Northern California Geological Society
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Geological Field Trip Guidebook
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The Confluence, North & Middle Forks of the American River

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Front cover: from the south and above, looking north to the confluence of the North and Middle Forks of the American River. The contrast between the deeply incised canyons and the weakly dissected uplands is quite noticeable. The uplands seen here are, for the most part, remnants of the pre-volcanic land surface of the Sierra. Various bedrock structures find expression in these uplands, and may sometimes also be discerned within the canyons, in this image.

The image was rendered in POV-Ray, and the land surface was defined using six (or eight, I forget) U.S.G.S. 7.5 minute DEMs. A blue light illuminates the surface from high above, and a gold light illuminates it from low in the west. The surface itself is made from several hundred thousand, perhaps over a million, triangles. Only part of it is seen here; it extends south to Folsom reservoir, and is also slightly clipped to the east, west, and north.

The non-convex zonohedron seen below has icosahedral symmetry, and is related to quasi-crystals. It was modeled in Mathematica, and is derived from one of the Archimedean solids, the truncated icosahedron, using an algorithm I devised.

--Russell Towle <rustybel@foothill.net>
GUIDE TO THE GEOLOGY OF THE WESTERN SIERRA NEVADA: SACRAMENTO TO THE CRYSTAL BASIN

By
David L. Jones, Russell Graymer, David Lawler, and David Wagner

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Description of Stops

Day 1:

Stop 1. (10:00 AM) Swan Lake. Upper Cretaceous conglomerate deposited on quartz diorite.

Stop 2. (10:30 AM) Volcano Hill. Fossiliferous quartzite of the Ione Formation containing large palm fronds.

Stop 3, US 80, Auburn (11:30 AM), overview, Auburn dam site and west Bear Mountain fault zone. View of incised canyons cut during the Pleistocene.

Stop 4, Highway 49, (Optional) at confluence of North and Middle Forks, American River, accreted island arc volcanics (Jurassic?) overlain by turbidities and sedimentary melange containing blocks of chert and volcanics.

Stop 5, (noon), Cool quarry terrane, basalt and limestone of an accreted seamount of Permian age (half-mile walk up the middle fork); LUNCH STOP

Stop 6, (2:00PM), Pilot Hill: accreted basalt and chert of Late Triassic to Early Jurassic age.

Stop 7, (3:00 PM) Logtown Ridge and Mariposa Formations, Calaveras terrane, and Melones fault at Chili Bar; half-mile walk along the bank of the South Fork.

Stop 8, (Highway 50 to Forebay road, 4:30 PM), Shoo Fly quartzose flysch.

Stop 9 Shoo Fly f2t folds

Stop 10, Shoo Fly, graded quartzite beds.

5:30 PM arrive at Lava Cap winery for catered dinner.

Day 2: Assemble at Cleveland Corral on Icehouse road north of US 50. 8:30 AM.

Stop 11. (9:00 AM), Cleveland Corral, Miocene? gravel and Mehtren Fm deposited directly on foliated diorite. This nonconformity records a major episode of uplift (12-16 km) that occurred before deposition of the superjacent series. Timing and magnitude of younger, post-Mehrten uplift are subjects of current debate.

Stop 12. (9:30 AM), Diorite intruded into quartz mica schist on west limb of antiform; penetrative fabric of the diorite is parallel to that of the mica schist; dike of younger granite is not deformed. The same f2t folds that deform the Shoo Fly at stop 11 fold both the mica schist and diorite. Implication of this structural relation is that the diorite was
originally intruded as a sill-like body parallel to the fabric in the Shoo Fly, and was later folded by a post - 145, pre - 90 my old deformation.

Stop 13, (10:00 AM), Same rock assemblage on east limb of south-plunging antiform.

Stop 14. (10:30 AM), Weber Mill Road; migmatite and gneiss at diorite-Shoo Fly contact; foliation dips east

Stop 15, (11:00 AM), Pyroxenite and gabbro that overlies diorite; contact may be an east-dipping thrust fault along which the diorite is locally mylonitized. Diorite is more deeply weathered than pyroxenite because of its higher feldspar content, but removal of this weathered material is hindered by the overlying, more erosion-resistant pyroxene

Stop 16, (11:30 AM), Top of Whitehall slide; most of the slide material is weathered diorite

Stop 17, (12:30), lunch stop: Mehrten Formation, 4 my to 10 my old volcanic lahars.

Stop 18. Placerville, Landecker mine (2:30 PM); one of the few active placer mines remaining in the Placerville area; features of interest include: depositional contact of intervolcanic gravels (Oligocene to early Miocene) on slate bedrock; faulted contacts of Valley Springs rhyolite tuff; basal gravels of the Mehrten Formation.
EXPLANATION

Ti  IONE FORMATION, Eocene
K  Upper Cretaceous marine strata
Kg  Cretaceous granitic rocks, < 100 my old
JKg  Jurassic and Lower Cretaceous dioritic rocks
ls  limestone
PSFsl  Shoo Fly slate
PSFf  Shoo Fly flysch
PSFq  Shoo Fly quartzite
um  ultramafic rocks and gabbro
NORTHERN CALIFORNIA GEOLOGICAL SOCIETY

GEOLOGY OF THE CENTRAL SIERRA NEVADA

David L Jones, Russell W. Graymer, David Lawler, and Dave Wagner

October 11 and 12, 1997

Introduction and Overview

The Sierra Nevada Foothills are made up of accreted seafloor rocks and sedimentary and volcanic strata that range in age from Paleozoic to Jurassic. The rocks are metamorphosed from upper amphibolite to lowest greenschist grade. They are intruded by a suite of Jurassic to Cretaceous plutons, and are cut by multiple faults. Early workers (for example, Lindgren and Turner, 1894, Chandra, 1961) divided the rocks into formations based on lithology and sparse megafossil information. The recognition of a north - northwest trending set of faults (the Foothills fault system) enabled the subdivision of the Sierra Foothills into lithotectonic belts (Clark, 1960). Subsequent workers have modified these belts in various ways. Although definition of belts differs, Figure 1 shows the major faults of the Foothills fault system and the various belts bounded by them. This field focuses on rocks between the edge of the Sacramento Valley on the west and the crest of the Sierra to the east.

Emphasis on this trip will be on: 1) The pre-Cenozoic basement rocks that form the framework of the Sierra; 2) Cretaceous and Cenozoic sedimentary and volcanic rocks deposited on this crystalline basement; and 3) speculations concerning the post-batholithic history of the range, with special attention devoted to analysis of the conflicting theories concerning uplift of the range at various times.

Tectonic belts in the central Sierra Nevada

As shown on figure 2, we recognize 5 tectonic belts lying between the Cenozoic cover of the Great Valley on the west and the continuous assemblage of Cretaceous plutonic rocks on the east that constitutes the main Sierran batholith. Each belt is fault-bounded and records differing histories of sedimentation, volcanism, plutonism, metamorphism, deformation, and uplift. Not until Cenozoic time did the basement rocks respond to tectonic activity as a single unit, and even that supposition may be questioned. The main characteristic features of each belt are summarized as follows:

Western belt: a structurally complex assemblage of arc-derived volcanic rocks interspersed with thick units of fine-grained clastic rocks (flysch), mostly altered to slate. Named formations, from east to west, include the Copper Hill volcanics (mainly augite porphyry similar to the Logtown Ridge Formation of the Placerville belt), Salt Spring Slate, (similar in composition and age to the Mariposa Formation of Oxfordian age), and
the Gopher Ridge volcanics (containing abundant silicic tuff). Stratigraphic relations of
these three units are unknown, and only the Salt Spring Slate is dated by fossils. Intrusive
rocks include the Penryn pluton (Stop 1; figure-) which was emplaced at mid-crustal levels
and has a well-developed aureole of amphibolite schist that shows evidence of multiple
deformations (figs -,-). Age of emplacement of this pluton is about 130 my.

Upper Cretaceous and younger strata unconformably overlie these older crystalline
rocks (stop 1), although locally the basal strata have been excised by a nearly flat detach-
ment fault. Upper Cretaceous strata were deposited in shallow marine setting with abun-
dant oysters, clams, snails, and other fossils characteristic of subtidal environments. The
presence of dinosaur bones mixed with these marine forms indicates the existence of
nearby terrestrial environments to the east. The basal unconformity, as well as the pres-
ence of abundant granitoid clasts (up to tens of meters in maximum dimension) in Upper
Cretaceous debris flows, testify to and date the exhumation of once deeply buried plutonic
rocks. Total rock uplift during the Cretaceous is in the range of 16 kms. No subsequent
uplift is detectable, so these marine deposits at Folsom mark at null point, or hinge line,
between regions to the west that have subsided during the Cretaceous and Cenozoic, and
regions to the east that were uplifted during the Late Cretaceous and perhaps, during the
Cenozoic.

**Shingle Springs Complex:** This belts includes a wide variety metamorphic and plutonic
rocks bounded by the eastern and western strands of the Bear Mountains fault zone. The
bulk of the assemblage consists of the Pine Mountain Intrusive complex, including diorite,
quartz diorite, gabbro, and ultramafic rocks. The gabbro is an early phase, and is intruded
by the less mafic varieties. A belt of metamorphosed diabase and gabbroic dikes or sills
occur to the north of the Pine Mountain intrusives, and a septum of metasedimentary
rocks, including marble, occurs to the south. The Pine Mountain intrusives are dated at
about 165 my. Amphibolite - grade metamorphic rocks occur extensively throughout this
belt, and uplift from mid-crustal depths is probable.

Only one small patch of Miocene volcanic rocks (Mehrtan Formation) overlies the
Shingle springs complex; this patch is located near the auburn dam site, where it is cut by
post-Miocene faults.

**Placerville belt:** With the advent of terrane theory, Blake and others (1982) divided the
Sierra Foothills into terranes. Some terranes are equivalent to lithotectonic belts, while
others are not. The Placerville Belt contains rocks originally assigned by Blake and others
(9182) to both the Bucks Lake and Foothills Terranes. Recent work has added to and
changed the original terrane definitions. Edelman and Sharp (1989) redefined the rocks in
the Placerville Belt to consist of two terranes, the Tuolumne and Slate Creek Terranes,
and a Callovian to Kimmeridgian (Middle to Late Jurassic) overlap assemblage. The rocks
described in this paper lie within an area designated by them Tuolumne Terrane and over-
lap assemblage.

Defining the Callovian to Kimmeridgian rocks as overlap assemblage constrains
accretion of the overlapped terranes to the continent in pre - Callovian time. Schweickert
and others (1988), on the other hand, used structural data to suggest that accretion of the
Placerville Belt rocks occurred in the Late Jurassic (Kimmeridgian or later). These works
also differ in definition of terranes and terrane boundaries, and in the significance of the Foothills fault system. Reasons for these differing interpretations lie in the extreme structural and lithologic complexity of the region coupled with the lack of detailed mapping in many critical areas and the paucity of Geochronological data. Recent work has enabled us to make some progress in this area.

Terrane Assemblages within the Placerville belt:

Biostratigraphic data, coupled with lithologic associations of the cherts, and combined with structural investigations and previously published fossil data, has allowed us to separate the central part of the Placerville Belt into five terranes (Figs. 2 and 3). These terranes are fault-bounded packages of rocks with distinct stratigraphic and structural histories, as described below.

The **Mother Lode Terrane** includes the well-known Logtown Ridge and Mariposa Formations. It also includes a basal unit composed of tectonic slivers of Permian chert, basalt, serpentinite, and gabbro. The chert slivers contain radiolarians of late Permian age. These slivers are overlain by Bathonian to Callovian basaltic sandstone and argillite. Radiolarians of middle Jurassic (Callovian to Bathonian) age were identified in chert - argillite from these beds. The sandstone and argillite is depositionally overlain by the upper Callovian to Oxfordian andesitic to basaltic breccia of the Logtown Ridge Formation. Clasts of the volcanic breccia vary in composition from about 50 percent volcanic in western outcrops to almost 100 percent volcanic in eastern outcrops. In addition, eastern outcrops are interbedded with massive and pillow-shaped lava, while western outcrops are interbedded with pebbly mudstone. These relationships indicate that the Logtown Ridge formation formed on the western side of an oceanic island arc, and received detritus from non-volcanic sources farther west. These rocks are depositionally overlain by Oxfordian to Kimmeridgian slate and conglomerate of the Mariposa Formation. The pebble to cobble size clasts in the conglomerate contain chert, porphyry volcanic rocks derived from underlying strata, and sandstone, quartzite, and granite probably derived from a continental source. Along strike to the south of the studied area, the conglomerate and slate grade into olistostrome deposits mapped as Central Belt melange by Duffield and Sharp (1975). These rocks had been considered to predate the Logtown Ridge Formation (Behrmann, 1977, for example), but the presence of porphyry volcanic detritus derived from the Logtown Ridge Formation in beds of the olistostrome (Graymer and Jones, 1991), along with the gradational relationship along strike with the Mariposa Formation, shows that these rocks, at least in part, postdate the Logtown Ridge Formation, and are probably Mariposa equivalent. The ages of the Callovian to Kimmeridgian formations of this terrane are well controlled by occurrence of ammonites, *Buchia*, and related fossils (Imlay, 1961). Chert pebbles in the conglomerate of the Mariposa Formation contain radiolarians of the Late Triassic age group, while pebbly mudstone beds within the Logtown Ridge Formation contain chert pebbles bearing late Permian radiolarians. The presence of late Permian radiolarians, which have not been described anywhere else in the Sierra Nevada Foothills, in clasts in the Logtown Ridge Formation demonstrates the depositional relationship between the scraps of relatively unmetamorphosed Permian basement and overlying Middle to Late Jurassic strata. The western part of the terrane is faulted against serpentinite and metavolcanic rocks along the Bear Mountains fault zone (Miller and Paterson, 1991), whereas the
younger parts of the terrane to the east are repeated at least five times by imbricate thrust faults and isoclinal folds. We interpret the Mother Lode Terrane to consist of Permian seafloor rocks unconformably overlain by Middle to Late Jurassic arc related volcanic rocks, derived from both eastern (oceanic arc) and western (unknown terrane) sources, and Late Jurassic turbidites containing continental detritus. Although the contact between the basal Permian rocks and the Bathonian to Callovian basaltic sandstone is faulted in places and obscured in all others, we interpret it to have been originally depositional because of: 1) the presence of late Permian chert in clasts of overlying strata, 2) the presence of large amounts of basaltic detritus almost certainly derived from the underlying Permian rocks in the basaltic sandstone at the base of the younger strata, and 3) the structural position of Permian rocks at the base of the Mother Lode Terrane.

The Mount Ararat Terrane structurally overlies the Mother Lode Terrane along a highly folded northeast trending thrust fault (Fig. 4). The Mount Ararat Terrane is made up of two faults - bounded subterranes. The structurally lower subterrane is composed of serpentinite matrix melange containing blocks of basalt, gabbro, diabase, argillite, amphibolite and mica schist, as well as Late Triassic and Triassic to Jurassic chert. The structurally higher subterrane is a chaotic unit made up of Late Triassic chert depositionally overlying basalt, and chert - basalt diamicite with clasts containing Late Triassic and Early Jurassic radiolarians. We designate these two structural blocks as subterranes because the structurally higher rocks are geographically restricted to an area within that of the structurally lower rocks. The Mount Ararat Terrane probably represents debris flows derived from, and volcanic rocks of, one or more Triassic to Jurassic seamounts (the This Pine Mountain intrusive series comprises upper subterrane) that formed on Triassic (?) seafloor which subsequently has been tectonically dismembered and combined with non-ophiolite rocks to form the serpentinite matrix melange (the lower subterrane).

The American River Terrane is overthrust by the Mount Ararat Terrane along a highly folded east - west trending thrust fault (Fig. 2). The structural base of this terrane is composed primarily of sedimentary melange (olistostrome) with a matrix of slate, sandstone, and pebble conglomerate containing blocks (olistoliths) up to 100 meters in diameter of chert, basalt, and limestone. The chert olistoliths contain radiolarians Late Triassic and Early Jurassic age, while the matrix includes chert argillite containing Middle Jurassic (Aalenian to Bajocian) radiolarians. The olistostrome is interbedded in the western part of the terrane with phyllitic andesite tuff. These sedimentary and volcanic rocks have been mapped previously as Clipper Gap formation, and were previously dated as Paleozoic based on the age of corals and other fossils in the limestone blocks (Chandra, 1961). The Fossiliferous blocks, however, give only a maximum age for the olistostrome (Day and others, 1985). To the north, another assemblage of rocks has been mapped as "Clipper Gap Formation" by Edelman and others (1989), but that assemblage is older, because it contains interbedded Triassic slate and chert, and is lithologically dissimilar. The Colfax Formation, composed of chert pebble to boulder conglomerate, sandstone, and slate overlies the Middle Jurassic Clipper Gap Formation. The chert pebbles and boulders contain Late Triassic to Early Jurassic radiolarians, and are identical in age and lithology to chert blocks found as olistoliths in the Clipper Gap Formation, reflecting the depositional relationship between the two (Day and others, 1985). However, it should be noted that a de-
positional contact between the Clipper Gap and Colfax Formations is not exposed anywhere in the study area. The Colfax Formation has been dated as Early Callovian (Middle Jurassic) based on ammonites and associated fossils (Imlay, 1961). We interpret this terrane to represent early Middle Jurassic (Aalenian to Bajocian) debris flow deposits overlain by (and in part supplying sediment for) late Middle Jurassic (Callovian) turbidites. Original provenance of the clasts and olistoliths is unknown.

The fourth terrane in the field area is the Cool Quarry Terrane. It also is overthrust by the Mount Ararat Terrane, and it in turn lies structurally above the American River Terrane. This terrane is composed of basalt, pillow basalt, basaltic tuff, gabbro, and basalt breccia with intercalated Permian fossiliferous limestone and marble. Although no radiolarians were discovered in this terrane, a well-preserved Permian trepostome bryozoan was found in the limestone, and crinoid columnals are locally abundant in basaltic tuff. Only a small scrap of this terrane remains exposed in the northernmost part of the study area (Fig. 2). We interpret this terrane to represent a fragment of a Permian seamount.

The French Creek Terrane is the fifth terrane in the area studied. It is in high angle fault contact with the western part of the Mother Lode Terrane and it is overthrust along its northern margin by the Mount Ararat Terrane. It is composed of upper green schist to amphibolite facies pelitic schist, metachert, metabasalt, and mafic to intermediate metaintrusive rocks. While this terrane contains no known fossils, 40Ar/39Ar analysis has provided an age of metamorphism of about 190 Ma for these rocks, so protolith ages must be Early Jurassic or older (Graymer, 1992). This terrane probably formed by medium to high grade metamorphism of volcanic arc related rocks, the presence of chert suggesting oceanic rather than continental arc volcanism.

All rocks and structures within the Placerville belt are cut by the Coloma pluton, which yields K/Ar ages of about 143 my. This pluton was emplaced at relatively shallow depths, as manifested by the lack of an amphibolitic auroile; in most places, local hornfelsing of slate is the only evidence of thermal alteration. The Coloma pluton itself is cut by the Melones fault; locally the granitic rocks are altered to mylonite within the fault zone. Subhorizontal kink bands occur both east and west of the fault, as seen at stop 7, and these structures appear to be the last manifestation of deformation along this fault.

Rocks of the Placerville belt are overlain by Eocene auriferous gravels, Oligocene to Miocene gravels and rhyolitic tuffs of the Valley Springs Formation, and gravel and andesitic lahars of the Mio-Pliocene Merhren Formation.

**Calaveras belt:** East of the Melones fault, another persistent belt composed of volcanic and sedimentary rocks extends nearly the entire length of the foothills. The dominant rocks present are slate and phyllite, marble, quartzose metasandstone (some with disrupted bedding), greenstone (metaturf), and at the structural base of the assemblage, a belt of augite-porphyry meta andesite. In the past, this assemblage has been considered to be Late Paleozoic in age, but recently conodonts of Triassic age have been extracted from several marble lenses, and Early Jurassic isotopic ages determined from the basal volcanic rocks (Harris and others, 1993?). The entire assemblage, thus, is probably Mesozoic in age.
The Melones fault zone is marked by a persistent band of serpentinite (locally talc schist), with blocks of gabbro, marble, granite, phyllite, and other rock type present locally.

**Feather River belt:** An assemblage of serpentinite, gabbro, and other ophiolite rocks bounds the eastern limit of the Calaveras belt and separates that assemblage from the extensive Shoo fly complex to the east. This belt appears to connect with the Feather River Peridotite to the north. It is poorly exposed within the region of this field trip, and will not be visited. The extension of the belt south of Placerville is uncertain.

