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# Geologic map and structure sections of the Little Indian Valley - Wilbur Springs geothermal area northern Coast Ranges, California

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This report (map) is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS. Released in response to a Freedom of Information Act request.

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# INTRODUCTION

The purpose of this geologic map and accompanying structure sections (sheets 1 and 2) is threefold. First, we attempt to portray the complex geology and structure of the area and relate it to the regional tectonic framework. Second, the map and sections depict and establish the timing of different structural events and features associated with tectonic regimes before and after inception of strike-slip movement of the San Andreas fault system. Third, we attempt to relate the structure of the area to the probable occurrence of geothermal resources. The map and sections are a product of the Geothermal Research Program of the U.S. Geological Survey.

# SUMMARY

In the Little Indian Valley and Wilbur Springs areas of northern California, the structural relations of the Franciscan assemblage, Coast Range ophiolite, and Great Valley sequence place important constraints on the timing of juxtaposition of these tectonostratigraphic terranes. On this map we have delineated structures associated with pre-Tertiary tectonism and also structures associated with much later deformation of Pliocene and Pleistocene age. The later deformation has occurred since initiation of oblique strike-slip and tension tectonics associated with propagation of the San Andreas fault system. Potential geothermal resources in this area are related to pre-Tertiary and late Cenozoic structures.

In the map area, the upper plate of the Coast Range thrust consists of the Coast Range ophiolite, melange, and the Great Valley sequence. Locally, the highly disrupted Coast Range ophiolite of Jurassic age is part of a tectonic melange containing abundant clasts of ophiolitic material, mixed with mudstone and sandstone containing fossils of Late Jurassic age. These deformed rocks are bounded above by the Stony Creek(?) thrust zone. In the upper plate of the Stony Creek(?) thrust are Tithonian (Upper Jurassic) to Hauterivian(?) (Lower Cretaceous) strata (chert, ophiolitic breccia, conglomerate, sandstone, mudstone, and sedimentary serpentinite) of the Great Valley sequence. These strata, along with the deformed rocks below the Stony Creek (?) thrust, are folded around the southeast-plunging Wilbur Springs antiform. East of the map area, overlying Upper Cretaceous (Turonian and younger) rocks of the Great Valley sequence postdate deformation in the upper plate of the Coast Range thrust, which occurred between Valanginian (Early Cretaceous) and Cenomanian or Turonian (Late Cretaceous) time.

In the lower plate of the Coast Range thrust, Franciscan rocks are separated into two tectonostratigraphic terranes that are juxtaposed along the northwest-trending Bartlett Springs fault zone, probably by major Cenozoic right-slip movement. Franciscan rocks immediately beneath the thrust, in the core of the Wilbur Springs antiform, consist of the slaty argillite and metasandstone of Little Indian Valley. This terrane is separated into two subterranes based on degree of cataclasis of the metasandstone. The structurally lower, least reconstituted subterrane of Little Indian Valley contains numerous fossil mollusks of Late Jurassic (Tithonian) and Early Cretaceous (Valanginian) age. Both subterranes show axial-plane cleavages that indicate they were isoclinally folded at least twice. The rocks were then refolded a third time, with rocks in the upper plate of the Coast Range thrust, into open southeast-plunging folds. The metamorphic mineral

assemblage of these rocks includes pumpellyite and possible lawsonite of low blueschist facies. The age and deformational relation of the Franciscan rocks with coeval rocks in the upper plate imply that the argillite and metasandstone were folded, metamorphosed, and accreted to the Coast Range ophiolite between Valanginian and Cenomanian or Turonian time. This metamorphism, folding, and accretion were contemporaneous with deformation in the upper plate of the Coast Range thrust that included the formation of melange, imbricate thrusting, and protrusion on the sea floor of sedimentary serpentinite breccias.

Southwest of the Bartlett Springs fault zone, Franciscan rocks consist of metasandstone and tuffaceous meta-argillite, locally with conspicuous and abundant lenses of tuffaceous metachert and basaltic flows that are locally cut by mafic and keratophyric intrusive rocks. These rocks typically display moderate to strong cataclasis and conspicuous metamorphic mineral assemblages (albite+quartz+lawsonite±pumpellyite±crocidolite±aegirine±jadeite), indicating metamorphism to blueschist facies. This terrane of the Franciscan assemblage is similar and possibly correlative with Franciscan rocks referred to as the Yolla Bolly terrane (Blake and others, 1981). The metasandstone-metachert terrane of the map area displays evidence of at least three sets of folds, similar to the rocks northeast of the Bartlett Springs fault zone: (1) early-stage flattening of metasandstone detrital grains and associated axial-plane cleavage; (2) outcrop- to map-scale folding of the early cleavage into northeast- to northwest-trending isoclinal folds with axial-plane cleavage; and (3) later, broad, open map-scale folds and warps trending south-southeast to south-southwest. In the map area and near Clear Lake, the metacherts contain radiolarian faunas indicative of a Late Jurassic (Tithonian) and Early Cretaceous (possibly Aptian or Albian) age. North of the map area, a lithologically similar terrane of Franciscan rocks near Hull Mountain yielded Early Cretaceous (possibly Aptian or Albian) radiolarians (C. D. Blome, written commun., 1981), and metasandstones contain molluscan fossils of Cenomanian age (Blake and Jones, 1974). These relations and K-Ar data suggest that folding and metamorphism of the metasandstone-metachert terrane southwest of the Bartlett Springs fault zone occurred no earlier than Aptian or Albian time, and possibly much later (post-Cenomanian).

Sources of heat for geothermal resources in the Little Indian Valley-Wilbur Springs area are probably related to the Clear Lake Volcanics. The Wilbur Springs geothermal area lies on the southeast-plunging nose of the Wilbur Springs antiform, in the upper plate of the Coast Range thrust. Active hot springs, extensive hydrothermal alteration, and mercury-gold mineralization are evidence of present and past hydrothermal circulation. Reservoir permeability is provided (1) by two northwest-trending strike-slip fault zones, probably related to the San Andreas fault system, that converge in the Wilbur Springs area, along the crest of the antiform, and (2) by conjugate northeast-trending normal faults that straddle the converging strike-slip faults. Hydrothermal convection is enhanced in this area by concentrated fracturing and probable raised pore pressures along the crest of the antiform. A prominent negative gravity anomaly over the area is probably due largely to hot water in the open fracture network of the reservoir rocks. Nearby basaltic andesite of the Clear Lake Volcanics, dated at 1.66±0.08 m.y., may be a precursor to the present heat source beneath the area.

At Chalk Mountain northwest of Wilbur Springs, geothermal potential at depth may be indicated by active fumaroles, although thermal springs issuing from the base of Chalk Mountain are only about 20°C. The presence of young dacitic flows and intrusives there and nearby, along the Bartlett Springs fault zone, further suggest that geothermal potential may exist, perhaps beneath the Cache Formation of Pliocene and Pleistocene age.

## TERRANES FORMED BY PRE-TERTIARY ROCKS

### Upper plate of the Coast Range thrust

An extensive terrane of ophiolitic rocks, commonly referred to as the Coast Range ophiolite, is depositionally overlain in the map area by late Mesozoic rocks of the Great Valley province that are known as the Great Valley sequence (Bailey and others, 1964). The Great Valley sequence and Coast Range ophiolite form the upper plate of the complexly deformed Coast Range thrust. Largely coeval rocks of the Franciscan assemblage form the lower plate.

