: MAAC, Maacama; HLDS, Healdsburg; RC, Rodgers Creek; WN, West Napa; CGV, Concord-Green Valley; HAY, Hayward; CAL, Calaveras; PA, Paicines. Red barbs indicate thrust faults. Neogene volcanic rocks east of San Andreas Fault are shown in pink. Other features shown east of San Andreas Fault are structural basins (yellow) associated with active strike-slip faulting and selected folds (blue) associated with active compression. Geologic features are derived mainly from 1:750,000 geologic map of California (Jennings, 1977), revised locally from sources cited in fig. 3.

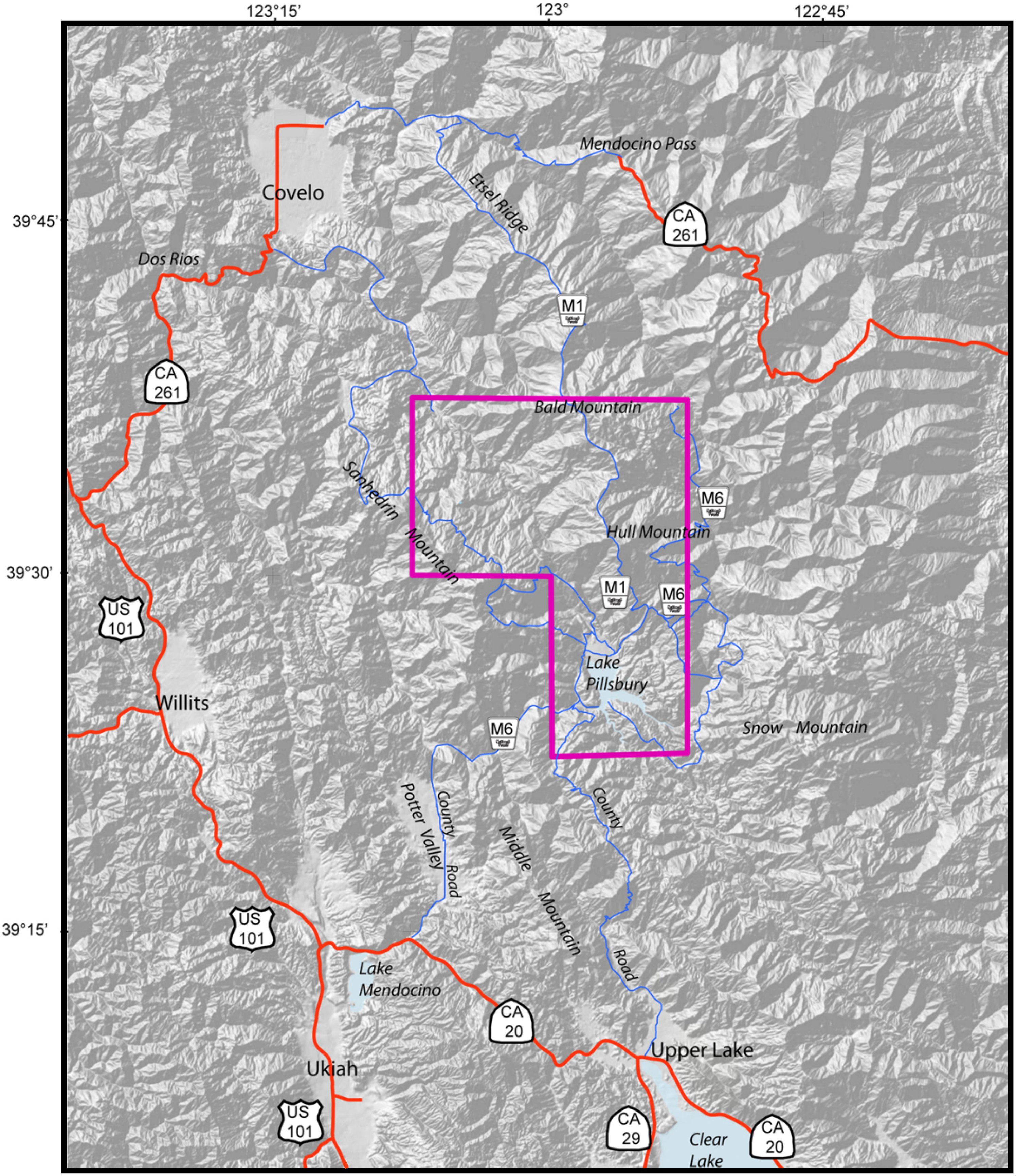


Figure 2. Map of northern California showing location of map area (magenta outline) and prominent geographic features and roads, plotted on 30-m hillshade base. U.S. Hwy 101 and State Hwy 261 and 20 (paved roads), heavy red line; U.S. Forest Service Routes M1 and M6 and county roads (paved and gravel roads), thin blue line.

Acknowledgments

The USGS funded geologic mapping conducted in the area of this investigation originally as part of a Wilderness Mineral Resource Potential study. The current investigation and preparation of this geologic map for publication has been funded in part by Pacific Gas and Electric Company (PG&E) as part of a cooperative research agreement with the USGS, in cooperation with the Western Geology and Geophysics Team and the National Cooperative Geologic Mapping and Earthquake Hazards Reduction Programs. PG&E geologist William Page accompanied the authors in the field and provided important background information and supportive field data from unpublished earthquake hazards and dam safety investigations for PG&E. Scott Steinberg of PG&E also has been supportive of this investigation. James Lienkaemper of the USGS provided preliminary fault data from his aerial photo interpretive studies of the Bartlett Springs Fault Zone for integration with the framework geology presented in this study.

Geologic Setting

The study area lies in a portion of the northern California Coast Ranges largely underlain by structurally complex and variably metamorphosed marine sedimentary and volcanic rocks of the Franciscan Complex. These rocks range in age from Early Jurassic to early Late Cretaceous and are distributed regionally in northwest-trending belts. The area encompasses the boundary between highly sheared mélange of the Franciscan Central belt and more coherent rocks of the Franciscan Eastern belt, which are texturally reconstituted and metamorphosed to high pressure (blueschist grade) mineral assemblages (Irwin, 1960). Recent work has further subdivided the Eastern belt and shown that it structurally overlies the Central belt mélange along a regional thrust (Blake and Jones, 1974; Jayko, 1983). Within the study area, this thrust boundary is complex and has been disrupted by northwest-trending shear zones associated with the active Bartlett Springs Fault and Cenozoic motion of the Pacific-North American plate boundary system (DePolo and Ohlin, 1984).

The Bartlett Springs Fault zone is one of the faults along the eastern boundary of the wide transform zone separating the Pacific and North American plates. Previous investigations clearly indicate that this complex fault zone exhibits evidence of Quaternary movement (McLaughlin and others, 1990), as well as possible creep (J.J. Lienkaemper, personal commun., 2009; Lienkaemper and Brown, 2009; Svarc and others, 2008). Isolated masses of serpentinite, assigned to the Jurassic Coast Range Ophiolite, are locally present along the Bartlett Springs Fault Zone, as well as along older thrust faults. The serpentinite is most likely derived from south and east of Lake Pillsbury, from the main belt of Coast Range Ophiolite that occurs along the west side of Sacramento Valley.

Landslides mask many geologic features, and their distribution and character significantly influences slope stability, other surface and near surface processes, and regional hydrologic conditions. Noting the distribution of vegetation sensitive to the underlying rock type on air photos was useful in extending ground observations to larger areas. This is especially apparent where the southern exposure of slopes intensifies the differences in vegetation cover of three different lithologies:

- metasandstone at high elevations (900 m plus) is generally covered by conifers;
- mélange, largely composed of intensely sheared argillite is grass covered;
- metasandstone at low elevations (550–900 m) supports brush.

These vegetation differences are less apparent on north-facing slopes or where cattle grazing and logging has occurred. Serpentinite on Sanhedrin Mountain is usually grass covered, differing from the surrounding metasandstone, which supports conifers.

Quaternary Deposits

Landslide Deposits

Landslides are the most widespread and possibly the most significant Quaternary deposit of the area. Extensive landslide deposits occur throughout the study area; shallow, large earthflows are most common. Numerous small slumps, earthflows, and debris flows were observed in the field but are too small to be shown on the map. Most commonly, landslide deposits occur within mélange, especially on south-facing slopes, along the contact where mélange is overlain by schist, and near fault zones where shearing has weakened the bedrock. Landslides composed entirely of serpentinite talus are present near Devils Rock Garden. Prominent large earthflows occur along the Mendocino Pass Road, on the west slope of Black Butte, at Blue Slide Creek, on the west slope of Etsel Ridge, and at Mendenhall Creek. The movement of these earthflows is accomplished by a combination of block gliding, slumping, and viscous flow. Studies of similar earthflows in Franciscan mélange of the northern California Coast Ranges has shown them to be shallow features, with a thickness between 30 and 35 m. They are active during the wet winter season, when they add significant amounts of material to creeks flowing around the landslide toes (Kelsey, 1978).

Alluvial Fan and Stream Terrace Deposits

Quaternary stream terraces and associated alluvial deposits are present at stream intersections and meanders. Several levels of stepped surfaces associated both with stream terraces and alluvial fans have also been mapped (Sheet 1) along the east and west sides of Lake Pillsbury basin. Elsewhere, terraces or alluvial flats may have developed at the toes of large landslides, where water action has reworked slide debris and created flat topographic surfaces adjacent to active stream channels (deposits in Squaw Valley northeast of Lake Pillsbury may be related to this process). Holocene strath terraces of the Eel River and Elk Creek are typically about 4 m above the active river channels and consist of about 2 m of alluvium on a bedrock bench. The terrace deposits are composed of a poorly sorted to unsorted basal boulder horizon that fines upward into sand and silt.

Along Elk Creek, at least two undifferentiated terrace levels are preserved. Upper surfaces of the higher terraces are 13 to 14 m above the active creek channel. The deposits on these terraces are composed of a basal boulder horizon on a bedrock bench, 8 to 9 m above the creek level, overlain by sand and silt and coarse angular colluvium. The lower terrace surfaces are 5 m above the creek level and are underlain by well-stratified gravel and sand couplets. The gravel layers average 0.3 m thick and are composed of imbricated cobbles and pebbles separated by an equal thickness of coarse sand. The bedrock below the gravel is not clearly exposed. The higher terrace is well vegetated and was not examined in enough detail to establish its age. The lower terrace may be Holocene.

Gravelly Valley Area and Margins of Lake Pillsbury Basin

Quaternary alluvial fan and stream terrace deposits of at least three generations are mapped in the Gravelly Valley area and along the east and west margins of Lake Pillsbury basin, based partly on the distribution of the deposits and partly on recognition of multiple generations of stepped geomorphic strath terraces and alluvial fan surfaces (young, old, and very old). Gravelly Valley is a small structural basin related to a right step in the Bartlett Springs Fault Zone. Lake Pillsbury, an artificial lake, covers the southern portion of the basin. Older, dissected fan and terrace deposits (units Qoa, Qfo, Qto, Qfvo, and Qtvo) are present along the east side of Gravelly Valley and along the northeast and southwest sides of Lake Pillsbury. The older terrace deposits appear to be either faulted on their northeast side on the east side of the basin or their depositional contact on bedrock is buttressed against a scarp on a strand of the Bartlett Springs Fault Zone. On the southwest, older fan and terrace deposits are overlain and locally incised by younger, inset alluvial units. The older terrace deposits that flank Lake Pillsbury basin were described by Irwin (1960, p. 54) as follows:

> "An ancient valley surface appears to have developed at an altitude of about 2,300 feet in the vicinity of Lake Pillsbury. On the east side of the lake, weakly consolidated sands and gravels are exposed from the artificial 1,800 - foot level of the lake to as high as 2,300 feet above sea level; on the west side of the lake the gravels cap a ridge, and the base of the terrace gravels is about 200 feet above the lake."

Thus the older terrace deposits demarcate an ancient basin, broader than the present-day valley but owing its existence to the same kind of structural controls. A prominent remnant of older fluvial gravels (Qoa) is exposed along the county road to Upper Lake southwest of Scott Dam, at elevations between about 2,000 and 2,200 ft. These gravels are perched, tilted, and cut by the Logan Spring Fault, which probably is one of the bounding faults of ancient Lake Pillsbury basin. The gravels along the Logan Spring Fault apparently originally draped the fault scarp then were cut, tilted, and left perched on the uplifted southwest side of the fault zone during early development of the Lake Pillsbury pull-apart basin. Other unfaulted older fluvial gravel remnants southwest of the Logan Spring Fault may represent extra-basinal deposition.

Large areas on the west side of Lake Pillsbury north of Scott Dam and on the northeast side of Lake Pillsbury east and southeast of Sunset Point Campground are mapped as older alluvial gravel (Qoa). Several younger strath terraces on the west side of the reservoir (Qto, Qtvo) and younger alluvial fan surfaces on the northeast side (Qfo, Qfvo), which are mapped on the basis of their geomorphic surface expression, are depicted as capping or incising the older alluvial deposits. In several places, however, areas mapped as strath terraces and fan surfaces were found to directly overlie Mesozoic bedrock, suggesting that the distribution of the older alluvial gravel in these areas (Qoa) is exaggerated. The older alluvial gravel deposits that are shown along the east and west sides of the reservoir may be more accurately characterized as a generalized unit whose distribution was mapped by linking the geomorphic surfaces of several thin terraces and fans of different age that are separated by poorly exposed bedrock. The thick deposits of older gravel implied by the present mapping, thus, may be largely absent, may include areas of bedrock, or may have a more complex distribution. More detailed mapping of the older and younger terrace and fan units around the reservoir margin will be necessary to resolve this issue.

The younger fluvial terraces and alluvial fan deposits (Qt, Qty, and Qfy) include deposits in a broad flat terrace that occupies much of the floor of Gravelly Valley, as well as the much smaller terrace deposits of Salmon and Smokehouse Creeks just above the valley. The large alluvial surface (unit Qal) on the west side of Salmon Creek appears to mark an older channel that delivered sediment to the Gravelly Valley terrace (unit Qfo). Linear scarps and exposed faults cut the Salmon Creek and Gravelly Valley fans and align with the Bartlett Springs Fault Zone, reflecting the recency of displacement on this fault.

The geometry of Gravelly Valley-Lake Pillsbury basin and its bounding faults, as well as the sedimentologic character of the basin fill, are similar to other fault-bounded Neogene structural basins in northern California (McLaughlin and Nilsen, 1982; Nilsen and McLaughlin, 1985). Uplifted, older alluvial stream and fan terraces along the basin margins indicate that the ancient valley described by Irwin (1960) was at least 4.5 km wide and 6.5 km long. Recent gravity and magnetic data suggest that the maximum depth of the sedimentary basin beneath Lake Pillsbury and Gravelly Valley is about 400 m (Langenheim and others, 2007). Subsequent faulting and downcutting by the modern braided stream channels (Qal) has narrowed the aggradational portion of Gravelly Valley basin and its extension beneath Lake Pillsbury.

Early Tertiary(?) and Mesozoic Basement Rocks

Basement rocks of the map area are chiefly assigned to the Franciscan Complex but also include rocks of the Coast Range Ophiolite and Great Valley Sequence that are interleaved with each other and with the Franciscan Complex.

Great Valley Sequence

Ophiolitic Mélange and Sedimentary Rocks of Split Rock

Along the southwest side of the Bartlett Springs Fault Zone in Lake Pillsbury basin, bedded shale and sandstone are interleaved with blocks of mafic volcanic and plutonic rocks, serpentinite, and minor chert in a sheared serpentinitic and argillitic matrix. These rocks were named the Blue Slides Formation by Etter (1979); although some of the unit includes coherently bedded, fossiliferous lower Great Valley Sequence strata, the rocks are collectively penetratively disrupted and best characterized as mélange. The Blue Slides Ridge area for which Etter named this unit is also outside of the map area. We therefore informally rename the rocks beneath and along the southwest side of Lake Pillsbury basin as the "ophiolitic mélange and sedimentary rocks of Split Rock" for the map feature of that name (composed of serpentinite) in the map area.