**Shoo Fly complex:** A vast assemblage of quartzose metamorphosed sedimentary rocks lies east of the Feather River ultramafic belt and makes up the bulk of the country rock intruded by the Cretaceous batholith in the central Sierra Nevada. To the north, this assemblage has been subdivided into a number of lithic units of probable Ordovician age (Harwood, 1993), none of which has been clearly identified in the region of interest along the South fork of the American River. Subdivisions of the Shoo Fly are apparent in this region, however, even though their boundaries are not yet well delimited. As shown on fig. 2) The western - most part of the Shoo Fly consists mainly of slate with minor siliceous shale or chert; this appears to grade eastward into quartzoze flysch, and then into massive quartzite with minor flysch.

All Shoo Fly rocks are metamorphosed, with reconstitution of the rocks changing from slate on the west to quartz mica schist on the east. Two or more periods of deformation are recorded by foliations and lineations, and by refolded foliation. In the region between the Middle fork and the North Fork of the American River, Harwood (1993) mapped a series of east trending, east plunging mesoscopic folds that do not deform overlying Upper Paleozoic and Mesozoic rocks. We have not observed these folds in the area south of the Middle Fork, where, the youngest fold system trends north - south and plunges gently in either direction. A Late Jurassic dioritic pluton intruded into the ShooFly is folded by this deformation (stop - ).

The Shoo Fly Complex is intruded by both Cretaceous and Late Jurassic plutons. The older plutons are syntectonic, have amphibolitic aureoles, exhibit penetrative deformational structures parallel to those in the intruded metamorphic rocks, and have been uplifted from mid-crustal levels (12 km or more). In the Icehouse road area (stop - ), a syntectonic pluton was intruded as a sill-like body, and was folded in the latest deformation which occurred in the interval between 145 and 100 my. In contrast, Cretaceous plutons generally are not penetratively deformed or exhibit only local, narrow bands of penetrative deformation, lack amphibolitic aureoles, are not folded, have contacts that crosscut foliation of the country rock, and have been uplifted 6 to 8 kms.

**Geologic History and Tectonic Implications**

The new understanding of stratigraphic and structural relationships among the diverse rock types present in the central part of the Placerville Belt, discussed above, has several implications for previously unresolved questions relating to the Placerville Belt and the Sierra Foothills as a whole. First, lithologic units cannot be traced from the northern to southern parts of the belt because the presence of terranes with completely different stratigraphic histories in the study area disrupts continuity and precludes the possibility of
through-going geologic units. This bears directly on attempts to correlate units from different parts of the belt as part of a single large terrane (such as the Tuolumne Terrane of Edelman and Sharp, 1989, or the Foothills Terrane of Blake and others, 1982). The Placerville Belt is made up of many terranes, not just one or two. The tectonostratigraphic relationships of the terranes are summarized in Figure 3. It is important to note that in the Callovian the American River Terrane was the site of pelite (now slate) and chert pebble conglomerate - turbidite deposition (Callovian Colfax Formation), whereas the Mother Lode Terrane was the site of oceanic arc related volcanogenic sandstone, volcanic breccia, and volcanic flow deposition (Bathonian to Callovian volcanic sandstone and Callovian to Oxfordian Logtown Ridge Formation). These two depositional environments (arc and turbidite) must have been separated by many kilometers in the Callovian, but are now structurally juxtaposed. Another relationship that shows the separate nature of the terranes is the 190 Ma metamorphism of the French Creek Terrane. The upper greenschist to amphibolite grade metamorphism is limited to that terrane within the study area, showing that other rocks in the area of comparable age or older which are relatively unmetamorphosed (Cool Quarry and Mount Ararat Terranes, and Permian rocks in the Mother Lode Terrane) were separated from the French Creek Terrane at the time of metamorphism. The third constraining relationship is that the Mount Ararat Terrane cannot be in the same stratigraphic sequence as the Cool Quarry or Mother Lode Terranes because Triassic ophiolite could not have formed over older rocks. In addition to the five terranes described herein, Edelman and others (1989) described two terranes in the northern part of the Placerville Belt, the Slate Creek and Fiddle Creek Terranes, that seem to be distinct from terranes described here. Especially persuasive is the presence of Late Triassic (F2) radiolarians in the slates of the Fiddle Creek Terrane (Hietanen, 1981), proving it distinct from the Late Triassic ophiolitic rocks of the Mount Ararat Terrane.

The classification of the late Middle to Late Jurassic rocks in the Mother Lode Terrane as part of a separate terrane, rather than an overlap assemblage, is further supported by the observation that the Callovian to Kimmeridgian rocks in the Placerville Belt have a depositional link (interpreted as an unconformity) with Permian seafloor rocks (gabbro, basalt, and chert). This observation does not support the idea that they were deposited on (or over) high grade metamorphic rocks to the west (the so-called "Bear Mountains Ophiolite") as proposed by many workers (including Behrman, 1977, Saleeby, 1982, Edelman and Sharp, 1989, Herzog and Sharp, 1992). The high-grade metamorphism that took place about 200 Ma (Behrman, 1977) in the "Bear Mountains Ophiolite" would certainly have affected the relatively unmetamorphosed Permian seafloor rocks if they had been in the same tectonostratigraphic sequence. The fact that the Permian seafloor rocks are relatively unmetamorphosed shows that they belong to a separate terrane. Although overlying rocks could have been deposited after amalgamation of the two sets of older rocks after the 200 Ma metamorphic event, there is no evidence to link the overlying strata to the high grade rocks, and the presence of relatively unmetamorphosed Permian seafloor rocks along the only structural contact between the high grade metamorphic rocks and the Jurassic strata suggests that there was no depositional relationship.

As shown above, the Mother Lode and American River Terranes were distinct in the early Callovian. The continuous record of deposition in the Mother Lode Terrane
from that time into the Kimmeridgian demonstrates that structural juxtaposition (amalga-
mation) of the two terranes occurred during or after the Kimmeridgian. Because two
other terranes (the French Creek and Mount Ararat Terranes) are in direct fault contact
with the Mother Lode Terrane, final structural juxtaposition of these terranes must have
also taken place after the deposition of the Mariposa Formation. It is probable that the
amalgamating faults formed at the continental margin during sequential accretion of the
various terranes. Because the French Creek Terrane is west of the Mother Lode Terrane,
it probably accreted after the Mother Lode Terrane. And because the Mount Ararat Ter-
rane’s southern boundary fault cuts the fault between the French Creek and Mother Lode
Terranes (Fig. 2), the Mount Ararat Terrane was definitely accreted after the French
Creek Terrane. The Cool Quarry Terrane is not in contact with the Mother Lode Terrane,
so it is possible that it amalgamated with the American River Terrane before the Kimme-
ridgian. It is probable, however, that this amalgamation occurred after the deposition of
the Callovian Colfax Formation, because there is no evidence of basaltic tuff or limestone
in the conglomerate that derived from the underlying rocks. While the structural relation-
ship between the American River and the Mother Lode Terranes does not preclude the ac-
cretion of the American River Terrane before the Mother Lode Terrane, the Callovian age
of the Colfax Formation indicates that the American River Terrane accreted after the Early
Callovian. A plausible resulting history of accretion is as follows; the American River Ter-
rane accreted first, after the Early Callovian, followed by the Cool Quarry Terrane, and,
after the Kimmeridgian, the Mother Lode Terrane, followed by the French Creek and fi-
nally the Mount Ararat Terrane. The accretion was complete by the time of the intrusion
of the Coloma Pluton, which has yielded a preliminary U/Pb age from zircons of 143 Ma
(J.B. Saleeby, personal communication, 1991). These observations support the idea of
Late Jurassic (Nevadan) accretion proposed by Schweickert and others (1988). It should
be noted that there is ample evidence in the study area for deformation before Nevada
time, the 190 Ma metamorphism of the French Creek Terrane for example, but these
structures are limited in extent to single terranes. Because pre - Callovian structures are
terrane specific, and the Callovian and younger rocks are parts of different displaced terra-
nes, no evidence is seen within the study area for the pre - Callovian accretion proposed

Acknowledgments

We would like to thank J.B. Saleeby (Caltech) for providing radiometric dates of
plutons in the study area, and Paul Renne (Institute of Human Origins) for Ar/Ar dates of
metamorphic amphiboles. In addition we would like to thank Michelle Silk for providing
scanning electron micrographs of radiolarians, as well as Rex Hanggar for identifying car-
bonate fossils. We thank the Nielson family for allowing us to access their ranch lands.
References

Behrman, P.G., 1977, Paleogeography of Middle to Late Jurassic Island Arc, Sierra Nevada Foothills, and California: University of California, Ph.D. thesis.


Figure 1

Lithotectonic belts in the Sierra Nevada Foothills and the major boundary faults. (FRT=Feather River Terrane, CLV=Calaveras Terrane, PB=Placerville Belt, NSI=Northern Sierra Terrane, WB=Western Belt, DPT=Don Pedro Terrane, SVC=Smartville Complex, SSC=Shingle Springs Complex, BBF=Big Bend Fault, DPF=Dogwood Peak Fault, GHF=Gillis Hill Fault, WCF=Wolf Creek Fault, MF=Melones Fault, BMFZ=Bear Mountains Fault Zone) Only faults mentioned in the text are labeled.
Figure 2  A. Distribution of terranes in the study area within the Placerville Belt (ART=American River Terrane, CQT=Cool Quary Terrane, MAT=Mount Ararat Terrane, MLT=Mother Lode Terrane, FCT=French Creek Terrane).
Figure 3  Tectonostratigraphic relationships within the various terranes of the study area. Bars on the left show the age range of radiolarian age categories. Time scale has been subdivided into epochs and ages. The vertical arrow represents the depositional link described in the text. Note each terrane is fault bounded, and that all faults predate the 143 Ma Coloma Pluton. Also note the different rocks of Callovian age in the American River and Mother Lode Terranes.
Figure 4  Detailed Map of the Placerville area. described above.
M2g      Coloma Pluton granodiorite

Mother Lode Terrane
Jcg       Conglomerate
Jms       Mariposa formation slate
Jlv       Logtown Ridge formation Volcanic breccia
Jbs       Basaltic sandstone and Argillite

American River Terrane
Mzsm      Olistostrome
Mzv       Andesite and basalt, flows And tuffs

Mount Ararat Terrane
Jbc       Basalt, chert, and diamicite
Trom      Serpentinite melange Blocks mapped indicated By small two and three letter Groups (ie. um, ch, amp, sch, Bas, etc.)

French Creek Terrane
nv        Phyllite derived from andesite
ms        Slate
mb        Greenschist and amphibolite Derived from mafic volcanics

Not Terrane Specific
sp        Serpentinite

For more information, please refer to Graymer (1992)
Tectonic implications of radiolarian cherts from the Placerville Belt, Sierra Nevada Foothills, California: Nevadan-age continental growth by accretion of multiple terranes

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ABSTRACT

We have recognized several age groups of radiolarians in cherts in a belt of rock in the Sierra Foothills between the Melones–Gillis Hill fault and the Bear Mountains–Wolf Creek–Big Bend faults. They are Late Permian, Late Triassic, early Jurassic, Middle Jurassic, and late Middle Jurassic in age. The biostratigraphic control provided by recognition of these groups, combined with study of lithologic assemblages related to them, has enabled us to divide this belt in the area between the Cosumnes River and the Middle Fork of the American River into five terranes; Mother Lode, French Creek, Mount Ararat, Cool Quarry, and American River. The slate and volcanic breccia of the Mother Lode Terrane (Mariposa and Logtown Ridge Formations) are depositionsally linked to unmetamorphosed Late Permian basalt, chert, and gabbro which we propose represents basement of the stratigraphic sequence. In addition, the late Middle Jurassic Collar Formation is depositionsally linked to the early Middle Jurassic olistostrome (Clipper Gap Formation) in the American River Terrane. Recognition of separate terranes and the stratigraphy within them indicate that terrane amalgamation (probably during accretion to North America) is constrained to be younger than Callovian, and that the Nevadan orogeny was the result of accretion of multiple terranes to the continental margin during the period of 163–141 Ma.

INTRODUCTION

This paper presents new age data for 29 samples of chert and chert-argillite beds and clasts in the Sierra Nevada Foothills near Placerville, California, based on radiolarians and conodonts extracted from the samples. These new dates provide important constraints on age of deposition and time of deformation of several important lithologic units that are widespread in the Sierran Foothills. They also demonstrate that there are multiple distinct, fault-bounded, lithologic packages (terranes) in the area studied, and that amalgamation of these packages took place for the most part in post-Callovian to Kimmeridgian time. Our recognition of multiple terranes in this area, and their timing of amalgamation, differs from recently published interpretations (Edelman and Sharp, 1988; Herzig and Sharp, 1992). In addition, and perhaps more importantly, the presence of multiple terranes sheds new light on the process of orogeny and accretion of terranes to the continental margin. Rather than being the result of accretion of one regional terrane, the continent in this area grew by episodic accretion of somewhat smaller terranes. The possibility of orogeny by episodic accretion of smaller terranes may have ramifications on the study of continental growth worldwide.

The Sierra Nevada Foothills are made up of accreted sea-floor rocks and sedimentary and volcanic strata that range in age from Paleozoic to Jurassic. The rocks are metamorphosed from upper amphibolite to lowest greenschist grade. They are intruded by a suite of Jurassic to Cretaceous plutons and cut by multiple faults. Early workers (for example, Lindgren and Turner, 1894; Chandra, 1961) divided the rocks into formations based on lithology and sparse macrofossil information. The recognition of a north-northwest–trending set of faults (the Foothills fault system) enabled the division of the Sierra Foothills into lithotectonic belts (Clark, 1960). These belts have been modified by subsequent workers (Duffield and Sharp, 1975; Day and others, 1985; Edelman and others, 1989). Although definition of belts differs, Figure 1 shows the major faults of the Foothills fault system and the various belts bounded by them. This study focuses on rocks between the Melones–Gillis Hill–Dogwood Peak faults on the east and the Bear Mountains–Wolf Creek–Big Bend faults on the west, an area herein called the “Placerville Belt.”

With the advent of terrane theory, Blake and others (1982) divided the Sierra Foothills into terranes. Some terranes are equivalent to lithotectonic belts, but others are not. The Placerville Belt contains rocks originally assigned by Blake and others (1982) to both the Bucks Lake and Foothills Terranes. Recent work has added to and changed the original terrane definitions. Edelman and Sharp (1989) redefined the rocks in the Placerville Belt to consist of two terranes, the Tuolumne and Slate Creek Terranes, and a Callovian to Kimmeridgian (Middle to Late Jurassic) overlap assemblage. The rocks described in this paper lie within an area designated by them as “Tuolumne Terrane” and “overlap assemblage.”

Defining the Callovian to Kimmeridgian rocks as an overlap assemblage constrains accretion of the overlapped terranes to the continent in pre-Callovian time. Schweickert and others (1988), on the other hand, used structural data to suggest that accretion of the Placerville Belt rocks occurred in the Late Jurassic (Kimmeridgian or later). These works also differ in definition of terranes and terrane boundaries, and in the significance of the Foothills fault system. Reasons for these differing interpretations lie in the extreme structural and lithologic complexity of the region coupled with the lack of detailed mapping in many critical areas and the paucity of geochronological data. Some other previ-
ously unresolved questions relating to the Placerville Belt are considered. (1) What are the stratigraphic and structural relationships of the diverse lithologies present in the belt? (2) Can units be correlated between the southern and northern parts of the belt? (3) Do the late Middle and Late Jurassic rocks represent overlap assemblage or separate terranes? (4) What is the timing of faulting and folding of the rocks in the belt? The new bio-stratigraphic data presented in this study enable the resolution of these questions, at least for the area studied.

**NEW RADIOLARIAN AGE DETERMINATIONS**

The radiolarian faunas examined in this study fall into six age categories, five of which delineate distinct age ranges, whereas one is more general and overlaps several of the other age categories (Table 1; Fig. 2). In some cases, radiolarians of an age category were found in only one rock assemblage; but in other cases, radiolarians of an age category were found in several different rock assemblages. The important relationship between age and rock type is discussed below in this paper.

The oldest datable cherts in the study area are early Late Permian (Guadalupian). Cherts of this age are denoted F1 (Fig. 2). They contain *Folliculites scholasticus* (Fig. 3; Table 1), a species that is limited to the Guadalupian age. *Folliculites scholasticus* has not been identified anywhere else in the Sierra Nevada.

The next age category (F2) is Late Triassic (Karnian? to Norian), characterized by species of the genera *Capnuchosphaera* (Fig. 3), *Capnodoce*, and others as shown in Table 1, genera that are limited in age range to the Karnian and Norian. Many radiolarians in these faunas are identified tentatively as Norian species (Biome, 1984), and so cherts containing these radiolarians can probably be further constrained in age to the Norian. In addition to radiolarians, several cherts of this age category also contained conodonts, suggesting a Triassic or older age. Conodont genera were not identified, but conodonts became extinct at the end of the Triassic.

The only identifiable radiolarians in the third age category (F3) are from the genus *Canoptum*, which ranges in age from Late Triassic (Karnian) at least to Middle Jurassic (Bajocian). Because lack of preservation prevents species identification, cherts of this category can be given only this general age.
### TECTONIC IMPLICATIONS OF CHERTS

#### TABLE 1. RADIOLARIAN ASSEMBLAGE FOR SAMPLES IN THIS STUDY

<table>
<thead>
<tr>
<th>Radiolarian fauna</th>
<th>Age range</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F8</th>
<th>F9</th>
<th>F10</th>
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<tr>
<td><em>Canopus</em> sp?</td>
<td>Karman-Bajocian</td>
<td>X</td>
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<td><em>Capinodoceras extensum</em></td>
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<td><em>Capinodoceras media</em></td>
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<td>Karman-Norian</td>
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<tr>
<td><em>Capinodoceras colemani</em></td>
<td>Norian or older</td>
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<td><em>Crucella</em> sp?</td>
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<td><em>Ferrumium</em> sp?</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td><em>Ferrumium pyriforme</em></td>
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<td>X</td>
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<td><em>Follicularia scholasticus</em></td>
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<tr>
<td><em>Hsiui</em> sp?</td>
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<td><em>Perv marginosa</em> sp?</td>
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<td>X</td>
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<td><em>Perv marginosa</em> sp?</td>
<td>Piensbachian-Cretaceous</td>
<td>X</td>
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<td><em>Perv marginosa media</em></td>
<td>Piensbachian</td>
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<td><em>Sarda</em> sp?</td>
<td>Piensbachian-Norian</td>
<td>X</td>
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<tr>
<td><em>Sarda longispina</em></td>
<td>Norian</td>
<td>X</td>
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<tr>
<td><em>Sarda venata</em></td>
<td>Norian</td>
<td>X</td>
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<tr>
<td><em>Trilococapsa</em> sp?</td>
<td>Alenian-Kimmeridgian</td>
<td>X</td>
<td>X</td>
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<tr>
<td><em>Xenorus</em> sp?</td>
<td>Karman-Norian</td>
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<td>X</td>
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<tr>
<td><em>Xenorus</em> fasciae*</td>
<td>Norian</td>
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<td><em>Xenorus</em> largum*</td>
<td>Karman-Norian</td>
<td>X</td>
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<tr>
<td><em>Zarthus</em> sp?</td>
<td>Piensbachian-Bajocian</td>
<td>X</td>
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(X = positive identification; ? = tentative identification. Samples are listed by field number, age group, and terrane in which they were located. For sources of age ranges of radiolarians, see Figure 3. GSA Data Repository Item 9413, radiolarian sample information and site descriptions, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.)

The fourth age category (F4) is Early Jurassic. It contains radiolarians which include the genera *Pareconocorymna* (Fig. 3), *Canopus*, and others (Table 1). The age range for these genera overlap between Pliensbachian and Bajocian time. We have identified the *Pareconocorymna*, however, as belonging to the species *P. media*, which is confined in range to the Pliensbachian (middle to late Early Jurassic; Pessagno and Poisson, 1979).

Middle Jurassic radiolarians characterize the fifth age category (F5). These include species of the genera *Trilococapsa*, *Canopus*, *Crucella*, and others. The fauna of this age category are poorly preserved; however, the presence of the genus *Trilococapsa* limits the age to Aalenian or younger, and the presence of *Canopus*, and probably *Zarthus*, limits the age to Bajocian or older (Pessagno and Blome, 1980). Therefore this age category can be limited to Aalenian and Bajocian.

