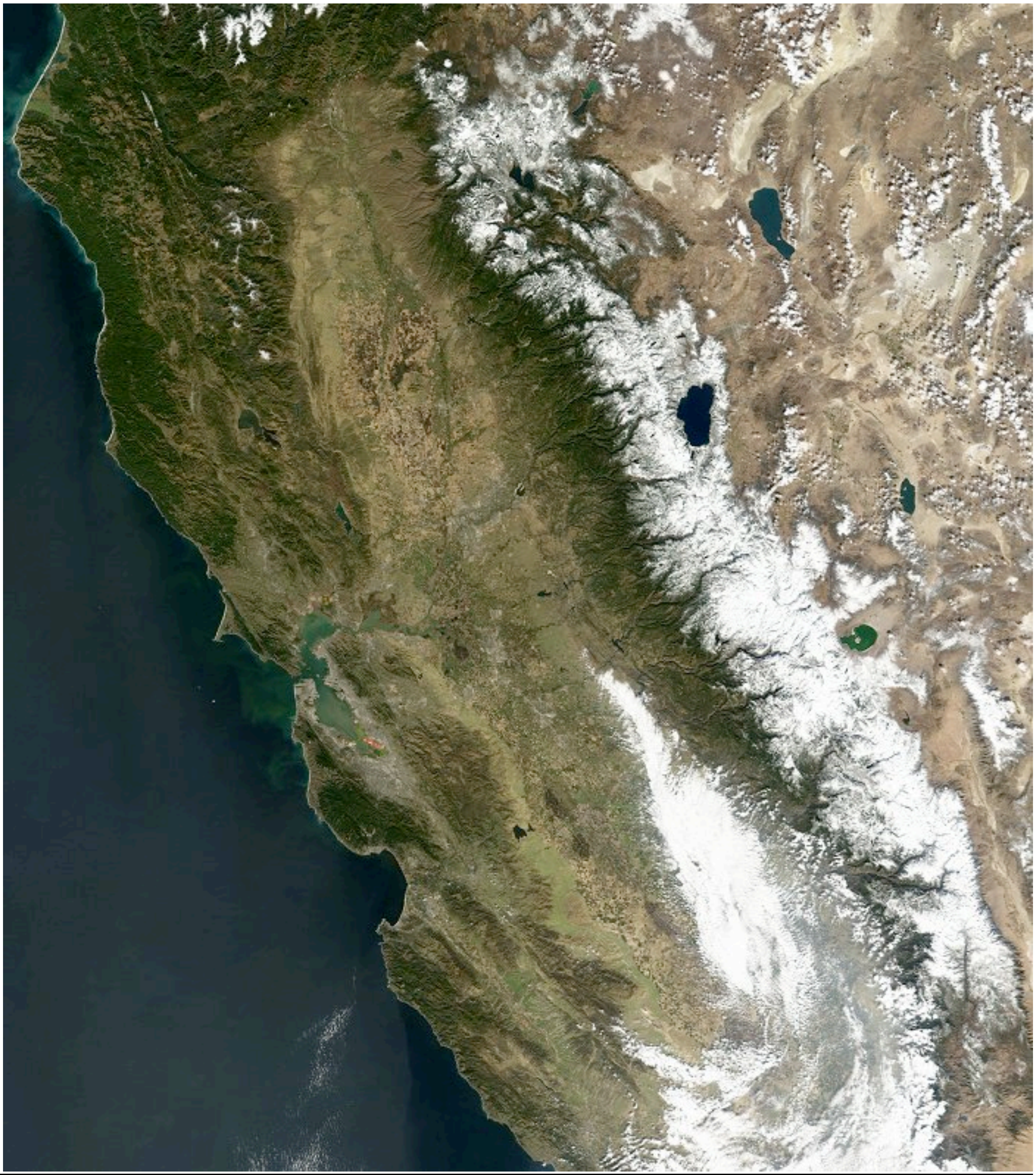
Convergent Margins: from Sierra to Sea

Field Trip Guide: June 13-16, 2011



Field leaders: Simon Klemperer and Julie Fosdick
Edited by Simon L. Klemperer

About the Field Trip:

The Convergent Margins field trip was designed and coordinated by faculty and graduate students in the Sedimentary Research Group and participants of *GEOPHYS 171: Tectonics Field Trip* at Stanford University. The objective of this trip is to examine the regional tectonic architecture and the resulting geology of California from the Sierra Nevada, across the Great Valley to the Coast Ranges and the Pacific Ocean. Many of the stops and their descriptions are compiled from previous field trips as well as other published guide books.