We correlate these rocks across the Bartlett Springs Fault Zone (fig. 3) with the right-laterally separated Mélange of Grizzly Creek (McLaughlin and others, 1990), 45–53 km southeast of the Lake Pillsbury area. The Mélange of Grizzly Creek is exposed northeast of the Bartlett Springs Fault Zone between the west side of Little Indian Valley and Wilbur Springs. Serpentinite matrix- and ophiolite-block mélange mapped as far south as Lake Berryessa (Graymer and others, 2002) may also correlate with the ophiolitic mélange and sedimentary rocks of Split Rock and with the Mélange of Grizzly Creek.

Minimum distributed dextral displacement of the ophiolitic mélange and sedimentary rocks of Split Rock is constrained southeast of Lake Pillsbury by an unusual serpentinite-specific cold-seep fossil assemblage that includes the Lower Cretaceous (Hauterivian) brachiopod *Peregrinella whitneyi*. Northeast of the Bartlett Springs Fault Zone, *Peregrinella whitneyi* occurs in sedimentary serpentinite that structurally overlies the Mélange of Grizzly Creek near Wilbur Springs (McLaughlin and others, 1990; Campbell and others, 1993; Campbell and Bottjer, 1995; Campbell and others, 2002; Kiel and others, 2008). This unique fossil cold seep assemblage is also found entrained along the Bartlett Springs Fault Zone in the Rice Valley area, 6–8 km southeast of Lake Pillsbury in similar rocks overlying ophiolitic mélange (Berkland, 1973; Campbell and others, 1993; Campbell and others, 2002; Kiel and others, 2008). The Rice Valley rocks, together with the Split Rock mélange unit are dextrally separated ~47–53 km from the Wilbur Springs area, which may represent a minimum amount of long-term distributed right-lateral displacement across the Bartlett Springs Fault Zone. It is also possible that this apparent dextral displacement is actually accounted for by oblique reverse slip and that dextral slip has been much less. The only other *Peregrinella whitneyi* locality reported in northern California is ~82

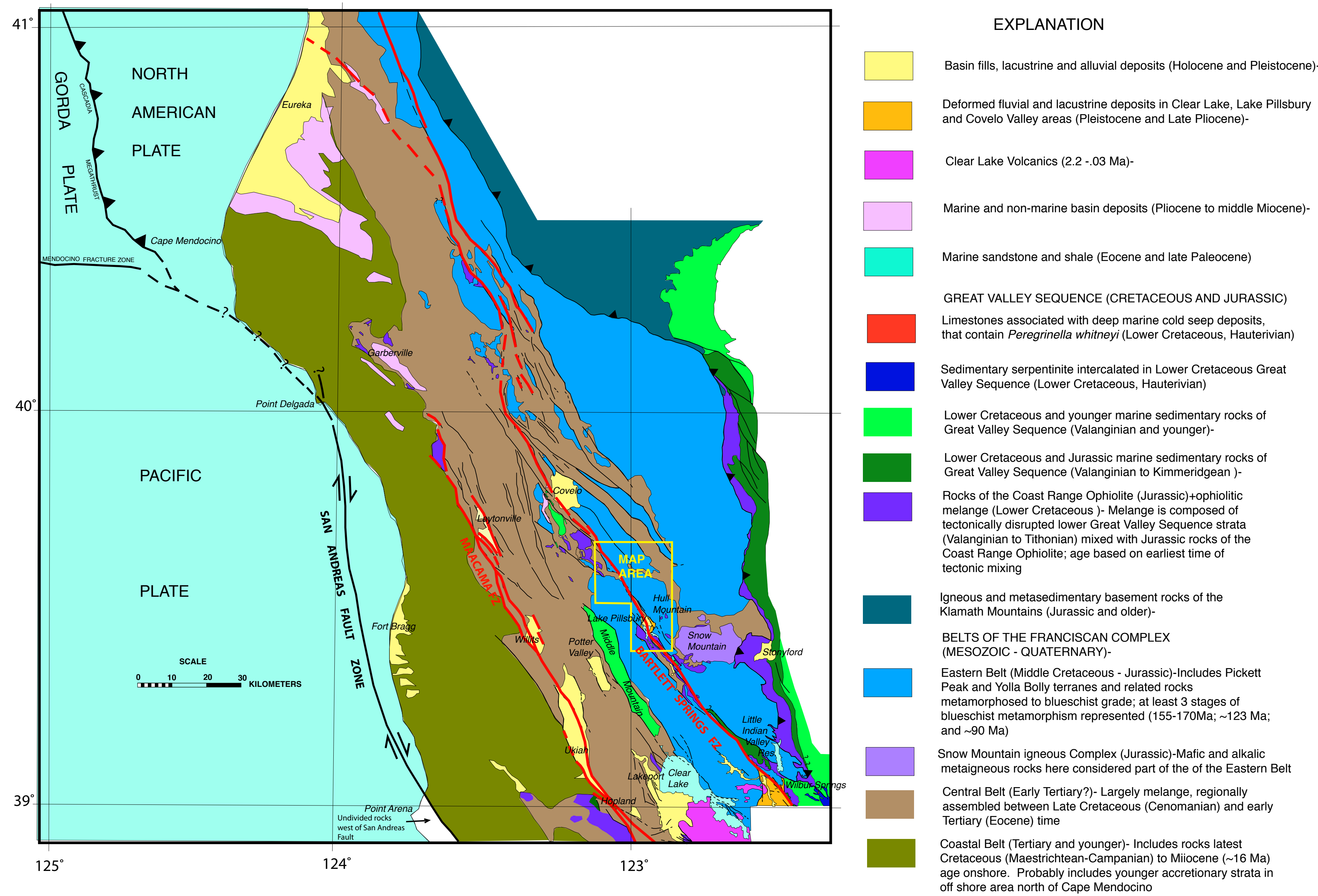


Figure 3. Generalized geologic map of northern California showing location of the map area, Lake Pillsbury, the Bartlett Springs Fault Zone, the Maacama Fault Zone, and the distribution of principal belts of the Franciscan Complex. Eastern belt of the Franciscan Complex includes rocks of the Yolla Bolly, Pickett Peak, and East Clear Lake terranes. The active Bartlett Springs and Maacama Fault Zones are shown in red; other faults in black. Regional extent of the Bartlett Springs Fault Zone is based, in part, on Lienkaemper (personal commun., 2010). Geology north of Lake Pillsbury is largely from McLaughlin and others, 2000; Jayko and others, 1989; and Blake and others, 1992, 1999. Geology surrounding Lake Pillsbury is based on this investigation; Etter, 1979; and Berkland, 1973. Geology around north side of Clear Lake incorporates unpublished field work by McLaughlin (1979–1981). Area south of Covelo and Willows 30' X 60' quadrangles is compiled from McLaughlin and Ohlin, 1990; Suppe and Foland, 1978; Hearn and others, 1995; Jennings and Strand, 1960; and Wagner and Bortugno, 1982.

km south of Lake Pillsbury near Knoxville, along the southward continuation of the Wilbur Springs sedimentary section (Kiel and others, 2008). This southern occurrence thus raises the possibility of even larger displacement along the Bartlett Springs Fault Zone if the slip is indeed right lateral. Only two other Hauterivian cold-seep localities are known in California and they occur in the southern Coast Ranges: one is near Coalinga; the other is northwest of Santa Barbara (Campbell and Bottjer, 1995; Kiel and others, 2008).

Fossil localities in the clastic rocks of this unit within (table 1, map nos. 5, 6) and outside the map area (Irwin, 1960; Berkland, 1973; Blake and Jones, 1974; McLaughlin and others, 1990) show that the depositional age of the sedimentary rocks is Early Cretaceous to Late Jurassic and that the tectonic (and possibly olistostromal) mixing of rocks in the ophiolitic mélange was Early Cretaceous (ca. Hauterivian) or younger. The apparent minimum right-lateral separation of the Split Rock and Grizzly Creek mélange units and *Peregrinella whitneyi*-bearing strata along the Bartlett Springs Fault Zone (ca. 47–53 km) is much larger than expected (implying a slip rate of at least 12–18 mm/yr), if the Bartlett Springs Fault Zone has only existed since passage of the Mendocino Triple Junction at this latitude ~3–4 Ma (Wilson and others, 2005). Observed right-lateral displacement along the Bartlett Springs Fault Zone, however, could include a 4 Ma and older component of translation inherited from the Cretaceous and Tertiary subduction margin that existed at this latitude prior to establishment of the San Andreas transform system. If so, then the present Bartlett Springs Fault Zone is a reactivated older crustal structure that has accommodated significant, but presently unconstrained, pre-San Andreas dextral displacement.

Coast Range Ophiolite

Ultramafic Rocks and Serpentinite of the Coast Range Ophiolite

Serpentinite occurs in lenticular masses along high- and low-angle faults and as mélange blocks in the map area. The serpentinite bodies are composed of tectonized dunite and peridotite in a sheared matrix of serpentine minerals.

Exposures of serpentinite along faults within and between units of the Franciscan Complex, which are crossed by US Forest Service Road M1 north of Hull Mountain and just northeast of Monkey Rock, contain chromatite having ratios of platinum group metals (palladium, platinum, and rhodium) indicative of ophiolite parentage (Page and others, 1982). This and field evidence from adjoining areas suggest that the serpentinite is derived from the lower part of the Coast Range Ophiolite.

Aeromagnetic data over the map area (Langenheim and others, 2007; Ohlin and others, 1984) exhibits local positive magnetic anomalies that generally correspond with serpentinite bodies or to mafic igneous rocks in the ophiolitic mélange and sedimentary rocks of Split Rock and the Coast Range Ophiolite. These rocks appear to dip beneath the Sanhedrin Mountain and Hull Mountain units of the Franciscan Eastern belt on either side of the Bartlett Springs Fault Zone and they are interleaved with or overlie mélange of the Franciscan Central belt. The Central belt, in turn, structurally underlies the Eastern belt in this area. These structural relations suggest that the Coast Range Ophiolite and Great Valley Sequence rocks are structurally imbricated with the Franciscan Complex and (or) repeated by folding. These imbricate structural relations that included emplacement of the Franciscan Central belt beneath the Coast Range Ophiolite, Great Valley Sequence, and Eastern belt of the Franciscan Complex apparently postdated the Cretaceous metamorphism and structural stacking of Eastern belt Franciscan rocks and their initial emplacement beneath the Coast Range Ophiolite and Great Valley Sequence (McLaughlin and Ohlin, 1984; Blake and others, 1988).

Franciscan Complex

The Franciscan Complex of northern California is considered worldwide to be the type example of a Mesozoic subduction complex. In the Eastern Coast Ranges, the Franciscan Complex largely consists of two broad structural belts: the Eastern and Central belts that are, in turn, subdivided into numerous tectonostratigraphic units. In the map area, rocks of the Central belt are mapped as mélange with local mafic intrusives. The Eastern belt is divided into five tectonostratigraphic units in the map area, based on differences in lithology, degree of metamorphism, and style of deformation. An additional Franciscan unit described here consists of a suite of metamorphosed mafic dikes and sills that locally intrude the Eastern belt (intrusives of Monkey Rock). Table 2 summarizes significant differences in these bedrock units and relates them to previously published work in the area.

In the Lake Pillsbury area, the Central and Eastern Franciscan belts, the Great Valley Sequence, and Coast Range Ophiolite are complexly interleaved along faults that are younger than low-angle faults that bound and structurally stack tectonostratigraphic units of the Eastern belt to the northeast. This younger west-northwest-oriented belt of imbricate faults is traceable southeastward through the Clear Lake region into the greater San Francisco Bay area. Northeast of Lake Pillsbury and the Bartlett Springs Fault Zone, imbricate complexity diminishes and a simpler structural stacking of the

Table 1. Localities and information for fossils collected from the Lake Pillsbury and adjacent region of Mendocino, Lake, and Glenn Counties, California.

Map no.	Field no.	Locality description	Longitude (W)	Latitude (N)	Collector(s)	Identified By	Map unit	Fossils present	Age	Reference
1		Near Calamese Rock	-122.932173	39.6046426		D.L. Jones	Franciscan Complex, Metasandstone and argilite of Mendocino Pass	*Buchia*	Early Cretaceous (Valanginian)	Blake and Jones, 1974
2	ECH-55A	Head of Mendenhall Ck	-122.969948	39.576803	H.N. Ohlin, 1981	C.D. Blome	Franciscan Complex, chert in Melange of Central Belt	Radiolaria: *Parvicingula(?) procera, Pessagno; Parvicingula sp., ?Podobursa sp., Pseudodictyomitra sp.*	Late Jurassic (Tithonian)	This report
3		NE side of Hull Mountain	-122.91717	39.549536		D.L. Jones	Franciscan Complex, metasandstone of Hull Mountain	*Inoceramus*	early Late Cretaceous, Cenomanian(?)	Blake and Jones, 1974
4	ECH-25	Elk Ck, S of Confluence with Mendenhall Ck	-123.009122	39.5312182	H.N. Ohlin, 1981	C.D. Blome	Franciscan Complex, chert in metasandstone of Hull Mountain	Radiolaria: *Archaeodicdyomitra sp., aff.A.simplex Pessagno; Pseudodictyomitra sp.; Thanarla sp.*	Early Cretaceous (probably Aptian- Albian)	This report
5		S shore of Lake Pillsbury, SW of Rocky Point	-122.949899	39.4095043	W.P. Irwin, 1960	R.W. Imlay	ophiolitic melange and sedimentary rocks of Split Rock	*Buchia piochii (Gabb)*	Late Jurassic, middle Tithonian	Irwin, 1960
6	F-10	Tributary to Rice Ck, N of Split Rock	-122.933941	39.3936711	S.D. Etter, 1979	No confirmed identification	ophiolitic melange and sedimentary rocks of Split Rock	*Buchia (sp.)*	probably Late Jurassic (Tithonian), based on proximity to locality 5	Etter, 1979

Central belt structurally overlain by units of the Eastern belt, the Great Valley Sequence, and the Coast Range Ophiolite is evident.

All of these Franciscan rocks, including the intrusives of Monkey Rock, are metamorphosed to pumpellyite or blueschist grade. Generally in this area, rocks of textural zones 2 to 3 (Blake and others, 1967) are of high blueschist grade and the growth of lawsonite and aragonite accompanied their textural reconstitution. Numerous blocks in mélange of the Central belt are of high blueschist grade, composed largely of sodic amphibole. These high-grade blueschist blocks, however, are tectonically mixed with rocks of much lower metamorphic grade.

Diabase Intrusives into Mélange of the Central belt

Several diabase sills and dike-like intrusives are mapped along U.S. Forest Service Route M1, about 1.5–2 km north of the Intrusive rocks of Monkey Rock. These intrusive rocks are mapped as a separate unit from the Monkey Rock intrusives, because they are not noticeably metamorphosed and intrude mélange of the Central belt, which, as discussed below, is younger than the metasandstone of Hull Mountain and has been shown to include tectonic slabs of the Yolla Bolly terrane elsewhere in northern California (McLaughlin and others, 1987; Blake and others, 1985). These intrusives are likely 89 Ma or younger, more than 6 m.y. younger (and possibly much younger) than the inferred age of the Monkey Rock intrusives (described later).

Unless the intrusives at Monkey Rock are younger than their inferred Cenomanian age or the diabase intrusives into the mélange of the Central belt are themselves part of a large mélange block or slab, these Central belt intrusives cannot be correlated with the Monkey Rock unit. If the diabase intrusives were the same age as the Monkey Rock unit, then their intrusive relation to the mélange would suggest that the Central belt mélange and metasandstone of Hull Mountain were juxtaposed by early Late Cretaceous time (ca. 95 Ma; Echeverria, 1980; Mattinson and Echeverria, 1980), which is inconsistent with our observations. Since Yolla Bolly terrane rocks north of the map area were assembled, deformed, and metamorphosed prior to being juxtaposed with the Central belt (McLaughlin and others, 1987; Blake and others, 1985), we consider it unlikely that these mafic intrusive rocks are correlative with metamorphosed intrusives that cut the metasandstone of Hull Mountain. Though these intrusives into the Central belt have not been carefully studied petrographically, the relations described here predict that they are younger than the high P/T metamorphism associated with the intrusives of Monkey Rock.