Upper plate of the Stony Creek(?) thrust

Coast Range ophiolite

Most of the Coast Range ophiolite in the map area consists of extensively sheared and serpentinized harzburgite and dunite, locally intruded by isolated or discontinuous bodies of gabbro and diabase or overlain by basalt flows, breccia, and tuff. No intact lower portion (ultramafic and cumulate ultramafic and mafic rocks) of the ophiolite section was found preserved in the map area. Tectonic inclusions or diapirs of underlying rocks belonging to the Franciscan assemblage are present in a few areas. A partly intact but abbreviated section of vesicular basalt flows that contains red radiolarian chert (Pessagno, 1977; Hopson and others, 1981) forms the upper part of the ophiolite near Eagle Rock (fossil loc. 41). Southeast of the Eagle Rock locality, faulted ophiolitic rocks consisting of gabbro at the base, overlain by mudstone, black to green radiolarian chert, and detrital(?) serpentinite, were described by Pessagno (1977, loc. NSF-917) as occurring in a northeast-trending tributary to Sulphur Creek near a hot spring. However, efforts to relocate this section were unsuccessful. Extensive intact ophiolite terranes elsewhere in the Clear Lake region were described by McLaughlin and Pessagno (1978) and also discussed by Hopson and others (1981). In these intact ophiolite terranes, the lower tectonized ultramafic section is locally overlain by cumulate ultramafic rock that is succeeded upward by cumulate gabbro, diabase sills, and (or) basaltic flows and flow breccia. Lenses of tuffaceous radiolarian chert are locally intercalated with the basalt flows. In the map area, no such intact section of ophiolite exists. Instead, the ophiolite is largely a tectonic melange, and only the upper basaltic part of the section is intact. The intact basaltic part is depositionally overlain by basal pelagic and terrigenous rocks of the Great Valley sequence.

The isotopic age of the Coast Range ophiolite, based on U-Pb dating of zircons in plagiogranites in the noncumulate gabbro section at numerous other Coast Range localities, ranges from about 153 to 170 m.y. (Mattinson, 1980; Hopson and others, 1981). K-Ar ages of 140-141 m.y. are reported for amphiboles from gabbroic inclusions (possibly dismembered dikes) within the tectonized ultramafic part of the Coast Range ophiolite near Wilbur Springs

(Maxwell, 1974). These ages are questioned by Hopson and others (1981), who suggest that the dated amphibole was a product of late uralitization associated with serpentinization.

East of the map area, Upper Cretaceous strata of the Great Valley sequence are thought to unconformably overlie ophiolitic rocks, based on the presence of a major northwest-trending positive magnetic anomaly whose source rocks are 2-2.5 km deep (Williams and Curtis, 1977; Cady, 1975). Along the crest of the magnetic anomaly, 55 km east of Wilbur Springs, augite and quartz-hornblende diorite have been encountered in oil and gas wells near Sutter Buttes, at depths between 6,500 and 6,900 feet (Williams and Curtis, 1977). Our inspection of thin sections of these rocks (University of California, Berkeley, collection 134) shows that the gabbro and quartz diorite have cumulate textures typical of ophiolitic rocks. The amphiboles in these rocks are actinolitic and occur as late or secondary minerals, probably the result of uralitic alteration. The gabbro is K-Ar dated at 136 m.y. and the quartz diorite at 138 m.y. (Williams and Curtis, 1977). However, these ages, which approximate the Valanginian Stage of the Lower Cretaceous, are probably maxiumum ages for the uralitic alteration. They can be interpreted as dating either the late stages of formation of Lower Cretaceous oceanic crust or some hydrothermal event (serpentinization?) associated with pre-Late Cretaceous tectonism. This late magmatic or hydrothermal event occurred at the same time that Valanginian and younger strata of the Great Valley sequence were being deposited west of Sutter Buttes. The K-Ar age of 140-141 m.y. from a gabbroic inclusion near Wilbur Springs (Maxwell, 1974) suggests that uralitization may have begun as early as Late Jurassic (Tithonian) time in that area. However, poorly understood complexities in the deep structure of the Sacramento Valley beneath the Great Valley sequence may preclude direct comparisons of ophiolitic rocks beneath Sutter Buttes with those of the Coast Range ophiolite.

The age of the upper part of the ophiolite in the map area was dated paleontologically by Pessagno (1977). In the vicinity of Eagle Rock northwest of Wilbur Springs (fossil loc. 41), pillowed vesicular basalt is interbedded with red manganiferous radiolarian chert containing a radiolarian fauna of Late Jurassic (early Tithonian) age (subzone 2B of Pessagno, 1977). At the nearby section described by Pessagno (1977, loc. NSF-917, above), chert is reported to grade downward into mudstone and sandstone, which in turn is in fault contact with the ophiolite. The chert is overlain by mudstone and detrital(?) serpentinite. Radiolarians from this locality are also of Late Jurassic (early Tithonian) age, but somewhat younger (subzone 2B to zone 3) than the fauna from locality 41, suggesting that the igneous ophiolitic rocks are no younger than subzone 2B in this area. North of the map area at Paskenta, the well-dated Coast Range ophiolite section is considerably older, since terrigenous strata of the Great Valley sequence overlie the ophiolitic rocks, and contains subzone 2A and older radiolarian fauna (Hopson and others, 1981; D. L. Jones, oral commun., 1981). These important differences in the ages of pelagic and terrigenous sections in the Wilbur Springs and Paskenta areas, together with the highly disrupted aspect of the ophiolitic rocks in the Wilbur Springs area, suggest that the late stage of Coast Range ophiolite evolution was complex. Off-ridge seamount volcanism following formation of the ophiolite, as proposed by Hopson and others (1981) for basalts to the north at Stonyford, and even late imbricate thrusting in the upper plate of the Coast Range thrust may account for part of these age differences.

## Great Valley sequence

Approximately 7,000 ft of the Upper Jurassic (Tithonian) through Lower Cretaceous (Hauterivian?) section of the Great Valley sequence underlies much of the eastern and southeastern parts of the map area. The base of the Great Valley sequence is mapped at the first appearance of terrigenous sedimentary rocks that directly overlie the igneous section of the Coast Range ophiolite and (or) tuffaceous cherts in the upper part of the igneous section. Locally this contact is depositional, but in most places in the map area depositional relations are obscured by later shearing and faulting. Terrigenous rocks at the base vary from tuffaceous mudstone and basaltic sandstone to coarse sedimentary breccia. The breccia typically is composed of basalt, diabase, gabbro, and minor plagiogranite detritus derived from the underlying ophiolite. At a few localities black to green tuffaceous radiolarian chert is intercalated with the basal mudstone and sandstone.

Coarse breccias of ophiolite detritus and associated basaltic sandstones are widespread in the northern Coast Ranges, from Paskenta to the Geysers-Clear Lake region and as far south as Lake Berryessa, but they do not occur in the Diablo Range (Blake and others, 1982). The breccias are channeled or downfaulted into the upper parts of the Coast Range ophiolite in the Geysers-Clear Lake area (McLaughlin and Pessagno, 1978). These breccias may represent talus shed from the ophiolite that accumulated at the base of submarine fault scarps (McLaughlin and Pessagno, 1978; Hopson and others, 1981). The breccias possibly are deep-ocean equivalents of fault-scarp breccias deposited along the fault margins of some well-studied marine and nonmarine pull-apart basins of the Coast Ranges. They may thus provide evidence of sedimentation penecontemporaneous with basin-margin uplift along the west side of the Great Valley sequence. By this model the depositional basin of the Upper Jurassic and Lower Cretaceous part of the Great Valley sequence may have formed through oblique rifting, similar to that in the Gulf of California.

The basal beds of the Great Valley sequence typically grade up into thin-bedded black to green turbiditic mudstones and siltstones (basin plain and (or) slope facies), with abundant interbedded carbonate concretions and lenses. A few thick lenses of pebble to cobble conglomerate with abundant well-rounded clasts of quartzite, vein quartz, and chert are also locally present within the Upper Jurassic (Tithonian) mudstones. Conspicuous fine- to coarse-grained, thin- to thick-bedded lenses of lithic sandstone of Late Jurassic (Tithonian) to Early Cretaceous (Valanginian) age, containing abundant intermediate volcanic detritus, chert, and felsite, are widespread in a major synclinal fold southwest of Wilbur Springs and along Rocky Ridge north of Chalk Mountain, approximately 0 to 1,500 ft above the base of the terrigenous section.