The youngest assemblage (F6) is probably late Middle Jurassic. It contains radiolarians of the genera *Trilococapsa*, *Pareconocorymna*, and others. The presence of poorly preserved radiolarians probably of the genus *Pareconocorymna* indicates a possible age of Bajocian or younger. B. Murchey, however, has tentatively identified these radiolarians as indicative of a Bathonian to Callovian age (1991, personal commun.), and so an age of late Middle Jurassic is probably correct. It should be noted that Bahrman (1977) collected chert-argillite from a locality near where our sample was collected, and he reported an even younger age of Late Jurassic (Oxfordian to Kimmeridgian), based on radiolarian species tentatively identified by E. Pessagno.

In addition to radiolarians, we have identified a Permian trepostome bryozoan from carbonate rocks also containing corals, algal pods, and crinoid stems (R. Hangar, 1989, personal commun.) within a large limestone body near the confluence of the North and Middle Forks of the American River north of Cool (Fig. 4).

#### TERRANE ASSEMBLAGES

The new biostratigraphic data, coupled with lithologic associations of the cherts, and combined with structural investigations and previously published fossil data, have allowed us to separate the central part of the Placerville Belt into five terranes (Figs. 4 and 5). These terranes are fault-bounded packages of rocks with distinct stratigraphic and structural histories, as described below.

**The Mother Lode Terrane.** This terrane includes the well-known Logtown Ridge and Mariposa Formations. It also includes a basal unit composed of tectonic slivers of Permian chert, basalt, serpentinite, and gabbro. The
Figure 2. Age range of radiolarian age categories (F1–F6, as explained in the text) and genera (Cr, Crucella; T, Trilocula; P, Praeconocaryomma; H, Hsium; Pv, Parvicingula; C, Canopytum; Pr, Parabaulella; Pa, Pantanellum; Ca, Capnodoe; Cp, Capnusraphoera; S, Sarca; Fe, Ferrisia; X, Xenoroma). “Con” shows age range of Conodants. Age ranges from Ishiga, 1991; Ishiga and Miyamoto, 1986; Pessagno and Blome, 1980; Pessagno and Poisson, 1979; Pessagno and Whalen, 1982; Pessagno and others, 1979, 1984.

Chert slivers contain radiolarians of age group F1. These slivers are overlain by Bathonian to Callovian basaltic sandstone and argillite. Radiolarians of age group F6 were identified in chert-argillite from these beds. The sandstone and argillite are depositionally overlain by the upper Callovian to Oxfordian andesitic to basaltic brecchia of the Logtown Ridge Formation. Clasts of the volcanic brecchia vary in composition from about 50% volcanic in western outcrops to almost 100% volcanic in eastern outcrops. In addition, eastern outcrops are interbedded with massive and pillow lava, whereas western outcrops are interbedded with pebbly mudstone. These relationships indicate that the Logtown Ridge Formation formed on the western side of an oceanic island arc and received detritus from nonvolcanic sources farther west. These rocks are depositionally overlain by Oxfordian to Kimmeridgian slate and conglomerate of the Mariposa Formation. The pebble- to cobble-sized clasts in the conglomerate contain chert; porphyry volcanic rocks derived from underlying strata; and sandstone, quartzite, and granite probably derived from a continental source. Along strike to the south of the studied area, the conglomerate and slate grade into olistostrome deposits mapped as Central Belt mélangé by Duffield and Sharp (1975). These rocks had been considered to predate the Logtown Ridge Formation (Behrmann, 1977, for example), but the presence of porphyry volcanic detritus derived from the Logtown Ridge Formation in beds of the olistostome (Graymer and Jones, 1991), along with the gradational relationship along strike with the Mariposa Formation, shows that these rocks, at least in part, postdate the Logtown Ridge Formation, and are probably Mariposa equivalent. The ages of the Callovian to Kimmeridgian formations of this terrane are well controlled by occurrence of ammonites, Buchia, and related fossils (Imlay, 1961). Chert pebbles in the conglomerate of the Mariposa Formation contain radiolarians of the Late Triassic (F2) age group, whereas pebbly mudstone beds within the Logtown Ridge Formation contain chert pebbles bearing Permian (F1) radiolarians. The presence of F1 radiolarians, which have not been described anywhere else in the Sierra Nevada Foothills, in clasts in the Logtown Ridge Formation demonstrates the depositional relationship between the scraps of relatively unmetamorphosed Permian basement and overlying Middle to Late Jurassic strata (Fig. 6). The western part of the terrane is faulted against serpentinite and metavolcanic rocks along the Bear Mountains fault zone (Miller and Paterson, 1991), whereas the younger parts of the terrane to the east are repeated at least five times by imbricate thrust faults and isoclinal folds. We interpret the Mother Lode Terrane to consist of Permian sea-floor rocks unconformably overlain by Middle to Late Jurassic arc-related volcanic rocks, derived from both eastern (oceanic-arc) and western (unknown terrane) sources, and Late Jurassic turbidites containing continental detritus. Although the contact between the basal Permian rocks and the Bathonian to Callovian basaltic sandstone is faulted in places (as in Fig. 7), and obscured in all others, we interpret it to have been originally depositional because of (1) the presence of F1 chert in clasts of overlying strata, (2) the presence of large amounts of basaltic detritus almost certainly derived from the underlying Permian rocks in the basaltic sandstone at the base of the younger strata, and (3) the structural position of Permian rocks at the base of the Mother Lode Terrane.

The Mount Ararat Terrane. This terrane structurally overlies the Mother Lode Terrane along a highly folded northeast-trending thrust fault (Fig. 7). The Mount Ararat Terrane is made up of two fault-bounded subterranes. The structurally lower subterranes is composed of serpentinite matrix mélangé containing blocks of basalt, gabbro, diabase, argillite, amphibolite, and mica schist, as well as Late Triassic (F2) and Triassic to Jurassic (F3) chert. The structurally higher subterranes is a chaotic unit made up of Late Triassic (F2) chert depositionally overlying basalt, and chert-basalt diamicite with clasts containing Late Triassic (F2) and Early Jurassic (F4) radiolarians. We designate these two structural blocks as subterranes because the structurally higher rocks are geographically restricted to an area within that of the structurally lower rocks. The Mount Ararat Terrane probably represents debris flows derived from, and volcanic rocks of, one or more Triassic to Jurassic seamounts (the upper subterranes) that formed on Triassic(? seafloor which subsequently has been tectonically dismembered and combined with nonophiolite rocks to form the serpentinite matrix mélangé (the lower subterranes). The American River Terrane. It is overthrust by the Mount Ararat Terrane along a highly folded east-west-trending thrust fault.
The structural base of this terrane is composed primarily of sedimentary mélange (olistostrome) with a matrix of slate, sandstone, and pebble conglomerate containing blocks (olistoliths) of chert, basalt, and limestone up to 100 m in diameter. The chert olistoliths contain radiolarians of age groups F2, F3, and F4 (Late Triassic and Early Jurassic), whereas the matrix includes chert argillite containing Middle Jurassic (F5) radiolarians. The olistostrome is interbedded in the western part of the terrane with phyllitic andesite tuff. These sedimentary and volcanic rocks have been mapped previously as Clipper Gap Formation, and they were previously dated as Paleozoic based on the age of corals and other fossils in the limestone blocks (Chandra, 1961). The fossiliferous blocks, however, give only a maximum age for the olistostrome (Day and others, 1985). To the north, another assemblage of rocks has been mapped as “Clipper Gap Formation” by Edelman and others (1989), but that assemblage is older, because it contains interbedded Triassic slate and chert, and is lithologically dissimilar. The Middle Jurassic Clipper Gap Formation is overlain by the Colfax Formation, composed of chert pebble to boulder conglomerate, sandstone, and slate. The chert pebbles and boulders contain Late Triassic to Early Jurassic radiolarians (F2, F3, F4) and are identical in age and lithology to chert blocks found as olistoliths in the Clipper Gap Formation, reflecting the depositional relationship between the two (Day and others, 1985). It should be noted, however, that a depositional contact between the Clipper Gap and Colfax Formations is not exposed anywhere in the study area. The Colfax Formation has been dated as early Callovian (Middle Jurassic) based on ammonites and associated fossils (Imlay, 1961). We interpret this terrane to represent early Middle Jurassic (Aalenian to Bajocian) debris-flow deposits overlying (and in part supplying sediment for) late Middle Jurassic (Callovian) turbidites. Original provenance of the clasts and olistoliths is unknown.

Cool Quarry Terrane. The fourth terrane in the field area is also overthrust by the Mount Ararat Terrane, and it in turn lies structurally above the American River Terrane. This terrane is composed of basalt, pillow basalt, basaltic tuff, gabbro, and basalt breccia, with intercalated Permian fossiliferous limestone and marble. Although no radiolarians were discovered in this terrane, a well-preserved Permian trepostome bryozoan was found in the limestone, and crinoid columnals are locally abundant in basaltic tuff. Only a small scarp of this terrane remains exposed in the northernmost part of the study area (Fig. 4). We interpret this terrane to represent a fragment of a Permian seamount.

The French Creek Terrane. The fifth terrane in the area studied is in high-angle fault contact with the western part of the Mother Lode Terrane, and it is overthrust along its northern margin by the Mount Ararat Terrane. It is composed of upper-greenschist- to amphibolite-facies pelitic schist, metachert, metabasalt, and mafic to intermediate metatransgressive rocks. Although this terrane contains no known fossils, 40Ar/39Ar analysis has provided an age of metamorphism of about 190 Ma for these rocks, and so protolith ages must be Early Jurassic or older (Graymer, 1992). This terrane probably formed by medium- to high-grade metamorphism of volcanic-arc-related rocks, the presence of chert suggesting oceanic- rather than continental-arc volcanism.
Figure 4. (A) Distribution of terranes in the study area within the Placerville Belt (ART, American River Terrane; CQT, Cool Quarry Terrane; MAT, Mount Ararat Terrane; MLT, Mother Lode Terrane; FCT, French Creek Terrane). (B) Distribution of radiolarians and other fossils in the terranes in the study area. F1–F6 correspond with radiolian age categories described in the text (italics indicate radiolarians from interbedded chert or chert argillite; roman type indicates radiolarians from chert clasts). A, ammonite-bearing assemblages from Imlay, 1961; B, bryozoan-bearing assemblage described in text.
Tectonic Implications of Cherts

Late Jurassic
  Kimmeridgian
  Oxfordian
  Callovian
  Middle Jurassic
  Bathonian
  Bajocian
  Aalenian
  Toarcian
  Early Jurassic
  Pliensbachian
  Hettangian/Sinemurian
  Late Triassic
  Rhaetian
  Norian
  Carnian
  Middle Triassic
  Ladinian
  Anisian
  Early Triassic
  Scythian
  Ochoan
  Late Permian
  Guadalupian
  Wordian

Coloma Pluton

Key to Symbols
  • volcanic tuff
  • marble and limestone
  • argillite
  • sandstone
  • slate
  • volcanic breccia
  • conglomerate
  • chert
  • basalt
  • diatomaceous
  • serpentinite mélangé
  • olistolith
  • tectonic slivers
  • thrust fault
  • unconformity

Figure 5. Tectonostratigraphic relationships within the various terranes of the study area. Bars on the left show the age range of radiolarian age categories. Time scale has been subdivided into epochs and ages. The vertical arrow represents the depositional link described in the text. Note that each terrane is fault bounded, and that all faults predate the 143 Ma Coloma Pluton. Note also the different rocks of Callovian age in the American River and Mother Lode Terranes.

Tectonic Implications of New Data

The new understanding of stratigraphic and structural relationships among the diverse rock types present in the central part of the Placerville Belt, discussed above, has several implications for previously unresolved questions relating to the Placerville Belt and the Sierra Foothills as a whole. First, lithologic units cannot be traced from the northern to southern parts of the belt because the presence of terranes with completely different stratigraphic histories in the study area disrupts continuity and precludes the possibility of throughgoing geologic units. This bears directly on attempts to correlate units from different parts of the belt as part of a single large terrane (such as the Tuolumne Terrane of Edelman and Sharp, 1989, or the Foothills Terrane of Blake and others, 1982). The Placerville Belt is made up of many terranes, not just one or two. The tectonostratigraphic relationships of the terranes are summarized in Figure 5. It is important to note that during Callovian time the American River Terrane was the site of pelite (now...
Permian rocks in the Mother Lode Terrane were separated from the French Creek Terrane at the time of metamorphism. The third constraining relationship is that the Mount Ararat Terrane cannot be in the same stratigraphic sequence as the Cool Quarry or Mother Lode Terranes because Triassic ophiolite could not have formed over older rocks. In addition to the five terranes described herein, Edelman and others (1989) described two terranes in the northern part of the Placerville Belt, the Slate Creek and Fiddle Creek Terranes, that seem to be distinct from terranes described here. Especially persuasive is the presence of Late Triassic (F2) radiolarians in the slates of the Fiddle Creek Terrane (Hietanen, 1981), proving it distinct from the Late Triassic ophiolitic rocks of the Mount Ararat Terrane.

The classification of the late Middle to Late Jurassic rocks in the Mother Lode Terrane as part of a separate terrane, rather than an overlap assemblage, is further supported by the observation that the Callovian to Kimmeridgian rocks in the Placerville Belt have a depositional link (interpreted as an unconformity) with Permian sea-floor rocks (gabbro, basalt, and chert). This observation does not support the idea that they were deposited on (or over) high-grade metamorphic rocks to the west (the so-called "Bear Mountains Ophiolite") as proposed by many workers (including Behrmann, 1977; Saleebey, 1982; Edelman and Sharp, 1989; Herzog and Sharp, 1992). The high-grade metamorphism that took place about 200 Ma (Behrmann, 1977) in the "Bear Mountains Ophiolite" would certainly have affected the relatively unmetamorphosed Permian sea-floor rocks if they had been in the same tectonostratigraphic sequence. The fact that the Permian sea-floor rocks are relatively unmetamorphosed shows that they belong to a separate terrane. Although overlying rocks could have been deposited after amalgamation of the two sets of older rocks after the 200 Ma metamorphic event, there is no evidence to link the overlying strata to the high-grade rocks, and the presence of relatively unmetamorphosed Permian sea-floor rocks along the only structural contact between the high-grade metamorphic rocks and the Jurassic strata suggests that there was no depositional relationship.

As shown above, the Mother Lode and American River Terranes were distinct in early Callovian time. The continuous record of deposition in the Mother Lode Terrane from that time into the Kimmeridgian demonstrates that structural juxtaposition (amalgamation) of the two terranes occurred during or after the Kimmeridgian. Because two other terranes (the French Creek and Mount Ararat Terranes) are in direct fault contact with the Mother Lode Terrane, final structural juxtaposition of these terranes must have also taken place after the deposition of the Mariposa Formation. It is probable that the amalgamating faults formed at the continental margin during sequential accretion of the various terranes. Because the French Creek Terrane is west of the Mother Lode Terrane, it probably accreted after the Mother Lode Terrane. And because the Mount Ararat Terrane's southern boundary fault cuts the fault between the French Creek and Mother Lode Terranes (Fig. 4), the Mount Ararat Terrane was definitely accreted after the French Creek Terrane. The Cool Quarry Terrane is not in contact with the Mother Lode Terrane, and so it is possible that it amalgamated with the American River Terrane before the Kimmeridgian. It is probable, however, that this amalgamation occurred after the deposition of the Callovian Colfax Formation, because there is no evidence of basaltic tuff or limestone in the conglomerate that derived from the underlying rocks. Although the structural relationship between the American River and the Mother Lode Terranes does not preclude the accretion of the American River Terrane before the Mother Lode Terrane, the Callovian age of the Colfax Formation indicates that the American River Terrane accreted after the early Callovian. A plausible resulting history of accretion is as follows: the American River Terrane accreted first, after the early Callovian, followed by the Cool Quarry Terrane, and, after the Kimmeridgian, the Mother Lode Terrane, followed by the French Creek and finally the Mount Ararat Terrane. The accretion was complete by the time of the intrusion of the Coloma Pluton, which has yielded a preliminary U/Pb age from zircons of 143 Ma (J. B. Saleebey, 1991, personal commun.). These observations support the idea of Late Jurassic (Nevadan) accretion proposed by Schweickert and others (1988). It should be noted that there is ample evidence in the study area for deformation before Nevadan time, the 190 Ma metamorphism of the French Creek Terrane, for example; these structures, however, are limited in extent to single terranes. Because pre-Callovian structures are terrane specific, and the Callovian and younger rocks are parts of different displaced terranes, no evidence is seen within the study area for the pre-Callovian accretion proposed by Edelman and Sharp (1989).
CONCLUSIONS

The ability to unravel at least part of the geologic complexity in this area is due in large part to the geochronologic control provided by study of radiolarian cherts. Increasing the amount of geochronologic data, both biostratigraphic and isotopic, available in the Sierra Nevada Foothills is an important next step toward better understanding of this complex region. Note, however, that whereas some radiolarian age categories are associated with only one lithologic assemblage in one terrane, other age categories are associated with multiple lithologic assemblages. For example, radiolarians of age group F2 are found in conglomerate pebbles in the Mother Lode Terrane, in tectonic blocks of chert in the serpentinite matrix mélangé of the Mount Ararat Terrane, and in olistoliths in the American River Terrane. Likewise, similar lithologies
may have very different ages. For example, chert-pebble conglomerate in the Morher Lode Terrane (Mariposa Formation) is late Oxfordian to Kimeridgian, whereas chert-pebble conglomerate in the American River Terrane (Colfax Formation) is early Callovian. These examples demonstrate the importance of combining lithologic study with biostratigraphic data. Combining all rocks of one age group into a single category would obscure important information regarding the different depositional regimes of the various lithologies. It is precisely the juxtaposition of rocks that formed in very different geologic settings at the same time that proves the displaced nature of the terranes in the area.

By combining detailed mapping, depositional analysis, and biostratigraphic data, we have been able to distinguish five different terranes in the study area. The structural relationships between the terranes, as well as the ages of formations within them, reveal that they probably accreted episodically between the early Callovian (165 Ma) and the time of intrusion of the Coloma Pluton (143 Ma). The episodic accretion is clearly related to the period of deformation known as the Nevadaan Orogeny, which by original definition is that period during which the youngest prebatholithic rocks in the Sierra Foothills were deformed (Hinds, 1934). The Nevadaan Orogeny, therefore, is the period between 165 and 143 Ma. Finally, we propose the model of orogeny by episodic accretion of smaller terranes as an alternate model of continental growth and deformation that may be applicable in other studies of active continental margins.

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Stratigraphic and Structural Significance of New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates from the Placerville Belt, Sierra Nevada Foothills, California

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Abstract
Three new $^{40}\text{Ar}/^{39}\text{Ar}$ plateau dates were obtained from rocks in the Placerville Belt, two from amphibole schist in the French Creek Terrane (FCT), one from an amphibole schist clast within volcanosedimentary breccia (Logtown Ridge Formation) within the Mother Lode Terrane (MLT). The ages are all about 190 Ma, approximately the same age as reported for the adjacent but tectonically separated Shingle Springs Complex ("Bear Mountains Ophiolite"). We suggest that the FCT in the Placerville Belt is part of the same accreted complex as the SSC. While the SSC/FCT complex does not form the basement for the MLT, the presence of clasts of metamorphic rocks of similar age and lithology suggests that the SSC/FCT was a sedimentary source that lay west of the depositional basin at the time of Logtown Ridge Formation deposition (late Callovian to middle Oxfordian). The Bear Mountains Fault is not a major terrane boundary in this area. Instead, the major boundary fault is part of a complex set of faults formed by accretion and extensional tectonics during the Nevadan Orogeny (155 - 143 Ma). The Bear Mountains Fault here is a post - accretion attenuation fault. This type of fault is different from the reported nature of the Bear Mountains Fault elsewhere in the Sierra Nevada Foothills.

Introduction

This paper presents new Ar/Ar age data from the Placerville Belt, and discusses the implications of the data on the nature of the Bear Mountains Fault and for understanding geologic relationships both within the belt and with a metamorphic complex to the west (the so-called "Bear Mountains Ophiolite", herein designated the Shingle Springs Complex). The Placerville Belt (see Figure 1) is a complex collage of accreted terranes in the Sierra Nevada Foothills, bounded on the east by the Melones - Gillis Hill Fault and on the west by the Big Bend - Wolf Creek - Bear Mountains Fault Complex (Graymer and Jones, 1991). The structural and lithologic relationships within the belt and between the belt and adjacent terranes are controversial and poorly understood. However, most recent workers have asserted that this belt represents rocks accreted to the continental margin during some period of orogeny. If the addition of material to continents at active margins is to be understood, the lithologic and structural relationships in areas such as the Placerville Belt must first be examined.