Central belt

The Central belt of the Franciscan Complex is generally the structurally lowest and least metamorphosed of the Franciscan units exposed in the map area, although complex faulting locally has disrupted this structural stacking and placed the Central belt rocks over rocks of the Eastern belt. The Central belt is a mélange (after the terminology of Hsu, 1968), composed principally of sheared argillite with phacoids of slightly foliated, thin bedded, lithic greywacke sandstone. Landscapes underlain by mélange have a subdued topographic expression, except where resistant blocks of rock stand out in relief. The subdued topographic expression is partly a result of extensive landsliding. Resistant blocks within the mélange have diverse lithologies and metamorphic grade. The small blocks (meters to hundreds of meters in diameter) are popularly referred to as "knockers", but here we refer to them as blocks. Larger bodies of shear-bounded rock having lenticular to irregular map-scale geometries are as much as tens of kilometers long and here are referred to as "tectonic slabs".

The blocks include native and exotic blocks. Native blocks are those composed of argillite and sandstone similar to and of the same metamorphic grade as the matrix of the mélange, derived from an originally intact tectonostratigraphic sequence that has been penetratively sheared and disrupted. The originally intact sequence may have included sandstone, argillite, polymict conglomerate, chert, mafic volcanic rocks, diorite, diabase, or gabbro. Exotic blocks generally show evidence of being far-travelled and derived from disparate sources. Blocks considered to be clearly exotic include those with unusually high P/T metamorphic mineral assemblages, such as eclogite, garnet amphibolite, and high-grade blueschist blocks that indicate a mantle source and (or) deep structural burial. Less metamorphosed blocks and slabs that are considered exotic include pelagic chert and limestone containing microfossils (foraminifers or radiolaria) that indicate oceanic deposition at equatorial latitudes. These pelagic rocks commonly are associated with mafic oceanic volcanic rocks and are overlain by metaclastics derived from the continental margin, and they may or may not be far travelled (McLaughlin and Pessagno, 1978; Murchey and Jones, 1984).

Though likely present in the map area, tectonic slabs are not individually delineated in the Central belt but, instead, are included as part of the undivided mélange. Tectonic slabs include native block lithologies, and some have compositions similar to the exotic blocks, although high-grade blueschist, amphibolite, and eclogite are nearly all blocks enclosed by mélange matrix or found along the contacts between slabs and mélange matrix. The slabs are usually

Table 2. Comparison of map units from the Franciscan Complex, the Great Valley Sequence, and the Coast Range Ophiolite in the Lake Pillsbury region, California.

Map unit (this study)	Belt of Franciscan Complex (Irwin, 1960)	Tectonostratigraphic terrane (Blake and others, 1982)	Lithology	Metamorphic mineral assemblage[1]	Textural zone (Blake and others, 1967)	Outcrop-scale deformation character
Melange of Central Belt	Central	Central terrane	Matrix of argillite interbedded with lithic, fine grained, thin bedded metasandstone surrounding both native and exotic blocks. Metasandstone to argillite ratio < 1	q ± ab ± lw (incipient) ±p ± ar ± w ± cl	Textual Zone 1(matrix sandstone)	Penetratively sheared argillite with metasandstone phacoids and intact metasandstone slabs exhibiting open folds with amplitudes up to 1000 ft
Metasedimentary rocks of Sanhedrin Mountain	Eastern	Yolla Bolly terrane	Structurally high portion has abundant, thick, continuous metachert lenses and less commonly metagreenstone interbedded within lithic to quartzofeldspathic metasandstone and argillite	q ± ab ± lw (prominent) ± p ± w ± cl ± gl	Textural Zone 2	Locally sheared but coherent metagraywacke and argillite; with vertical open folds in metachert; 1 direction of foliation
Metasandstone of Hull Mountain	Eastern	Yolla Bolly terrane	Medium to coarse grained metasandstone with abundant chert detritus in upper part, fine grained, thin bedded metasandstone with interbedded argillite, metachert and metagreenstone in lower part	q ± ab ± lw prominent) ± p ± w ± cl ± jd(?)	Textural Zone 1 to 2	Broken formation in upper and lower parts; outcrop size folds in middle part; 2 directions of foliation
Metasedimentary rocks of Mendocino Pass	Eastern	Pickett Peak terrane, lower part	Uniform fine to medium grained, thin to medium bedded metasandstone with interbedded argillite and rare lenses of metaconglomerate, metachert and metagreenstone	q ± ab ± lw ± p ± w ± cl	Textural Zone 2	Slightly sheared but coherent metagraywacke and argillite; 1 direction of foliation

Table 2. (cont.) Comparison of map units from the Franciscan Complex, the Great Valley Sequence, and the Coast Range Ophiolite in the Lake Pillsbury region, California.

Map unit (this study)	Belt of Franciscan Complex (Irwin, 1960)	Tectonostratigraphic terrane (Blake and others, 1982)	Lithology	Metamorphic mineral assemblage[1]	Textural zone (Blake and others, 1967)	Outcrop-scale deformation character
Metamorphic rocks of Black Butte and Bald Mountain	Eastern	Pickett Peak terrane	Well foliated, schistose nature of lithologic components is the most distinguishing feature	q±ab±lw (prominent) ± p ± ar (rare) ±w ± cl ± epidote (rare) ± cr (common in metavolcanic rocks)	upper Textural Zone 2 to Textural Zone 3	Schistose; with large scale folds and 2 directions of foliation
Metamorphic rocks of Lake Pillsbury	Eastern	Pickett Peak terrane	Well foliated, schistose character of lithologic components is the most distinguishing feature	q ± ab ± lw (prominent) ± p ± ar (rare) ± w ± cl ± epidote (rare) ± cr (common in metavolcanic rocks)	upper Textural Zone 2 to Textural Zone 3	Schistose; with large scale folds and 2 directions of foliation
Ophiolitic melange and sedimentary rocks of Split Rock	N.A.	Elder Creek terrane	Serpentinite matrix and argillitic matrix melange, locally including blocks of basalt, diabase, gabbro, chert, and intact slabs of clastic sedimentary rocks of Great Valley Sequence			Extensive penetrative shearing in melange matrix; intact slabs folded but otherwise intact
Coast Range Ophiolite	N.A.	Elder Creek terrane	Blocks of dunite and peridotite in a matrix of serpentine group minerals			Generally extensively sheared and serpentinized

[1] q=quartz; ab=albite; lw=lawsonite; jd=jadeitic pyroxene; gl=glaucophane; cr=crossite; p=pumpellyite; ar=aragonite; w=white mica; c=chlorite

internally coherent, exhibiting bedding and a relatively coherent though disrupted stratigraphy, and often are complexly folded internally and broken by faults.

The mélange matrix and block lithologies locally reflect compositions of the tectonostratigraphic units bounding the mélange. We infer this relation to indicate tectonic incorporation of some materials from the bounding tectonostratigraphic units. For example, a wedge-shaped body of mélange of the Central belt, which locally separates the metasedimentary rocks of Sanhedrin Mountain from the metasandstone of Hull Mountain in the Forks Creek area, has a matrix of argillite and metasandstone that is petrographically similar to the metasandstone of Hull Mountain. Blocks in the Central belt mélange of the Forks Creek area, however, also include greenstone (pillow basalt) and basic metavolcanic rocks of high blueschist grade.

Another wedge of mélange mapped within the metasandstone of Hull Mountain that traverses Mendenhall Creek is typical of Central belt mélange that crops out southwest of the Chimney Rock shear zone. The most abundant blocks in this mélange wedge are relatively small (diameters <2 m) and are composed of greenstone and chert that co-occur with fewer and smaller blocks of sandstone, conglomerate, and blueschist. Northeast of the Chimney Rock Shear Zone and east of Bald Mountain, however, the mélange includes large tectonic slabs of greenstone, locally containing interleaved chert beds and less abundant, distinctive, black chert-pebble conglomerate. North of the map area, slabs of greenstone in mélange northeast of Chimney Rock are as much as 2 km long by 0.6 km wide.

Age of the Central belt

Fossils from mélange of the Central belt in all of northern California range in age from Early Jurassic (Pliensbachian) to Early Tertiary (Eocene or younger). It is instructive to sort the age data into two broad categories: (1) ages from pelagic chert (radiolaria) and limestone (foraminifers) deposited on oceanic basement (McLaughlin and Pessagno, 1978; Murchey and Jones, 1984; Sliter, 1984) and (2) ages from fossils in terrigenous submarine fan turbidites and hemipelagic deposits sourced from the continental margin (Blake and Jones, 1974; Blake and others, 1984; Lucas-Clark, 2007). Radiolaria and foraminifers in the pelagic cherts and limestones associated with oceanic basement range in age from Early Jurassic (Pliensbachian) to Late Cretaceous (Coniacian) and were largely deposited on oceanic crust inferred to have drifted northward from equatorial paleolatitudes. One pelagic chert fossil locality in the map area is from a mélange block in rocks of the Central belt (map loc. no. 2 on table 1, and on the geologic map, sheet 1) and is assigned to the Late Jurassic (Tithonian) based on radiolarians.

Dinoflagellates in the terrigenous and hemipelagic deposits regionally are generally Late Jurassic (Tithonian) to middle Cretaceous (Albian) in age and macrofossils (mostly *Buchia*, a few *Inocerami* and ammonites) are Late Jurassic (Tithonian) to Late Cretaceous (Campanian) in age. One tectonostratigraphic terrane of the Central belt (San Bruno Mountain terrane) in the San Francisco Bay Region contains detrital zircons of Eocene age and is, thus, Eocene or younger (Snow and others, 2010). It is possible, however, that the San Bruno Mountain terrane is actually part of the Coastal belt of the Franciscan Complex, which does not crop out in the Lake Pillsbury region. In general, however, the ages of terrigenous rocks of the Central belt overlap the age of the pelagic rocks deposited in oceanic settings, but they also are, in part, significantly younger.

Radiometric dating of white mica separates from blocks of high-grade blueschist in the eastern part of the Lake Pillsbury region by potassium-argon methodology (Lehman, 1974) yielded ages as old as 155 Ma. Zircons separated from a block of plagiogranite metamorphosed to pumpellyite-grade in mélange of the Central belt on O’Neil Ridge, about 10 km north of the map area, yielded a Pb-U age of 161 Ma (J. Mattinson, written commun., 1982).

The presence of unmetamorphosed rocks in the mélange, together with the paleontologic and radiometric ages, collectively indicate that metamorphism of mélange components preceded their penetrative disruption and incorporation into the Central belt. In the map area, the age of the youngest fossils in the mélange and in slabs of Eastern belt rocks juxtaposed with it indicate that mélange formation (that is, the mixing of mélange components) is Late Cretaceous (Cenomanian) or younger. As pointed out above, however, Central belt mélange formation is shown elsewhere to be at least Campanian or younger and may be as young as Eocene (Snow and others, 2010), based on the ages of tectonostratigraphic terranes incorporated in mélange matrix of the Central belt. This age distribution of mélange components of the Central belt could indicate that the mélange itself youngs toward the southwest. Blocks of pelagic limestone as young as Coniacian, however, are present in the Central belt east of Garberville (McLaughlin and others, 2000; Sliter, 1984), clearly indicating that mélange mixing occurred <89 Ma north of the map area.

Eastern belt

Yolla Bolly terrane

Metasedimentary rocks of Sanhedrin Mountain

This unit is present in the southwestern part of the map area where it structurally overlies mélange of the Central belt along the East Flank Thrust, which locally is cut by younger, steeper faults that bring Central belt rocks and serpentinite upward against and locally over, the adjacent Sanhedrin Mountain unit. In the Lake Pillsbury area this unit of the Eastern belt is largely separated from the metasandstone of Hull Mountain along the northwest-trending, high-angle Bartlett Springs Fault Zone. The Bartlett Springs Fault Zone has also exhumed and laterally juxtaposed rocks of the Central belt with the metasedimentary rocks of Sanhedrin Mountain and with the metasandstone of Hull Mountain. In the southern part of the map area, aeromagnetic data (Langenheim and others, 2007) and field relations suggest that the ophiolitic mélange and sedimentary rocks of Split Rock locally underlie the metasedimentary rocks of Sanhedrin Mountain along the steep southwest-dipping Logan Springs Fault that, in turn, might cut a relatively flat, unexposed fault (the East Flank Thrust?) at depth.

The metasedimentary rocks of Sanhedrin Mountain, together with the metasandstone of Hull Mountain are a distinctive suite of metamorphosed sandstone and argillite, locally with thick lenses of interleaved chert and sparse lenses of greenstone. Both of these Eastern belt units correlate with the Yolla Bolly terrane of Blake and others (1982). In the map area, chert lenses are much more abundant and continuous in the metasedimentary rocks of Sanhedrin Mountain than in the metasandstone of Hull Mountain northeast of the Bartlett Springs Fault Zone. Many of the chert lenses in the Sanhedrin Mountain unit are manganiferous and have been mined for that commodity in the past. The structurally lower part of the metasedimentary rocks of Sanhedrin Mountain are to the northeast, adjacent to the Bartlett Springs Fault Zone, where the unit is predominantly quartzofeldspathic sandstone with local sheared lenses of conglomerate and tuffaceous greenstone.

Although geochemically similar (table 3), the framework-grain composition of the metasedimentary rocks of Sanhedrin Mountain differs from that of the metasandstone of Hull Mountain in having generally more abundant quartz and only rare chert detritus. Topographically high on Sanhedrin Mountain, and apparently structurally higher in the Sanhedrin Mountain unit, the metasandstone is more lithic, with more abundant chert and volcanic rock detritus, possibly indicating partial equivalence with the metasandstone of Hull Mountain northeast of the Bartlett Springs Fault Zone. The metasandsandstone of the Sanhedrin Mountain unit is texturally reconstituted to Textural Zone 2 (Blake and others, 1967) with a corresponding strong slaty planar fabric evident in the metaclastic rocks and cherts.

Individual lenses of chert in this unit are mappable for as much as 1.5 km with structural thicknesses as much as 300 m. Manganese mines and prospects within chert lenses occur in three places outside the boundary of, but near, Elk Creek Roadless area.

Mafic volcanic rocks in this unit include tuff, basaltic pillow flows, breccia, and diabase.

Although no fossils have been found in this unit in the map area, it was assigned a middle Cretaceous age by Jordan (1975) and Etter (1979). The mapping of Etter (1979) and the regional synthesis of Blake and others (1982) suggests that the metasedimentary rocks of Sanhedrin Mountain are continuous for at least 65 km to the southeast as part of the Yolla Bolly terrane, locally referred to as the East Clear Lake terrane by McLaughlin and Ohlin (1984). Correlative rocks in the Clear Lake area contain metachert with radiolarians having a Late Jurassic (Tithonian) to Early Cretaceous (probably Aptian or Albian) age (McLaughlin and Ohlin, 1984). If in part correlative with the metasandstone of Hull Mountain as suggested above, then part of this unit could be as young as Cenomanian.

As with the metasandstone of Hull Mountain, discussed below, the metasedimentary rocks of Sanhedrin Mountain may include minor, undivided zones of mélange, as suggested by scattered blocks of high-grade blueschist and serpentinite in a few areas, surrounded by Textural Zone 2 metagraywacke of the Sanhedrin Mountain unit.