This is an original compilation of previously published material. Key guidebooks from which we have freely borrowed material include: Moores et al., 2006; Shervais et al., 2010; Ingersoll et al., 1981; 1984; Schweikert & Graham, 1981; Ingersoll & Graham, 1984; Elder, 2001; and Konigsmark, 1998 & 2002.

On behalf of all the participants we would like to express our gratitude to the faculty and students who have contributed their time and effort into logistical and academic support, which has all been necessary for making this a more valuable learning experience. We also thank the faculty and staff in the School of Earth Sciences at Stanford University for their cooperation and encouragement in recognizing the value and importance of "seeing rocks in the field". Finally, we are sincerely grateful to the Department of Geophysics, and to donors of the School of Earth Sciences and the Lawton Fund who have provided critical financial support to making this field trip possible.

Enjoy!

Guide-book assembly team:

Blair Burgreen
Julie Fosdick
Simon Klemperer
Matthew Malkowski
Larisa Masalimova
Theresa Schwartz
Glenn Sharman

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Summarized Field Trip Itinerary

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Leave Stanford by 2 pm (no later to avoid Sacramento traffic)

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Stop 0.2 – Active growth fault

Stop 0.3 – Brief stop at Donner summit overview if we arrive in daylight – gorgeous view!

Disperse for group dinner in town of Truckee

Day 1: Sierra Nevada batholith and accreted terranes

Drive I-80 west to Auburn and take HWY 49 North to Grass Valley

Stop 1.1 – Magma mingling and batholith geology (Donner lake overview)

Stop 1.2 – Miocene volcanics and debris avalanche

Stop 1.3 – Oligocene ignimbrites

Stop 1.4 – Shoo Fly Metamorphic Complex

Stop 1.5 – Emigrant Gap; paleo-valley relief, Miocene volcanic on batholith basement

Stop 1.6 – Melones serpentinized fault zone

Stop 1.7 – Eocene auriferous gravels and hydraulic mining

Stop 1.8 – Gold Run: Eocene auriferous gravels and hydraulic mining

Stop 1.9 – Smartville Complex Pillow Basalts

Stop 1.10 – Sheeted Dikes and Pillows, Lake Oroville Campground

Continue on to Lake Oroville Campground. Dinner and campfire and campground

Day 2: Great Valley Group

Stop 2.1 – Miocene Lovejoy Basalt (Table Mountain)

Stop 2.2 – Great Valley Group on Sierran basement

Drive west across Central Valley toward town of Willows. Scenic drive through coast range hills.

Stop 2.3 – Bidwell Point Conglomerate

Stop 2.4 – Gravelly Ridge Conglomerate and basaltic sandstone

Stop 2.5 – Cache Creek (Salt Creek Sequence Bounday)

Stop 2.6 – Cache Creek (Sites locality)