The "Bear Mountains Fault"

The so-called "Bear Mountains Fault" is considered by most workers (e.g., Miller and Paterson, 1991) to be a zone of highly sheared rocks separating the Placerville Belt and rocks to the west. The type of fault motion, orientation, and width of this zone, however, as well as the rock types within it, vary along its length (see Figure 3). At the far southern end of the Sierra Foothills (Area 1 in Figure 3) the structure has been described as a zone of ductile shear up to 1.5 km wide, probably formed by reverse faulting (Saleeby, et al., 1989). It should be noted that the fault has been described in that area as occurring within a single unit of sandstone and slate, and
so cannot be considered a terrane boundary fault. On the other hand, other workers farther north (Area 2) interpreted the BMFZ as a zone up to 10 or more kilometers wide of sedimentary matrix melange that experienced intense deformation in a major intra-arc reverse fault of moderate to large scale displacement (Miller and Paterson, 1991). Still farther north, in the Bear Mountains themselves (Area 3), the fault zone consists of two strands with a belt of serpentinite matrix melange between. The western strand is a steep, east-dipping reverse fault that places the melange over the volcanic and sedimentary rocks to the west. The rocks of the foot wall are metamorphosed to garnet-bearing mica schist, probably reflecting a deep level of overthrusting. The eastern strand is a steep, east dipping attenuation fault. The rocks in the hanging wall (Placerville Belt) have undergone considerably less metamorphism than those west of the fault zone (lower greenschist grade at most), indicating a lack of deep burial. The lack of deep burial is consistent with attenuation faulting. To the north of the area of this study (Area 4), the BMFZ has been considered the southern continuation of the Big Bend - Wolf Creek Fault (Edelman, et al., 1989, Day, et al., 1985, Saleeb, 1990), which is a steeply east dipping reverse fault that forms the boundary between the Placerville Belt and rocks to the west. The BMFZ in the area of the study (Area 5) is unlike any of the parts of the fault to the north or south, as described below.

Previous Interpretations of Placerville Belt Tectonostratigraphy

The rocks in the Placerville Belt have been interpreted as a pseudo stratigraphic sequence (Behrman, 1978, Saleeb, 1982, Sharp, 1988, Edelman and Sharp, 1989). The base of the so-called sequence is the "Bear Mountains Ophiolite", amphibolite grade metamorphic rocks mostly exposed within the Bear Mountains Fault Zone, and thought to represent accreted seafloor. We feel that the ophiolite designation is misleading because in the study area it contains such non-ophiolite lithologies as meta-andesite, meta-sandstone, and marble. Therefore the ophiolite designation is discarded herein and this unit is referred to as the Shingle Springs Complex (SSC). The SSC is supposed by previous workers to be overlain by "Central Belt Melange," (see Figure 2a) an olistostrome containing blocks of Tethyan limestone, conglomerate, chert, basalt, and other lithologies. The SSC and melange are thought to form the amalgamated basement on which was deposited a Middle to Late Jurassic sequence of volcanic, volcanoclastic, and epiclastic rocks (including the Logtown Ridge Formation, see below). However, the contact between these units is everywhere faulted, so the depositional relationship between them is unproved. Recent work (Graymer and Jones, 1993) suggests that Middle to Late Jurassic rocks were deposited on unmetamorphosed Permian seafloor, and that the "Central Belt Melange" cannot be placed into a stratigraphy above the SSC (see Figure 2b). This article demonstrates that a depositional relationship does exist between the rocks of the SSC and Callovian to Kimmeridgian volcanosedimentary strata, but as sedimentary source rather than as basement.

New Work

Two samples from the French Creek Terrane (FCT, see Figure 4) were dated. This terrane is bounded on the west by the Bear Mountains Fault, to the south and east by fault contacts with the Middle to Late Jurassic volcanic and sedimentary rocks of the Mother Lode Terrane (MLT), and to the north is overthrust by the Late Triassic to Early Jurassic serpentinite melange of the Mount Ararat Terrane (MAT, see Graymer, 1992, for complete descriptions of
terranes in this area of the Placerville Belt.) The FCT consists of lower amphibolite to greenschist grade metamorphic rocks derived from a wide variety of rocks including basalt, andesite, chert, sandstone and mudstone. Serpentinite is also present within the terrane. The two samples were collected from outcrops of hornblende amphibolite schist that contain amphibole grains up to 2 mm in length.

The third dated sample was collected from the western member of the Logtown Ridge Formation in the Mother Lode Terrane (MLT). The Logtown Ridge Formation is characterized by andesite porphyry breccia, with common plagioclase and augite porphyroclasts. The formation is part of a stratigraphic sequence that may be linked to a basement of unmetamorphosed Permian seafloor rocks (Graymer and Jones, 1993). The Logtown Ridge Formation in the type locality on Logtown Ridge in eastern part of the MLT is composed solely of volcanic flows and breccias with andesite clasts, whereas breccias in the western part have a large component of non-volcanic clasts, including Permian limestone of Eastern Klamath affinity, granite, chert, and amphibolite schist. This east-west variation in clast composition suggests that volcanic clasts were derived from a volcanic arc east of the basin, and non-volcanic clasts were derived from sources west of the basin. The sample is from a clast of hornblende amphibolite schist found in the western portion of the formation, probably derived from andesite or intermediate plutonic protolith.

The samples were dated by $^{40}\text{Ar}/^{39}\text{Ar}$ analysis using laser step-wise heating of multigrain hornblende separates weighting between 5 to 20 mg. The separates were incrementally heated by stepwise increasing power output from an Ar-ion laser with defocused beam. Released Ar was measured with an automated mass spectrometer using a cryocooled cold-trap on the extraction line to help remove condensable gasses. Stepwise heating allows the separation of gas fractions related to less stable parts of the mineral grain, and therefore provides a more accurate age. At high temperature, the Ar ratios reach a constant value, or plateau, which defines the age of the sample after the equation

$$t = (l)^{-1} \ln \left[ \left( \frac{^{40}\text{Ar}^*}{^{39}\text{Ar}} / \frac{^{39}\text{Ar}}{^{39}\text{Ar}} \right) + 1 \right]$$

where $t$ is the age of the sample, $l$ is the decay constant, $^{40}\text{Ar}^*$ is radiogenic $^{40}\text{Ar}$, and $J$ is a constant related mainly to the irradiation of the sample before measurement. A plateau is defined as three or more contiguous steps with apparent ages that overlap the mean at the 2s level (Renne and Basu, 1991).

The results of the testing are shown in Figure 5. They clearly show that metamorphism of the FCT leading to amphibole K/Ar equilibration occurred about 190 Ma, and that the metamorphism of the amphibolite clast in the Logtown Ridge Formation occurred about the same time (187 Ma). The samples from the FCT are relatively unaltered, as shown by the consistent values of argon released throughout stepwise heating. The MLT clast, on the other hand, is considerably altered, as shown by the inconsistent and dispersed values for the first 60% of argon released.

**Implications of New Data**

The FCT has previously been included in the Shingle Springs Complex ("Bear Mountains Ophiolite" Saleeby, 1990). However, the SSC is of higher metamorphic grade than the FCT and
is separated from it by the Bear Mountains Fault, and so has been considered a separate unit by other workers (Wagner, et al., 1981, Miller and Paterson, 1991). The first implication of this study is that the FCT and SSC do derive from the same accreted terrane. Rocks from the SSC have been dated previously yielding K/Ar (hornblende) dates of about 190 Ma (Behrman, 1977), the same as those in the FCT, and U/Pb (zircon) ages of more than 300 Ma (Saleeby, 1982). The K/Ar (hornblende) ages probably reflect the same metamorphic event dated by this study, whereas the older U/Pb (zircon) dates may reflect a previous metamorphic event or protolith age. In addition, the two units are made up of metamorphic rocks with similar protoliths. Therefore, the SSC and the FCT almost certainly were derived from the same accreted terrane, and the FCT is a fragment that has been tectonically added to the Placerville Belt. The difference in metamorphic grade reflects structural displacement during and after accretion which juxtaposed rocks metamorphosed at different levels in the same complex.

The similarity in age between the clast from the MLT and SSC/FCT complex suggests that it was derived from the SSC/FCT during a period of uplift and erosion. Behrman (1977) suggests that the "Bear Mountains Ophiolite" forms the basement for deposition of MLT sedimentary and volcanic rocks. However, the MLT is structurally above and may be stratigraphically linked to a basement of unmetamorphosed Permian seafloor, as described above. Therefore, occurrence of SSC/FCT clasts in the Logtown Ridge Formation indicates that one of the western sedimentary sources for the basin was the metamorphic complex of the SSC/FCT (see Figure 6). The slight difference in age between the clast and amphibolites in the FCT is probably due to variations in age of mineral closure in different parts of a large metamorphic complex.

The occurrence of rocks from the same accreted terrane (SSC/FCT) on both sides of the Bear Mountains Fault indicates that, at least in this area, the fault is not a major terrane bounding suture. A major suture in this area is represented by the fault boundary between the FCT and the MLT. The spatial relationship of the two terranes indicates that the FCT/SSC was accreted after the MLT by wedging below it (see Figure 2b). Even though the terrane bounding structure was originally a thrust fault, the present sense of offset of the bounding fault is extensional, and the original sutured relationships have been destroyed. The bounding fault is cut by the overthrust of the MAT, indicating that the accretion of the SSC/FCT and the MLT, as well as the post-accretion extension, were completed before the obduction of the MAT. The overthrust fault is cut by the 143 Ma Coloma Pluton (age from U/Pb analysis of zircon, Saleeby, 1991, personal communication), whereas the accretion of the MLT postdates the formation of the Kimmeridgian (156 - 150 Ma, Harland, et al., 1982) rocks within it. Therefore the accretion of these terranes occurred in the period of about 154 - 143 Ma, which we suggest is within the age range of the Nevadan Orogeny.

The Bear Mountains Fault in this area is thus a relatively young attenuation fault. It cuts, and therefore postdates, both the FCT/SSC - MLT terrane bounding fault and the MAT overthrust. It juxtaposes rocks of higher metamorphic grade in the footwall against rocks of lower grade in the hanging wall, demonstrating the attenuation nature of motion on it. Motion on this fault probably also consisted of some strike slip offset. It is important to note that the tectonic nature of the Bear Mountains Fault in this area is very different than in areas to the north and south, where it does form major terrane boundaries and has different senses of offset.
Conclusions

The three new $^{40}$Ar/$^{39}$Ar dates from rocks in the Placerville Belt have given significant insight into the stratigraphy and tectonics of this region. They show that the FCT in the Placerville Belt is from the same accreted complex as the SSC ("Bear Mountains Ophiolite"), which has the same metamorphic age and lithology, and though the SSC/FCT complex does not form the basement for the MLT, the presence of clasts of metamorphic rocks of similar age and lithology suggests that the SSC/FCT was one of the sedimentary sources that lay west of the depositional basin at the time of Logtown Ridge Formation deposition (late Callovian to middle Oxfordian).

The occurrence of the same metamorphic complex on both sides of the Bear Mountains Fault show that it is not a major terrane boundary in this area. The Bear Mountains Fault here is a post accretion attenuation fault, which is different from the nature of the fault elsewhere. The varying nature of the Bear Mountains fault is a significant area for future study. The identity of the fault as a continuous single tectonic entity is very doubtful, and therefore observations, such as timing of offset, made on the fault in one place may not be valid for other sections of the fault. Careful study to classify the nature of the various sections of the Bear Mountains Fault, as well as the relationships between them, is vital to the understanding of Sierran geology.

The terrane sutures in this area are multiple faults that lie east of the Bear Mountains Fault. These structures were active in the period between 155 - 143 Ma, which we assign to the Nevadan Orogeny. This orogeny was a period of multiple structural episodes, including both compressional and extensional deformation. In addition, interpretation of this new data agrees with the model of post-Kimmeridgian (Nevadan) terrane accretion west of the Melones Fault (Schweikert, et al., 1988).

Acknowledgments

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**Figure Captions**

**Figure 1** Lithotectonic Belts of the Sierra Nevada Foothills and their bounding faults. Numbered areas are locations of parts of the "Bear Mountains Fault" referred to in figure 3. (PB=Placerville Belt, SSC=Shingle Springs Complex, SVC=Smartville Volcanic Complex, WB=Western Belt, CLV=Calaveras Terrane, DPT=Don Pedro Terrane, FRT=Feather River Terrane, NSI=Northern Sierra Terrane, BMFZ="Bear Mountains Fault Zone", WCF=Wolf Creek Fault, BBF=Big Bend Fault, MF=Melones Fault, GHF=Gillis Hill Fault.) Area 5 is the area of this study.

**Figure 2** A - Supposed tectonostratigraphic relationships of rocks in the Placerville Belt and "Bear Mountains Ophiolite" (after Saleeby, 1982, Edelman and Sharp, 1989). B - Observed tectonostratigraphic relationships in the study area of this report (after Graymer, 1992).

**Figure 3** Sketch maps of structural relationships described for different parts of the "Bear Mountains Fault Zone" and related faults (see figure 1 for location of each area). Scale varies.
1. After Saleeby, et al., 1989
2. After Miller and Paterson, 1991
3. Modified from Parkinson, 1976
5. This paper (see figure 4)

**Figure 4** Generalized geologic map of the study area. Circled numbers indicate locations of rocks sampled for Ar/Ar study, and correlate with numbers on figure 5.

**Figure 5** Results of stepwise laser heating and Ar/Ar analyses of samples in this study. Circled numbers refer to sample localities shown in figure 4.

**Figure 6** Cartoon map of the Callovian to Oxfordian Proto - Pacific Ocean showing the relative locations of terrane elements and deposition of the Logtown Ridge Formation in the Mother Lode Terrane from and eastern volcanic source and western non-volcanic sedimentary sources, including the Shingle Springs Complex/French Creek Terrane.
A

Volcanosedimentary sequence (including Logan Creek Formation)  
\- Unconformity

Sheeted dikes and gabbro (about 160 Ma)

- Central Belt Melange

- Unconformity?

- "Bear Mountains Ophiolite"

B

Middle Sheeted dikes and gabbro (about 160 Ma)

\- Intrudes

\- Logtown Ridge Formation

\- Unconformity

\- Central Belt Melange

\- "Tectonic blocks of unmetamorphosed seafloor rocks"

MLT

Age unknown, possibly as young as Late Jurassic

 uncertain contact?
A

Volcanosedimentary sequence (including Logtown Ridge Formation) ?

Unconformity

Central Belt Melange ?

Unconformity?

"Bear Mountains Ophiolite" ?

B

Middle Sheeted dikes and gabbros (about 160 Ma).

Early Late Permian

Intruders

MLT

Logtown Ridge Formation

Unconformity

Uncertain contact?

Age unknown, possibly as young as Late Jurassic

Central Belt Melange

Tectonic blocks of unmetamorphosed seafloor rocks
Attenuation fault
Thrust fault
Serpentinite melange
Sheared sedimentary rocks
Slate
Greenschist-amphibolite grade metamorphic rocks
Attenuation fault
Thrust fault
Serpentinite melange
Sheared sedimentary rocks
Slate
Greenschist-amphibolite grade metamorphic rocks
Oxf. - Kimm. Slate
Call. - Oxf. volcanoclastic breccia (Logtown Ridge Fm.)
Bath. - Baj. volcanic sandst. and argillite
Broken Perm. seafloor rocks
Serpentinite melange
Gabbro - diorite
Amphibolite grade
meta - andesite
Undifferentiated amphibolite to greenschist grade
meta - volc. and meta - sed. rocks, and serpentinite
Apparent age (Ma)

Cumulative fraction $^{39}\text{Ar}$ released

1. JPLV-3
   - $191.3 \pm 0.5$ Ma

2. JPLV-4
   - $189.4 \pm 0.7$ Ma

3. JPLV-8C
   - $186.6 \pm 1.4$ Ma
Logtown Ridge Arc

Limestone + Granite

Logtown Ridge Formation western sedimentary sources

North America

MLT

Plate Motion

SSC/FCT
Logtown Ridge Arc

North America

Plate Motion

Limestone - Granite

Logtown Ridge Formation western sedimentary sources

SSC/FCT
Geologic History of the Placerville Belt
By
Russell Graymer

Introduction
The history of the Placerville Belt is one of multiple accretion of displaced terranes at the western margin of the North American continent. The history of the belt as a whole is dominated by the timing and mechanism of accretion and attendant deformation, as well as by deformation and igneous intrusion that postdate terrane amalgamation. The history of deposition and formation of the rocks belongs to the unique pre amalgamation history of each terrane, many of which also have distinct periods of deformation. Together, the separate history of each terrane and the history of accretion and deformation of terranes as they came together makeup the history of the Placerville Belt and constrain tectonic models of formation of the Sierra Nevada foothills.

The stratigraphy of the various terranes and the timing of structural events have been described in previous chapters. What follows is a model of plate motion, terrane formation, and terrane accretion that best fits the information observed in the area of this report, as well as taking into consideration data reported in the literature. In some ways it is similar to models proposed previously, but it varies greatly from previous models in: 1) The position and relationship of Jurassic volcanic arcs, 2) mechanism of terrane accretion; 3) length of travel by some rock units, and 4) timing of accretionary events.

Late Triassic to Early Jurassic
The initial situation in the Late Triassic and Early Jurassic is one of a subduction margin west of the previously accreted Calaveras terrane facing the proto Pacific (See Figure -). The Permian limestone and basalt seamount of the Cool Quarry Terrane (CQT) has already formed on Paleozoic oceanic crust. Between the subduction zone and the seamount, pelagic sedimentation is forming major bodies of chert, which will form the chert olistoliths and pebbles in the American River Terrane (ART). Fragments of older arc - related or continental crust containing of McCloud - type limestone, granite, and metamorphic rocks lies southwest of the CQT seamount. This will be the western source terrane for clasts in the Logtown Ridge formation of the Mother Lode Terrane (MLT). Farther south and west is an ocean - ocean subduction zone that is forming an arc on Permian - Triassic ophiolite that is the protolith of the Shingle Springs Complex (SSC) and the French Creek Terrane (FOT). Finally, south and west of the subduction zone, an active seamount is forming on Triassic ophiolite, which will become the Mount Ararat Terrane (MAT), with the seamount and related sedimentary rocks forming the upper plate and the Triassic ophiolite forming the lower plate. It is important to note that the position of this terrane is not well constrained, and that while the placement of the terrane in this position is consistent with the simplest explanation of the observed relationships, it is not the only possible position. This tectonic regime is bounded on the south - west by an ocean spreading center that may be the forerunner of today's East Pacific Rise.

Early to Late Jurassic
In the early to middle Jurassic (Toarcian to Aalenian) the situation has evolved in two ways (See Figure -). Paleozoic limestone and Triassic - Jurassic chert along with pillowed basalt (possibly from Paleozoic oceanic crust related to the limestone) have been uplifted and are shedding blocks into a deep ocean depositional basin. These landslides deposits form the olistostrome unit of the ART. It is possible that the uplift of these oceanic rocks occurred because they were accreted to the continent (as shown in the figure), but there is no direct evidence for this. Paleozoic limestone may in the Calaveras Terrane, but Triassic to Jurassic chert, as
well as pillowed basalt, does not and so requires this source terrane that is today completely unexposed in the area. Meanwhile, in the center of the ocean basin, arc rocks, predominantly andesite, shale, and limestone, along with the ophiolitic rocks the arc formed on, mostly basalt, gabbro, and peridotite, are overthrust by a hot crustal layer which forms a doubled crust. The resulting metamorphism at amphibolite to upper greenschist facies reaches its peak about 190 Ma, when amphibole recrystallization locks in the K - Ar isotopic ratios. These metamorphic rocks form the present SSC and FCT.

**Late Middle - Jurassic**

Later in the middle Jurassic (Bathonian to early Callovian) three events are occurring (See Figure -). Part of the depositional basin of the American River Terrane has moved closer to the continental shelf, and shale and conglomerate of the Colfax formation are forming, probably in a coastal delta, although the absence of large bodies of sandstone is unusual for the deltaic environment. About 300 to 500 km to the southwest (given an average plate motion of 3 to 5 cm per year and a difference in age of accretion of about 10 million years) the ocean - ocean subduction zone that would lead to the Logtown Ridge formation arc is initiating. Deformation associated with this has uplifted the Permian seafloor there and the resulting erosion forms the sediments of the Brandon formation. About 150 to 250-km southwest of that depositional environment, reinitiated subduction has formed a volcanic arc over the metamorphic rocks of the SSC.