Metasandstone of Hull Mountain

This unit is mapped largely east of the Bartlett Springs Fault Zone. From map relations along the Thatcher Butte Fault, the unit is inferred to structurally overlie serpentinite and mélange of the Central belt, above a folded Thatcher Butte Fault Zone that is inferred to be present at the base of the metasandstone of Hull Mountain. Where exposed along Elk Creek, the metasandstone of Hull Mountain consists of fine-grained, thin-bedded metasandstone with interbedded argillite. The metasandstone contains abundant chert and silicic to intermediate volcanic rock fragments, which are distinct in the metasandstone of Hull Mountain. Intervals of broken formation composed of argillite and abundant lenses and blocks of radiolarian chert, chert breccia, porphyritic pillow basalt, and tuff are locally present within the metasandstone unit and are well exposed in lower Mendenhall Creek, where they are interlayered and folded at outcrop scale.

A zone of tuffaceous rocks is interlayered in the metasandstone of Hull Mountain along Forest Service Road M1 north of Hull Mountain and south of Monkey Rock (fig. 2). This fine-grained metatuff locally contains blue sodic amphibole, light green hornblende (edenite?), pumpellyite, and stilpnomelane, compatible with the metamorphic grade of the enclosing metasandstone and argillite (table 2).

Outcrops of the metasandstone of Hull Mountain in places exhibit a foliation that crosscuts an earlier platy fabric, suggesting that these rocks have been subjected to at least two periods of deformation. Thin sections of the metasedimentary rocks exhibit lawsonite grains that formed along a prominent early foliation. That foliation and co-planar lawsonite, in turn, are deformed by a younger planar fabric.

Chert is also present as sporadic blocks and lenses within the Hull Mountain metasandstone unit, though it is less abundant than in the metasedimentary rocks of Sanhedrin Mountain. Several lenses and pods of manganiferous chert and chert breccia are exposed along upper Elk Creek. One lens of this chert has a thickness of 80 ft (24 m) and contains an Early Cretaceous (Aptian or Albian) radiolarian fauna (table 1, map no. 4). Another large lens of chert 0.8 km southeast of the summit of Hull Mountain was not visited during this study, but it was previously mapped by Lehman (1974) and is apparent on air photos. This 0.4-km-long lens is surrounded and likely is enclosed by metasandstone that contains Cenomanian fossils (table 1, map no. 3). This setting is similar to that of the chert block in upper Elk Creek (table 1, map no. 4) containing the Aptian or Albian radiolarian fauna.

Well-bedded, medium- to coarse-grained metasandstone with interbeds of chert pebble conglomerate and grit locally overlie the chert lenses along Elk Creek. This metasandstone is compositionally similar and the same metamorphic grade as the metasandstones that underlie the cherts, having the same lithic detrital content.

The stratigraphically youngest part of the metasandstone of Hull Mountain comprises a broken formation in which mulluscan fossils are found that are assigned a Late Cretaceous (Cenomanian?) age (table 1, map no. 3). These rocks represent the youngest dated part of the Yolla Bolly terrane of the Eastern belt (Blake and others, 1982). The Aptian or Albian radiolarian fauna in the cherts along Elk Creek (table 1, map no. 4) corroborate continued post-Valanginian deposition of Yolla Bolly terrane strata, suggested earlier by Blake and Jones (1974), based on the fossils at locality 3 (table 1). The chert data fill part of the depositional gap between the Valanginian and Cenomanian for the Yolla Bolly terrane and suggests more continuous deposition between the Tithonian and Cenomanian.

The apparent 25 my gap between the Albian and Valanginian in the radiolarian cherts may be related to incomplete sampling of the chert section. Cherts sampled in this investigation either were random grab samples from a part of the chert section or were pointedly sampled at the top middle and (or) bottom of chert sections, but they were not systematically sampled from bottom to top. Since the cherts formed in an ocean-floor setting of very low sediment accumulation rate, the age range of the chert section is condensed. About 70 m of radiolarian chert section elsewhere in the Franciscan Complex represents ~100 m.y. of pelagic deposition (McLaughlin and Pessagno, 1978; Murchey and Jones, 1984). Chert recrystallization and poor preservation are also problems in cherts of the Yolla Bolly terrane, as a result of metamorphism and hydrothermal reactions. In sections that have not been systematically sampled (and none were in the study area), the complete range in age of the cherts may not be represented.

Intrusives of Monkey Rock

North of Hull Mountain, in the Monkey Rock area, gabbroic dike and sill-like bodies that intrude the Cenomanian(?) and older metasandstone of Hull Mountain, have well-preserved chilled intrusive contacts (Layman, 1977; Echeverria, 1980). The intrusives trend northwest discontinuously for 1 km, and the thickest body measures 20 m (Layman, 1977). At Monkey Rock and at a locality along the Hull Mountain road 1 km to the southeast, the intrusives exhibit chilled margins and the surrounding metasandstone shows evidence of baking along the contact.

Metamorphic minerals present within the gabbro include lawsonite, pumpellyite, albite, blue sodic amphibole, carbonate, stilpnomelane, chlorite, quartz, and white mica (Layman, 1977). This mineral assemblage is consistent with the metamorphic grade of the surrounding sandstone (table 2), indicating that intrusion pre-dated blueschist-grade metamorphism.

Elsewhere in the northern Coast Ranges, intrusives into metasandstones of the Yolla Bolly terrane have been noted in many places, and these intrusive relations are considered typical of this terrane (Blake and others, 1985). Far to the south, at Ortigalita Peak in the Diablo Range, U-Pb dating of a similar but larger gabbroic intrusive into correlative Franciscan rocks has yielded an age of 95 Ma (Cenomanian, Mattinson and Echeverria, 1980). A single event of blueschist metamorphism that followed folding of wallrock greywacke and post-folding intrusion of the gabbro was dated at 92 Ma (Turonian). The Ortigalita Peak gabbro, as well as the intrusives at Monkey Rock and elsewhere in rocks correlative with the Yolla Bolly terrane, have previously been noted to be similar in their chemistry, the timing of their intrusion relative to deformation of the enclosing Yolla Bolly wall rocks, and the timing of their metamorphism to blueschist mineral assemblages (Echeverria, 1980; Mattinson and Echeverria, 1980; Blake and others, 1985). Observed relations at Monkey Rock are consistent with those of the dated rocks of the Diablo Range, strongly suggesting that they may be correlative (Blake and others, 1985; McLaughlin and Ohlin, 1980; Echeverria, 1980).

Pickett Peak terrane?

Metasedimentary Rocks of Mendocino Pass

This unit is present only in the northeastern corner of the map area, in two fault-bounded wedges between mélange of the Central belt and structurally overlying schistose rocks of Black Butte and Bald Mountain. It is tentatively assigned to the Pickett Peak terrane as possibly correlative with the Valantine Spring Formation (Blake and others, 1992). Regionally, the metasedimentary rocks of Mendocino Pass occurs as an extensive structural wedge composed of slightly sheared, moderately foliated metasandstone and interbedded argillite, with rare structurally interleaved lenses of metachert and greenstone. The unit is distinguished by its uniform, coherent nature, in contrast with the underlying mélange of the Central belt, and by a moderate foliation, differing from the pronounced foliation and recrystallized metamorphic character of structurally overlying schist.

Buchias that occur in a small, structurally isolated slab of the metasedimentary rocks of Mendocino Pass along the road between Hells Half Acre and Bear Rock, about 0.4 mi (0.6 km) south of Calamese Rock, are Early Cretaceous (Valanginian) in age (table 1, map no. 1; also locality 29 of Blake and Jones, 1974). The fossils occur with clasts of volcanic breccia, as much as 12 cm in diameter, dispersed in sheared metasandstone. Correlation of this isolated structural slab to the metasedimentary rocks of Mendocino Pass is based on the uniform and characteristic metamorphic grade and composition of the metasandstone, its structural position beneath the metasandstone and metavolcanic rocks of Black Butte and Bald Mountain, and its position above mélange of the Central belt.

The thrust fault contact between the metasedimentary rocks of Mendocino Pass and the overlying Black Butte and Bald Mountain unit is marked by shearing and (or) serpentinite throughout the study area. The relations found in similar rocks to the northeast (Bishop, 1977; Blake and others, 1967), however, suggest that the metasedimentary rocks of Mendocino Pass may have once increased in metamorphic grade gradually upward toward the metamorphic rocks of Black Butte and Bald Mountain, in the sense of Blake and others, 1967. In the map area, significant parts of this intervening metamorphosed section are apparently missing and possibly have been structurally removed by later low-angle faulting that post-dated metamorphism and accompanied unroofing and exhumation of the Franciscan Complex. If so, then metamorphism of both of these units would have post-dated the Early Cretaceous (Valanginian, 136–140 Ma) depositional age of the metasedimentary rocks of Mendocino Pass and predated later structural erosion during unroofing and exhumation of the Franciscan Complex.

Pickett Peak terrane

Metamorphic Rocks of Black Butte and Bald Mountain

This unit is the structurally highest unit of the Franciscan Complex in the map area. These rocks structurally overlie mélange of the Central belt, as well as the metasedimentary rocks of Mendocino Pass along low-angle faults inferred to be thrusts. As suggested above, however, the low-angle fault separating the metamorphic rocks of Black Butte and Bald Mountain from the metasedimentary rocks of Mendocino Pass could also have a later extensional history associated with uplift and unroofing of the Coast Ranges (for example, see Jayko and others, 1987).

These metamorphic rocks are present in the map area as an isolated slab at Bald Mountain, but, outside of the map area to the northeast, the unit underlies Black Butte. To the southeast of Black Butte, the unit is contiguous with rocks previously mapped as the South Fork Mountain Schist (Ghent, 1965; Blake and others, 1967; Lehman, 1974; Bishop, 1977; Brown and Ghent, 1983). These rocks are also considered to be a part of the Pickett Peak terrane of the Eastern belt (Irwin and others, 1974; Blake and others, 1982), which is in fault contact with rocks of the Coast Range Ophiolite to the east.

The metamorphic rocks of Black Butte and Bald Mountain are dominantly metasandstone and phyllite and, from regional map relations and drill hole data (CDWR, 1966), have a structural thickness of up to 3 km. Only small isolated lenses of metavolcanic rock occur within the map area, although a 500–1,000-m-thick lens of pillowed, upright metavolcanic rocks occurs to the north, in the high Coast Ranges at Black Butte in an abandoned cirque formed during Pleistocene glaciation (Bishop, 1977). In the map area, these rocks are reconstituted to Textural Zone 2 of Blake and others (1967) but reconstitution increases to Textural Zone 3 toward the north with increasing topographic elevation. The Textural Zone 2 metasandstone of the map area contains only small amounts of pumpellyite and lawsonite.

The structural outlier at Bald Mountain is largely medium- to coarse-grained metasandstone with lenses of stretched pebble conglomerate that structurally overlies finer grained, laminated metasandstone and argillite containing blocks and lenses of foliated mafic volcanic rocks and gabbro. The finer grained, lower part of the section is well exposed in the headwaters of the Eel River and the Cushman Lake-Hells Half Acre area. Coarse-grained metasandstone overlies the finer grained section at Bald Mountain, along the Hull Mountain Road, and north of Devils Rock Garden. A large mass of fine-grained to pegmatitic, foliated metadiabase, possibly intrusive into the Bald Mountain rocks, is present just north of Bald Mountain Peak, outside of the map area (Coyote Rock of Plaskett Ridge 7.5' quadrangle).

The thickness of the structural outlier of this unit at Bald Mountain is approximately 700–1,000 m, significantly less than at Black Butte. Based on two crosscutting foliations and associated fold trends, multiple periods of deformation are indicated. In thin section, however, only one high P/T metamorphic event is evident for these rocks, because lawsonite is not specifically coplanar with either of the foliations in the Bald Mountain unit, which is in contrast to the deformation of coplanar lawsonite seen in the metasandstone of Hull Mountain. This suggests that the two fold trends and planar fabrics at Bald Mountain are both younger than the high P/T metamorphic event in these rocks (see later discussion on metamorphic fabric development).

Numerous Early Cretaceous (~Aptian-Valanginian), whole-rock, K-Ar dates, generally interpreted as maximum metamorphic ages, have been reported for metasandstone from the Black Butte and Bald Mountain rocks. Suppe and Armstrong (1972) dated three samples of metagraywacke in the vicinity of Black Butte that yielded ages of 127, 125 and 123 Ma. Lehman (1974) reports ten whole-rock dates from south of Black Butte ranging from 119 to 129 Ma and three dates from the Bald Mountain area of 127, 133 and 138 Ma. Both Lehman (1974) and Lanphere and others (1978) indicate that their ages cluster around 120 Ma, suggesting a regional metamorphic event in the Early Cretaceous (~Aptian). This agrees with recent Pb/U detrital zircon ages from metachert and with $^{40}Ar/^{39}Ar$ metamorphic ages, both from the South Fork Mountain Schist of the Pickett Peak terrane (Dumitru and others, 2009). Significantly, this metamorphic age is considerably older than the Cenomanian depositional age (ca. 99–94 Ma) of lawsonitic metasandstones in the metasandstone of Hull Mountain (part of the Yolla Bolly terrane). This implies a later high P/T metamorphism, as well as younger metamorphic textural fabrics, that postdated the early blueschist event and possibly accompanied and overprinted the late blueschist event, which is consistent with observations in the field and in thin section.

Metamorphic Rocks of Lake Pillsbury

This unit includes foliated fine-grained pelite and metasandstone (Textural Zone 3 to high Textural Zone 2 of Blake and others, 1967) and rare intercalated mafic metavolcanic rocks. The unit was questionably correlated with the South Fork Mountain schist of the Pickett Peak terrane of the Eastern belt (Blake and others, 1982; Irwin and others, 1974) by Etter (1979), who considered it to have been metamorphosed to blueschist grade about 137 Ma, based on a whole-rock K-Ar age on metasandstone (Suppe and Foland, 1978). If this metamorphic age is representative, the depositional age of the metaclastic rocks would be older than earliest Cretaceous (latest Berriasian-earliest Valanginian). This age, however, is older than a more recent Pb/U determination of ~123 Ma for youngest deposition in the Pickett Peak terrane and an $^{40}Ar/^{39}Ar$ determination of ~120 Ma for the metamorphic age of these rocks (Dumitru and others, 2009). These recent dates are here regarded as more representative and reliable than the earlier K-Ar dates.

Geochemistry of Metasedimentary Rocks

Whole-rock chemical analyses run on 17 metasandstone samples from the principal metasedimentary units of the map area are summarized in table 3. Compositions shown for metasandstone blocks and matrix of the Central belt and for the metasandstone of Hull Mountain are determined from the averages of eight whole-rock, major-oxide analyses, whereas the composition of metasandstone from the Sanhedrin Mountain map unit is represented by only one analysis. For a more regional comparison, the averaged major-oxide composition from seven Yolla Bolly terrane localities in the Clear Lake area, south of Lake Pillsbury and the Bartlett Springs Fault Zone (East Clear Lake terrane of McLaughlin and Ohlin, 1984), are also summarized. Metasandstone samples from the Hull Mountain and Sanhedrin Mountain units are generally similar in chemical composition to analyses from the Yolla Bolly terrane in the Clear Lake area. Metasandstone samples from mélange of the Central belt have generally lower silica contents than samples from the other units and are higher in TiO_2, $FeO+Fe_2O_3$, and MgO, reflecting a generally higher percentage of mafic volcanic lithic detritus in the Central belt metagraywackes.

Table 3. Major oxide compositions of principal metasandstone units of the Franciscan Complex, Lake Pillsbury region, California.