Detrital serpentinite occurs at several stratigraphic horizons in the Great Valley sequence in the map area, especially in the vicinity of Wilbur Springs. These units vary in texture from thin-bedded fine-grained turbiditic serpentinite sandstones to coarse debris-flow breccias. Clasts of other ophiolitic lithologies also occur in these serpentinites, including gabbro cumulates and basalt (Carlson, 1981). Occurrences of garnet amphibolite, blueschist, greenschist, and metachert clasts were also found in the serpentinite breccias (Carlson, 1981). These lithologies are found as large blocks in melange of the Central terrane of the Franciscan assemblage, many tens of kilometers west of the map area. The temperature and pressure conditions implied by the clasts in these sedimentary serpentinite breccias suggest a provenance that included subducted rocks, lower crust, and upper mantle rocks. The occurrence of these clasts in the sedimentary serpentinite breccias is possibly the result of diapirism and protrusion of upper mantle and lower crustal material onto the sea floor during Late Jurassic and Early Cretaceous (Neocomian) time (Carlson, 1981).

Numerous fossils from localities in the map area indicate that the Great Valley sequence ranges in age from Late Jurassic (early Tithonian) to Early Cretaceous late Neocomian, possibly Hauterivian. Radiolarians from tuffaceous chert interbedded with mudstone near the base of the terrigenous section are of early Tithonian (subzone 2B to zone 3) age (Pessagno, 1977). Overlying strata contain abundant mollusks (Buchia sp.) indicative of ages between the middle Tithonian (Late Jurassic) and Valanginian (Early Cretaceous) (table 1 and fossil localities on geologic map). Several occurrences of the brachiopod Peregrinella Whitneyi (Gabb) have been found in calcareous reef-like lenses in detrital serpentine, structurally below the Tithonian and Valanginian part of the section. These fossils indicate a latest Neocomian age, no older than Hauterivian, and suggest that this part of the section may be imbricated by unmapped thrusts which are younger than Hauterivian, but older than the Wilbur Springs antiform, and possibly associated with the Stoney Creek thrust.

One additional fossil locality of interest in strata of the Great Valley sequence is at the dam site at the south end of Little Indian Valley (fossil loc. 32). At this locality, a specimen of Inoceramus sp. of probable Late Cretaceous age and numerous intermixed broken fragments of Buchia sp. of Late Jurassic or Early Cretaceous age were collected from highly sheared mudstone within a southwest-dipping fault zone with probable reverse and strike-slip components. The tectonically mixed rocks at this fossil locality suggest that since Late Cretaceous time rocks that were initially at least several kilometers apart have been juxtaposed along the fault zone. Other intact Great Valley sequence strata of Late Cretaceous age are south and east of the map area.

Lower plate of the Stony Creek(?) thrust

Melange of Grizzly Creek

An extensive tectonic melange, incorporating rocks of the Coast Range ophiolite and the Great Valley sequence, is conspicuous beneath the southwest exposures of the Great Valley sequence west of Walker Ridge and the lower part of the Great Valley sequence exposed along Rocky Ridge. It is well exposed northwest and southeast of California Highway 20 and along Grizzly Creek southwest of Wilbur Springs. This melange is not to be confused with the sedimentary breccias of ophiolite debris, discussed earlier, that structurally overlie the tectonic melange or are locally incorporated into it. Tectonic melange below the base of the Great Valley sequence has a regional distribution similar to the sedimentary breccias. We have recognized the melange from Paskenta to as far south as Lake Berryessa, but its extent beyond these areas is unknown. In the Rocky Ridge area, this melange is composed largely of ophiolitic rocks (gabbro cumulates, diabase, basalt, diabase breccia) and less abundant Buchia-bearing mudstone, sandstone, and conglomerate, engulfed in a matrix of penetratively sheared serpentinite.

However, southwest of Walker Ridge, abundant large sheared masses of Tithonian shale (fossil locs. 2, 3, 5, and 6) with brittle deformed carbonate lenses are fully involved in the melange, in addition to sheared blocks of diabase, diabase breccia, gabbro, and serpentinite. In this area the melange of Grizzly Creek is largely confined to a plate between the Coast Range thrust and a structurally higher thrust (exposed along California Highway 20 west of Gibson Hill) that is possibly part of the Stony Creek thrust zone (Brown, 1964). Long-term melange formation penecontemporaneous with formation of the ophiolite and sedimentation of the Great Valley sequence seems unlikely in the map area due to a lack of evidence for ductile or soft-sediment deformation in the incorporated Great Valley strata. Rather, there is abundant evidence of brittle shearing, suggesting that the deformation occurred sometime after lithification in post-Neocomian time, either as distributed deformation between imbricate fault slices or, possibly, during decollement. This deformation may have occurred during accretion of the various terranes of the Franciscan assemblage in the lower plate of the Coast Range thrust. Less pronounced shearing is also evident in the rocks overlying this structurally higher thrust, in strata of Valanginian age (fossil loc. 4), indicating that the melange formed after Valanginian time. This observation is in direct conflict with the proposal of Hopson and others (1981) that ophiolite melange in the Elder Creek and Paskenta areas formed prior to the Tithonian.

## Lower plate of the Coast Range thrust

### Franciscan assemblage

Deformed rocks assigned to the Franciscan assemblage structurally underlie the Coast Range ophiolite in the north-central part of the map area. They also form the basement terrane southwest of the Bartlett Springs fault zone. The various structural units of the Franciscan assemblage in the map area are subdivided according to their lithologic character, degree of textural metamorphism, and nature of bounding contacts.

### Argillitic rocks of Little Indian Valley

Beneath the Coast Range thrust, two units composed mainly of argillite and minor metasandstone occupy the north-central part of the map area, most prominently in the vicinity of Little Indian Valley. Both of these units display pronounced slaty axial-plane cleavage and isoclinal to recumbent folds that generally plunge east-southeast to south-southeast. Most of these rocks are only slightly reconstituted texturally (textural zone 1 of Blake and others, 1967), but locally thin thrust-bounded sheets of phyllite and slate (low to high textural zone 2 of Blake and others, 1967) occur high in the section, close to the Coast Range thrust, and elsewhere in a few fault-bounded patches. The slightly reconstituted slaty argillites and metasandstones (textural zone 1) contain chlorite and pumpellyite; the more highly reconstituted rocks (textural zone 2) locally may contain trace amounts of incipient lawsonite in addition to pumpellyite and chlorite. The identification of lawsonite, however, is questionable, due to the extremely fine grain size and poorly defined petrographic properties of the mineral presumed to be lawsonite in these rocks. The argillites and arkosic sandstones commonly are calcareous and may contain minor bioclastic detritus (shell fragments). Some of the calcite in the carbonate assemblages locally is converted to aragonite. Conspicuous detritus derived from intermediate volcanic (andesitic) and plutonic rocks, chert, and felsite are also present, along with chloritized biotite, white mica, and minor fibrous green to brown amphibole. Minor lenticular to blocky masses of basalt flows, tuffs, intrusive rocks, limestone, and chert occur sporadically in these units. Some occur as rare large clasts or sheared lenses within intact argillite or metasandstone; others occur as clasts within a unit of melange near Little Indian Valley reservoir.

Molluscan fossils occur at numerous localities in silicified nodular carbonate concretions from slightly reconstituted Franciscan argillites underlying ridges east and west of Little Indian Valley Reservoir (fossil locs. 15, 16, 17-19, 21-23, and 24-26). The molluskan faunas consist chiefly of Buchia sp., and a few gastropods (loc. 26), indicative of Late Jurassic (middle Tithonian) through Early Cretaceous (Valanginian) ages. A partial ammonite of indeterminate age was also collected from these rocks (loc. 20).

It is noteworthy that the Franciscan argillitic rocks of Little Indian Valley are similar in lithology and age to rocks of the terrigenous section of the Great Valley sequence in the upper plate of the Coast Range thrust. The local lithologic similarities in rocks above and below the Coast Range ophiolite in the Wilbur Springs area led Taliaferro (1943) to propose a gradational, depositional relation between the Franciscan and "Knoxville" (Late Jurassic) part of the Great Valley sequence. However, Taliaferro failed to recognize the significance of: (1) the metamorphism and deformation of rocks below the Coast Range ophiolite; (2) the tectonic contact at the base of the ophiolite; (3) the depositional relations of rocks overlying the ophiolite; and (4) the youngest rocks beneath the Coast Range ophiolite, which are Early Cretaceous (Valanginian) rather than Late Jurassic in age in this area. He believed the ultramafic part of the ophiolite section to be intrusive everywhere into the upper part of the Franciscan and lower part of the "Knoxville".