**Middle to Late Jurassic**

By the late Callovian to Oxfordian the Logtown Ridge arc is fully developed (See Figure -). At least one continental fragment forms the western sediment source for the Logtown Ridge formation, the source of limestone, granite, and metamorphic clasts. It is probable, however, that some of these clasts come from an exposed portion of the metamorphic rocks of the SSC. The fragment containing granite and limestone is probably separated from the arc by strike slip fault; and so does not become part of the terrane upon amalgamation. During this time it is probable that the ART and COT are accreted to the continental margin. Although several models have been proposed for the mechanics of terrane accretion, the model of crustal wedging seems to best fit the relationships observed in the area (See Figure 7-5). This mode of accretion is best known from the Franciscan terranes of the California Coast Ranges that also formed at an obliquely convergent margin. The Gopher Ridge volcanic arc is also fully developed at this time, but it is probably several hundred kilometers to the southwest of the Logtown Ridge arc. This separation is necessary because of the interposition of the SSC and MAT rocks. It is demonstrated by the more silicic nature of the Gopher Ridge volcanics, and by the absence of limestone and related clasts in the Gopher Ridge. The relatively unrelated nature of these arcs is an important feature of this tectonic model. Volcanism over the SSC is continuing, as evidenced by the intrusion of the 160 Ma Pine Hills gabbro and gabbronorite.

**Late Jurassic**

By the Kimeridgian, the volcanic arcs of the Logtown Ridge and Gopher Ridges have been dead for several million years, and the volcanioclastic rocks have been draped with distal turbidites (Mariposa Formation and Salt Springs Slate). In the case of the Mariposa, this has given way to conglomerate and olistostrome deposition as the Mother Lode Terrane approaches the continental margin (See Figure -). Some of the clasts, especially chert, probably derive from the now accreted ART. Others, specifically pyroxene porphyry volcanics and detrital pyroxenes, were eroded from the underlying volcanioclastic strata. However, limestone clasts contain Tethyan fauna unlike any found in the ART, COT, Calaveras Terrane, or the underlying strata of the MLT. This is indicative of a western sediment source similar to that documented for the Logtown Ridge formation. It is probable that this source was an atoll or similar high built on the Permian to Triassic oceanic
crust that lay south and west of the MLT. Conversely, the area of the Salt Spring slate is undergoing reactivation of arc volcanism that is forming the overlying Copper Hill volcanic formation.

About 152 Ma, the Mother Lode Terrane is accreted to the continental margin (See Figure -). The mode of accretion is again crustal wedging, as shown by the overthrust nature of the previously accreted American River terrane. It is during this period that the strata of the Mother Lode Terrane are isoclinally folded and foliated sub-parallel to bedding. Because the original idea of the Nevadan orogeny was that of the structural event that caused the deformation of the youngest (Kimmeridgian) Foothills metamorphic rocks, prior to the deposition of Great Valley sedimentary rocks, I will define this as the beginning of the Nevadan Orogeny. At this point the continental margin is clearly convergent, which is normally related to arc volcanism. However, the relationship between any volcanic strata and this convergent margin is not well understood at this time. No volcanic rocks of this period exist in the area of study (or in the Placerville Belt as a whole to my knowledge). Still resting in the ocean basin to the south and west are the rocks of the SSC, MAT, and the Western Belt (See Figure 7-8). The Copper Hill arc is probably dying out at this time.

About 150 Ma, the Shingle Springs Complex is accreted to the continental margin by means of crustal wedging (See Figure -). The underthrust nature of this fault contact is demonstrated by the present position of the FCT and SSC in the field area, juxtaposed with MLT strata along extensional faults, implying that the SSC and FCT rocks had to be structurally lower than now relative to the MLT. The restriction of these rocks to the northern portion of the foothills may be due to the relatively smaller size of the terrane or to right lateral faulting which occurred after accretion. The compressive deformations associated with this accretion are the second phase of the Nevadan Orogeny. During this time the MLT was intruded by small porphyry plutons. It is unknown why these plutons are limited to the MLT, but their mafic composition rules out remelting of MLT strata.

This is followed by a period of extensional deformation, which is well demonstrated in the MLT (See Figure 7-10). It is during this period that the FOT is detached from the SSC and added to the Placerville Belt. The normal fault that separates the FCT and the SSC at this time is the precursor of the present Bear Mountains fault in the field area. The normal faulting may be related to overthickening of the crust, similar to that seen in compressive margins, such as the Himalayas, today. This extensional deformation is the third phase of the Nevadan Orogeny.

About 147 Ma the MAT is obducted over the continental margin in a large east directed nappe (See Figure -). It is important to note that this is a departure from the normal accretionary mode of crustal wedging. The reason for this departure is unknown, but the overthrust position of the MAT is well exposed at the present time. The obduction of the MAT seems to have had little deformatonal effect on the previously accreted terranes, but it is evident that the MAT itself was profoundly deformed at this time. It is probable that much of the deformation of the Triassic ophiolite into serpentinite matrix melange occurred during obduction, as evidenced by the inclusion of opaque ophiolite rocks in the melange, probably entrained from previously accreted terranes. This is the fourth phase of the Nevadan Orogeny. It should be noted that the direction of nappe overthrusting is deduced from the model, and since the position of the MAT with respect to the other terranes is not well constrained it should be considered a working hypothesis.

Following the obduction of the MAT, the Western Belt accreted about 146 Ma. This accretion was again by crustal wedging (See Figure 7-12), as is well evidenced by the present relationship between the Placerville Belt and the Western Belt. This accretion was accompanied by major compressive deformation in the previously accreted terranes. It is at this time that the El Dorado Fault is formed, the SSC is thrust over it's volcanic arc, and the MAT suture is well folded. The foliations of at least the MLT are probably somewhat re-folded at this time as well. This is the fifth and final phase of the Nevadan Orogeny, which therefore is defined as a multi-phase period of terrane accretion and deformation, both compressional and extensional, that oc-
urred between about 152 - 146 Ma.

The end of the Nevadan Orogeny is followed by a period of extensional tectonics (See Figure 7-13). The Bear Mountains Fault in the area of study forms at this time. Probably concurrent with the normal faulting is the intrusion of the Coloma Pluton and associated granodiorite and diorite bodies about 143 Ma. The final phase in the formation of the Placerville belt is a period of compression that postdates the Coloma Pluton (See Figure 7-14). This compression causes the reverse faulting of the Melones Fault and the western "Bear Mountains Fault". The cause of this compression is unknown, but may be related to accretion of terranes not exposed in the Sierra f60t hills. There are relatively minor structural events that post-date the Melones fault in the Placerville Belt, probably related to emplacement of the Sierra Nevada batholith, but the tectonic history of the Placerville Belt is relatively complete with the formation of the Melones Fault.
Figure 1. Cartoon maps of the proto-Pacific showing the relative locations of terrane elements. Not to scale.

A. Early Jurassic
B. early Middle Jurassic
C. Bathonian to Callovian
D. Callovian to Oxfordian
E. Kimmeridgian
F. Oxfordian

Figure 2. Cartoon cross section of Callovian to Oxfordian continental margin showing structural relations between accreted terranes.

Figure 3. Cartoon cross section of 152 my continental margin showing structural relations between accreted terranes.

Figure 4. Cartoon cross section of post-Oxfordian (~150my) continental margin showing structural relations between accreted terranes.

Figure 5. Cartoon cross section of continental margin at ~148 my showing structural relations of accreted terranes.

Figure 6. Cartoon cross section of continental margin at ~147 my showing structural relations of accreted terranes.

Figure 7. Cartoon cross section of continental margin at ~146 my showing structural relations of accreted terranes.

Figure 8. Cartoon cross section of continental margin at ~143 my showing structural relations of accreted terranes.

Figure 9. Cartoon cross section of continental margin at <143 my showing structural relations of accreted terranes.
Figure 1. Cartoon maps of the proto-Pacific showing the relative locations of terrane elements. Not to scale.

A. Early Jurassic
B. early Middle Jurassic
C. Bathonian to Callovian
D. Callovian to Oxfordian
E. Kimmeridgian
F. Oxfordian
About 152 Ma

Limestone + Granite

SSC

Plate Motion

TR Seafloor

MAT

TR Seafloor

WB

Jurassic Seafloor
Figure 2. Cartoon cross section of Callovian to Oxfordian continental margin showing structural relations between accreted terranes.

Figure 3. Cartoon cross section of 152 my continental margin showing structural relations between accreted terranes.

Figure 4. Cartoon cross section of post-Oxfordian (~150my) continental margin showing structural relations between accreted terranes.

Figure 5. Cartoon cross section of continental margin at ~148 my showing structural relations of accreted terranes.
Figure 2. Cartoon cross section of Callovian to Oxfordian continental margin showing structural relations between accreted terranes.

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Figure 4. Cartoon cross section of post-Oxfordian (~150my) continental margin showing structural relations between accreted terranes.

Figure 5. Cartoon cross section of continental margin at ~148 my showing structural relations of accreted terranes.
Figure 6. Cartoon cross section of continental margin at ~147 my showing structural relations of accreted terranes.

Figure 7. Cartoon cross section of continental margin at ~146 my showing structural relations of accreted terranes.

Figure 8. Cartoon cross section of continental margin at ~143 my showing structural relations of accreted terranes.

Figure 9. Cartoon cross section of continental margin at <143 my showing structural relations of accreted terranes.
Figure 6. Cartoon cross section of continental margin at ~147 my showing structural relations of accreted terranes.

Figure 7. Cartoon cross section of continental margin at ~146 my showing structural relations of accreted terranes.

Figure 8. Cartoon cross section of continental margin at ~143 my showing structural relations of accreted terranes.

Figure 9. Cartoon cross section of continental margin at <143 my showing structural relations of accreted terranes.
Figure 1. Cartoon maps of the proto-Pacific showing the relative locations of terrane elements. Not to scale.

A. Early Jurassic
B. early Middle Jurassic
C. Bathonian to Callovian
D. Callovian to Oxfordian
E. Kimmeridgian
F. Oxfordian

Figure 2. Cartoon cross section of Callovian to Oxfordian continental margin showing structural relations between accreted terranes.

Figure 3. Cartoon cross section of 152 my continental margin showing structural relations between accreted terranes.

Figure 4. Cartoon cross section of post-Oxfordian (~150my) continental margin showing structural relations between accreted terranes.

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Figure 6. Cartoon cross section of continental margin at ~147 my showing structural relations of accreted terranes.

Figure 7. Cartoon cross section of continental margin at ~146 my showing structural relations of accreted terranes.

Figure 8. Cartoon cross section of continental margin at ~143 my showing structural relations of accreted terranes.

Figure 9. Cartoon cross section of continental margin at <143 my showing structural relations of accreted terranes.
The Chico Formation at Granite Bay, Placer County, California

Richard P. Hilton and Patrick J. Antuzzi

Abstract

Outcrops of Chico Formation at Granite Bay in Placer County provide evidence toward a greater understanding of the Campanian paleoenvironment of central California. In the Campanian the site was an offshore marine shelf but the rocks contain fossils from three distinct environments: the offshore shelf, an intertidal environment and a terrestrial environment. The fossils collected include numerous plants that were probably once waterlogged flotsam that settled to the bottom. These range from various seeds, dicotyledonous leaves, and an equisetum to portions of ferns and cycad fronds. One large fern stem cast is complete with frond scars and buds, adventitious roots and prop branches along the trunk.

The fauna includes numerous bivalves, gastropods, ammonites, baculites, a nautilus and a scaphopod. Two snails (possibly new) appear to be nonmarine, one ammonite is the first of its genus to be found on the North American Pacific coast and one bivalve may be a new species. Other invertebrates include arthropod? burrows, three species of urchin and a crinoid. Vertebrates include five shark species and a boney fish. There are two types of marine turtle never seen before on the west coast and skull fragments from the first mosasaur from the Chico Formation. A long bone fragment is consistent with a Theropod dinosaur and is the first evidence of a carnivorous dinosaur from California.

This site probably contains the most diverse group of Upper Cretaceous fossils from the state.

At Granite Bay west of Sacramento in Placer County, outcrops of Chico Formation provide evidence toward a greater understanding of the Campanian (~80 million years ago) paleoenvironment of central California. Exposed during grading and ditching for house construction, and now under homes and pavement, the area contains offshore marine fossils, fossils from a nearshore environment, plus fossils from the terrestrial environment.

The outcrop area at Granite Bay

The authors had collected in the area for many years prior to the time when the site was to be developed. Placer County officials were aware that the area was a sensitive paleontological site and in order to satisfy the environmental impact to paleontological resources the contractor was asked to hire a consultant to monitor excavation and collect fossils on site. The author, Richard Hilton, a paleontologist and Professor of Geology at Sierra College, was hired as consultant and co-author Pat Antuzzi, a local fireman and amateur fossil collector, volunteered to help. Pat made most of the important fossil finds.

The site is located just off East Roseville Parkway at Swan Lake. (map 1) Exposures of Chico Formation made by heavy equipment enabled us to more readily see the extent of the Formation in the Granite Bay area. A map shows where grading and ditching exposed Chico Formation. (map 2)
Map 1. Street map showing major fossil locations and where the turbidite was exposed.

Map 2. Chico Formation was exposed during grading and ditching within the shaded areas.
outcrop of Chico Formation occurs at what is today Negro Bar State Park on the
north side of the American River across the river from old Folsom.

Lindgren (1911) identified the Chico Formation as Upper Cretaceous
(late Coniacian-middle Campanian) in age. In Granite Bay it lies with
nonconformity on the granitic rocks of the Rocklin Pluton and sometimes below
the Eocene Ione Formation as well as the younger Plio-Pleistocene Turlock Lake
Formation. Evidence from ammonites *Hoplitoplacenticeras* and
*Metaplacenticeras* collected at the Granite Bay site indicates that the Chico
Formation here ranges from upper lower Campanian to upper Campanian (Jim
Haggart, Canadian Geological Survey, oral communication, 1997).

During its deposition the site was probably an offshore shelf area. High in
the section large subrounded granitic boulders, greenstone, schist, fragmented
unweathered slate plus abundant fossil shell hash contained in a massive turbidite
indicate a possible steep cliff-lined shore to the east.

**Summary of Chico Formation stratigraphy and lithology at Granite Bay.**
Described from the bottom to the top, oldest to youngest, A-L (see fig. 1).

**A. Basal conglomerate of the Chico Formation.**
A basal conglomerate of as yet undetermined thickness was noted in the site
of the Swan Lake dam spillway. Unfortunately, before it could be completely
measured most of the exposure was destroyed in the reconstruction of the dam.
The basal conglomerate contains well-rounded pebbles, cobbles and boulders that
appear to be of typical Sierra Nevada metamorphic and granitic rocks. In a road
cut on Beckenham Drive the conglomerate comes in direct contact with the
granite and no marine fossils are found. Lenses of shale here and in the dam site
contain occasional dicotyledonous leaves and *Araucariaceae* branches. The upper
portion of the conglomerate grades into sandstone (not shown in the cross
section); both the conglomerate and the sandstone contain sparse fragmental fossil
gastropods and bivalves.

**B. Light brown, fine siltstone.**
Lying over the basal conglomerate and the sandstone is a light brown, fine
siltstone containing concretions up to 1.5 meters thick. The unit is a minimum (its
base is not exposed) of 3.5 meters in thickness. It contains sparse bivalves,
gastropods, ammonites, baculites, nautilus and boney fish teeth.

**C. Large limestone concretion layer.**
This one-meter-thick unit is a nearly continuous limestone concretion.
Fossils include marine turtle bones (*Protostegids* and *Cheloniids*) and a bone
fragment consistent with a theropod dinosaur.

The layer also contains many bivalves, gastropods, ammonites, baculites,
and many large nautilus as well as wood fragments riddled with fossil bivalve?
burrows. One concretion contained a 63-cm-long cast and mold of a fern trunk.
Numerous types of large seeds including Araucariaceae seeds have come from this unit as well.

D. Blue grey siltstone with lenses of coarse sandstone.

This 1.5-meter-thick unit contains a few nautilus with scarce bivalves and gastropods. It also contains some unpetrified original wood, some with bivalve? burrows.

E. Coarse sandstone and siltstone.

This 40-cm-thick layer contains bivalves, gastropods, ammonites, baculites, wood (some with bivalve? burrows), leaves, and an occasional shark tooth.

F. Blue grey siltstone.

This unit is approximately 1/2 meter thick. Fossils rare.

G. Fine sandstone and siltstone.

This unit is 1.2 meters thick and contains fossil leaves, wood (some with bivalve? burrows), some gastropods and bivalves, occasional large nautilus and baculites. Ammonites are rare.

H. Blue grey siltstone.

This unit is approximately 4 meters thick with a layer near the middle containing roughly spherical concretions 40-60 cm in diameter. Fossils are rare; some marine turtle bone fragments.

I. Clay rich siltstone.

This unit is approximately 2.8 meters thick. It contains some bivalves and gastropods, ammonites, baculites, leaves, wood (some with bivalve? burrows) and scarce turtle bone fragments. A broken skull with teeth of a mosasaur was found here.

J. Turbidite layer.

By far the most interesting unit unearthed at the site was a 1.8-meter-thick turbidite layer that thinned away to the north and south. The largest clast found was 2.14 meters x 1.20 meters. Most of the large boulders like this one were foliated quartz diorite, while others were made of schist and greenstone. Smaller clasts (many centimeters in diameter), although sometimes made of foliated quartz diorite, consisted of rip up shale torn away from the sea bottom. These clasts contained rare mollusk fossils. Contained with the rip up material were slate, schist and minor greenstone clasts. The predominant small pebble- and gravel-sized clasts were predominantly made of unweathered slate typical of the Mariposa Formation (Imlay, 1961).

The matrix is almost a coquina (mass of shells) of mostly broken clams, oysters and snails, with a scattering of shark teeth, fish bones and teeth, urchin spines and limpets. Some reptile? bone fragments were found. The presence of large, subrounded granitic boulders, fragmented slate, schist and greenstone contained in a coquina of fossil shell hash (indicating a nearshore environment of accumulation) suggest a possible steep cliff-lined shore.
K. Clay rich shale with biotite flakes.
   This unit is approximately 1.5 meters thick. It contains some fossil shell fragments.
L. Loosely consolidated fine sandstone with minor biotite sand lenses.
   This 90-cm-thick unit contains sparse fossil shell fragments.

M? Second Turbidite?
   Huge granitic boulders many meters across were found lying on top of the site. This and the fact that two turbidites are found to the south of the site may indicate that an even larger turbidite once covered the area.

Three paleoenvironments
This unique locality of Chico Formation contains evidence of three distinct paleoenvironments; offshore, nearshore and terrestrial.

1. **Offshore environment**
   A. The predominant deposition at the site was of fine sands, silts and clays originally deposited offshore on the continental shelf in a low energy environment of deposition. Fossils such as *Indogrammatodon* and *Inoceramus* (both bivalves), normally found in still deeper water, confirm this (Louella Saul, L.A. County Museum, oral communication, 1997). These finer clastic sedimentary rocks contain numerous bivalves, gastropods, ammonites, baculites, a nautilus and a schaphopod (Wyatt Durham, U.C. Berkeley, oral communication 1995; Louella Saul, L.A. County Museum, oral communication, 1997; Jim Haggart, Canadian Geological Survey, oral communication, 1997). One ammonite, a *Nowakites*, is the first of its genus to be found on the west coast of North America (Jim Haggart, Canadian Geological Survey, oral communication, 1997). Another mollusk, an *Opis* may be new species (Louella Saul, L.A. County Museum, oral communication, 1997).
   Other invertebrates include arthropod? burrows and a crinoid (Rich Mooi, California Academy of Sciences, oral communication, 1997). Vertebrates include two types of marine turtle, a protostegid and a primitive cheloniid that have previously never been seen on the west coast of North America (James Parham and Howard Hutchinson, U.C. Berkeley, oral communication, 1997). Finally, and perhaps the most important find, was portions of a skull from the first mosasaur to be found from the Chico Formation (Sam Welles, U. C. Berkeley, oral communication, 1997).

2. **The nearshore environment**
   Fossils and rocks have been brought in by turbidites from the nearshore environment. A turbidite is formed when a large mass of sediment (rocks, sand, mud and broken shells) is dislodged and flows as a turbulent cloud of water and
sediment, called a turbidity current, into deeper water. Typically, when it slows
down the larger, heavier pieces settle out first with the smaller sediment settling
toward the top. The largest clast found in the turbidite was 2.14 meters x 1.20
meters and was made of a foliated quartz diorite. Most of the large boulders like
this one were foliated quartz diorite but others were made of schist and
greenstone. Smaller clasts, although sometimes made of foliated quartz diorite,
also consisted of rip up shale from the sea bottom as the turbidity current moved
over it. The predominant small clasts were made of unweathered slate typical of
the Mariposa Formation, a possible indication of a beach with cliffs, with eroding
fresh slate to the east.