Major oxide[1] (%)	Metasandstone of Hull Mountain[2]	Metasedimentary rocks of Sanhedrin Mountain[3]	Yolla Bolly terrane of the Clear Lake area (East Clear Lake terrane of McLaughlin and Ohlin, 1984)[4]	Metasandstone from Melange of Central Belt[5]
SiO2	71.4	70.8	70.3	67.6
Al_2O_3	13.8	15.2	14	14.9
Fe_2O_3	1.3	1	1.2	2
FeO	3.5	3.1	3.1	4.8
MgO	2.2	1.8	2.5	3.6
CaO	1.6	1.1	2.6	1.5
Na_2O	3.3	4.2	4	3.4
K_2O	1.8	2	1.5	1.1
TiO_2	0.63	0.55	0.62	0.71
P_2O_5	0.13	0.14	0.16	0.19
MnO	0.29	0.02	0.05	0.09
Totals (dry, excluding CO_2)	99.9	99.9	100	99.9

[1] All values derived from whole rock analyses, using atomic absoption methodology described under "single solution" in U.S. Geological Survey Bulletin 1401. Samples analyzed by Branch of Analytical Laboratories, U.S. Geological Survey, Reston, VA, in 1982. Analysts: F. Brown, R. Somers and Z. Hamlin. Totals for each rock unit are recalculated to100%, ignoring H_2O+, H_2O- and CO_2.

[2] Average of 8 samples from map area

[3] Calculated from 1 analysis

[4] Average of 7 samples from Clear Lake area

[5] Average of 8 samples from map area

Structure

Folding and Development of metamorphic Fabric

The inferred chronology of deformation fabrics and metamorphism for the Franciscan Complex is summarized in table 4. Metamorphic fabrics are not systematically mapped in the Pickett Peak or Yolla Bolly terrane units of the map area, but more detailed work in adjacent areas by others, combined with our field observations provide a framework for the chronology of deformation and metamorphism. An early period of isoclinal folding affected rocks of the Pickett Peak terrane regionally, including the Black Butte and Bald Mountain unit, the Mendocino Pass unit, and the metamorphic rocks of Lake Pillsbury. Although it was not directly observed in the map area, it is inferred to exist because of the strong slaty to schistose, bedding-parallel foliation present in these rocks. This D1 deformation is inferred to correspond with an early blueschist metamorphic event about 120 Ma (Dumitru, 2009). Jayko (1983) described northeast trending isoclinal folds (F1) synchronous with strong schistosity (S1) and blueschist metamorphism in correlative rocks of the Pickett Peak terrane north of the study area.

Northwest-trending isoclinal folding (F2A) related to development of axial plane cleavage (S2A) was observed in the metasandstone of Hull Mountain along U.S. Forest Service Road M-1 near Hull Mountain summit. Jayko (1983) reports similarly oriented folds and cleavage in rocks of the Yolla Bolly terrane north of the map area, and McLaughlin and others (1990) describe similarly oriented folding and axial plane cleavage in Yolla Bolly terrane rocks of the Clear Lake area to the south. The presence of this deformation (D2A) at Hull Mountain is important, because it accompanied blueschist metamorphism of rocks that have a Cenomanian fossil age (table 1, map no. 3). D2A is ,for the most part, expressed as bedding-parallel cleavage in the metasandstone of Hull Mountain and in the metasedimentary rocks of Sanhedrin Mountain.

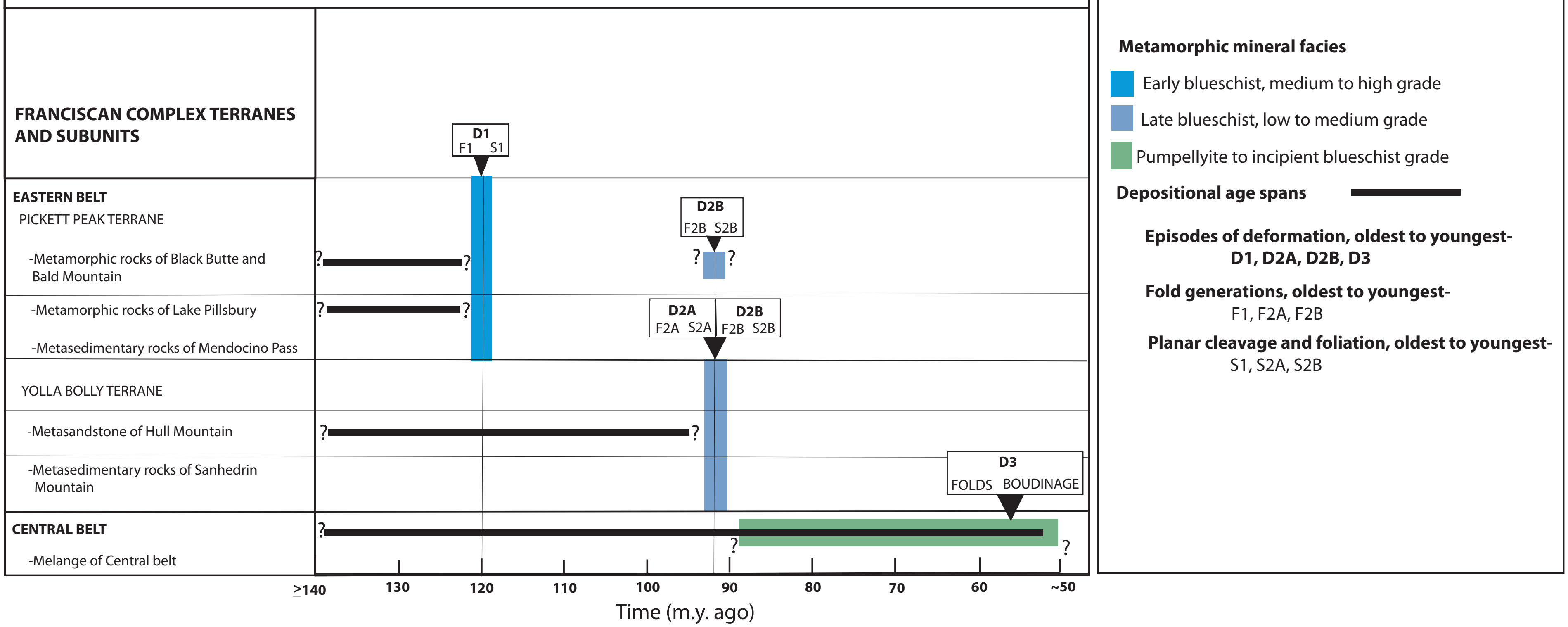
A third period of deformation in the Yolla Bolly terrane (D2B) is characterized by variably inclined, tight to isoclinal, northeast-trending folds (F2B) that are accompanied by a local, axial-plane cleavage (S2B). The folds generally plunge south, are overturned to the southeast, and are commonly present as outcrop-scale folds in the metasandstone of Hull Mountain (Etter, 1979). An axial-plane cleavage present in the structurally low portion of the Hull Mountain unit along Elk Creek cuts the earlier bedding-parallel foliation (S2A) in the hinge area of tight, inclined folds. The axial-plane cleavage is ostensibly related to the F2B event on the basis of style and overprinting relations, but later folding has reoriented the cleavage toward the northwest. The S2B foliation is also inferred to correspond to the planar fabric, seen in thin sections, that deforms lawsonite tabs coplanar with an earlier foliation (S2A).

A near vertical, northeast-trending, locally intense crenulation cleavage that is assigned to (S2B) cuts the compositional layering of the metagraywacke and argillite of Bald Mountain at a high angle in the Cushman Lake area and in the headwaters of the Eel River. This young-generation planar fabric that overprints D1 deformation in these Pickett Peak terrane rocks is not recognized in other Pickett Peak terrane units of the map area. Either the metamorphic rocks of Mendocino Pass and the metamorphic rocks of Lake Pillsbury were uplifted above the stability field of blueschist prior to D2A and D2B deformation or the later blueschist metamorphism and deformation event is expressed more subtly and is unrecognized in the other Pickett Peak terrane units.

The tight to isoclinal F2B fold style and the associated (S2B) cleavage observed in the Hull Mountain and Bald Mountain metasedimentary units post-dates the Cenomanian depositional age of the Hull Mountain metagraywacke and accompanied or post-dated blueschist metamorphism. These relations are similar to the chronology and timing of penetrative deformation observed in the area east of Clear Lake to the south (McLaughlin and Ohlin, 1984), suggesting that blueschist metamorphism that accompanied or post-dated F2A and F2B probably occurred in Cenomanian time or later. If the F2B and S2B structures of D2B are the same in the metasandstone of Hull Mountain and the metasedimentary rocks of Black Butte and Bald Mountain (table 4), then this deformation postdates D-1 and D2A and may correspond with blueschist metamorphism about 92 Ma that postdated the approximately 95 Ma intrusion of mafic dikes into the metasandstone of Hull Mountain and Yolla Bolly terrane elsewhere (Echeverria, 1980; Mattinson and Echeverria, 1980). This relation, speculatively, suggests that the Yolla Bolly terrane and the Pickett Peak terrane rocks of Black Butte and Bald Mountain were subjected to the same high P/T metamorphic event and associated deformation about 92 Ma, though their present structural positions relative to each other were probably established later, during uplift and exhumation of the coast ranges.

Folding that is attributed to a later episode of deformation that included burial and metamorphism to pumpellyite or incipient lawsonite grade (D3) and that also included the development of boudinage, is locally present in mélange of the Central belt. This deformation was not accompanied by the prominent flattening and textural reconstitution associated with development of cleavage and schistocity in the metaclastic rocks of the Yolla Bolly and Pickett Peak terranes (Textural Zones 2 and 3 of Blake and others, 1967). One of the folds observed within the mélange is tight and upright and plunges N. 20º W. at 30º and may be related to the development of anastamosing shear. An even later set of folds that

Table 4. Summary of chronology of deformation fabrics in Franciscan Complex, Lake Pillsbury region, California.



trend N. 35–55º W. and that are close spaced to open, with horizontal to shallow southeast-plunging axes, is inferred from the attitudes of bedding, cleavage, and mélange shear fabric. This late folding generally increases in intensity near high-angle, northwest-trending faults with wavelengths that decrease from hundreds to tens of meters toward the faults. Examples of this relation are seen along Elk Creek near the Bartlett Springs Fault Zone, suggesting that at least some of the folds have formed in the late Cenozoic.

The late folds may include an early subset of northwest-trending folds in Paleocene to early Eocene strata in the Rice Valley area south of Lake Pillsbury (Berkland, 1973; Suppe and Foland, 1978; Etter, 1979). The Paleogene strata overlie low-angle thrust faults, which are also folded and cut by the high-angle, northwest-trending faults. A later subset of northwest trending folds are also related to high-angle faulting and are nearly coaxial with the early Eocene or younger subset of folds.

Mélange Fabric

Several subparallel zones of mélange strike northwest across the study area. Contacts between distinct mélange zones and between coherent units and mélange are interpreted as faults, because of the presence of prominent shearing and abrupt changes in metamorphic grade and (or) lithology across contacts.

Contacts between mélange blocks and mélange matrix are clearly sheared, but by convention we herein show their boundaries as normal contacts because individual blocks are often too small to delineate at map scale with the same line weight used for faults, and also because the mélanges themselves are considered to be zones of faulted rock tens of meters to kilometers thick. The mélange matrix that encloses blocks is comprised of generally argillitic rock with pervasive, closely spaced, anastamosing planes of failure having the character of a fault zone.

Associated with matrix of the mélange are large, intact tracts of rock characterized as blocks or slabs that may have been (1) initially emplaced over the mélange by overthrusting and subsequently deformed by younger normal to translational faulting, folding, or uplift; (2) engulfed in the mélange matrix and carried with the matrix for large distances during oblique, low-angle translation and accretion in the Mesozoic and early Tertiary; or (3) sheared away from the immediately adjacent Mesozoic to early Tertiary margin then mixed with mélange components derived from more disparate, farther removed locations and translated laterally and vertically during the oblique accretion process (McLaughlin and Ohlin, 1984; McLaughlin and others, 1988). The large detached slab of metamorphic rocks of Black Butte and Bald Mountain in the map area may be an example of (1) and (or) (3) in being separated to the northeast and southwest from mélange along a low-angle fault. Regionally, although a structural outlier, these rocks are in close proximity to the main Pickett Peak terrane of the Eastern belt and probably were emplaced over the Central belt mélange along the Board Ridge Thrust (see structure section). Large greenstone blocks and slabs (delineated as "v" on geologic map) in mélange east of Bald Mountain are examples of (2) and are likely to have been translated in the matrix of the Central belt from source regions unrelated to the immediately adjacent Eastern belt. Rocks of the Yolla Bolly terrane in the map area, including the metasandstone of Hull Mountain and the metasedimentary rocks of Sanhedrin Mountain, similar to the Black Butte and Bald Mountain rocks, are flanked by and structurally intercalated with mélange of the Central belt and may actually be underlain by the Central belt mélange at an undetermined depth. In contrast, however, these Yolla Bolly terrane rocks are largely bounded by vertical to moderately dipping faults, several that are clearly associated with the Bartlett Springs Fault Zone. The pre-late Cenozoic geometry of probable thrust faults that initially emplaced the Eastern belt (Yolla Bolly terrane) rocks over the Central belt have been highly modified in the map area. In addition, Cenozoic faults that evolved with the Bartlett Springs Fault Zone include complexly imbricated, moderately dipping reverse faults that appear to dip both to the northeast and southwest along the fault zone. All of these structures have contributed to observed fabric complexity of the mélange of the Central belt and to uncertainty in establishing depth distribution of Franciscan Complex units in the map area.

Bedding and stratal continuity of the metasandstone and argillite of Hull Mountain is progressively disrupted toward steeply dipping northwest-trending fault contacts with surrounding mélange. The metasandstone core area of the Hull Mountain unit is essentially intact except for shearing present in argillite intervals and near minor northwest-trending faults. The disrupted margins of the Hull Mountain metasandstone unit appear to contribute material to the matrix of the Central belt, at least locally, as do the disrupted margins of several other units of the Franciscan Complex and the Coast Range Ophiolite where in contact with mélange.

Where no late faulting has occurred along contacts of the intact metasandstone units of Hull Mountain and Sanhedrin Mountain with mélange, the contacts are marked by anastomosing shear planes characteristic of contacts of mélange matrix with the blocks. This deformational style may be characteristic of mélange fabric and contrasts with some observations of brittle-rock failure along Quaternary faults seen within the Bartlett Springs Fault Zone, where discrete shear planes bound randomly oriented breccia gouge. Regional relations indicate that anastomosing shear deformation is associated with mélange fabric of Late Cretaceous, as well as Paleogene, rocks of the Franciscan Complex (McLaughlin and others, 1994; McLaughlin and Ohlin, 1984).

Low-angle Faults

Several low-angle thrust faults mapped in this area are recognized by a sinuous map pattern and placement of metamorphosed Late Jurassic and Early Cretaceous rocks over Late Cretaceous or younger mélange of the Central belt.

Board Ridge Thrust

In the northeastern part of the map area, the metamorphic rocks of Black Butte and Bald Mountain and the metasedimentary rocks of Mendocino Pass are juxtaposed above mélange of the Central belt along two imbricate slices of the Board Ridge Thrust Zone (see structure section on map sheet). The upper imbricate thrust slice separating the metasedimentary rocks of Mendocino Pass from the metamorphic rocks of Black Butte and Bald Mountain is mapped as the Mendocino Pass Thrust, a deformed thrust fault that separates the same rock units north of the map area (Ohlin, unpublished mapping, 1983). The Board Ridge Thrust Fault is mapped as the lower bounding surface of both the Black Butte and Bald Mountain and Mendocino Pass units and is considered to truncate the Mendocino Pass Thrust. Based on drill-hole and map data outside of the report area (CDWR, 1966), the Board Ridge thrust regionally trends north-northwest to south-southeast and dips 8–18º E.

The metasedimentary rocks of Mendocino Pass are missing from their intermediate structural position between metamorphic rocks of Black Butte and Bald Mountain and the mélange of the Central belt over most of the map area. The metamorphic rocks of Black Butte and Bald Mountain and metasedimentary rocks of Mendocino Pass are also warped and folded into a synformal structure in the upper plate of the Board Ridge Thrust Zone (see cross section). We interpret the discordant relation of Central belt mélange fabric to shear fabric of the Board Ridge Thrust Zone to indicate that the thrusting post-dated Central belt mélange formation. Regionally, Central belt mélange deformation apparently continued into the Paleogene (McLaughlin and Ohlin, 1984), suggesting that motion along the Board Ridge Thrust is early Paleogene or younger. Post-early Eocene, southwest-vergent folding and thrusting described by Suppe and Foland (1978) is consistent with this timing.