Suppe and Foland (1978) reported the occurrence of Franciscan rocks near Goat Mountain, approximately 15 km northwest of the map area, that are similar to the Franciscan argillite and metasandstone of Little Indian Valley in lithology, metamorphic grade, and structural position and, therefore, may be correlative. They reported the presence of Buchia sp. of Tithonian and Valanginian age in a chaotic part of the unit and K-Ar whole-rock metamorphic ages of 135-137 m.y. for highly metamorphosed slaty to phyllitic parts of the unit. If the whole-rock metamorphic ages accurately date metamorphism, parts of the unit near Goat Mountain may have been metamorphosed to slate and phyllite at the time that rocks of the chaotic part were being deposited. Juxtaposition of the slate and phyllite with the chaotic rocks apparently occurred in post-Valanginian time.

The depositional ages of Franciscan rocks in Little Indian Valley indicate that they were accreted beneath the base of the Coast Range ophiolite and Great Valley sequence no earlier than latest Valanginian time and possibly much later in the Cretaceous (that is, as recently as Cenomanian time). This accretion may have triggered the extensive shearing and formation of the melange of Grizzly Creek, in the upper plate of the Coast Range thrust, that appears to span the same time frame.

Metasandstone, metachert, and metabasalt

Southwest of Little Indian Valley Reservoir, a unit composed chiefly of metamorphosed sandstone with abundant lenses of metamorphosed tuffaceous chert, vitric tuff, and basalt structurally overlies the argillitic rocks of Little Indian Valley. The metasandstone, metachert, and metabasalt unit does not appear beneath, and is apparently cut out by, the Coast Range thrust in the core of the Wilbur Springs antiform. However, this unit underlies the entire area southwest of the Bartlett Springs fault zone. Its absence in the core of the Wilbur Springs antiform suggests that the metasandstone and metachert along the southwest limb of the Wilbur Springs antiform are juxtaposed with respect to rocks to the northeast, perhaps in response to major strike-slip movement along the Bartlett Springs fault zone.

Metasandstone in this unit is reconstituted to the low to high textural zone 2 of Blake and others (1967) and, in contrast to the metasandstones of the Little Indian Valley unit, it commonly contains conspicuous lawsonite, in addition to pumpellyite, chlorite, and phengitic white mica. The metachert and metatuff locally display conspicuous concentrations of dark-blue amphibole (crocidolite) alined along bedding. The metachert generally is extensively recrystallized, but relict compressed radiolarians are usually visible. The metabasaltic rocks consist of pillowed flows, flow breccia, and aquagene tuff that locally contain conspicuous blue amphibole, lawsonite, and pumpellyite and, rarely, aegirine or jadeitic pyroxene.

West of the map area, part of the metasandstone, metachert, and metabasalt unit is a melange. This melange contains large blocks of blue amphibole- and white mica-bearing meta-igneous rocks, in addition to blocks of other less metamorphosed mafic rocks, metachert, and metatuff, dispersed in a matrix of lawsonitic metasandstone. Southwest of the Bartlett Springs fault, an undetermined part of the area mapped as metachert and metasandstone is melange.

The distinctive lithologic character of the metasandstone, metachert, and metabasalt unit and its blueschist-grade metamorphism led Blake and others (1981, 1982) to call it the Yolla Bolly terrane. Part of these rocks were named the Yolla Bolly Formation by Worrall (1981).

The metasandstone, metachert, and metabasalt unit of the map area is traceable to the southeast nearly to Lake Berryessa. To the west, the unit is traceable as far as the east side of Middle Mountain, where it is truncated by a broad steep-dipping melange belt marking the east side of the central belt of the Franciscan assemblage. Large tectonic slabs of metachert-metasandstone are imbricated into the central Franciscan belt in the Geysers area southwest of Clear Lake (McLaughlin, 1978, 1981; McLaughlin and others, 1981).

In spite of similarities in age, lithology, metamorphic grade, and the timing of metamorphism, original continuity between the various occurrences of metasandstone and metachert (Yolla Bolly terrane of Blake and others, 1982) in the Coast Ranges cannot be demonstrated. In each occurrence the metasandstone and metachert are complexly juxtaposed with other unrelated Franciscan terranes along steep and low-angle faults. For example, on this map we have interpreted the metasandstone and metachert as structurally overlying the argillitic rocks of the Little Indian Valley unit. In the Geysers area, the metasandstone and metachert are tectonically interleaved with melange and intact graywacke of the Franciscan central belt. The processes involved in accretion and juxtaposition of the various occurrences of the metasandstone, metachert, and metabasalt unit and dissimilar Franciscan rocks are poorly understood, but they may have involved large-scale fragmentation and northward translation along broad zones of right-lateral shear.

Radiolarians recovered from the metacherts interbedded with the metasandstone and metavolcanic rocks near Clear Lake (R. J. McLaughlin, unpub. data, 1982) suggest a Late Jurassic (Tithonian) to Early Cretaceous (possibly Aptian or Albian) age. This age span encompasses the range in depositional ages of the lithologically similar, possibly correlative metasandstone-metachert terranes elsewhere in the Coast Ranges. Suppe (1973) dated the metamorphism of metasandstone associated with metachert from localities north of Clear Lake and from the eastern Diablo Range to the south and found them to yield whole-rock K-Ar ages of approximately 89-112 m.y. (about Turonian to Albian), suggesting that deposition was earlier than middle-Late Cretaceous (about Turonian). Mattinson and Echeverria (1980) described occurrences near Ortigalita Peak in the Diablo Range that are at least in part Late Jurassic (Tithonian, subzone 2B), based on radiolarian assemblages in the metacherts. Blake and others (1981) reported Tithonian radiolarian assemblages from metachert and Valanginian mollusks (Buchia) from metasandstone of the Yolla Bolly area. In the Hull Mountain area, the metachert has yielded Early Cretaceous (possibly Aptian or Albian) radiolarians, and overlying metaclastic rocks cut by metamorphosed basaltic intrusive rocks contain even younger molluscan fossils, of Cenomanian age (Blake and Jones, 1974; C. D. Blome, written commun., 1982).

In the Diablo Range, U-Pb dating (Mattinson and Echeverria, 1981) indicates that deposition of the metasandstone, metachert, and metabasalt unit predated a fold event that was followed by intrusion of gabbro 95 m.y. ago (about Albian-Cenomanian time) and by a single event of metamorphism to blueschist grade about 92 m.y. ago (about Turonian time). Published whole-rock K-Ar ages on the metasandstone, metachert, and metabasalt unit (Suppe, 1973; Suppe and Armstrong, 1972; Lanphere and others, 1978) suggest either two discrete periods of metamorphism or more or less continuous blueschist metamorphism between about Albian (about 112 m.y. ago) and Turonian (about 89 m.y. ago) time, penecontemporaneous with deposition and deformation. During high-pressure low-temperature metamorphism, incomplete recrystallization can occur, such that metasandstones of the same textural grade are recrystallized to varying degrees, depending upon original grain size. Resultant whole-rock K-Ar dates are somewhere between the true metamorphic age and the aggregate age of the detrital sources. Thus whole-rock K-Ar ages of metasandstones probably should be regarded only as maximum metamorphic ages. On the other hand, metamorphic ages based on U-Pb dating of sphene presumably record the ages of minerals that crystallized in conjunction with high-pressure metamorphism (Mattinson and Echeverria, 1981). The U-Pb ages may, therefore, be more reliable indicators of metamorphism. However, this constraint does not preclude the possible occurrence of more than one blueschist metamorphic event.

The timing of accretion of the metasandstone, metachert, and metabasalt unit to the Franciscan assemblage of northern California is imprecisely known, due to the uncertainty of correspondence between deformation structures in the metasandstone, metachert, and metabasalt unit and the argillitic Franciscan rocks of the Little Indian Valley area.