The matrix of the turbidite is a coquina-like mass of broken mollusk shells.
Other fossils contained in the turbidite include three types of echinoderms, all
urchins, many types of mollusks including snails, clams, an oyster and a limpet.
Vertebrates include five species of shark and at least one boney fish. The turbidite
at Granite Bay thins away from the site as does the maximum clast size. This
seems to suggest that here a swale in the sea floor channelized the flow somewhat.
Huge granitic boulders resting on the site hint of a second turbidite that still
outcrops in a cut on Tiffany Street. A similar set of turbidites in the Chico
Formation can be seen at Negro Bar State Park, 5.2 km to the south in a cliff just
behind the boat ramp. There are two turbidites here separated by about one meter
of shale. The upper turbidite is about 20 cm thick. The lower turbidite is
approximately a meter thick and contains clasts at its base up to 15 cm long of
slate and other similar clasts to the Granite Bay turbidite.

Terrestrial environment

Terrestrial fossils found their way to the Granite Bay site in two ways: in
the turbidite and as flotsam that originally may have floated down rivers and
streams or tumbled from sea cliffs. This flotsam became waterlogged and settled
to the bottom, later to be covered by sediment and preserved. The plant fossils
range from numerous seeds and dicotyledonous leaves to gymnosperm branches
(Araucariaceae or Taxodiaceae) and portions of fern and cycad fronds (Howard
Schorn, Nan Crystal Ahrens, Diane Irwin, U.C. Berkeley; Bruce Tifney, U.C.
Santa Barbara; Bruce Doyle, U.C. Davis; Kirk Johnson, Denver Museum of
Natural History, oral communications, 1997). A large fern stem is complete with
frond scars, frond buds, adventitious roots and prop branches. Animal fossils
include two nonmarine? gastropods (Louella Saul, L.A. County Museum, oral
communication, 1997) and a limb bone fragment consistent with a theropod
dinosaur (Greg Erickson, U.C. Berkeley, oral communication, 1997).
Figure 2 (continued) Fossils collected from the Chico Formation at Granite Bay.

Conclusions

This locality contains marine fossils from an offshore shelf area, fossils from a nearshore environment, and fossils from the terrestrial environment as well. This small outcrop of Chico Formation probably contains the most diverse array of Late Cretaceous fossils found in California.

Acknowledgements

Special thanks go to all who helped in this project: Kristin Hilton, editing; Paula Noble/CSU Sacramento, science editing; Kendall Schinke, graphic preparation; Larry Clevenger/Placer County Planning Department for research; Patrick G. Embree/UC Davis student for research and fossil preparation; Doug Margraf and Susan Gardner/Sierra College for fossil preparation; Howard Schorn, Diane M. Erwin, Nan Crystal Ahrens/UC Berkeley Museum of Paleontology; Bruce Tifney/UC Santa Barbara, James Doyle/UC Davis and Kirk Johnson/Denver Museum of Natural History for paleobotanical identification; Samuel P. Welles, Greg Erickson, Pat Holroyd, Howard J. Hutchison and James Parham UC Berkeley Museum of Paleontology for fossil vertebrate identification; J. Wyatt Durham UC Berkeley and Louella Saul/LA County Museum for bivalve and gastropod identification; Richard Mool/California Academy of Sciences for echinoderm identification; and Michael Murphy/UC Davis, Peter Rodda California Academy of Sciences and James Haggart/Canadian Geological Survey for cephalopod identification.
Bibliography


Map 1. Street map showing major fossil locations and where the turbidite was exposed.

Map 2. Chico Formation was exposed during grading and ditching within the shaded areas.
Figure 2. Fossils collected from the Chico Formation at Granite Bay.
Figure 2 (continued)  Fossils collected from the Chico Formation at Granite Bay.

Conclusions

This locality contains marine fossils from an offshore shelf area, fossils from a nearshore environment, and fossils from the terrestrial environment as well. This small outcrop of Chico Formation probably contains the most diverse array of Late Cretaceous fossils found in California.

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Stratigraphic and structural relations along the Melones fault near Chili Bar

By
David L. Jones and David Lawler

Introduction

The Melones fault, a persistent structure that can be traced nearly the entire length of the Sierran foothills, separates the Motherlode belt (Logtown Ridge and Mariposa Formations) on the west from the Calaveras complex on the east (figure 1). At Chili Bar, on the South Fork American River, these lithic units, as well as the Melones fault, are particularly well exposed.

Logtown Ridge Formation at Chili Bar comprises a complex assemblage of volcanoclastic rocks, including tuff, breccia, volcanic sandstone, and volcanic conglomerate, all interbedded with black argillite and slate. Bedding features are well preserved, including graded bedding and cross bedding, although finer-grained rocks have a well-developed cleavage. Bedding facing directions are consistently eastward and upright. Volcanic rocks with both augite and feldspar porphyries are present, as is an unusual quartz porphyry. The Chili Bar exposures differ from the type Logtown Ridge in lacking volcanic flows, either massive or pillowcd, and in having a greater percentage of interbedded black slate. The western part of the Logtown Ridge is intruded by the Coloma pluton, whose border phase is a feldspar porphyry that was relatively cool so little contact metamorphic efforts were produced.

Mariposa Formation conformably overlies the Logtown Ridge. Characteristic lithology consists of slate with sandstone beds common in the lower portion. A lens of conglomerate containing granitic pebbles occurs 20 meters above the base, and this is the only conspicuous coarse-grained unit present. Minor thin beds of quartzose sandstone occur throughout the formation. Bedding features are well preserved, despite the presence of persistent slaty cleavage. Near the Melones fault, kink bands that trend NNW and plunge ~10° to the south refold this cleavage (figure 2). Metamorphic grade is lower greenschist facies.

Despite the excellent exposures of the Mariposa Formation near Chili Bar, only a few fossils have been found there to confirm the age and correlation of these strata with the type Mariposa of Mariposa county. Back in 1884, an ammonite identified by Imlay (1961) as Perisphinctes (Dichotomosphinctes?) spp. was found 2 miles north of Placerville in Big Canyon. Related forms of Oxfordian age are known elsewhere in the Mariposa Formation.

A nearly continuous belt of highly sheared serpentinite containing blocks of gabbro marks the Melones fault. Width of the serpentinite belt varies from a few feet to tens of meters. Locally the serpentinite is altered to talc schist, and in many places it contains blocks of marble, metavolcanic rocks, and granitoid rocks. Hydrothermal alteration is common along the fault, and many gold mines are situated either close to or on this
prominent structure. South of Placerville, the Coloma pluton is mylonitized and truncated by the fault, so the youngest movement is post-143 my.

**Calaveras complex** occurs east of the Melones fault throughout the extent of this structure. Characteristic Calaveras rocks include slate and phyllite, thin bedded quartzose sandstone (often with disrupted bedding), lenses and pods of marble varying in size from a few tens of meters to many kilometers, and altered tuffaceous volcanic rocks. In the past, this assemblage has been considered to be entirely late Paleozoic based on a few scattered fossils of that age. Recently, Triassic conodonts have been extracted from several marble lenses in the southern part of the belt (Bateman and others, 1985).

Volcanic rocks form the western-most part of the Calaveras complex throughout most of its extent. To the south, where these rocks form a wide belt, they have been designated the Don Pedro terrane (Blake and others, 1982) or the Sullivan Creek terrane (Sharp, 1983). The contact between these southern volcanic rocks and adjoining slate and phyllite has been designated the Sonora fault by Schweickert and others (1984). A thin band of augite porphyry andesite breccia represents the Don Pedro terrane at Chili Bar. A much thicker unit of similar volcanics occurs to the north on the Middle Fork American River. No dates are available for these rocks, but their assumed correlatives to the south yielded a Rb/Sr date of 187 ± 10 Ma (Bateman and others, 1985).

Marble is common in the Calaveras complex, particularly to the south in the vicinity of Columbia. In the Placerville region, blocks are smaller and scarcer, but one block is large enough to support commercial quarry operations. At Chili Bar, a small marble lens occurs within slate about .6 mile east of the Melones fault along Rock creek road. None of the marble lenses near Placerville has been dated. These scattered blocks, as well as the blocks to the south dated as Triassic, may represent olistoliths redeposited from a shallow water site. Rocks of similar age and character do not occur along the Triassic North American continental margin to the east.

Structures within the Calaveras complex have not been studied in detail in the Placerville region. To the south, in Amador and Calaveras Counties, recent studies by Jill Miller Perry (written communication, 1997) show that Calaveras rocks are metamorphosed to either upper greenschist or epidote-amphibolite facies and exhibit three periods of deformation. At Chili Bar, two periods of deformation are clearly visible: an early stage that produced a prominent slaty to phyllitic foliation, and younger kink bands that deform the early foliation. The orientation of both the foliation and kink bands is similar on the east and west sides of the fault (figure 2); foliation and axes of kink folds trend parallel to the fault, and early lineations trend NNE.

**Summary:** Excellent exposures in the Chili Bar area demonstrate the stratigraphic continuity between the Logtown Ridge and Mariposa Formations. The former can be interpreted as volcanogenic turbidites and volcanic debris flows derived from a nearby island arc. The arc itself, which may have lain to the east, has vanished. The Mariposa Formation represents distal turbidites derived from a continental source, as evidenced by the abundance of quartz detritus. Intertonguing of arc and continentally - de-
rived sediment clearly show that there were two separate source regions concurrently supplying sediment to the Mother Lode basin. A similar, but older, sequence appears to characterize the Calaveras terrane, with an andesitic basement of probable Early Jurassic age overlain by a thick, quartzose clastic assemblage that may represent a continental rise prism. This interpretation assumes that a depositional link existed between the volcanics and structurally overlying sedimentary rocks - an assumption so far unproven. Contrary to interpretations by Edelman and Sharp (1989), and many previous workers, no direct ties can be established between rocks east of the Melones fault and rocks west of the fault. Movement along the Melones fault is clearly post-Mariposa Formation and Coloma pluton. By classic definitions, this movement is "post Nevadan". The last stage of movement along this fault was compressional and produced fault-parallel kink bands in both the upper and lower plates.

The Calaveras complex has undergone more rock uplift that has the neighboring Motherlode belt. Upper greenschist or higher metamorphic facies of the Calaveras structurally overlie lower greenschist facies of the Motherlode belt; the Coloma pluton was emplaced in the upper crust, as it was relatively cool and did not generate an amphibolitic margin as did deeper-seated plutons. Much of this differential uplift can be attributed to compressive displacement (thrusting) on the Melones fault.

References cited


Imlay, R. W., 1961. Late Jurassic ammonites from the western Sierra Nevada, California. U. S. Geological Survey Prof. Paper 374D.
Figure 1. Geologic map of the Chili Bar area, South Fork American River.

Figure 2. Stereographic projection of structure data from the Chili Bar area. Solid line, trend of Melones fault at stop 6. + Pole to foliation west of fault; large circle, pole to foliation east of fault; small circle, l1 lineation, east of fault; triad, bedding-cleavage intersection west of fault; square, plunge of kink band axes east of fault; diamond, plunge of kink band axes west of fault.
Sketch Map of Chili Bar area, S. Fork American River

David L. Jones & David Lawler, 1997

Jkg - Coloma pluton, 143 my

JM - Mariposa Formation
  JMcg - conglomerate with granitic clasts

Jlr - Logtown Ridge Formation
  JLra - augite - porphyry volcaniclastics
  JLrqt - quartz - bearing volcaniclastics
  JLrvs - volcanic sandstone, conglomerate, and slate

JCs - Calaveras Complex, slate, phyllite, marble, & meta volcanics
JCv - Volcanic flows & breccia
Geology of the western belt near Rattlesnake Bar
By
David L. Jones

Introduction
The Penryn pluton (stop 1, figure A) effectively divides the western belt into northern and southern segments. The northern segment has been studied extensively north of I-80 (Day and other, 1985). South of I-80, in contrast, few studies have been published since the classic work of Clark (1964, 1976), and the relations of the northern and southern parts of this belt remain obscure. The northern segment is dominantly composed of the Smartville intrusive and volcanic complex that has been interpreted as a Jurassic rifted arc containing plutonic rocks as old as Early Jurassic and volcanic and volcanoclastic rocks as young as Middle to Upper Jurassic (Day et al., 1985). In the southern segment, the Smartville complex is not recognizable as a lithogenetic entity, although arc-derived volcanic and volcanoclastic rocks of Late Jurassic age are present.

Stratigraphy of the southern segment:

Clark (1964) subdivided the western belt south of the Penryn pluton in the Sacramento area into three formations that he considered to be in stratigraphic sequence, as follows from youngest to oldest:

Copper Hill volcanics, comprising a thick sequence of augite-porphyry tuff, tuff breccia, minor pillowed lava, silts and dikes, and graded volcanic sandstone. This unit resembles in lithology the Logtown Ridge Formation, but its stratigraphic position differs in that it overlies, rather than underlies, clastic rocks of Oxfordian age. No direct age determination is available.

Salt Spring Slate composed of black slate with minor amounts of graywacke, tuff, and thin beds of conglomerate. Fossils collected from several localities within this unit date it as Late Jurassic (Oxfordian) based on Buchia concentrica and thus it is equivalent to the Mariposa Formation in both age and lithology.

Gopher Ridge volcanics, including silicic tuff, tuff breccia, minor lava and argillite, and locally abundant felsite intrusives of rhyolitic to dacitic composition. According to Clark (1964) the upper part of the Gopher Ridge intertongues with the Salt Spring Slate, so that part of the formation, at least, may be Late Jurassic in age. The Gopher Ridge appears to have the same stratigraphic position as the Logtown Ridge Formation, but it differs from that eastern unit by containing much more silicic volcanic material.

Eastern margin of the Penryn pluton near Rattlesnake Bar:

The Penryn pluton of probable Early Cretaceous age intrudes the western belt as a balloon-like body that truncates the stratigraphic units described above. The pluton itself is composite, with local phases dominated by biotite, hornblende, and locally, both biotite and muscovite. Intrusion was syntectonic as the margin is strongly foliated. Early intru-
sive rocks that predate the main batholith include gabbro and pyroxenite. The former occurs as small separate, nearly circular bodies and the latter as long dikes that conform to the structural fabric of the enclosing rock (figure 1).

Intruded rocks consist of metavolcanics that are dominantly mafic in character, but which also include silicic varieties. Near the pluton, the mafic rocks are metamorphosed to amphibolite, and the silicic rocks to quartz mica schist. According to Wagner (1981), these metavolcanics may be altered equivalents of the Copper Hill volcanics. Clark (1976), on the other hand, included them with a belt of metavolcanics that we now place within the Shingle Springs complex that lies east of the western strand of the Bear Mountains fault. In this report, the Bear Mountains fault is placed at a large ultramafic body that structurally overlies the metavolcanic rocks in question (figure 1), not 2 miles farther west as shown by Clark.

The metavolcanic rocks intruded by the Penryn pluton have been deformed at least twice: an early deformation produced a strong foliation that was then refolded after intrusion of the batholith. Dikes and sills from the pluton were intruded parallel to this foliation, and were in turn, deformed by the second period of folding. As shown by figure 2, poles to the folded foliation define a plane whose pole lies on a trend of 64° and plunges 45°. This fold geometry is confirmed by direct measurements of the f2 fold axes, shown on figure 2 as open circles with crosses. The margin of the pluton also has been reoriented by this second phase of deformation.

The geometry of the f2 folds described above appears to be unique in the central foothills. For example, metabasaltic rocks that occur just to the east of the large ultramafic body shown on figure 1 exhibit a foliation that trends N-S with an amphibole mineral lineation that plunges steeply to the north. Likewise, the geometry of the youngest deformation recorded in rocks farther east near the Melones fault differ in that there kink bands plunge gently to the south.

**Ultramafic rocks**

Three ultramafic rock assemblages occur within the map area (figure 1). The largest body is bounded on the west by a thrust fault that places serpentinite on gabbro and metavolcanic rocks. This body consists of massive dunite with rod-like stringers of chromite that have been extensively mined. Where foliation is developed, it trends NNW parallel to the trace of the bounding thrust fault and dips steeply to the NE. The eastern half of this body comprises sheared serpentinite that locally exhibits tight isoclinal folds that plunge steeply to the south. Numerous thin dikes of gabbro and diabase that generally trend to the north intrude the sheared serpentinite. Dikes of pyroxenite similar in character to those that intrude metavolcanic rocks to the west intrude the massive dunite body, but they have not been observed within the sheared serpentinite unit.

Metabasalt containing a large marble lens is in fault contact with the eastern margin of the sheared serpentinite. This fault corresponds to the western strand of the Bear Mountains fault as portrayed by Wagner (1981) on the Sacramento sheet of the California
State Geologic map, and we have included these rocks within the Shingle Springs complex (see figure A). Foliation in both the marble and metabasalt trends N-S, dips steeply to the east, and f2 folds plunge 60° to the north - a geometry very different from that occurring to the west near the Penryn pluton margin. Thin bands of chloritic tuff occur within the marble lens, suggesting that originally a depositional relation existed between the basalt and limestone. A seamount with a carapace of limestone, similar to that of the Cool Quarry terrane, is the most probable setting. No fossils occur in the marble, but a late Paleozoic to Triassic age for this lens seems possible. Metamorphosed diabase, gabbro, and basalt occur in a broad tract east of the marble lens. These mafic rocks appear to constitute a sheeted dike or sill complex that has been over-printed by a pervasive penetrative metamorphic fabric that is parallel to the dike margins. A non-foliated offshoot of the Pine Hill quartz diorite intrudes these rocks, suggesting that both protolithic and metamorphic ages may be older than ~160 my.

Conclusions

The following conclusions may be drawn from the geologic relations described above:
1. The Penryn pluton was emplaced syntectonically at a mid-crustal level into an assemblage of volcanic rocks of probable Late Jurassic age metamorphosed to amphibolite grade. Continuing deformation after intrusion produced a unique set of east-plunging folds in both the metavolcanics and the pluton margin.
2. These folds do not occur in the structurally overlaying ultramafic rocks, suggesting that thrusting is younger than generation of the f2 folds.
3. Structures within the sheared serpentinite and the metabasalt to the east plunge steep north or south, suggesting an important component of strikeslip movement along the western strand of the Bear Mountains fault.
4. The metabasalt and marble unit may represent a Paleozoic or Triassic seamount.
5. As seen at stop one, the Penryn pluton was exhumed by late Campanian time (~70 my ago), indicating rock uplift since the Late Jurassic of 12 to 16 kms.

References cited


Figure 1. Sketch map of the Rattlesnake Bar area.

Figure 2. Stereographic projection of structural data from metavolcanic rocks intruded by the Penryn pluton. Filled circles - poles to foliation; open circles with cross, measured $f_2$ fold axes; "1" - computed fold axis from foliation data.
EXPLANATION

JKg – Penryn pluton, biotite, hornblende, muscovite granodiorite, ~ 130 my old
gb – gabbro
gbd – gabbro and diabase dikes
pyx – pyroxenite and hornblendite dikes
mva – metavolcanic rocks, including meta andesite & metarhyolite, metamorphosed locally to amphibolite and micaschist
ls – marble
mb – metabasalt
md – metagabbro & diabase dike or sill complex
um – ultramafic rocks
    umd – massive dunite
    ums – sheared serpentinite

strike and dip of foliation; line is trend of f2 fold axis
Shoo Fly complex in the central Sierra Nevada

By
David L. Jones

The Shoo Fly complex is a widespread and very thick structural assemblage of metamorphosed quartzose clastic rocks whose protoliths ranged from shale with minor chert to massive quartz sandstone. These rocks, which form the basement of the Northern Sierra terrane, are now reconstituted to slate on the west and quartz mica schist on the east. The Shoo Fly is structurally bounded on the west by the Feather River ultramafic complex, and, to the northwest, by slivers of Upper Paleozoic and Triassic rocks that are wedged between these ultramafic rocks and the Shoo Fly (Jayko, 1988; Harwood, 1993). The eastern margin is obscured by granitoid plutons of Cretaceous age. Upper Paleozoic and Mesozoic rocks of the Northern Sierra terrane that unconformably overlie the Shoo Fly to the north do not extend south of the Middle Fork American River. In addition, subdivisions of the Shoo Fly that have been discriminated north of the 39th parallel have not been recognized within the field trip area.

Within the drainage area of the South Fork, three broad subdivisions of the Shoo Fly can be discriminated (figure 2): a western belt of slate with minor chert and siliceous shale; a middle belt of interbedded sandstone and slate (flysch) with well developed graded beds; and an eastern belt consisting mostly of massive quartzite and quartz mica schist with only minor amounts of pelitic rock present. Contacts between these belts appear to be gradational, but as no fossils are known, the age relations of these belts have not been established.