Stop 2.7 – Monticello Dam

Stop 2.8 – SW Lake Berryessa: sedimentary serpentinite within basal GV group

Arrive at Bothe Campground in Napa County! Dinner and campfire at campground

Day 3: Franciscan Accretionary Complex and the San Andreas Fault

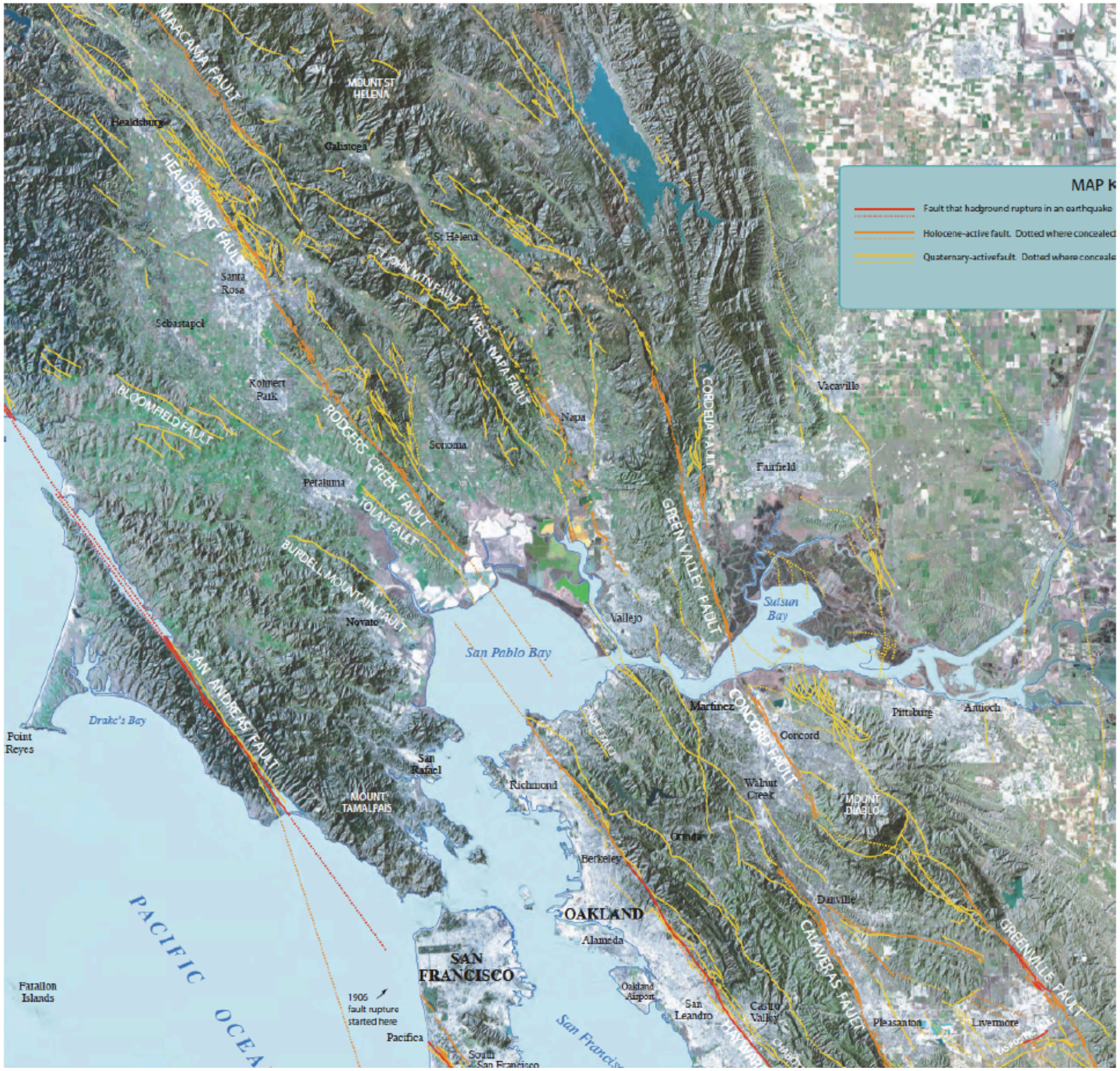
Stop 3.1 – Ring Mountain

Stop 3.2 – Marin Headlands

Stop 3.3 – Point Bonita Lighthouse