Metamorphosed ultramafic rocks

Lense-shaped slivers of serpentinized ultramafic rock, metamorphosed to chlorite±actinolite±talc±antigorite±glaucophane schist occur locally along fault zones cutting rocks of the Franciscan assemblage. These rocks are exposed in Bartlett Springs SE 7 1/2' quadrangle, along the road between Walker Ridge and Little Indian Valley, in secs. 9 and 10, T. 14 N., R. 6 W., and along a prominent splay of the Cross Spring fault zone in Sweet Hollow Creek canyon, in the road cuts of California Highway 20, NW1/4 of sec. 2, T. 13 N., R. 7 W. The serpentine mineral assemblage and local presence of glaucophane in these rocks indicate that the unit has undergone metamorphism to blueschist facies. However, original relations to the adjacent Franciscan rocks are unclear because of faulting.

## FOLDING

### Folds in Late Mesozoic rocks

Little Indian Valley to Wilbur Springs

At least three sets of folds are recognized in the area from Little Indian Valley to Wilbur Springs. Two sets were generated in post-Valanginian time, prior to emplacement of the Franciscan rocks of the Little Indian Valley area beneath the Coast Range thrust. In the weaker reconstituted Franciscan rocks (textural zone 1 to low zone 2), an early isoclinal fold generation (F-1) is locally recognized. In the slates and phyllites reconstituted to textural zones 2 to 3, a prominent low-angle, northwest-oriented slaty parting (S-1) at a low angle to the bedding also defines the axial plane of an early (F-1) fold generation. However, the relations of the folds defined by this early slaty cleavage to the similarly oriented folds in less reconstituted rocks is uncertain. The S-1 cleavage is folded into a second set of upright to recumbent, generally northeast- to southeast-plunging isoclinal folds (F-2) with prominent northwest-trending axial-plane cleavage (S-2). The intersection of this cleavage with S-1 and slip along S-1 and S-2 cleavages may produce crenulations on either the S-1 or S-2 planes.

The F-2 folds are truncated by the Coast Range thrust, and no axial-plane cleavage is recognized in the ophiolitic rocks or overlying Great Valley sequence in the upper plate of the thrust. However, a late generation of folds (F-3) postdates F-1, F-2, and the juxtaposition of Franciscan rocks in Little Indian Valley with rocks in the upper plate of the Coast Range thrust. The F-3 folds occur as broad to tightly appressed, N. 30°-45° W. trending, east- to southeast-plunging folds that cause the northwest trends of the F-2 axial planes to fan out in the direction of plunge of the F-3 folds and cause S-2 axial cleavages to dip toward F-3 anticlinal axes. The northwest-trending F-3 folds affect rocks in the upper and lower plates of the Coast Range thrust in the map area, producing the major anticlinal and synclinal folds of the Wilbur Springs and Grizzly Creek areas. The F-3 folds involve rocks as young as Cenomanian east of the map area (Rich, 1971). Upper Cretaceous rocks (Turonian to Campanian) unconformably overlap the more highly folded middle Cretaceous and older rocks of the Great Valley sequence, suggesting that the initial F-3 folding may have occurred in Cenomanian-Turonian time. It is probable that fold growth continued or was renewed later in the Cenozoic, in response to northeast-oriented compression related to right-lateral slip within the San Andreas tectonic province.

### Southwest side of Bartlett Springs fault zone

Southwest of the Bartlett Springs fault zone, Franciscan rocks have also been subjected to at least three generations of folding. Since these folds are poorly exposed in the map area, our conclusions here are based in part upon observations from somewhat better exposures in the adjacent area around the shoreline of Clear Lake. There, the earliest discernible folds (F-1) are evident locally at outcrop scale in metachert, where primary bedding (S) is folded into isoclinal and recumbent folds with refolded axial planes (S-1) that trend N. 46° E. to N. 75° W. The F-1 folds are refolded by a later, more commonly evident asymmetric isoclinal fold set (F-2), defined by northeast- to northwest-trending axial planes (S-2) that generally cut steeply across F-1. A third set of north- to northwest-trending, large-wavelength folds (F-3) are suggested by divergence of S-2 axial planes and changes in plunge directions of F-2 folds.

The metachert units are folded into early large-wavelength map-scale folds (F-1) that are upright to recumbent, or disharmonic. These folds have approximately N. 20°-40° W.-trending axial traces and, together with superimposed secondary folds, correspond to the F-1 and F-2 folds seen in outcrop. Later, broad, open, south-southeast- to south-southwest-trending warps, probably corresponding to F-3, are defined by broad deflections in the northwest-trending F-1 fold axes.

The timing of folding southwest of the Bartlett Springs fault zone is not easily related to that of folding of the Franciscan rocks to the northeast, even though both areas have experienced at least three generations of folding. Depositional and metamorphic ages (discussed earlier) suggest that folding of the metasandstone, metachert, and metabasalt unit occurred during two or more deformational events following the Aptian or Albian (less than about 134 m.y. ago). At least some of this folding may have occurred as late as post-Cenomanian time (post-92 m.y. ago).

## Folds in Cenozoic rocks

The Pliocene and Pleistocene Cache Formation, exposed in a large structural basin between the north fork of Cache Creek and California Highway 20, is folded into broad, open, low-amplitude warps that trend N. 30°-50° W., between the main faults of the basin margins. Small-scale east-oriented synclinal folds are also evident in local strata of the Cache which have been downdropped or compressed between minor normal faults. The folds are of Pleistocene age and formed in response to northeast-oriented compression accompanying uplift and right-lateral strike-slip movement along faults bounding the southwest and northeast sides of the depositional basin of the Cache Formation. The orientation of these Pleistocene folds is similar to that of the older F-3 fold set in late Mesozoic rocks to the northeast, suggesting that some late Cenozoic folding could be overprinted upon the earlier Late Cretaceous (F-3) folds.

## FAULTING

### Coast Range thrust and Stony Creek(?) thrust

The Coast Range thrust is a highly deformed, high- to low-angle, east-dipping regional thrust. Everywhere in the Coast Ranges, this thrust separates rocks of the Coast Range ophiolite and Great Valley sequence in the upper plate from those of the Franciscan assemblage in the lower plate (Bailey and others, 1970). As elsewhere in the Coast Ranges, the Coast Range thrust in this map area is extensively modified by later faulting and folding. The sole of the thrust is marked in most of the area by a thick sheet of highly to moderately sheared serpentinite derived from the Coast Range ophiolite. Inclusions of underlying Franciscan rocks are locally engulfed in the serpentinite. Southeast of Little Indian Valley, the Great Valley sequence overlies Franciscan rocks along a folded thrust that we tentatively correlate with the Coast Range thrust. However, the rocks immediately above this basal thrust consist of a melange of ophiolitic rocks, sheared and mixed together with mudstone and sandstone of the Great Valley sequence. The top of the disrupted Great Valley and ophiolite section is bounded by a structurally higher zone of thrusts that corresponds to the Stony Creek fault zone (Rich, 1971; Brown, 1964), which is probably coeval with or postdates emplacement of the Coast Range thrust. Coast Range and Stony Creek thrusting postdated Valanginian time and either postdated or accompanied at least two generations of folding and metamorphism in Franciscan rocks of Little Indian Valley. Later folding of these thrusts around the southeast-plunging Wilbur Springs antiform in Cenomanian-Turonian time established an upper limit for Coast Range and Stony Creek thrusting.

Large vertical and horizontal displacements of many tens to hundreds of kilometers across the Coast Range thrust are indicated by the contrasting metamorphic grades and deformational histories of rocks above and below the Coast Range thrust. Similarly, major movement of undetermined amount on the Stony Creek thrust is suggested by extensive disruption and imbrication of rocks between the Stony Creek and Coast Range thrusts.