North of the 39th parallel, most of the Shoo Fly is assigned to the Lang sequence of Ordovician? to Devonian? age. The Lang sequence is demonstrably older than Late Devonian, as it is overlain by the Sierra Buttes Formation of that age. One fossil locality is known from the Lang; Harwood (1993) reports that conodonts of Middle to Late Ordovician age were extracted from a lens of limestone interbedded with black argillite and greenish gray chert associated with gray slate and quartzite.

The gross structural relations within the Shoo Fly complex in the south Fork area are unknown. All rocks are penetratively deformed with pervasive slatey cleavage and flattened grains. At least two periods of folding can be recognized; an early, \( f_1 \) folding that produced the slatey cleavage, and a younger, \( f_2 \) event that folded this cleavage. \( f_2 \) fold axes are nearly horizontal and trend NNW-SSE (fig. -; stops 8 to 11). The mesoscopic steeply east-plunging folds mapped by Harwood (1993) in the Duncan Peak area to the north (see fig. B) are not recognizable in the South Fork drainage, although a refolded lineation produced by bedding-cleavage intersection may be the result of that deformation. These east-plunging folds mapped by Harwood appear to be pre-Late Devonian in age, as younger rocks that overlie the Shoo Fly do not exhibit this style of folding.

Granitoid rocks intrusive into the Shoo Fly include Jurassic diorite and Cretaceous hornblende biotite granodiorite. Jurassic dioritic intrusives are syntectonic in that
their margins are foliated in directions parallel to that in the adjoining mica schist. The
unnamed diorite pluton on Icehouse road was apparently intruded into the Shoo Fly as a
nearly flat sill-like body with a flat lower contact. This contact, as well as the foliation in
both the diorite and mica schist, has been folded around a gently south-plunging fold axis
that trends SSE (fig. -), and is interpreted to be the same fold system that produced the f2
folds in the Shoo Fly. Younger Cretaceous plutons (100 to 90 my old) lack penetrative
deformation and have intrusive contacts that cut across the structure fabric of the Shoo
Fly, rather than being parallel to this fabric as in the older dioritic plutons.

An undated pyroxenite and gabbro complex occurs in the eastern part of the Ice-
house road area in a position structurally above the folded Jurassic diorite (fig. -). No in-
trusive contacts are visible, nor are dikes or sills of gabbro seen cutting the diorite, nor
are diorite dikes seen cutting the gabbro. The contact between the diorite and pyroxenite-
gabbro complex appears to be a fault that dips to the east; locally the diorite under this
structure is strongly deformed with a mylonitic fabric that also dips east. The pyroxene-
gabbro complex is intruded by Cretaceous granodiorite, so it is probably older than 100
my.

This mafic-ultramafic complex caps the steep hill north of Whitehall, the site of a
large landslide in January 1997. The diorite beneath the gabbro is deeply weathered, but
is protected from continuous removal by the more resistant cap of pyroxenite. Most of the
material displaced in the landslide is weathered diorite, which accumulates slowing be-
neath the more resistant cap, and then slides periodically during periods of intense rain-
fall.
Figure captions

Figure 1. A. Sketch map of the Icehouse road area showing field stops.  
                B. Enlarged part of map showing structural data.

Figure 2. Stereographic plot of structural data from Icehouse road area. Circles, poles to foliation in mica schist and diorite; "1" is position of $f_2$ fold axis; "A", trend of Shoo Fly $f_2$ fold axis on South Fork American River; "B", trend of kink bands in Calaveras slate near Melones fault at Chili Bar.

Figure 3. Stereographic plot of structural data from Shoo Fly in the Duncan Peak area. Circles, poles to foliation; "1" = trend and plunge of $f_2$ fold axis. Data from Harwood, 1993.
LEGEND

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<th>Code</th>
<th>Description</th>
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</tr>
<tr>
<td>Tg</td>
<td>Gravel, Miocene or older</td>
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Looking northeast through Giant Gap to Green Valley

- Green Valley ditch
- Hayden Hill ditches
- Lovers Leap road
- Lovers Leap
- Giant Gap Ridge
- Pinnacles
- Giant Gap ditch
- Canyon Creek
CENOZOIC STRATIGRAPHY OF THE CENTRAL SIERRAN FOOTHILLS

Authors: David A. Lawler and David L. Jones

CENOZOIC GEOLOGY - SUMMARY

Recently available structural and stratigraphic evidence suggests a history of tectonic uplift of the Sierra Nevada Foothills region during Cretaceous times.

The Ione Formation and its fluvial facies equivalent in the northern Sierra, the Ancestral Yuba River sequence, represents one of the world's best preserved Eocene-age fluvial sequences, characterized by intact stratigraphic sequences interpreted as high elevation headwater tributaries, moderate elevation main paleochannel sequences, and low elevation deltaic and swamp environments.

The Valley Springs Formation and its equivalents represent a thirty to twenty million year period characterized by episodic rhyolitic ash eruptions derived from the Carson City-Dayton area of western Nevada. A significant portion of the Valley Springs age paleochannel drainages are preserved in the central Sierra Nevada region. Evidence of late Tertiary faulting along the Melones Fault in the Placerville region is best exhibited at the Landeker Hydraulic and Drift Mine site in Valley Springs Formation fluvial sediments as represents the last field trip stop.

The Mehrtens Formation represents a series of andesitic mudflows and volcanoclastic sediments occurred in the northern and central Sierra Nevada and Foothill region during the Miocene. The net result of of middle to late Tertiary volcanism was a shifting of the regional drainage direction from southwesterly to westerly. Remnants of andesite mudflows form resistant ridges that stand high above the present land surface. These flow remnants define the ancestral course of fluvial systems during Mehrtens Formation deposition period ten million to four million years ago, prior to entrenchment of the present Yuba, Bear, and American River drainages.

During latest Pliocene or earliest Pleistocene time, the Sierra Foothill pediment was beveled across Tertiary and older rocks along the entire western margin of the Sierra Nevada. Beginning in early Turlock Lake time, at least seven periods of glacial outwash deposition, followed by extensive periods of stability and soil formation and later by incision and dissection, appear to have been superimposed on a progressively subsiding Sacramento Valley basin.

Some mapped lineaments and faults, especially northwest-trending sets, may tensitional features associated with a hinge line along the boundary between the Sierra Nevada and the actively subsiding Sacramento and San Joaquin Valleys Basins (Schleman 1967), (Marchand and Allwardt 1978).
CENOZOIC SEDIMENTARY ROCK UNITS

IONE FORMATION

The lowest elevation exposures of the Ione Formation in the Volcano Hill area of Roseville consist of a bedded to massive coarse sand unit that is poorly to strongly consolidated. However, in adjacent areas the Ione Formation consists primarily of light-brown, tan and gray to pinkish or yellowish quartz sandstone with interbedded kaolinitic clay, usually near the base. The sandstone becomes conglomeratic and very strongly cemented near the top, where it locally contains marine fossils in areas north of the project area (Allen 1929). In many places these cemented beds form resistant westward-sloping cuestas over basement outcrops along the east margin of the San Joaquin Valley and in the western most foothills of the Sierra Nevada.

The interpreted lowest elevation Ione facies appears to have been deposited in a fluctuating swamp and deltaic environment close to the marine shoreline (Allen 1929) and (Gillem 1974). Lateritic soils containing crystalline iron oxides and abundant kaolinite (oxisols) formed on, beneath, and perhaps within the Ione. These, together with the plant megafossils, indicate a tropical or subtropical climate before, during and after the Ione deposition. MacGinitie (1941), Ely, Grant, and McCleary (1977) have discussed some aspects of lateritic crust remnants on the buried and exhumed Ione surface in eastern Stanislaus and Merced Counties (Marchand 1982).

This formation represents the oldest known Cenozoic sedimentary unit in the region, and its geology has been described by various workers Lindgren (1911), Allen (1929), Merrill (1982). Wood 1995, Lawler 1995, and Lawler and Schorn 1997. This rock unit is known to contain scientifically significant specimens of plant macrofossils and invertebrates (molluscs). MacGinitie (1941) has described the Chalk Bluffs Flora from this rock unit, which represents one of the most diverse fossil Eocene floras known in the world and serves as a standard of reference. Leopold (1984) has described the palynoflora from the Chalk Bluff flora localities.

Petrified logs and wood fragments represent the most readily identified fossils resources within westernmost Ione Fm. as observed at the second field trip stop at Roseville -Volcano Hill. However, the depositional origin of the westernmost portion of the Ione Formation has been debated. Marchand (1982) published data which suggested a continental deposition rather than a brackish water or marine deposition, as suggested by other writers (Allen 1929). Burrow-trace fossils have been described by Merrill (1984) located adjacent to the Ione Formation. These trace fossils are interpreted as representing activities performed by different organisms existing in different microenvironments within a braided stream alluvial environment.
Further sedimentologic study and examination of facies relationship will provide toward a
more comprehensive understanding of the paleoenvironments during the deposition of the
Ione Formation.

MEHRTEN FORMATION
The Mehrten Formation geology has been described by various workers (Curtis 1954,
Slemmons (1966), Helley and Harwood 1985). In general, the formational name includes
all Miocene age - temporarily correlative andesitic pyroclastic and detrital sedimentary
rocks and flows deposits on or at the margin of the Sierra Nevada in east-central
California.

During late Miocene times, deposition of andesitic mudflow material ever large regions of
the Sierra Nevada resulted in a subsequent shifting of existing drainage directions from
primarily southwesterly to westerly. Remnants of andesite mudflows form resistant ridges
and stands high above the present land surface east of the Sunset area. Several of these
flow remnants have preserved underlying pre-Merthen fluvial systems (i.e. Valley Springs
and Ancestral Yuba age equivalent paleochannel deposits).

The Mehrten rock unit contains scientifically significant fossil vertebrate faunas as well as
floras. Wagner (1975) has described mammalian faunas from three of the four described
stratigraphic units (members) of the Mehrten Formation in Stanislaus County (northeast
San Joaquin Valley). Condit (1944) described the Remington Hill Flora from Nevada
County, California.

VALLEY SPRINGS FORMATION
The geology of Valley Springs Formation geology has been previously described by
workers including Piper et. al. (1939), Macdonald (1941), Slemmons (1964), and Deino
(1979). Axelrod (1944) described a small flora from near the type locality in Calaveras
County.

The Valley Springs Formation and its equivalents represent a thirty to twenty million year
period characterized by episodic rhyolitic ash eruptions derived from the Carson City-
Dayton area of western Nevada (Deino 1979). A significant portion of the Valley Springs
age paleochannel drainages are preserved in the Placerville District of the central Sierra
Nevada region. Clear evidence of post-Valley Springs deposition - late Tertiary faulting
along the Melones Fault can be observed at the Landeker Hydraulic and Drift Mine site
outside Placerville.

The attached geologic map and cross sections indicate that Valley Springs Formation ash
units and overlying fluvial sediments exist within an elevated block (horst structure) on the
Melones Fault Zone at the Landeker Mine. Detrital "rhyolite eggs" within the fluvial
sequence are undoubtedly derived from the underlying Valley Springs (Nine Hills tuff?)
dominant rhyolite ash unit.
Regional stratigraphic implications of auriferous gravels in the Placerville District focus on the discovery that the majority of paleochannels are Valley Springs age and not Eocene or Ione as traditionally thought by many previous workers.

Sierran uplift tectonic implications of this field trip focus on the fact that significant late Tertiary movement along the Melones has occurred along the Melones Fault at the western margin of the Central Sierra Nevada, thus bringing into doubt classically-held theories of regional-wide late-Tertiary and/or Quaternary uplift of the Sierra Nevada Range.
Map of Placerville District, El Dorado County. The map shows mine locations. After Clark and Carlson, 1956.
EXPLANATION

TM - Mehrten FM
TMv - andesitic lahars
TMg - gravel with volc. clasts
TVS - Valley Springs Fm.
TVSs - rhyolitic sand & mudstone
TVSr - massive, cliff-forming rhyolite
TVSgu - upper gravel
TVSgl - lower gravel

MCs - slate of Calaveras and Mariposa Fms.

Geologic sketch map by David L. Jones and David Lawler, 1997.

Geologic sketch of the Landecker Mine, Placerville, CA
Schematic vertical profile, Landecker Mine
ANCESTRAL YUBA RIVER (EARLY TERTIARY AGE)

AURIFEROUS FLUVIAL DEPOSITS

BY

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ANCESTRAL YUBA RIVER (EARLY TERTIARY AGE)
AURIFEROUS FLUVIAL DEPOSITS

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INTRODUCTION

Vast quantities of unmined gold-bearing gravel in Northern California, on the divides between the North Fork of the American River and the South Fork of the Feather River. This gravel was deposited by an immense prehistoric river system called the ancestral Yuba. It existed approximately 60 to 40 million years ago, during the early Tertiary period, and extended over a large area of the present day northern and central Sierra Nevada Range. (Figure 1).

A major portion of the total placer gold from Tertiary deposits in California has been produced from the ancestral Yuba: estimated at nearly 12 million ounces and worth approximately $5 billion. Much of this was produced during the period of 1850 to 1884 when hydraulic mining was developed and extensively used in California. In 1884 a court injunction prohibited widespread use of hydraulic mining, leaving large volumes of virgin gold-bearing gravels unworked.

The area of the ancestral Yuba shown on this map contains the largest remaining deposits of Tertiary gold-bearing gravel in the Sierra Nevada. A significant gold resource exists here, with relatively good access and channel exposures. The small-scale miner has the opportunity to exploit these small, rich accumulations which large mining companies pass by, due to limited ore reserves. Much of this mining can be carried out at reasonably small expense, and encouraging results can be obtained rapidly.

GENERAL GEOLOGIC HISTORY

Formation of the Ancestral Yuba River Deposits

Voluminous quantities of gold-bearing gravel were deposited in the ancestral Yuba River drainage system, mainly during the Paleocene and Eocene times of the early Tertiary period. Geologic investigations indicate that this vast river system probably originated along highlands or the crest of the ancestral Sierra Nevada Range in western Nevada, and flowed westward into a marine basin located in the present day Sacramento Valley. The early history of the ancestral Yuba River during the Paleocene to early Eocene was characterized by rapid downcutting and high relief of surrounding areas. Much of the gold that was constantly being supplied to the drainage was concentrated in the 50 to 100 feet of gravel covering the floor of the river valleys.
During Paleocene to middle and late Eocene times, the river valleys became broader and extended their basins eastward. The formerly rugged landscape was transformed into a gentle one. Sediment thickness increased in the river valleys, and extensive flood plains and river meanders formed as the rivers continued to accumulate rather than downcut. Semitropical climatic conditions, high precipitation (estimates range from 200-600 inches per year), and lush closed canopy-type rainforest vegetative cover caused intense chemical weathering and breakdown of less resistant rocks in the river sediments. By the end of the early Tertiary, golder-bearing river deposits had accumulated that were up to 400-600 feet thick and well over a four miles wide in some places.

**Volcanic Episode**

Intermittent volcanism began at the end of the Eocene in the ancestral Sierra Nevada and surrounding areas and continued until Pliocene times. Mudflows and volcanic ash covered much of the Sierra, including the ancestral Yuba. Widespread mudflows of andesite and rhyolite composition (Valley Springs and Mehrten Formations) effectively protected the softer gold-bearing sediments from extensive erosion. During this period new river systems formed and established drainage patterns different from those of the ancestral Yuba system.

**Rise of the Sierra Nevada**

Recent geologic and tectonic investigations and reevaluation of the channel gradients of the Ancestral Yuba River System suggest that the northern Sierra Nevada Range may have existed as early as late Cretaceous times. This new tectonic model (cf. Dr. David Jones - unpublished data) contrasts drastically with classic Sierran uplift model characterized rapid uplift and westward tilting of the northern Sierra and marked subsidence of volcanic activity by the Late Pliocene (+3 m.y.) times.

Since Pliocene times, the volcanic cover has been largely eroded, exposing much of the ancestral Yuba gold-bearing deposits, with the essentially modern-day Sierra rivers systems, such as the Yuba and the American River drainage, quickly downcut into topographic lows during Pleistocene times (perhaps in response to increased precipitation), and establishment the deeply incised canyons, which are so spectacular and so rich in placer gold today.

**HISTORY OF MINING**

Placer gold was first discovered by the forty-niners in the streams and rivers of the Sierra Nevada. Later it was traced to the prehistoric river deposits on the divides between river canyons. Miners discovered that his gold-bearing gravel was partially covered by extensive volcanic cover but was exposed numerous places between the North Fork of the American and the Bear Rivers, and between the South and Middle Forks of the Yuba River.
Hydraulic Mining

Small scale mining methods, such as use of a gold pan, sluice, or rocker box were replaced by hydraulic mining, initially developed in 1852. This method used vast systems of canals and large diameter iron pipes connected with huge nozzles (monitors) to cheaply mine large volumes of gravel. Hydraulic mining was used extensively on the gold-bearing deposits of the ancestral Yuba from 1855-1884.

During the nearly 30 year period, an estimated 250 million cubic yards of material were mined from the ancestral Yuba deposits and washed into nearby river drainages. At the Malakoff hydraulic pit near North Bloomfield (now a scenic state park), nearly one cubic mile of material was removed. The accumulations of hydraulic mine debris rapidly lowered river gradients, choking and filling channels where they emptied into the Central Valley. Subsequent repeated silting and flooding destroyed vast acres of farmland and led to more than ten years of litigation between farmers and miners, culminating in the famous court case Woodruff vs. North Bloomfield Gravel Mining Co. In 1884 a court injunction was issued, effectively banning extensive hydraulic mining in California. Legislative attempts to revive hydraulic mining were unsuccessful and the large hydraulic operations shut down. As a result, significant quantities of gold-bearing gravel were left unworked.

Drift Mining

Drift mining, which had been common 10 to 20 years earlier, was revived and extensively used following the shutdown of the hydraulic mines. The richest gold-bearing gravels at the base of the ancestral Yuba deposits were extracted by driving an underground tunnel into bedrock close to and along the gravel-bedrock contact. It has been estimated that nearly 30 million cubic yards of gravel were mined using this method (Gilbert, 1917).

Dredge Mining

Floating bucket line and clamshell type dredges were developed at the turn of the century and rapidly became the leading producers of placer gold in California until World War II. The vast deposits of hydraulic tailings from earlier mining of the ancestral Yuba and Feather River deposits were mined using these methods.

SEDIMENTARY GEOLOGY AND GOLD DEPOSITS

Channel Location and Extent

Accuracy of channel locations varies with the state of knowledge about a particular area. Where a sizable channel segment has been eroded by major existing river drainages or is under thick volcanic cover, its approximate location is shown.
The ancestral Yuba River Map shows the probable maximum extent of the ancestral Yuba channel, as indicated by geologic field data. This does not imply that in-situ (in place) gravel is present throughout the channel areas. Erosion may have removed a part or nearly all of gravel deposits in certain locations prior to historic mining.

**Lower Gravels and Channel Base**

An idealized section across the ancestral Yuba River channel is shown in Figure 3. The gold bearing gravel deposits can be divided into a lower and upper unit (Yeend, 1974).

The deeper portion of the channel is occupied by the lower gravel, which tends to be a coarse, poorly sorted mixture of cobbles, pebbles, sand, and clay. Large boulders up to 6-10 feet in diameter are also common. The lower gravel can be divided into an upper red gravel and a lower blue gravel, the color being simply a function of whether the gravels are in a chemically oxidized or reduced state. Thus, the term "Blue Lead" refers to bluish gravels which occur below the water table, as noted by Lindgren (1911). The lower gravel contains relatively high gold concentrations and was the unit most actively sought by the early miners. It ranges from 70-140 feet in thickness.

Depending upon local bedrock geology, a deep gut or groove may exist in the center of the channel, shown on the map by a double line. These basal areas have yielded high gold concentrations.

**Upper Gravels**

The upper gravels or bench gravels overlie the lower gravels and are considerably finer and better sorted. They tend to be compositionally more mature and thus named the "white gravels" for the proportionally greater amount of quartz clasts. The upper gravel also contains many beds of sand- and clay- sized material. Thickness of this unit may vary up to 400 feet.

**Gold Size**

Figure 4 shows the occurrence, weight, and discovery date of famous gold nuggets found in the lower gravels of the ancestral Yuba. The source of these large gold masses was likely nearby high grade lode pockets which were scoured out by the channel. Larger flakes and nuggets of gold are found associated with the coarse, bouldery portions of the lower gravel more commonly than in the upper gravels. Gold particles as small as 400 mesh (Tyler mesh size) have been recovered from the upper gravels.
Gold Values

Gold values in the upper and lower gravels vary widely along the ancestral Yuba and it is difficult to provide accurate information since many mine areas had been exploited and exhausted before production figures were recorded. However, areas such as Liberty Hill, French Corral, and Smartsville had relatively high values due to the exclusive presence of lower gravels (Yeend, 1974) while unknown factors created extremely rich gold deposits in the lower gravels at Indiana Hill, Dutch Flat and Debec drift mines.