East Flank Thrust

The East Flank Thrust (CDWR, 1969) is exposed on the northeastern slope of Sanhedrin Mountain. The thrust places moderately foliated rocks of the metasedimentary rocks of Sanhedrin Mountain on the southwest, over mélange of the Central belt to the northeast. The East Flank Thrust strikes variably at N. 65–88º W., with dips ranging from 7º N. to 28º S. South of Crocker Place, the thrust is cut by west-trending faults that are subparallel to, or branch from, the Crocker Creek Fault. The Foot Trail Fault that merges with or truncates the Crocker Creek Fault cuts the East Flank Thrust near the west edge of the map area.

Regional mapping in the area (CDWR, 1969) indicates that a regional thrust underlies the metasedimentary rocks of Sanhedrin Mountain. Aeromagnetic data in the area (Langenheim and others, 2007) further suggest that magnetic rocks, presumably associated with the ophiolitic mélange and sedimentary rocks of Split Rock and with mélange of the Central belt, extend southwestward in the subsurface beneath the metasedimentary rocks of Sanhedrin Mountain. Gravity data (Langenheim and others, 2007) are also consistent with this geometry. The East Flank Thrust may be the surface exposure of this deformed regional thrust extending beneath the metasedimentary rocks of Sanhedrin Mountain. More speculatively, the East Flank Thrust might be a young thrust fault that has accommodated north-south compression across the active Bartlett Springs Fault Zone, though evidence of youthful displacement on the East Flank Thrust is lacking.

Northeast Trending Faults and Lineaments

Steep-dipping to vertical faults and lineaments that trend N. 45º E. to approximately east-west are present in the metasedimentary rocks of Sanhedrin Mountain and in the metasandstone of Hull Mountain. Lateral offsets of metachert and metavolcanic layers across these faults are as much as 500 m and show both right-lateral and left-lateral apparent motion. Apparent vertical offsets were not measured.

Chimney Rock Shear Zone

The Chimney Rock Shear Zone (CDWR, 1966) is characterized to the north of the map area as two subparallel faults bounding a 0.2 km to 0.7 km wide zone of shearing that strikes N. 30–40º W. and has a vertical dip. However, this "shear zone" includes several parallel subsidiary faults, locally increasing the composite width of the fault zone to 3 km. A prominent strand of the shear zone passes through the Cushman Lake and Hells Half Acre areas in the northeastern corner of the map area. Faults composing the shear zone are marked by prominent topographic lineaments and elongate slivers of serpentinite; an example is present in the map area at Hells Half Acre.

Prominent lineaments marking the shear zone continue south beyond the map area to the vicinity of the Eel River, where the faulting either dies out or is offset by an east-west-trending fault. The offset continuation of this shear zone possibly extends to the southeast, toward Snow Mountain. North of the map area, the fault zone is either truncated by or merges with the Bartlett Springs Fault Zone immediately north of Round Valley. The overall length of the shear zone from the Eel River to the Round Valley region is approximately 55 km, based on faults shown by Jennings and Strand (1960) and Jennings (1977).

An apparent right-lateral offset of about 300 m, present along the Chimney Rock Shear Zone east of Bald Mountain where metamorphic rocks above the Board Ridge thrust provide an offset reference, is best explained by vertical, up-to-the-east displacement across the Chimney Rock Shear Zone rather than by strike slip.

Right-lateral restoration of the metasedimentary rocks of Black Butte and Bald Mountain to a position contiguous with similar rocks east of the Chimney Rock Shear Zone southeast of the map area requires offset on the order of tens of kilometers, which, if valid, would preclude ending or truncation of the Chimney Rock Shear Zone near the Eel River, as discussed above. Age constraints for movement along the Chimney Rock shear zone are poorly constrained, but, if motion along the Board Ridge thrust occurred in post-early Eocene time, then Chimney Rock Shear Zone displacement has also occurred since the early Eocene. The prominence of lineaments along the shear zone, especially where it traverses mélange, suggest youthfulness. Although no Quaternary deposits are known to be offset along the Chimney Rock Shear Zone, late Cenozoic activity is suggested by spatial association of the shear zone with a major pull-apart basin at Round Valley (Jayko and others, 1989). However, if faults of the Chimney Rock Shear Zone are offset by east-west-trending faults, then significant Quaternary active faulting seems unlikely.

Thatcher Butte Fault

The Thatcher Butte Fault (CDWR, 1969; Jayko and others, 1989) trends N. 50º W., is nearly vertical, and is subparallel to the Chimney Rock Shear Zone. The fault has been mapped far to the northwest, to the northeast side of the Covelo structural basin (Jayko and others, 1989), where rocks of the Pickett Peak and Yolla Bolly terranes of the Eastern belt on the southwest are juxtaposed with mélange of the Central belt of the Franciscan Complex to the northeast along the length of the fault.

In the Long Doe Ridge area, the Thatcher Butte Fault forms a boundary between mélange of the Central belt and the metasandstone of Hull Mountain. In that area, the fault is lined with sheared slivers of serpentinite and is oriented at a high angle to mélange fabric of the Central belt. To the southeast, the fault is truncated by east-west-trending faults that also may offset the Chimney Rock Shear Zone outside of the map area (see previous section).

The northeast strand of the Thatcher Butte zone of faulting is mapped as cutting across the Board Ridge Thrust east of The Devil's Rock Garden and Barley Lake. In this area, east-west-trending faults also join the Thatcher Butte Fault at its juncture with the Board Ridge Thrust. The Thatcher Butte Fault, at this juncture, splays east from fault contacts between the metasandstone of Hull Mountain with serpentinite and mélange. East of this juncture the fault zone slices through the metamorphic rocks of Black Butte and Bald Mountain. The fault continues eastward, as a nearly east-west fault strand within the metamorphic Rocks of Black Butte and Bald Mountain, to where it offsets the contact between the Black Butte and Bald Mountain rocks with the Central belt at the eastern edge of the map area. This strand of the Thatcher Butte Fault Zone is probably up on the north side, with largely normal and possibly minor sinistral displacement. Contemporaneity of the Thatcher Butte Fault and Chimney Rock Shear Zone is suggested by their similar orientations and crosscutting relations with older and younger faults.

Elsewhere in the northern Coast Ranges, rocks correlative with the metasandstone of Hull Mountain (Yolla Bolly terrane of Blake and others, 1982) lie structurally above mélange of the Central belt that also is imbricated with ophiolitic rocks, including serpentinite. In the map area, this regional relation is complicated by a possible component of dip slip along the Thatcher Butte Fault that has displaced the metasandstone of Hull Mountain downward relative to the mélange or to unrecognized strike-slip that has juxtaposed rocks of different structural levels along the Thatcher Butte fault. Aeromagnetic data across this boundary (Langenheim and others, 2007) are consistent with a locally steep southwestward dip along this section of the fault.

Regional geologic relations (Blake and others, 1985, 1988; McLaughlin and others, 1988, 2000; Jayko and others, 1989) show that rocks of the Central and Eastern belts of the Franciscan Complex were juxtaposed after earlier Mesozoic (mid-Cretaceous) subduction and high P/T metamorphism of the Eastern belt rocks beneath the Coast Range Ophiolite and Great Valley Sequence. The Central belt is viewed regionally as having been juxtaposed beneath the Eastern belt along west-vergent thrust faults associated with an obliquely convergent late Mesozoic to early Tertiary subduction margin. This subduction zone at that time had stepped west of the thrust system that juxtaposed the Eastern belt with the

Coast Range Ophiolite and Great Valley Sequence. The original thrust-fault boundaries between the Mesozoic units of the Eastern belt were mildly to severely deformed by folding and shearing during the later Cretaceous to early Tertiary oblique convergence that also unroofed the Coast Ranges and by even later overprinting by transpressional faulting. The Thatcher Butte Fault appears to have initiated and to have been active during this late Cretaceous to early Tertiary and later oblique convergence. The steep regional geometry of the Thatcher Butte Fault (Jayko and others, 1989) and its regional position separating Eastern and Central belt rocks suggests that it must have a significant translational component, but it could have evolved from a folded, originally subhorizontal thrust boundary between the Central and Eastern belts. Alternatively, the fault may have formed as a separate system of steep-dipping faults that postdate the warped and folded older subduction-zone thrusts of the map area but predate the presently active Bartlett Springs Fault system.

Northwest-Trending Faults Traversing Metasandstone of Hull Mountain

Southwest of the intersection of the Thatcher Butte Fault with east-west-trending cross faults in the Devils Rock Garden area, several faults that traverse the metasandstone of Hull Mountain parallel faulted contacts with the Central belt mélange and locally are lined by serpentinite. In this area the fault contact between the metasandstone of Hull Mountain and mélange of the Central belt strikes N. 50–70º W. and dips steeply to the northeast, suggesting up-to-the-east reverse slip, at least locally. The subsidiary faults within the metasandstone of Hull Mountain bound coherent sub-blocks of the Hull Mountain unit, separating these rocks from less coherent broken formation along outer margins of the sub-blocks. The parallelism of these subsidiary faults within the main Hull Mountain Fault block with the Thatcher Butte Fault and the presence of serpentinite along many of the sub-block faults suggests that they may have been generated with the Thatcher Butte fault and that the faults may extend through the metasandstone of Hull Mountain to ultramafic and Central belt mélange sources beneath the block or deeper.

Sanhedrin Creek Fault

The Sanhedrin Creek Fault trends N. 20–30º W. and forms the local boundary between mélange of the Central belt on the southwest and the metasandstone and argillite of Hull Mountain to the northeast. At the northern boundary of the map area, this fault appears to merge toward the Elk Creek Segment of the Bartlett Springs Fault Zone. To the southeast, the fault intersects the Forks Creek Fault. The map pattern of the Sanhedrin Creek Fault indicates that it is nearly vertical at the surface, possibly with a steep dip component toward the northeast. Incision of alluvium into terrace deposits in the valley that formed at the confluence of Sanhedrin and Elk Creeks at the northwestern corner of the map area appears to align with the probable extension of the fault north of the map area.

East-West-Trending Faults

Faults and lineaments that strike east-west and have steep to vertical dips offset all structural features except the Bartlett Springs Fault Zone. Faults of this trend northeast of the Bartlett Springs Fault Zone occur in a 2-km-wide zone extending from the area near the confluence of Bear and Elk Creeks to the area between Hull Mountain and Bald Mountain. North of Mendenhall Creek, these faults exhibit apparent right- and left-lateral offsets, generally in the range of 100 m. Directly north and through the summit of Hull Mountain, other east-west-trending lineaments may be related to faults that right-laterally offset the Board Ridge Thrust east of the map area. To the east, near the Eel River, east-west-trending faults may offset or terminate the Chimney Rock Shear Zone.

Two prominent east-west-trending faults are present on the northeast flank of Sanhedrin Mountain.

Forks Creek Fault

The Forks Creek Fault (CDWR, 1969) dips vertically and juxtaposes the metasandstone and argillite of Hull Mountain against mélange of the Central belt east of Sanhedrin Creek. Although an apparent 180-m, left-lateral offset of the contact of serpentinite with mélange across the Forks Creek Fault is mapped near the west side of the map area, consistent evidence of this sense of strike-slip is lacking. Because the displaced serpentinite-mélange contact appears to dip eastward, down to the north dip-slip may better explain displacement on the Forks Creek Fault.

Crocker Creek Fault

This fault, named herein, trends, in part, along Crocker Creek, the east-west drainage that is about 0.8 km south of Crocker Place, and is notably marked by a closed depression where the fault crosses the jeep trail running west from Crocker Place and south of hill 3088. The fault strikes N 85º W to S 85º E, dips vertically to steeply southward, and, based on the closed depression, has probably experienced Quaternary movement.

Reverse motion along the Crocker Creek fault is suggested by its orientation relative to regional stress directions and its position relative to the Bartlett Springs Fault Zone. The length of the Crocker Creek Fault, measured from the Bartlett Springs Fault Zone to the Foot Trail Fault, is about 4.5 km. At its east end, the Crocker Creek Fault bends southeastward into the Bartlett Springs Fault Zone, possibly suggesting that there is a steep dip toward the south or that the fault is truncated by steeply dipping northwest-trending splays from the Island Segment of the Bartlett Springs Fault Zone. At its west end, a steep southward dip for the fault is also suggested by the map pattern of its trace crossing topography between upper Crocker Creek drainage and the fault's intersection with serpentinite in the Foot Trail Fault Zone southwest of hill 3088.

Foot Trail Fault

The Foot Trail Fault (CDWR, 1969) strikes N. 55–60º W., dips vertically, and is locally marked by a narrow elongate body of serpentinite near the intersection with the Crocker Creek Fault. A short fault mapped in sec. 2, T. 19 N., R. 11 W., suggests that the Foot Trail Fault possibly continues to the southeast and joins the Bartlett Springs Fault Zone. To the northwest, the fault trends beyond the study area, but aerial photographic reconnaissance suggests the fault dies out within a kilometer of the map boundary. The total length of the Foot Trail Fault is about 16 km, assuming the fault joins the Bartlett Springs Fault Zone to the southeast at Fuller Creek. The Foot Trail Fault truncates the presumably active Quaternary Crocker Creek Fault, suggesting that the Foot Trail fault could be a splay of the active Bartlett Springs Fault Zone. The East Flank Thrust is right-laterally offset about 1.7 km by the Foot Trail Fault near the west boundary of the map area.

Boardman Ridge Fault Zone

The Boardman Ridge Fault Zone consists of two linear branched fault segments: (1) a branched north-trending southwest segment that is about 3 km long, defined on the basis of the east and west fault margins of a serpentinite body and (2) a northwest-trending northeast splay that is about 9 km long, defined by air-photo alignment of a series of topographic features in the metasandstone of Hull Mountain (aligned saddles, aligned sharp ridge segments, anomalously deep and straight drainages, and local abrupt linear boundaries between intricately dissected and more subdued topography). The aligned topographic features are inferred to be fault related, because their alignment subparallels segments of the Bartlett Springs Fault Zone observed in the field. Alternatively, the aligned features could be controlled by metamorphic fabric, such as slaty partings and axial-plane cleavage in metaclastic rocks of the metasandstone and argillite of Hull Mountain.

Squaw Creek Fault Zone

The Squaw Creek Fault Zone, about 1.5–2.7 km southwest of and parallel to the Boardman Ridge Fault Zone, is defined mostly on the basis of air-photo alignment of topographic features in the metasandstone of Hull Mountain, similar to the Boardman Ridge Fault Zone. This linear feature is mapped for about 13 km northwestward from the southeastern edge of the map. This fault zone and the Boardman Ridge Fault Zone do not intersect the east-west lineaments shown west of Hull Mountain. These fault zones could be older than any faulting associated with the lineaments. Speculatively, the Squaw Creek and Boardman Ridge fault zones may be cogenetic with the Thatcher Butte fault and Chimney Rock shear zones, that pre-date the Bartlett Springs Fault Zone.

Bartlett Springs Fault Zone

The Bartlett Springs Fault Zone (BSFZ) traverses the study area from southeast of Lake Pillsbury, extending northwestward along Elk Creek, to the northwest corner of the map area. The fault zone was first noted by Irwin (1960) who commented on a major shear zone near Wilbur Springs that "*trends northwestward to Lake Pillsbury and perhaps beyond*." The fault zone was first mapped within the study area by the California Department of Water Resources (1969) as the Elk Creek Fault, which they extended southeastward to near the confluence of Mendenhall and Elk Creeks. Maxwell (1974) shows a shear zone "*of possible strike-slip origin*" that corresponds to the Bartlett Springs Fault Zone. Etter (1979) described the fault zone in detail south of Lake Pillsbury, where he named it the Hot Springs Shear Zone and suggested apparent right-lateral movement along the zone. McLaughlin and Nilsen (1982) linked the various segments of the fault zone, including the segment passing through the study area, and named it the Bartlett Springs Fault Zone. McLaughlin and others (1990) have mapped the fault zone geology in detail in the Wilbur Springs area.