Stop 3.4 – Corona Heights Fault in San Francisco

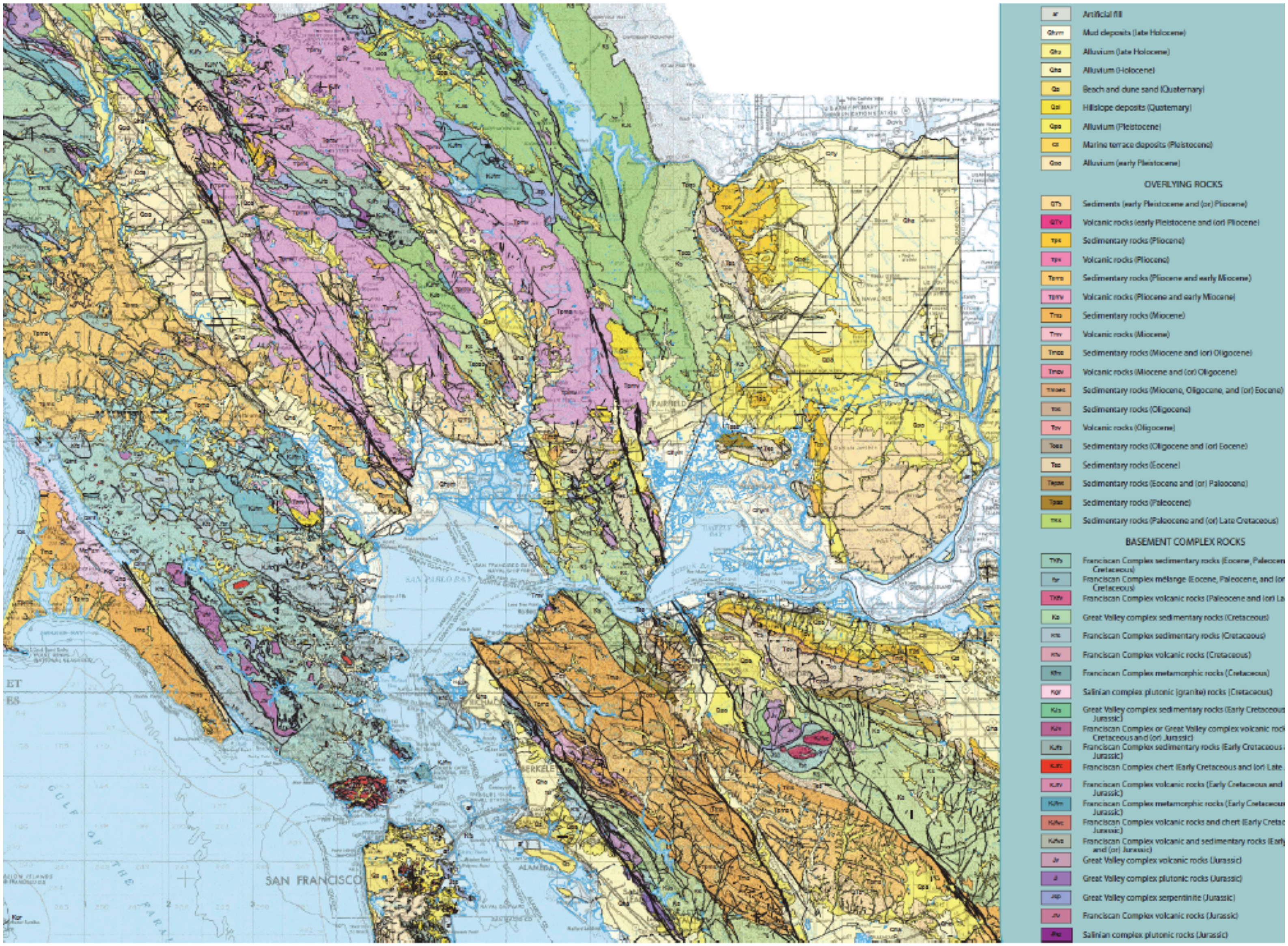
Return to Stanford



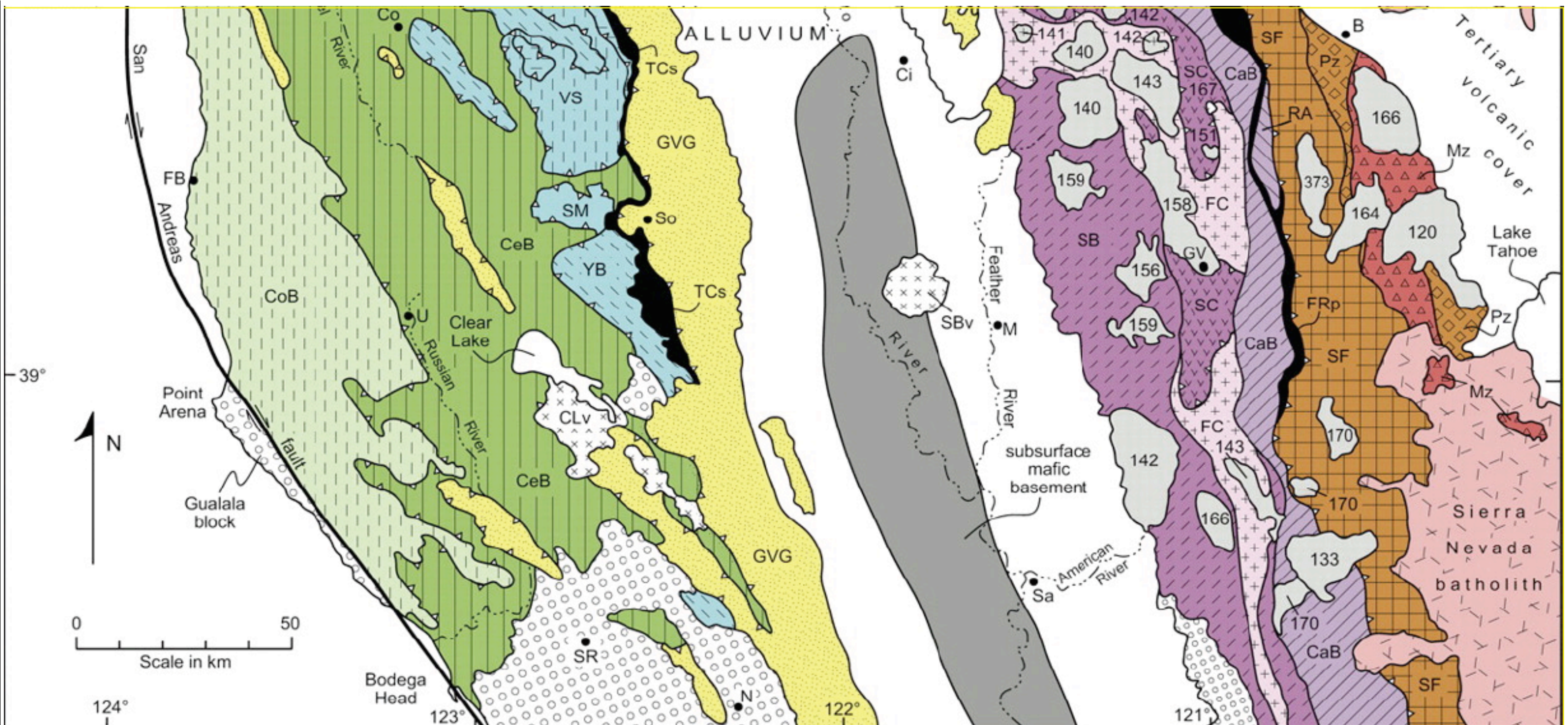
U.S. Geological Survey
Scientific Investigations
Map 2919