Intervolcanic Channels

Intervolcanic channels, not shown on this map, represent river systems formed during periods of volcanism in the later Tertiary. They are geologically younger than the ancestral Yuba and reflect a general change in drainage pattern. These channel deposits have an overall lower placer gold content than deposits of the ancestral Yuba. However, some sections of these intervolcanic channels have "robbed" or eroded gold from the ancestral Yuba where they crossed. The rich gold deposits in the intervolcanic channel developed by the ruby drift mine in Sierra County are an excellent example of this situation.

OTHER HEAVY MINERALS

Detrital heavy minerals commonly found in the ancestral Yuba deposits are ilmenite, zircon, sphene, amphibole, epidote, chlorite, siderite, and pyrite. Ilmenite and zircon are the most common heavy minerals in the upper gravels (Yeend, 1974).

Secondary sulphides such as pyrite are common in the lower bluish (reduced) gravels. Gold-bearing sulphides termed "sulpherets" were reportedly recovered from several hydraulic and drift mines along the southern tributary of the ancestral Yuba and assayed as high as 15 ounces of gold per ton. Lindgren (1911) has reported a similar occurrence from a gravel mine in Butte County, California.

Detrital platinum has been recovered from several hydraulic mines along the ancestral Yuba in Sierra and Plumas Counties. Alluvial diamonds have also been reported from heavy mineral concentrates derived from the gravels. Most notable was the occurrence of a number of diamonds up to 7.25 carats, recovered from the French Corral gravel mines (Whitney, 1880).

MAP LEGEND - DESCRIPTIVE NOTES

Map Symbols
The map symbols designate important features such as distribution, location, and extent of the ancestral Yuba river deposits, as well as locations of major hydraulic pits and drift mines, historic townsites, land ownership, etc. Points of interest can be located relative to present day roads, towns, streams, and the Yuba River drainage system.
Map Index

The map index lists locations of important hydraulic and drift mines, historic townsites and historic nugget discoveries.

Topographic Data

The topographic base provides information on the elevation of different parts of the ancestral Yuba deposits, steepness of slopes in river canyons and surrounding areas. Note that the ancestral Yuba deposits are commonly located 500 to 1,000 feet above the present major drainages.

Historic Townsites

Townsites occupied during the 19th Century and now abandoned are shown in gold on the map and listed in the index. The existence of most of these townsites or settlements was related directly or indirectly to mining activities along the ancestral Yuba.

Topographic Index Map

Topographic index map shows the location of the ancestral Yuba within the particular 7.5 and 15 minute USGS quadrangle maps. This is particularly useful for persons interested in a detailed area requiring larger scale maps.

Land Ownership

The land ownership base is useful in quickly determining whether a given area is public or private. Within public lands, those managed by the U. S. Forest Service are designated. For more detailed information on public land status, check with the appropriate USFS, BLM (Bureau of Land Management), County, or State Lands offices. Private land ownership can be checked in more detail at the respective county offices. Always obtain permission from private landowners prior to entering their property.
BIBLIOGRAPHY


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Figure 1(right). Tertiary channels and dredge fields, Sierra Nevada. After Lindgren(1911) and Clark(1970). (Courtesy of California Div. of Mines and Geology)
Figure 3. Idealized section across the ancestral Yuba River channel. After Petersen (1968).

<table>
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<th>Location</th>
<th>Date Found</th>
<th>Weight (troy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar Star claim, Dutch Flat district</td>
<td>1876</td>
<td>288 oz.</td>
</tr>
<tr>
<td>Minnesota, Alleghany district</td>
<td>1850's?</td>
<td>266 oz.</td>
</tr>
<tr>
<td>Remington Hill, Nevada County</td>
<td>1855</td>
<td>186 oz.</td>
</tr>
<tr>
<td>Live Yankee claim, Alleghany dist</td>
<td>1854-62</td>
<td>12 nuggets, 30-176 oz.</td>
</tr>
<tr>
<td>Remington Hill, Nevada County</td>
<td>1869?</td>
<td>107 oz.</td>
</tr>
<tr>
<td>Lowell Hill, Nevada County</td>
<td>1865</td>
<td>58 oz.</td>
</tr>
<tr>
<td>Ruby mine, Alleghany district</td>
<td>1930's-40's</td>
<td>Nuggets up to 57 oz.</td>
</tr>
<tr>
<td>Steelman-Hayes Claim, Downieville district</td>
<td>1886</td>
<td>39 lbs</td>
</tr>
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Figure 4. Large nuggets and gold masses from ancestral Yuba channel. After Clark (1970).
Dutch Flat; Bear River on the left, the North Fork of the American on the right.
Uplift of the Sierra Nevada: fact or fancy?
By
David L. Jones

Introduction

The debate over Sierran uplift has now been going on for at least 100 years with no reconciliation in sight. The advocates of uplift far outnumber the skeptics, even though there is little agreement among the devotees as to the amount, timing and mechanisms of uplift. The basic uplift story that many ascribe to goes something like this, with apologies for gross over simplification and avoidance of literary attributes (for a comprehensive review of the literature from a skeptic's point of view, see Schaffer, 1997):

An early period of uplift and erosion of the Sierra Nevada during the Cretaceous resulted in formation of a deeply weathered peneplain with low relief by early Eocene time. During the Eocene, rivers with gentle gradients flowed across this peneplain carrying quartz and chert detritus from Nevada. This sediment was deposited as auriferous gravels in the foothills and as the clay-rich fluvitile and lacustrine deposits of the Ione Formation in the eastern part of the Great Valley. Following the Eocene, volcanogenic deposits and gravels of the Valley Springs and Mehrten Formations accumulated within the broad Eocene channels. Various episodes of uplift have been ascribed to the interval between deposition of the Eocene auriferous gravels and the Mehrten, during the Mehrten, and in post Mehrten time. Deep canyon cutting during the Plio-Pleistocene is considered a manifestation of post-Mehrten uplift. Total post-Eocene cumulative uplift is variably estimated to be in the range of 1 to 2 miles, with the Sierra Nevada having been tilted westward as a rigid block. Under this tilted block interpretation, Sierran uplift along the eastern crest is balanced by equal subsidence in the Great Valley to the west.

Many of the postulates of the above scenario are testable using standard geologic techniques, as outlined below. Before evaluating these concepts, however, it is necessary to define a few simple terms, as follows:

Uplift - a meaningless term unless the type of uplift is specified.
Rock uplift - change in elevation of a rock mass with respect to some arbitrary datum, such as sea level or calculated depth of emplacement or burial. Changes in elevation of the land surface are not specified nor implied.
Topographic uplift - increase in topographic elevation of the land surface.
Exhumation - unroofing, or exposure at the land surface, of rock that was previously buried.

An examination of available data geologic data that might have some bearing on the later tectonic history of the Sierra Nevada leads to the following tentative assertions. These apply only to that part of the mountain system centered on the America River drainage where the most complete record of Tertiary deposition is preserved.
1. Rock uplift in the Sierra during the Cretaceous was asymmetrical, with more uplift on the west than to the east. The most extreme uplift was under the Great Valley, where most of the upper crust was removed. Cretaceous plutons in the crestal region have undergone about 50% less rock uplift than older plutons to the west. Evidence in support of post-Eocene rock uplift has not been presented.

2. Jurassic and Early Cretaceous plutons in the western foothills were exhumed by Late Cretaceous (Campanian) time and underwent no further topographic or rock uplift.

3. The Sierra Nevada was not tilted as a rigid block; subsidence of the great Valley exceeds uplift in the mountains. Consequently, dip of strata buried under or along the edge of the Great Valley cannot be projected eastward to establish topographic elevations of the mountains.

4. Detritus in the Eocene auriferous gravels was not derived from Nevada, but from local sources with the Sierra. Eocene stream gradients were not gentle, and no evidence supports the notion of widespread lateritic weathering of pre-Eocene bedrock. A relatively steep (~1.5°) westward sloping topographic gradient could have existed from at least Late Cretaceous time to the present.

5. Measured stream gradients of Eocene, Miocene, and upper reaches of modern rivers are essentially identical.

6. Canyon cutting commenced after the Mehrten debris flows clogged all major drainages. The presence of these deeply incised canyons is the best argument available to support the concept of topographic uplift in Plio-Pleistocene time, but other explanations are possible.

7. The steep eastern scarp of the Sierra is a result of normal faulting related to extension and crustal thinning in the Great Basin. Nevada rocks have subsided; Sierran rocks have also subsided locally (e.g., Lake Tahoe basin), but not to the same extent as rocks farther east. The crust under the Sierra has remained relatively thick, and the high topographic elevation of the range is a manifestation and expression of the presence of a thick crust under the Sierra and a thinner crust to the east and west. The long westward slope of the Sierra is a fossil topographic feature formed at an earlier time when the crust under Great Basin was even thicker than the present day Sierran crust.

**Summary of critical evidence**

**Rock uplift during the Cretaceous**

Using aluminum-in-hornblende (AH) geobarometry, Ague and Brimhall (1988) calculated the depth of emplacement for granitoid plutons of the Sierra Nevada. Their data have been recast in figure 1 from depth of emplacement to amount of rock uplift, in kilometers. Two notable features are apparent from inspection of this figure: 1) rocks of the southern tail of the batholith have been elevated more than those in the northern part, and the western part of the batholith has been elevated more than the eastern part. A simple time-distance graph of these results along line A-A' is shown in figure 2, with the zero point, or hinge line, being the Upper Cretaceous deposits at Folsom that rest on the exhumed Penryn pluton. A more revealing analysis of these data is shown in figure 3, wherein the exhumation of plutonic rocks is partitioned in time. According to this figure,
cumulate rock uplift of Sierran plutonic rocks during the Cretaceous is 15 kilometers or more. The Penryn pluton was close to sea level by late in the Cretaceous, and it remains at that position today. This stable area marks the hinge line between regions to the west that have subsided during the Cretaceous and Cenozoic, and areas to the west that are at higher topographic elevations, and which may have undergone additional uplift during the Cenozoic. Several options are possible: line 1 represents the present slope at the base of the Mehrten Formation of about 1.5°. This slope could be either the original slope at the time of deposition or some combination of original slope and renewed uplift, as represented schematically by line 2. Data bearing on these options will be discussed in a later section.

Rock uplift data derived from AH analyses are generally consistent with mineralogical criteria and with thermodynamic calculations. Western plutons that are uplifted the most (12 to 16 km) are syenitic with amphibolitic aureoles indicative of temperatures and pressures of mid-crustal regions. Cretaceous plutons of the crestal region have been uplifted less (8 to 10 km), lack amphibolite aureoles, and clearly post-date regional penetrative high temperature metamorphism. Ague (1997) has reexamined some of the samples originally studied by Ague and Brimhall, and using thermodynamic calculations involving tremolite, pargasite, phlogopite, quartz, and K feldspar, has found close agreement between these two techniques. Ague (1997) also points out that a third measurement of deep levels of emplacement of plutonic rocks—the presence of magmatic epidote, characterizes the southern tail of the Sierran plutons that have been uplifted 16 km or more.

Implications of this record of rock uplift during the Cretaceous for crustal structure of the Sierra Nevada and adjoining Great Valley are profound. As shown in fig. 4, the crust under the western Sierra is about 40 km thick, with the bulk of this material exhibiting seismic velocities > 6.0 km/s. The upper crust is thickest under the Sierran crest, and thins dramatically to the west. Under the San Joaquin Valley, an upper crustal layer with velocities < 6.0 km/s is missing, and the lower crust with velocities of 6.5 km/s or greater is very close to the depositional base of the Great Valley sequence (GVS). If we superimpose the rock uplift data of figure 1 onto this crustal profile, and project these data westward, we see that the amount of rock uplift essentially balances the amount of missing upper crust recorded by the velocity data. This pattern of increasing rock uplift and loss of upper crust to the west is not consistent with the westward-tilted block model discussed above. Instead, it suggests that the Sierra through time has been tilted eastward! The presence of lower crustal material just a few kilometers below the base of the GVS is the probable explanation for the linear gravity and magnetic highs that occur in the subsurface from Bakersfield north to Red Bluff. This dense, magnetic belt composed of lower crust mafic rocks has been referred to as the "Great Valley ophiolite". The mechanisms by which the upper crustal layers have been removed remain unspecified. Crustal thinning coupled with rapid erosion could effectively accomplish this. Indeed, the overall pattern of figure 1 suggests that the Sierran block has slid eastward away from the region now occupied by the Great Valley. This movement would force the denser rocks of the lower crust to be uplifted to upper crustal levels. The presence of major attenuation faults within the foothills belt (e.g., the eastern Bear Mountains fault), is consistent with this
speculation of crustal thinning being involved in the elimination of the upper crustal layers

The profile of the erosion surface beneath Cretaceous and Cenozoic rocks in both the great Valley and the Sierra Nevada is shown in figure 5. Data are taken from Jachens and others (1996). The slope of buried basement rocks at the base of the sedimentary column west of Folsom averages about 6.5°; the slope of basement rock east of Folsom averages about 1.5°. This difference suggests that subsidence to the west exceeds uplift to the east. This is supported by the fact that up dip projection of basal Cretaceous and Eocene erosional surfaces yields unacceptably high mountain elevations, as shown in figure 6. Present coastal elevations should be 37,000', rather than <10,000', if a planar Cretaceous erosion surface had tilted uniformly. Greater subsidence to the west than to the east is consistent with the difference in crustal structure of the two areas described above.

**Tilted Surfaces within the Sierra Nevada.**

The single argument in favor of Neogene uplift is that modern rivers, such as the American, have incised their channels far below the level of rivers that flowed from Eocene through Pliocene time. For example, at Lava Cap winery near Placerville, the base of the Mehren is at an elevation of 2560'. The elevation of the South Fork 1 mile to the north is 1400' So the river has lowered its bed by nearly 1200' during the past 2 to 3 my. The average slope at the base of the Mehren Formation is ~1.53° (figure 7) with the eastern portion of the outcrop belt averaging about 1.7° and the western half averaging about .99°. At Chili Bar, the present slope of the South Fork channel is 0.6°, and a few miles upstream, it varies from ~1.27° to 1.69°. Not much difference is seen between the slope of the erosional surface at the base of the Mehren and the erosional surface at the base of the modern river.

The key consideration here is what was the initial slope over which the Eocene and younger rivers flowed? The Eocene streams deposited coarse conglomerates containing boulders and cobbles in early phases (blue gravel), and cobbles to pebbles in later phases (white and red gravels). The present rivers carry comparable clast sizes, so gradients were probably about the same as indicated by the slope measurements given above. The Mehren lahars however, moved huge volcanic and granitic clasts for over 100 km. The largest granitic clast that we have found in the Mehren near Placerville is more about 3 meters in long dimension; andesite boulders near Folsom are one to two meters in diameter. What is the minimum slope required for long-distance transport of boulders of this size in a mudflow? If post-Mehren topographic uplift amounted to 5000', than the maximum slope possible at the base of the Mehren was 0.63° (fig 7) or less than ½ the slope of the South Fork above Chili Bar. Comparison with movement of modern lahars could shed additional light on this problem, but a regional gradient of ~0.5° during the Mio-Pliocene seems to be too gentle to accommodate down-slope movement of large blocks.

Lindgren (1911) argued that because of post-Eocene westward tilt of the Sierra Nevada, west-flowing Eocene rivers should show higher gradients than do north or south
flowing rivers. Careful measurement of preserved portions of the Eocene ancestral Yuba River shows that the slope of the west flowing channels average about 1.74°, and the slope of the south-flowing channels average about 1.65°. Lindgren’s prediction is verified! But the uplift necessary to produce this difference is only 553', an amount that can easily be explained by isostatic uplift resulting from erosion.

The provenance of clasts in the auriferous gravels reflects mainly local sources. In the blue gravels, cobbles of quartzose graywacke similar to that of the Shoo Fly, and hornfelsed argillite similar to argillite in the Sailors Canyon Formation, are abundant. Chert and quartz pebbles predominate in the upper gravels, along with scarcer meter-size blocks of chert, but none is similar to well-studied Paleozoic chert that is abundant in western Nevada in the Golconda and Roberts Mountains allochthons. Either the size or the character of the clasts does not support the concept of low-gradient rivers carrying detritus a long distance from the east during the Eocene.

In summary, the problem of initial dip on sub-Eocene and sub-Miocene erosional surfaces remains the key to solving the uplift problem. None of the data cited in support of Neogene tilting of these surfaces withstands close scrutiny, although the Eocene river data do permit modest tilting and topographic uplift of about 500'. Additional Neogene topographic uplift above this amount is possible but unproven.

Reasons for Pleistocene gorge cutting are still elusive. By the end of deposition of the Mehrten, the established drainage network had effectively been destroyed by filling of channels with volcanic debris flows. The post-Mehrten newly integrated drainage system that exists today had to create new channels, but glaciation came along just about this time to add another new wrinkle to the puzzle. Perhaps the gorges are the result of concentration of runoff in a smaller number of major rivers, coupled with augmented flow resulting from melt of glacial ice. These changes could lead to rapid erosion and the cutting of deep gorges. Who Knows? But Neogene topographic uplift may not be the only answer!

The message from all of this is clear: rock uplift can be measured using a range of established mineralogical and geochemical techniques; topographic uplift is very difficult to measure because of a lack of suitable reference points. In terms of evolution of the Sierra Nevada, the Cretaceous rock uplift is far, better documented, tectonically more significant, and poses more fundamental questions than does Cenozoic topographic uplift. The big story is in the rocks!

Selected References

Note: An extensive bibliography exists that is pertinent to the question of topographic and rock uplift of the Sierra Nevada. Only a few key papers are cited here, but they provide an introduction to the problems.


Figure captions

**Figure 1.** Results of Aluminum-in-hornblende geobarometry of plutonic rocks in the Sierra Nevada. Data from Ague and Brimhall, 1988. Heavy line - outline of the main plutonic belt; A-A', location of uplift curve of fig. 2.

**Figure 2.** Graph of rock uplift as a function of the distance from the Folsom hinge line.

**Figure 3.** Graph of rock uplift as a function of time. See text for explanation of lines 1 & 2.

**Figure 4.** Structure section across the southern San Joaquin Valley and southern part of the Sierra Nevada. Crustal velocities i km/s. Uplift data from Ague and Brimhall, 1988.

**Figure 5.** Profile of elevation of crystalline rocks beneath Cretaceous and Eocene erosional surfaces. Data from Jachens and others, 1996.

**Figure 6.** Up-dip projections of basal Cretaceous and Eocene strata in the eastern part of the Sacramento Valley.

**Figure 7.** Slope of Tertiary erosion surfaces and deposits in the Sierra Nevada.
DISTANCE FROM HINGELINE

ROCK UPLIFT (Km)

A

A'

0

10 20 30 40 50 60 70 80 90 100

15

12

9

6

3

0
UPLIFT OF WESTERN SIERRA NEVADA PLUTONS

CRETACEOUS SHALLOW PLUTONS

WESTERN JURASSIC & LOWER CRETACEOUS PLUTONS

present slope, base of Mehrten = 1.53

Max. Neogene uplift of crestal area of Sierra

Combined pre-Neogene uplift and original slope

large boulders in late Campanian debris flows near Folsom
Crustal structure of the southern Sierra Nevada (modified from Fliedner & Ruppert, 1996), with projected uplift data from Ague and Brimhall, 1988
ELEVATION OF BASEMENT ROCKS
Subsidence data projected to crest of SN

Projected base of Eocene, 5.4°
Projected base of Cretaceous
Base of Great Valley sequence (Cretaceous), 6.65°
Projected base of Pleistocene, 1.4°

Elevation of projected surface
37,000' (11.2 km)
30,000' (9.1 km)
7,700' (2.3 km)

Slope of west-flowing Eocene rivers = 1.74°
Slope of south-flowing Eocene rivers = 1.65°
Uplift - post Eocene = 1 (553')
NEOGENE EROSIONAL SURFACE AT BASE OF MEHR TEN FM.

average slope at base of Mehrten = $1.53^\circ$

Folsom .99$^\circ$

Placerville

slope = $0.63^\circ$

pre-uplift slope if uplift = 5,000'

Sillan crest

WHAT IS THE MIN. SLOPE NEEDED TO CARRY 1–2 M LONG BLOCKS IN MEHR TEN LAHARS???
Main Sierran batholithic belt

Rock uplift, in kms

Uplift of Sierran Plutonic Rocks

Data from Ague and Brimhall, 1988