### Bartlett Springs fault zone

A major northwest-trending, steep-dipping fault zone as much as 1 km wide, that diagonally bisects the Bartlett Springs SE 7 1/2' quadrangle, is here named the Bartlett Springs fault zone. On the basis of our reconnaissance and Jennings' map, (1977) the fault zone is traceable northwestward for at least 120 km, to the south side of Round Valley. North of Round Valley, the Lake Mountain fault zone of Herd (1978) may be the continuation of the Bartlett Springs fault zone. The fault zone was first delineated southeast of Lake Pillsbury by Irwin (1960) and by Etter (1979) later, who named it the Hot Springs shear zone in that area. Immediately southeast of the area of this map, the Bartlett Springs fault zone corresponds in part to the Wilson, Kennedy, and Hunting faults, mapped by Lawton (1956). The Wilson fault of Lawton and its extension is traced southeast for at least 25 km, to the vicinity of Knoxville (Lawton, 1956; Irwin, 1960; Jennings, 1977). It probably connects with, or steps southeastward to, the north end of the Green Valley fault zone, another 15 km southeast of Knoxville, near Lake Berryessa. The Green Valley fault zone connects with the active Concord-Hayward-Calaveras faults, extending the zone for about 300 km southeastward from Lake Berryessa to the main San Andreas fault near Hollister, Calif. Thus, the Bartlett Springs fault zone is part of a major zone of right-slip that is at least 460 km long and is associated with the San Andreas fault system.

Within the map area, the Bartlett Springs fault zone offsets fluvial deposits of the Pliocene (Blancan) and Pleistocene Cache Formation. The Cache Formation is overlain and intruded along the fault zone by volcanic rocks of the Clear Lake Volcanics. These volcanic rocks include early basalt and later dacite of Chalk Mountain (B. C. Hearn, J. Donnelly-Nolan, and F. E. Goff, unpub. mapping, 1982). The basalts are correlated with other early basalts of the Clear Lake Volcanics dated at about 1.4-2.0 m.y. Similar basalts at nearby Schoolteacher Hill, outside the map area, and Coyote Peak near Wilbur Springs, have K-Ar dates of 1.66 m.y. The dacite of Chalk Mountain is probably of Jaramillo or early Brunhes age (Donnelly-Nolan and others, 1981; see discussion of Clear Lake Volcanics in map explanation). Shearing and hydrothermal alteration of the volcanic rocks indicate that the latest faulting is younger than 2.0 m.y. and possibly younger than 0.7 m.y., based on normal polarity of the dacite of Chalk Mountain.

The rake of slickensides on fault surfaces, the offsets and truncations of rock units, and a 610-m jog to the east in Cache Creek near Chalk Mountain indicate that the sense of slip along the Bartlett Springs fault zone is normal, down to the west, and has a locally prominent component of right-slip movement. Apparent post-Blancan vertical offsets of at least 2 m along the east side of the Cache Formation are locally evident along numerous subparallel traces of the fault zone in Benmore Canyon. The rakes of slickensides in caliche deposited by ground water along these faults show that the fault slip had both vertical and horizontal slip components. Maximum lateral offset of rocks predating the Cache Formation is undetermined. However, the juxtaposition of distinctly different units of the Franciscan assemblage across the fault zone suggests that lateral slip may be large--possibly as much as tens of kilometers or more. Maximum vertical displacement could be greater than 1.5 km down to the southwest, based on estimates of total thickness of the Cache Formation (Rymer, 1981; Brice, 1953), whose basin of deposition is structurally bounded on the northeast by the Bartlett Springs fault zone.

Northwest of the map area, geomorphologic evidence of Holocene faulting along the Lake Mountain fault zone has been presented by Herd (1978). Southeastward from Round Valley the continuation of this fault zone is marked by alinement or offset of numerous linear geomorphologic features such as elongate ridges, drainages and saddles, and alinement of thermal and nonthermal springs. Features such as prominent alined sag ponds, indicative of intensive late Pleistocene or Holocene surface faulting, have not been seen between the south end of Lake Pillsbury and the map area or between the map area and the north side of Lake Berryessa. However, such features are prominent along the Green Valley fault zone southeastward from Lake Berryessa. A 460-km-long fault zone, collectively composed, from south to north, of the Calaveras, Hayward, Concord, Green Valley, Bartlett Springs, Hot Springs, and Lake Mountain faults, has a most probable seismic capability, based on one-half the fault length (Mark, 1977), of an earthquake with a Richter magnitude of 7.9.

## Cross Spring fault

This steep-dipping normal fault bounds the Cache Formation on the west and merges with the Bartlett Springs fault zone in the vicinity of Wolf Creek, in the northwest corner of Bartlett Springs SE 7 1/2' quadrangle. Slip on the Cross Spring fault is normal and down to the east, forming the west boundary of the structural basin in which strata of the Cache Formation were deposited. Total vertical slip is unknown.

## Little Indian Valley fault zone

This 1.5-km-wide zone of steep, southwest-dipping to vertical faults crosses the north fork of Cache Creek at the south end of Little Indian Valley Reservoir. From southeast to northwest, the fault zone varies in trend from about east-west to about N. 30° W. Individual fault strands are superimposed on contacts between the lower and upper plates of the Coast Range thrust or follow the structural grain of Franciscan or Great Valley rocks along the southwest side of the Wilbur Springs antiform. Along the road from Walker Ridge to Little Indian Valley Reservoir, the fault zone is marked by lenticular zones of disrupted and sheared Great Valley sequence, Franciscan rocks, serpentinite, and silica-carbonate rock. Prominent southwest-dipping fault strands are exposed in cuts on the west side of the Cache Creek canyon at Little Indian Valley Dam. To the southeast, along Walker Ridge, subsidiary fault strands exhibit reverse offsets of the order of 1 m or less in strata of the Great Valley sequence. Larger strike-slip offset may have occurred along some of the faults that exhibit zones of pervasive crushing and shearing at least 2 m wide in this area. Major discontinuous splays of the Little Indian Valley fault zone apparently merge with the Resort fault zone north of Eagle Rock and southeast of the Elgin mine and Cherry Spring, in the Wilbur Springs SW 7 1/2' quadrangle. Thermal springs, hydrothermal alteration, and numerous mercury prospects and mines along or adjacent to the Little Indian Valley fault zone between Signal Rock and Cherry Spring suggest that the fault zone may have provided important conduits for circulation of geothermal fluids and for hydrothermal-related mineralization in the area.

No evidence of recent surface faulting is seen along the Little Indian Valley fault zone. However, the association of the fault zone with thermal springs and hydrothermal alteration indicates that motion has been recent enough to maintain open fractures. Observed reverse-slip is also compatible with the present north- to northeast-orientation of maximum regional compression (Bufe and others, 1981). The branching relation to the Resort fault zone suggests that most recent fault activity could be Pleistocene in age (see below). Maximum age of faulting is unknown.

## Resort fault zone

Part of the Resort fault zone, along the northeast limb of the Wilbur Springs antiform, was first mapped and named by Lawton (1956) and later included on the map of Rich (1971). This northwest-trending fault zone extends between the northwest and southeast corners of Wilbur Springs SW 7 1/2' quadrangle. The fault zone is 2 km wide, trends N. 30°-40° W., and consists of numerous straight north-northwest- to north-northeast-trending, steep-dipping faults that offset the Coast Range ophiolite and Great Valley sequence. Observed offset is largely normal block-type faulting, but the fault-zone orientation and the orientations of individual fault traces within the zone suggest that right slip and minor left slip were also important. Lawton (1956) estimated maximum vertical offset along the Resort fault zone to be 1,500-2,000 ft (456-610 m). Apparent right-lateral offset of sedimentary serpentinites of as much as 2 mi (3.2 km) in the Great Valley sequence is evident along the Resort fault zone in the southeast part of the map area.

The Resort fault zone was mapped on the basis of shearing and truncation of rock units, alined thermal springs, travertine deposits, and silica-carbonate rock. Northwest of Wilbur Springs resort, where the zone is largely within serpentinite, faults in the zone are delineated on the basis of thermal and nonthermal spring alinement, alinement of linear ridges and saddles, alinement of anomalous scarps that bound topographic troughs and depressions, and, locally, the presence of linear deposits of silica carbonate.

Latest surface faulting associated with the Resort fault zone may be at least as recent as 1.66±0.08 m.y., based on the age of basalt intruded along the fault zone and sheared into the lower part of the Great Valley sequence at Coyote Peak, northeast of Wilbur Springs. The basalt of Coyote Peak intruded along minor subsidiary north- to northwest-trending strands of the Resort fault zone. No evidence of Holocene surface faulting along the Resort fault zone was found.