Map of Quaternary-active
Faults in the San Francisco
Bay Region

Graymer et al., 2006

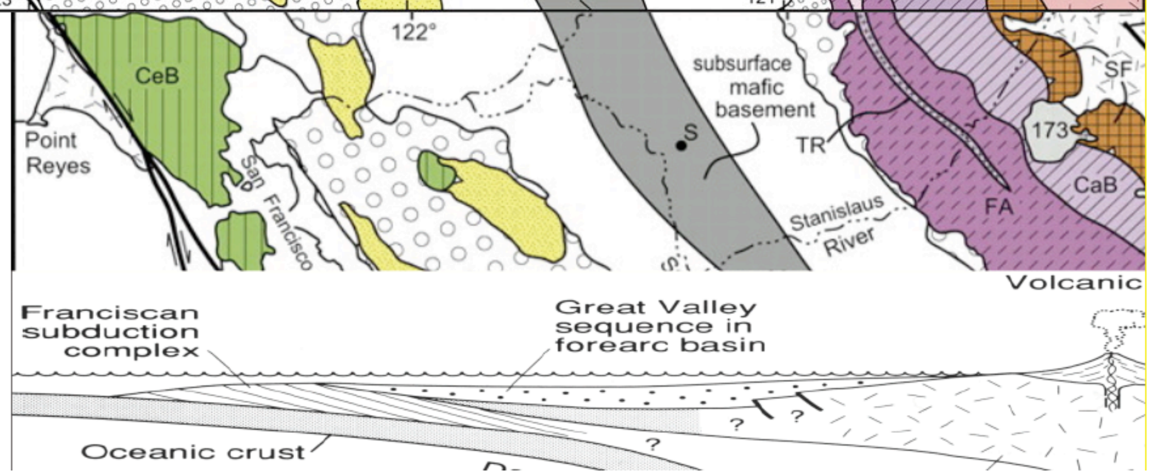


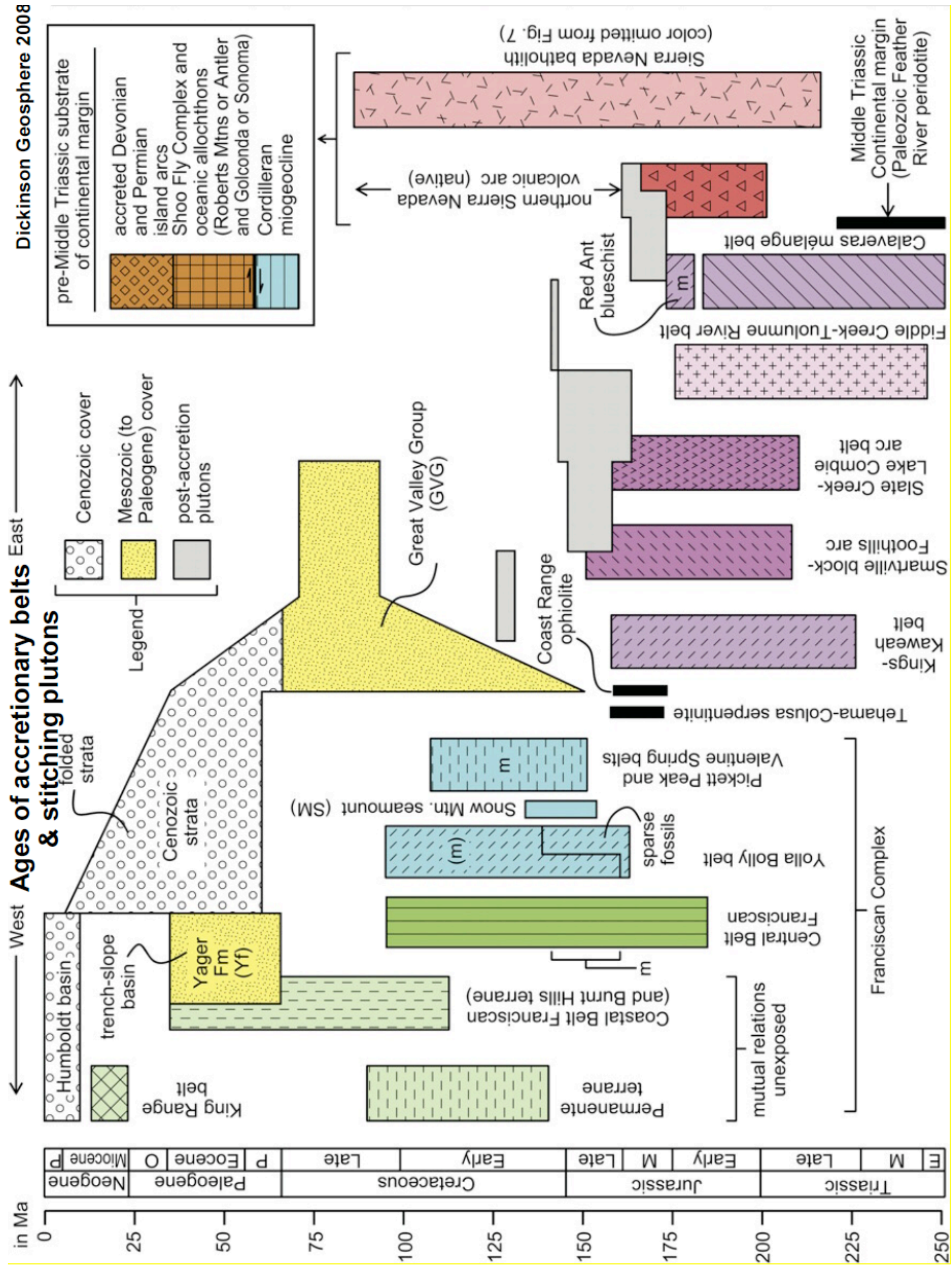
U.S. Geological Survey Scientific Investigations Map 2918   Geologic Map of the San Francisco Bay Region   Graymer et al. 2006