We map the Bartlett Springs Fault Zone as consisting of several stepped and interleaved segments, some of which are linked. We have assigned informal names to these segments to facilitate their description in different parts of the map area. Some named faults on the northeast and southwest sides of the Bartlett Springs Fault Zone that are subparallel high angle faults or that splay at a high angle from the main zone of faulting are described separately above. The informally designated segments of the Bartlett Springs Fault Zone includes those faults that we consider to be part of the through-going closely spaced faulting that exhibits evidence of latest Quaternary (late Pleistocene and Holocene) displacement and (or) creep.

The geology of the Bartlett Springs Fault Zone is complex. In addition to the displacement of Quaternary deposits, the faulting involves three major Franciscan units, as well as rocks associated with the Coast Range Ophiolite and the Great Valley Sequence. These rocks are displaced in the Bartlett Springs Fault Zone by fault sets of different generations and geometries. Depending on their geometry, these faults apparently are associated with dextral, reverse, normal, and possibly minor sinistral displacement.

Seismicity along the Bartlett Springs Fault Zone, together with triangulation measurements to the north of Lake Pillsbury in Round Valley and earthquake focal mechanisms, indicate that the fault zone is presently active (DePolo and Ohlin, 1984; Svarc and others, 2008; Lienkaemper and Brown, 2009; J. Lienkaemper, written commun., 2009). Recent small earthquakes in the Lake Pillsbury area have focal depths of 8–9.5 km and their epicenters plot along the Elk Creek and Rocky Point Segments of the Bartlett Springs Fault Zone. Though the depths and magnitudes of these small events and considerable fault-zone complexity preclude projection of the focal planes of the earthquakes from their foci to specific faults at the surface, the focal mechanisms favor both normal and reverse oblique slip on northwest-oriented fault planes that dip 50–60º to the southwest or northeast.

Main Bartlett Springs Fault Zone

The main through-going segments of the Bartlett Springs Fault Zone consist of five closely spaced, major, steeply dipping fault segments that trend N. 20–40º W. and are right-stepped or possibly go through a releasing bend across Lake Pillsbury basin. These principal segments of the active and creeping part of the Bartlett Springs Fault Zone are described below from north to south.

Elk Creek Segment

Mapping by CDWR (1969) and in this study indicate that the Elk Creek Segment extends northwestward along Elk Creek toward Round Valley from the northwestern corner of the map area. Within the map area, the Elk Creek Segment is mapped directly northeast of Elk Creek as one or two intersecting strands that locally entrain serpentinite (CDWR, 1969; this study). On this map, we extend the Elk Creek Segment southeastward from Mendenhall Creek as a right-releasing step or bend and continue this fault segment as the principal eastern boundary of the Lake Pillsbury pull-apart basin. We suggest that the Elk Creek Segment may intersect the Squaw Creek Fault Zone southeast of Lake Pillsbury at the Eel River south of Bear Mountain.

The Island Segment

North of Gravelly Valley, an elongate northwest-trending zone of mélange intervenes along the Bartlett Springs Fault Zone between the metasedimentary rocks of Sanhedrin Mountain and the metasandstone of Hull Mountain. For most of its length of exposure, the zone of mélange is bounded by a strand of the Elk Creek Segment on the northeast and by The Island Segment on the southwest. The slab of mélange pinches out northward just southeast of The Island along splays from both the Elk Creek and The Island segments in the vicinity of Smokehouse Creek. The slab of Central belt mélange is right-laterally separated by about 7.4 km from other mélange exposed southwest of The Island Segment, between the Forks Creek and the Crocker Creek Faults.

Summit Lake, immediately west of The Island, is a sag pond located in a small right step along a prominent zone of straight, through-going interleaved faults aligned with the northeast side of the metasedimentary rocks of Sanhedrin Mountain, as well as with local mélange and elongate bodies of serpentinite. Northwest of The Island-Summit Lake area, geomorphic expression of the Island Segment is less distinct due to thick forest cover. North of Sportsman Glade, at the confluence of Elk and Sulphur Springs Creeks, a north-northeast-trending sheared contact between mélange and the metasandstone of Hull Mountain is mapped as The Island Segment. North of this locality, a right-releasing bend or step is inferred to continue The Island Segment to an intersection with the Elk Creek Segment beneath a large landslide. Some young slip probably also splays westward to the Crocker Creek and Foot Trail Faults as suggested in their youthful expression west of the The Island Segment (see earlier discussion).

Gravelly Valley (Creeping) Segment

North of Lake Pillsbury, the Gravelly Valley Segment is identified on air photos by soil-color changes that form tonal limits on a Quaternary alluvial fan surface. Subtle fault scarps are present near Coyote Rocks (DePolo and Ohlin, 1984), where a diapir of serpentinite intrudes late Pleistocene and Holocene fluvial terraces and interfingers with Holocene colluvium along the Gravelly Valley Segment (T. Sawyer and W. Page, field reconnaissance, 2009). Topographic benches, uplifted Quaternary alluvial deposits (Qty, Qto, Qfo, Qfvo and Qoa), linear drainages, and vegetation lineaments are present along the east margin of Gravelly Valley. A pattern of aligned streams, linear depressions, and vegetation lineaments continues to the northwest along Salmon and Fuller Creeks and the ridge to the northeast, indicating continuity to the northwest with The Island Segment of the Bartlett Springs Fault Zone. Where a prominent strand of the Gravelly Valley Segment intersects U.S. Forest Service Route M6 at the east side of the Gravelly Valley airstrip, the road pavement is cut by a series of dextral left-stepped (transpressional) cracks. This segment of the Bartlett Springs Fault Zone is presently being monitored for fault creep (Svarc and others, 2008).

South of Lake Pillsbury, the Gravelly Valley Segment has been mapped along the crest and northeast side of McLeod Ridge as a series of left-stepped (transpressional) lineaments on aerial photographs (J. Lienkaemper, written commun., 2009; Lienkaemper and Brown, 2009). In that area, the fault zone appears to be largely in serpentinite and mélange of the Central belt but close to, or overprinted on, the northeast-dipping Mcleod Ridge fault that separates of the Central belt on the southwest from serpentinite of the Coast Range Ophiolite to the northeast. At the southeast corner of the map area, the Gravelly Valley lineaments parallel the Eel River Segment of the Bartlett Springs Fault Zone located about 0.5 km to the northeast.

Eel River Segment

This segment is a steeply northeast dipping fault at the southeast corner of the map area that juxtaposes the metasandstone and argillite of Hull Mountain on the northeast with ultramafic rocks of the Coast Range Ophiolite and mélange of the Central belt to the southwest. This segment continues to the southeast beyond the map area as a major offsetting segment of the Bartlett Springs Fault Zone. The main strand of the fault that bounds the northeast side of a large serpentinite body is queried to bend westward beneath Lake Pillsbury to join the Gravelly Valley segment. However, the fault probably also steps northeastward to southern strands of the Elk Creek Segment along the east side of Lake Pillsbury between the Eel River and Salt Spring Creek.

Rocky Point Segment

The Rocky Point Segment is another major bedrock fault that juxtaposes ultramafic rocks of the Coast Range Ophiolite, mélange of the Franciscan Central belt, and foliated Franciscan metamorphic rocks of Lake Pillsbury on the northeast with the ophiolitic mélange and sedimentary rocks of Split Rock on the southwest. Aeromagnetic data (Langenheim and others, 2007) suggests that the Rocky Point Segment dips steeply toward the southwest. Gravity data imply the presence of a thick section of low-density material west of the fault, probably corresponding, in part, to the ophiolitic mélange and sedimentary rocks of Split rock. The Rocky Point Segment is inferred to continue northward beneath the west margin of Lake Pillsbury, parallel with the southwestern strands of the Gravelly Valley Segment, a southwestern strand of the Island Segment near Lake Pillsbury Ranch, or it could possibly join the Northeast Ericson Ridge Fault. In terrace deposits along the western shoreline of Lake Pillsbury about 1 km north of Scott Dam, abrupt steep contacts of coarse boulder to cobble gravels on the west, with clayey grey silty to gritty mud to the east (lacustrine mudstone on map), are noted. Though a through-going fault has not yet been confirmed at the shoreline in this area, these contacts possibly are fault-related and associated with strands of the Rocky Point Segment.

Southwestern Bartlett Springs Fault Zone

As with the main fault segments, southwestern faults of the Bartlett Springs Fault Zone are described from north to south. These faults are as much as 2.5 km southwest of the main segments of the fault zone, and the southern of these faults are somewhat more northwest-oriented than the main through-going faults described above. Their offset of Pleistocene gravels along the southwest side of Lake Pillsbury basin, however, indicates a formative role in the evolution of the Lake Pillsbury pull-apart basin. Some of the faults are more clearly associated with dip-slip (both normal and reverse) than with strike-slip displacement.

Northeast and Southwest Ericson Ridge Faults

The Northeast Ericson Ridge Fault is inferred from aerial photographs on the basis of aligned saddles and subtle jogs in tributary drainages crossing this alignment. The trend of the features interpreted to be associated with the fault zone join with, or are truncated by, the Rocky Point Segment of the Bartlett Springs Fault Zone. The intersection of these faults occurs beneath Quaternary terraces along the west side of Gravelly Valley and the Lake Pillsbury basin. Continuation of the inferred fault feature northwest of the map area is unknown, and exposures of the fault zone in the map area have not been observed in the field. An approximately 3-km-long, unnamed, subparallel branched fault, 450–600 m northeast of the main Northeast Ericson Ridge Fault alignment, juxtaposes mélange of the Central belt to the east with metasandstone, argillite, and chert of Sanhedrin Mountain to the west. This unnamed fault may splay from the Gravelly Valley or Rocky Point Segments. The age of this faulting is probably younger than Eocene based on the timing of mélange formation (see earlier discussion of Franciscan Complex) but is otherwise unconstrained. The parallelism of these faults with the Logan Spring Fault Zone discussed below suggests that the faulting could be related, in part, to extensional opening of the Lake Pillsbury basin, although no expression of the faulting in older Quaternary deposits (Qfo) along the west side of the basin is recognized. This relation may indicate that the structural depression controlled by this faulting was initiated in the pre-Pleistocene (pre-Qfo), perhaps in Pliocene time.

The Southwest Ericson Ridge Fault locally juxtaposes metasandstone, argillite, and chert of Sanhedrin Mountain on the northeast with ophiolitic mélange and sedimentary rocks of Split Rock on the southwest. The fault appears to project southeastward beneath older alluvial terraces on the west side of Lake Pillsbury (Qoa), so that no obvious late Quaternary displacement is evident. As discussed earlier, however, unit Qoa is a composite unit in this area that may include significant areas of bedrock exposure and, as such, is unreliable for constraining the timing of Pleistocene displacement north of Scott Dam.

Parallelism of the Southwest Ericson Ridge Fault with the Logan Spring Fault to the south, like the Northeast Ericson Ridge Fault, however, suggests that all of these faults are of the same fault generation and, therefore, may have accommodated some component of basin-margin displacement that predated some uplifted older terrace deposits (Qoa, Qto) north of Scott Dam. Older terrace surfaces (Qtvo) are evident in topography at two different elevations in the fault block between the Northeast and Southwest Ericson Ridge Faults (one surface is at 2,640 ft, along the crest of Ericson Ridge; another is at 2,200 ft). The distribution of these surfaces suggests they are uplifted and (or) tilted relative to correlated Qtvo deposits and surfaces in the blocks northeast and southwest of the Ericson Ridge block. Although the ages of the high surfaces are presently unconstrained, we infer them to be Pleistocene; most displacement on the Northeast and Southwest Ericson Ridge Faults is, therefore, Pleistocene and may largely predate the late Pleistocene and younger terraces. Apparent dextral offset along the Southwest Ericson Ridge Fault is at least 2.0 km, based on the distribution of the ophiolitic mélange and sedimentary rocks of Split Rock. These relations and near parallelism of these faults to the main Bartlett Springs Fault Zone segments implies that the Southwest and Northeast Ericson Ridge Faults are steeply dipping transpressional dextral faults.

Logan Spring Fault Zone

The Logan Spring Fault Zone trends generally about N. 50º W. and is locally well exposed along the county road to Upper Lake south of Scott Dam (fig. 2). South of the Eel River, this curvilinear fault zone separates the ophiolitic mélange and sedimentary rocks of Split Rock on the east from the metasedimentary rocks of Sanhedrin Mountain to the west. Southwest of Scott Dam, a prominent remnant of uplifted fluvial gravel (unit Qoa), is entrained along the fault zone just southeast of Logan Spring. The gravels dip 35–42º northward, away from the fault and toward Lake Pillsbury basin, and the fault bounds the southwest side of the gravel. Serpentinite and silica carbonate entrained along the Logan Spring Fault are thrust northeastward over the gravel locally, and the gravel is also cut by subsidiary normal faults that dip 35º to the northeast. The main fault zone is apparently a moderate to steep southwest-dipping, east-verging, basin-bounding reverse fault. Gravity and aeromagnetic data (Langenheim and others, 2007) that suggest the presence of both magnetic and low density materials at depth southwest of the Logan Spring Fault Zone are consistent with a significant southwestward dip component to the fault. Logan Spring is a cold soda spring that vents along the fault, and the presence of silica carbonate sinter indicates that the fault has vented thermal fluid in the past. This relation suggests a connection to thermal springs that vent along the main Bartlett Springs Fault Zone to the southeast of the map area. Southeast of Logan Spring a queried southeastward splay of the fault zone is suggested to trend toward the Rocky Point Segment of the Bartlett Springs Fault Zone.

McLeod Ridge Fault

This fault separates a major body of ultramafic rocks assigned to the Coast Range Ophiolite on the northeast from mélange questionably assigned to the Central belt of the Franciscan Complex to the southwest. This fault has been mapped as a pre-late Cenozoic, northeast-dipping reverse or thrust fault (Etter, 1979). The map pattern of the fault contact between mélange and ultramafic rocks is consistent with a moderate northeast dip to the fault. However, youthful features associated with the southeastward continuation of the Gravelly Valley Segment of the Bartlett Springs Fault Zone appear to be partly superposed on, or straddle, the McLeod Ridge Fault. This may indicate that the McLeod Ridge Fault is actually an active strand of the Bartlett Springs Fault Zone, or possibly, that the Gravelly Flat Segment is too immature to have accumulated significant mappable offset south of Lake Pillsbury. The McLeod Ridge Fault intersects and may root in the vertical to steeply northeast-dipping Eel River Segment of the Bartlett Springs Fault Zone at the southeast corner of the map area. The fault also merges with or is truncated by the Rocky Point Segment of the Bartlett Springs Fault Zone just south of Lake Pillsbury. The geometry of the junction of the McLeod Ridge Fault and Rocky Point Segment and the distribution of the Franciscan rocks that intervene between these two faults require a crustal model that is substantially more complex than the series of close-spaced vertical en-echelon slices represented by the most youthful faults of the Bartlett Springs Fault Zone. To adequately understand the geometry of the Bartlett Springs Fault Zone in this area, the dip components of the McLeod Ridge Fault and of the Eel River, Gravelly Valley, and Rocky Point Segments of the fault need to be integrated with the distribution of framework geologic units. Detailed modeling of the gravity and of magnetic bodies from higher resolution aeromagnetic data might substantially clarify these very complex fault intersections at depth.

References Cited

Berkland, J.O., 1973, Rice Valley outlier—New sequence of Cretaceous-Paleocene strata in northern Coast Ranges, California: Geological Society of America Bulletin, v. 84, p. 2389–2406.

Bishop, D.G., 1977, South Fork Mountain Schist at Black Butte and Cottonwood Creek, northern California: Geology, v. 55, p. 595–599.