### Bad Ridge fault zone

The Bad Ridge fault zone, named herein, is a 3-km-wide, north-trending zone of discontinuous, nearly vertical faults at least 10 km long, along the east side of Bartlett Springs NE 7 1/2' quadrangle. The fault zone possibly connects with the Resort or Bear Valley faults of Lawton (1956). A prominent north to northeast splay of the fault zone is traceable southward from west of Stanton Glade to the north side of Little Indian Valley. The fault has not been mapped beyond Bartlett Springs NE quadrangle.

The Bad Ridge fault zone was mapped entirely within the Coast Range ophiolite, where it is delineated by a prominent series of alined drainages and small, alluviated, closed depressions bounded by sharp, straight scarps as much as several tens of meters high, many of which are traceable for several kilometers. Springs are alined along several of the faults. The sharpness of fault scarps and the abundance of closed depressions along the Bad Ridge fault zone suggest that surface faulting could be as recent as Holocene or late Pleistocene.

The complex graben-like structure of the Bad Ridge fault zone indicates at least several tens of meters of normal slip. However, the northeast to north-northwest orientation of faults in the zone suggests that right and left slip may also be significant.

## STRUCTURE OF GEOTHERMAL AREAS

### Wilbur Springs area

The Wilbur Springs area has long been known both for its thermal springs and for hydrothermal ore deposits (Waring, 1915; White, 1967; White and others, 1973; Moiseyev, 1968). In addition to exploration for metalliferous hydrothermal deposits and probable geothermal resources, there also has been minor oil exploration in east-dipping Neocomian strata of the Great Valley sequence along the northeast limb of the Wilbur Springs antiform.

White (1967) and White and others (1973) discussed the relation of mercury mineralization to hydrothermal fluids in the Wilbur Springs area, and Moiseyev (1966) reviewed evidence indicating that gold mineralization was associated with the same hydrothermal system(s) that deposited mercury. Donnelly-Nolan and others (1980) suggested that gold-mercury mineralization at Wilbur Springs, Knoxville, and elsewhere in the Clear Lake area is associated with chloride-rich connate waters in the Great Valley sequence that contributed to hydrothermal convective systems following intrusion of magmas of the Clear Lake Volcanics beneath the region.

We speculate that geothermal fluids and metalliferous deposits of the Wilbur Springs area are structurally controlled in three ways (see cross sections):

(1) The presumed magmatic heat source beneath the area possibly was intruded into the axial area of the Wilbur Springs antiform because northeast-oriented compression enhanced diapiric rise of magma into the anticlinally folded strata and may also have raised pore pressures of thermal fluids along the antiform crest.

(2) The junction between the right-slip Little Indian Valley and Resort fault zones at the crest of the Wilbur Springs antiform, together with conjugate northeast-oriented normal faults that cross this fault junction, is a zone of concentrated fracturing and extension that may have enhanced hydrothermal convection.

(3) The folded ophiolitic rocks and detrital serpentinites within and below the sedimentary section of the Great Valley sequence may locally act as impermeable barriers to channelize hydrothermal convection.

Numerous hot springs, including Wilbur Springs, are present along the Resort fault zone. Most of these thermal springs are vented in the axial area of the Wilbur Springs antiform, in the vicinity of the intersection of the Resort and Little Indian Valley fault zones, where the rocks are also extensively altered hydrothermally. In this broad area of intersection, several north-northeast-trending faults on the crest of the antiform intersect the northwest-trending Resort and Little Indian Valley fault zones, thus providing a concentrated zone of fractures for upward movement and convection of thermal fluids. Numerous mercury deposits are also present in the hydrothermally altered area of this fault junction. Both disseminated and free gold are associated with mercury mineralization in this area (Moiseyev, 1966; Becker, 1888).

A recent Bouguer gravity study of the Wilbur Springs area (Harrington and Verosub, 1981) shows two prominent negative anomalies: one over the Wilbur Springs area and one southeast of it. The source of the gravity lows was interpreted to be a hot-water reservoir, which can be modelled as either a sphere or a horizontal cylinder whose top is approximately 0.75 km deep. The gravity lows may also be interpreted as resulting from the combined effects of highly fractured rock, hot fluid in the open-fracture networks of the reservoir rocks, and pervasive silicification and deposition of low-density hydrothermal minerals in the fractures and pores. No commercial geothermal resource has yet been proven, although two geothermal exploratory wells have been drilled in the Wilbur Springs area.

### Chalk Mountain area

Chalk Mountain, located near the center of Bartlett Springs SE 7 1/2' quadrangle, is composed of dacite that intruded or flowed over the Cache Formation along the Bartlett Springs fault zone, possibly about 0.90-0.95 or less than 0.7 m.y. ago based on normal polarity (Donnelly-Nolan and others, 1981). A small lenticular intrusion of basalt is present on the south side of Chalk Mountain and may be correlative with the 1.66-m.y.-old basalt of Coyote Peak and Schoolteacher Hill. The presence of several dacite intrusives of similar composition along the Bartlett Springs fault zone suggests that the zone has been a major conduit of magma emplacement. Active hydrothermal alteration, prominent travertine aprons, thermal springs, and sulfur deposits around fumarolic areas at Chalk Mountain indicate that the rocks are locally fractured enough to have permitted shallow hydrothermal circulation. Mineral springs around the base of Chalk Mountain are only slightly thermal (about 20$^{\circ}$C), although some springs nearby and along the Bartlett Springs fault zone are warmer and may be connected to a deep geothermal system (Donnelly and others, 1978). The active fumaroles at Chalk Mountain may indicate the presence of a small magma body or a still-cooling intrusive at some depth beneath the area.