Blake, M.C., Jr., Irwin, W.P., and Coleman, R.G., 1967, Upside-down metamorphic zonation, blueschist facies, along a regional thrust in California and Oregon, *in* Geological Survey Research: U.S. Geological Survey Professional Paper 575-C, p. C1-C9.

Blake, M.C., Jr., and Jones, D.L., 1974, Origin of Franciscan mélanges in northern California: Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 345–357.

Blake, M.C., Jr., Howell, D.G., and Jayko, A.S., 1984, Tectonostratigraphic terranes of the San Francisco Bay rRegion, *in* Blake, M.C., Jr., ed., 1984, Franciscan geology of northern California: Pacific Section, Society of Environmental Paleontologists and Mineralogists, v. 43, p. 5–22.

Blake, M.C., Jr., Howell, D.G., and Jones, D.L., 1982, Preliminary tectonostratigraphic terrane map of California: U.S. Geological Survey Open-File Report 82-593, 9 p., 3 sheets.

Blake, M.C., Jr., Jayko, A.S., and McLaughlin, R.J., 1985, Tectonostratigraphic terranes of the northern Coast Ranges, California, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the Circumpacific Region, Earth Science Series, no. 1: Circumpacific Council for Energy and Mineral Resources, p.159–171.

Blake, M.C., Jr., Jayko, A.S, McLaughlin, R.J., and Underwood, M.B., 1988, Metamorphic and tectonic evolution of the Franciscan Complex, northern California, *in* Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States: Engelwood Cliffs, New Jersey, Prentice Hall, Rubey Volume VII, p.1035–1060.

Blake, M.C., Jr., Harwood, D.S., Helley, E.J., Irwin, W.P., Jayko, A.S., and Jones, D.L., 1999, Geologic map of the Red Bluff 30' x 60' quadrangle, California: U.S. Geological Survey Geologic Investigation Series Map I–2542, with pamphlet, 15 p.

Blake, M.C., Jr., Helley, E.J., Jayko, A.S., Jones, D.L., and Ohlin, H.N., 1992, Geologic map of the Willows 1:100,000 quadrangle, California: U.S. Geological Survey Open-File Report 92-271.

Bolt, B.A., and Oakeshott, G.B., 1982, Seismic and tectonic evaluation for Scott Dam and vicinity: unpublished report for Pacific Gas and Electric Company, San Francisco.

Brown, E.H., and Ghent, E.D., 1983, Mineralogy and phase relations in the blueschist facies of the Black Butte and Ball Rock areas, northern California Coast Ranges: American Mineralogist, v. 68, p. 365–372.

CDWR, 1966, Engineering geology of Dos Rios-Grindstone Tunnel: California Department of Water Resources, unpublished office report.

CDWR, 1968, Areal geology Hayshed-Grindstone and Elk-Grindstone tunnels: California Department of Water Resources, unpublished map.

CDWR, 1969, Areal geology, Elk Creek tunnel: California Department of Water Resources, unpublished office report.

Campbell, K.A., and Bottjer, D.J. 1995. *Peregrinella*—An Early Cretaceous cold-seep-restricted brachiopod: Paleobiology, v. 24, p. 461–478.

Campbell, K.A., Carlson, C., and Bottjer, D.J.,1993, Fossil cold seep limestones and associated chemosymbiotic macroinvertebrate faunas, Jurassic-Cretaceous Great Valley Group, California, *in* Graham, S., and Lowe, D., eds., Advances in the sedimentary geology of the Great Valley Group: Pacific Section, Society of Economic Paleontologists and Mineralogists, book 73, p. 37–50.

Campbell, K.A., Farmer, J.D., and Des Marais, D., 2002, Ancient hydrocarbon seeps from the Mesozoic convergent margin of California—Carbonate geochemistry, fluids and paleoenvironments: Geofluids, v. 2, p. 63–94.

Dehlinger, P., and Bolt , B.A., 1984, Seismic parameters along the Bartlett Springs fault zone in the Coast Ranges of northern California: Bulletin of Seismological Society of America, v. 74, p. 1785–1798.

DePolo, C.M., and Ohlin, H.N., 1984, The Bartlett Springs Fault Zone—An eastern member of the California plate boundary system: Geological Society of America, Abstracts with programs, v. 16, no. 6, p. 486.

Dumitru, T.A., Wakabayashi, J., and Wright, J.E., 2009, Time-varying accretion, nonaccretion, and high-pressure metamorphism in the Franciscan subduction complex, from the initiation of subduction until ca. 80 Ma: Geological Society of America Abstracts with Programs, v. 41, no.7, p. 404.

Echeverria, L.M., 1980, Oceanic basaltic magmas in accretionary prisms—The Franciscan intrusive gabbros: American Journal of Science, v. 280, p. 697–724.

Eric, J.H., 1948, Tabulation of copper deposits in California, *in* Jenkins, O.P., ed., Copper in California: California Division of Mines Bulletin 144, p. 199–387.

Etter, S.D., 1979, Geology of the Lake Pillsbury area, northern Coast Ranges: Austin, University of Texas, unpublished Ph.D. dissertation, 275 p.
Geomatrix Consultants, 1986, Final report, geological assessment of the seismic potential of the Bartlett Springs shear zone for Scott Dam, Lake County, California: Unpublished report for Pacific Gas and Electric Company, San Francisco.
Ghent, E.D., 1965, Glaucophane-schist facies metamorphism in the Black Butte area, northern Coast Ranges, California: American Journal of Science, v. 263, no. 5, p. 385–400.
Graymer, R.W., Jones, D.L., and Brabb, E.E., 2002, Geologic map and map database of northeastern San Francisco Bay region, California—Most of Solano County and parts of Napa, Marin, Contra Costa, San Joaquin, Sacramento, Yolo, and Sonoma Counties: U.S. Geological Survey Miscellaneous Field Studies Map MF-2403, version 1.0, scale 1:100,000, and pamphlet.
Hearn, B.C., Jr., Donnelly-Nolan, J.M., Goff, F.E., 1995. Geologic map and structure sections of the Clear Lake volcanics, northern California: U.S. Geological Survey Miscellaneous Investigation Series I-2362.
Hsu, K.J., 1968, Principles of mélanges and their bearing on the Franciscan Knoxville paradox: Geological Society of America Bulletin, v. 79, p. 1063–1074.
Irwin, W.P., 1960, Geologic reconnaissance of the northern Coast Ranges and Klamath Mountains, California, with a summary of the mineral resources: California Division of Mines Bulletin 179, 80 p.
Irwin, W.P., Wolfe, E.W., Blake, M.C., Jr., and Cunningham, C.G., Jr., 1974, Geologic map of the Pickett Peak quadrangle, Trinity County, California: U.S. Geological Survey Geologic Quadrangle Map GQ-1111, scale 1:62,500.
Jayko, A.S., 1983, Deformation in low-grade blueschists of the Eastern Franciscan Belt, Northern California: Geological Society of America, Abstracts with programs, v. 15, no. 5, p. 313.
Jayko, A.S., Blake, M.C., Jr., and Harms, Tekla, 1987, Attenuation of the Coast Range Ophiolite by extensional faulting and nature of the Coast Range "thrust," California: Tectonics, v. 6, p. 475–488.
Jayko, A.S., Blake, M.C., Jr., McLaughlin, R.J., Ohlin, H.N., Ellen, S.D., and Kelsey, Harvey, 1989, Reconnaissance geologic map of the Covelo 30' X 60' quadrangle, northern California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2001, map and pamphlet.
Jennings, C.W., comp., 1977, Geologic map of California: Sacramento, California Division of Mines and Geology, scale 1:750,000.
Jennings, C.W., and Strand, R.G., 1960, Ukiah sheet, geologic map of California: California Division of Mines and Geology, scale 1:250,000.
Jordan, M.A., 1975, Geology of the Round Valley, Sanhedrin Mountain area, northern California Coast Ranges: Austin, University of Texas, Ph.D. dissertation, 174 p.
Kelsey, H.M., 1978, Earthflows in Franciscan mélange, Van Duzen River basin, California: Geology, v. 6, no. 6, p. 361–364.
Kiel, S., Campbell, K.A., Elder, W.P., and Little, C.T.S., 2008, Jurassic and Cretaceous gastropods from hydrocarbon seeps in forearc basin accretionary prism settings, California: Acta Palaeoecology Polonica, v. 53, p.679–703
Lachenbruch, A.H., and Sass, J.H., 1980, Heat flow and energetics of the San Andreas fault zone: Journal of Geophysical Research, v. 85, no. B11, p. 6185–6222.
Langenheim, V.E., Jachens, R.C., Morin, R.L. and McCabe, C.A., 2007, Preliminary gravity and magnetic data of the Lake Pillsbury region, Northern Coast Ranges, California: U.S. Geological Survey Open-File Report 2007-1368, 22 p.
Lanphere, M.A., Blake, M.C., Jr., and Irwin, W.P., 1978, Early Cretaceous metamorphic age of the South Fork Mountain Schist in the northern Coast Ranges of California: America Journal of Science, v. 278, p. 798–815.
Layman, E.B., 1977, Intrusive rocks in the near-trench environment—Two localities in the northern California Franciscan complex: California, Stanford University, M.S. thesis, 55 p.
Lehman, D.H., 1974, Structure and petrology of the Hull Mountain area, northern California Coast Ranges: Austin, University of Texas, Ph.D. dissertation, 126 p.
Lienkaemper J.J., and Brown, J.N., 2009, Preliminary investigation of factors affecting the seismic potential of the Bartlett Springs fault zone, northern California: Eos, Transactions, American Geophysical Union, v. 90, no. 52, Fall Meeting, Abstract S51B-1403.
Lucas-Clark, J., 2007, Lithosphaeridium too—Two new dinoflagellate cyst species from the Cretaceous of California: Palynology, v. 31, p. 205–217.
Mattinson, J.M., and Echeverria, L.M., 1980, Ortigalita Peak gabbro, Franciscan complex—U-Pb dates of intrusion and high-pressure low-temperature metamorphism: Geology, v. 8, p. 589–593.
Maxwell, J.C., 1974, Anatomy of an orogen: Geological Society of America Bulletin, v. 85, p. 1195–1204.
McLaren, M.K., Wooddell, K.E., Page, W.D., van der Elst, N., Stanton, M.A., and Walter, S.R., 2007, The McCreary Glade earthquake sequence—Possible reactivation of ancient structures near Lake Pillsbury, northern Coast Ranges,

Mendocino County, California: Eos, Transactions of the American Geophysical Union, v. 88, no.52, Fall Meeting Supplement, Abstract S21A-0245.

McLaughlin, R.J., Blake, M.C., Jr., Griscom, A., Blome, C.D., and Murchey, B., 1988, Tectonics of formation, translation, and dispersal of the Coast Range ophiolite of California: Tectonics, v. 7, no. 5, p. 1033–1056

McLaughlin, R.J., Ellen, S.D., Blake, M.C. Jr., Jayko, A.S., Irwin, W.P., Aalto, K.R., Carver, G.A., and Clarke, S.H., Jr., 2000, Geology of the Cape Mendocino, Eureka, Garberville, and southwestern part of the Hayfork 30 x 60 Minute quadrangles and adjacent offshore area, Northern California: U.S. Geological Survey Miscellaneous Field Studies Map, MF-2336, *http://geopubs.wr.usgs.gov/map-mf/mf2336/*.

McLaughlin, R.J., and Nilsen, T.H., 1982, Neogene non-marine sedimentation and tectonics in small pull-apart basins of the San Andreas fault system, Sonoma County, California: Sedimentology, no. 29, 865–876.

McLaughlin, R.J., and Ohlin, H.N., 1984, Tectonostratigraphic framework of The Geysers-Clear Lake Region, California, *in* Blake, M.C., Jr., ed., Franciscan geology of northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, Book 43, p. 221–254.

McLaughlin, R.J., Ohlin, H.N., and Thormahlen, D.J., 1990, Geologic map and structure sections of the Little Indian Valley-Wilbur Springs geothermal area, northern Coast Ranges, California: U.S. Geological Survey Map I-1706, 1 map, scale 1:24,000, structure sections, explanation and interpretive text (2 sheets).

McLaughlin, R.J., and Pessagno, E.A., Jr., 1978, Significance of age relationships above and below Upper Jurassic ophiolite in the Geysers-Clear Lake region, California: U.S. Geological Survey Journal of Research, v.6, p. 715–726.

McLaughlin, R.J., Sliter, W.V., Frederiksen, N.O., Harbert, W.P., and McCulloch, D.S., 1994, Plate Motions recorded in tectonostratigraphic terranes of the Franciscan Complex and evolution of the Mendocino triple junction area: U.S. Geological Survey Bulletin, 1997, 60 p, 29 figures, 3 tables.

Murchey, B.L., and Jones, D.L., 1984, Age and significance of chert in the Franciscan Complex in the San Francisco Bay region, *in* Blake, M.C. Jr., ed., Franciscan geology of Northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 43, p. 23–30.

Ohlin, H.N., McLaughlin, R.J., Oscarson, R.L., Peterson, D.M., and Weed, R.B., 1983, Mineral resource potential of the Black Butte and Elk Creek Roadless Areas, Mendocino, Lake, and Glenn Counties, California—Summary Report: Miscellaneous Field Studies Map MF-1544-A, scale 1:62,500, map and pamphlet, 9 p.

Ohlin, H.N., and Spear, R.J., 1984, Black Butte and Elk Creek Roadless Areas, California, *in* Marsh, S.P., Kropschot, S.J., and Dickinson, R.G., eds., Wilderness mineral potential—Assessment of mineral-resource potential in U.S. Forest Service Lands Studied 1964–1984: U.S. Geological Survey Professional Paper 1300, p. 181–184.

Page, N.J., Cassard, Daniel, and Haffty, Joseph, 1982, Palladium, platinum, rhodium, ruthenium, and iridium in chromites from the Massif du Sud and Tiebaghi Massif, New Caledonia: Economic Geology, v. 77, no. 6, p. 1571–1577.

Sliter, W.V., 1984, Foraminifers from Cretaceous limestone of the Franciscan Complex, northern California, *in* Blake, M.C., Jr., ed., Franciscan geology of northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 43, p. 149–162.

Snow, C.A., , Wakabayashi, J., Ernst, W.G., and Wooden, J.L., 2010, Detrital zircon evidence for progressive underthrusting in Franciscan metagraywackes, west-central California: Geological Society of America Bulletin, v. 122, no. 1/2, p. 282–291.

Suppe, John, and Armstrong, R.L., 1972, K-Ar dating of Franciscan metamorphic rocks: American Journal of Science, v. 272, p. 217–233.

Suppe, John, and Foland, K.A., 1978, The Goat Mountain Schists and Pacific Ridge Complex—A redeformed but still-intact late Mesozoic Franciscan schuppen complex, *in* Howell, D.G., and McDougall, Kristen, eds., Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 431–451.

Svarc, J., Murray-Moraleda, J., McFarland, F. Nishenko, S., and Page, W., 2008, Assessment of creep on the Bartlett Springs Fault using GPS and alignment array measurements: American Geophysical Union Fall Meeting 2008, abstract #S11A-1720.

Trask, P.D., 1950, Geologic description of the manganese deposits of California: California Division of Mines and Geology Bulletin 151, 378 p.

Trask, P.D., Wilson, I.F., and Simons, F.S., 1943, Manganese deposits of California—A summary report (including tabulated data on manganese properties of California), *in* Jenkins, O.P., ed., Manganese in California: California Division of Mines Bulletin 125, p. 51–215.

Wagner, D.L., and Bortugno, E.B., 1982, Geologic map of the Santa Rosa quadrangle: California Division of Mines and Geology Regional Geologic Map Series Map 2A, scale 1:250,000.

Wilson, D.S., McCrory, P.A., and Stanley, R.G., 2005, Implications of volcanism in coastal California for the Neogene deformation history of western North America: Tectonics, v. 24, p. 1–22, TC3008,doi:10.1029/2003TC001621.