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TABLE 1. Fossil localities

| o. | USGS no. | Field no. | Collected by | Location | Fossils | Age assignment | Identified by |
|---|---|---|---|---|---|---|---|
| | Mr1074 | OG79-200 | Ohlin | NE1/4SE1/4, sec. 5, T. 14 N., R. 6 W. | Radiolaria: Mirifusus sp., Parvicingula sp. | Late Jurassic (late Kimmeridgian) | C. Blome |
| | M7400A, B | MG80-8A,B | McLaughlin | 1,700' N. 1,700' W of SE cor. sec. 35, T. 14 N., R. 6 W. | Mollusks: Turbo sp., Buchia piochii (Gabb), B. elderensis (Anderson) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7401 | MG80-21 | McLaughlin | 50' N., 2,050' W of SE cor. sec. 35, T. 14 N., R. 6 W. | Mollusks: Buchia elderensis (Anderson), B. piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7231 | MG79-220 | McLaughlin | 100' S, 2,600' W of NE cor. sec. 36, T. 14 N., R. 6 W. | Mollusks: Buchia cf. B. pacifica (Jeletzky) | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7232 | MG79-225 | McLaughlin | 300' E, 350' S, of NW cor. sec. 36, T. 14 N., R. 6 W. | Mollusks: Buchia elderensis (Anderson) or B. piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7233 | MG79-226 | McLaughlin | 250' S, 100' E, of NW cor. sec. 36, T. 14 N., R. 6 W. | Mollusks: Buchia elderensis (Anderson) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7185 | MG79-105 | McLaughlin | 250' S, 9,750' E. of 39°7', 30"N, 122°37'30"W, T. 15 N., R. 7 W. | Mollusks: Buchia sp. | Late Jurassic or Early Cretaceous | D. L. Jones, J. W. Miller |
| | M7186 | MG79-126 | McLaughlin | 1,300' N, 2,150' W of NE cor. sec. 12, T. 14 N., R. 7 W. | Mollusk: Buchia(?) sp. | Probably Jurassic or Early Cretaceous | D. L. Jones, J. W. Miller |
| | M7187 | MG79-129 | McLaughlin | 950' N, 150' W of NE cor. sec. 12, T. 14 N., R. 7 W. | Mollusk: Buchia elderensis (Anderson) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7188 | MG79-150 | McLaughlin | 2,700' N, 100'E of SW cor. sec. 31, T. 15 N., R. 6 W. | Mollusk: Buchia elderensis (Anderson), B. piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7189 | MG79-152 | McLaughlin | 3,200' N, 300' E of SW cor. sec. 31, T. 15 N., R.6 W. | Mollusk: Buchia piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7190 | MG79-154 | McLaughlin | 3,800' N, 200' W of SW cor. sec. 31, T. 15 N., R. 6 W. | Mollusk: Buchia elderensis (Anderson) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| | M7191 | MG79-155 | McLaughlin | 4,000' N, 400' W of SW cor. sec. 31, T. 15 N., R. 6 W. | Mollusk: Buchia cf.B. piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones J. W. Miller |
| | M7192 | OG79-56 | Ohlin | 5,100' N, 400' W of NE cor. sec. 2, T. 14 N., R. 7 W. | Mollusk: Buchia sp. | Late Jurassic or Early Cretaceous | D. L. Jones J. W. Miller |
| | M7170 | MG79-38 | McLaughlin | 600' N, 400' W of SE cor. sec. 28, T. 15 N., R. 6 W. | Mollusk: Buchia piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones J. W. Miller |
| | M7171 | MG79-36 | McLaughlin | 700' N, 200' E of SW cor. sec. 27, T. 15 N., R. 6 W. | Mollusk: Buchia elderensis (Anderson) | Late Jurassic (Tithonian) | D. L. Jones J. W. Miller |
| | M7172 | MG79-4 | McLaughlin | 900' S, 1600' E of NW cor. sec. 10, T. 14 N., R. 6 W. | Mollusk: Buchia pacifica (Jeletzky) | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7173 | MG79-5 | McLaughlin | 600' S, 1,500' E of NW cor. sec. 10, T. 14 N., R. 6 W. | Mollusk: Buchia sp., probably B. pacifica (Jeletzky) | Probably Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7174 | MG79-9 | McLaughlin | 950' N, 1,000' E of SW cor. sec. 3, T. 14 N., R. 6 W. | Mollusk: Buchia keyserlingi (Lahusen) | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7175 | MG79-15 | McLaughlin | 1,200' N, 900' E of SW cor. sec. 3, T. 14 N., R. 6 W. | Cephalopod: Indeterminate ammonite | Mesozoic | D. L. Jones, J. W. Miller |
| | M7176 | MG79-17 | McLaughlin | 2, 000' N, 900' E of SW cor. sec. 3, T. 14 N., R. 6 W. | Mollusk: Buchia sp. | Late Jurassic or Early Cretaceous | D. L. Jones, J. W. Miller |
| | M7177 | TG79-25 | Thormahlen | 750' N, 1,500' W of SE cor. sec. 3, T. 14 N., R. 6 W. | Mollusk: Buchia pacifica (Jeletzky) | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7180 | TG79-70 | Thormahlen | 1,500' S, 1,500' W of NE cor. sec. 30, T. 15 N., R. 6 W. | Mollusk: Buchia pacifica (Jeletzky) | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7181 | MG79-127 | McLaughlin | 200' N, 400' W of NE cor. sec. 12, T. 14 N., R. 7 W. | Mollusk: Buchia sp. | Late Jurassic or Early Cretaceous | D. L. Jones, J. W. Miller |
| | M7182 | MG79-141 | McLaughlin | 450' N, 800' E of NE cor. sec. 12, T. 14 N., R. 7 W. | Mollusk: Buchia keysserlingi(?) (Lahusen) | Early Cretaceous (probably Valanginian) | D. L. Jones, J. W. Miller |
| | M7183 | MG79-142 | McLaughlin | 400' S, 900' E of NE cor. sec. 12, T. 14 N., R. 7 W. | Mollusks: Turbo sp., Buchia sp., probably B. keyserlingi (Lahusen) | Early Cretaceous (probably Valanginian) | D. L. Jones, J. W. Miller |
| | M7006 | FG92-76 | Goff | 39°4' N, 122°29' W, W. edge of sec. 13, T. 14 N., R. 6 W. | Mollusks: Buchia pacifica (Jeletzky) | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| | M7155 | --- | McLaughlin | 1,900' S, 3,100' E of NW cor. sec. 10, T. 14 N., R. 6 W.--float in alluvium | Mollusk: Buchia sp., possibly B. uncitoides (Pavlow) | Late Jurassic or Early Cretaceous If B. uncitoides then Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |

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|---|---|---|---|---|---|---|
| M7012 | MG78-15 | McLaughlin | 1,000' N, 300' E of SW cor. sec. 28, T. 14 N., R. 5 W. | Brachiopod: Peregrinella whitneyi (Gabb) | Early Cretaceous (Barremian or Hauterivian | D. L. Jones, J. W. Miller |
| M7013 | MG78-48 | McLaughlin | 1,400' N, 2,200' E of SW cor. sec. 14, T. 14 N., R. 6 W. | Mollusk: Buchia crassicollis solida (Lahusen) sensu latu | Early Cretaceous (Valanginian) | D. L. Jones, J. W. Miller |
| M7014 | MG78-26 | McLaughlin | 1,400' N, 2,400' W of NW cor. sec. 2, T. 15 N., R. 7 W. | Mollusk: Buchia elderensis (Anderson), B. piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| M7015 | MG78-103 | Ohlin, McLaughlin | 450' S, 900' E of NW cor. sec. 9, T. 14 N., R. 6 W. | Mollusk: Inoceramus sp. | Probably Cretaceous (maybe Late Cretaceous) | D. L. Jones, J. W. Miller |
| M7016 | MG78-67 | McLaughlin | 1,350' N, 1,250' W of SE cor. sec. 9, T. 14 N., R. 6 W. | Mollusk: Buchia elderensis (Anderson) | Late Jurassic (Tithonian) | D. L. Jones, J. W. Miller |
| --- | MG81-2 | McLaughlin | 1,850' N, 1,450' E of SW cor. sec. 36, T. 14 N., R. 6 W. | Mollusk: Buchia piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, oral commun. |
| --- | MG81-3 | McLaughlin | 1,350' N, 2,500' E of SW cor. sec. 36, T. 14 N., R. 6 W. | Mollusk: Buchia piochii (Gabb) | Late Jurassic (Tithonian) | D. L. Jones, oral commun. |
| --- | --- | Carlson | 2,100' N 250' W of SE cor. sec. 29, T. 14 N., R. 5 W. | Brachiopods: Peregrinella whitneyi (Gabb) | Early Cretaceous (Barremian or Hauterivian) | D. L. Jones, J. W. Miller |
| --- | --- | Carlson | 2,600' N, 1,800' W of SE cor. sec. 28, T. 14 N., R. 5 W. | Brachiopods: Peregrinella whitneyi (Gabb) | Early Cretaceous (Barremian or Hauterivian) | D. L. Jones, J. W. Miller |
| --- | --- | Carlson | 2,800' N, 1,650' W of SE cor. sec. 28, T. 14 N., R. 5 W. | Brachiopods: Peregrinella whitneyi (Gabb) | Early Cretaceous (Barremian or Hauterivian) | D. L. Jones, J. W. Miller |
| --- | --- | Carlson | 300' N, 600' E of SW cor. sec. 26, T. 14 N., R. 5 W. | Brachiopods: Peregrinella whitneyi | Early Cretaceous (Barremian or (Gabb) | D. L. Jones, J. W. Miller Hauterivian) |
| --- | --- | Carlson | 850' N, 2,400' E of SW cor. sec. 35, T. 14 N., R. 5 W. | Brachiopods: Peregrinella whitneyi (Gabb) | Early Cretaceous (Barremian or Hauterivian) | D. L. Jones, J. W. Miller |
| --- | NSF997A,B,C | Pessagno | 0.35 mi S69°W of Eagle Rock, T. 14 N., R. 5 W. sec. 18 | Radiolarians: Parvicingula altissima, P. hsui sp., P. turrita, Mirifusus baileyi sp., M.(?) mediodilatata, Pedobursa sp., Saitoum pagei sp., Eucyrtidium(?) ptyctum, Archaeodictyomitra rigida sp. | Early Cretaceous (Tithonian, subzone 2B of Pessagno, 1977) | E. A. Pessagno, Jr. |

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