Accretionary tectonic belts

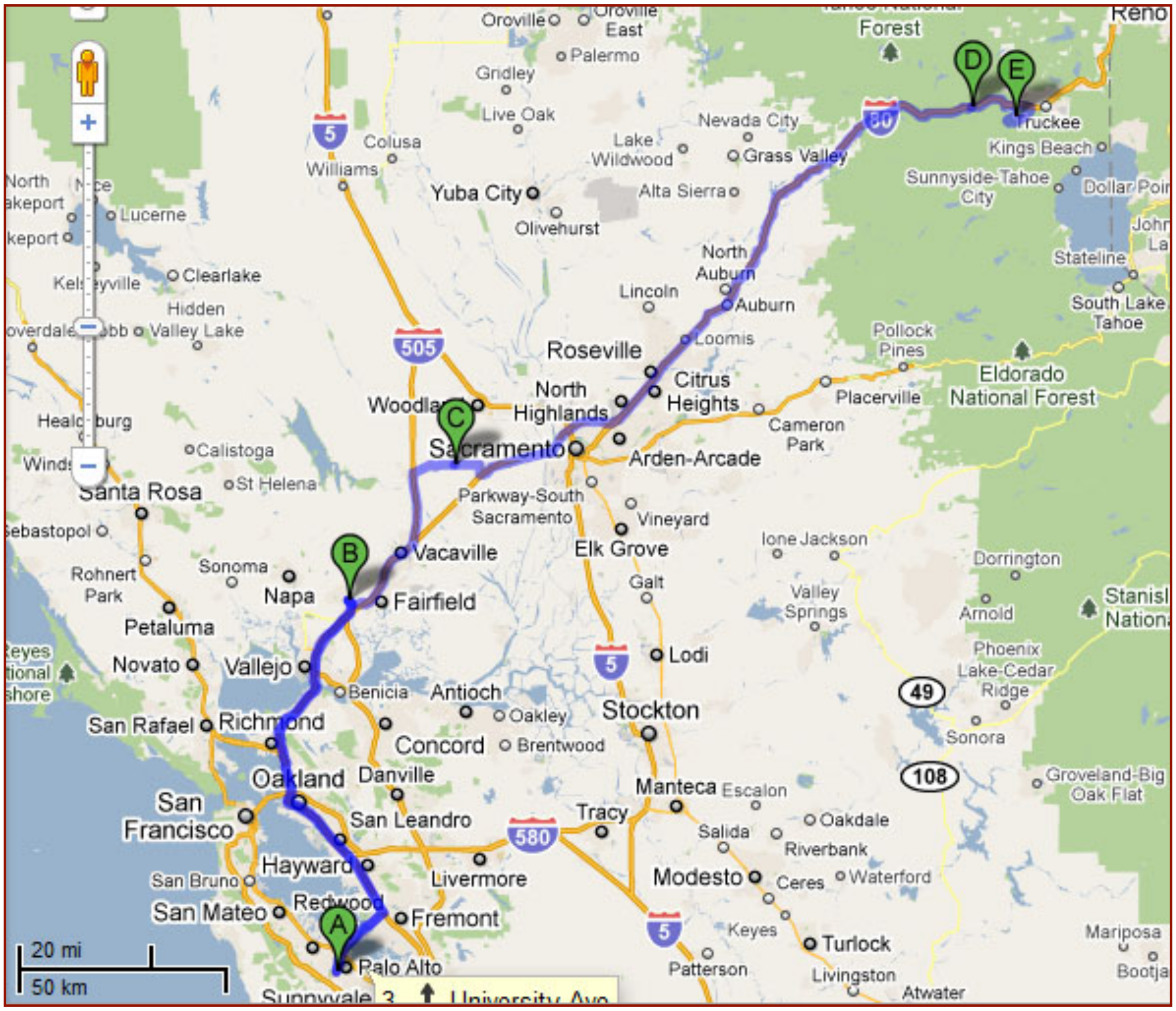
Dickinson, Geosphere 2008





Ages of accretionary belts & stitching plutons
Dickinson Geosphere 2008
West
East
in Ma
0
25
50
75
100
125
150
175
200
225
250
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
P
Miocene
O
Eocene
P
Late
Early
Late
M
Early
Late
M
E
Legend
Cenozoic cover
Mesozoic (to Paleogene) cover
post-accretion plutons
pre-Middle Triassic substrate of continental margin
accreted Devonian and Permian island arcs
Shoo Fly Complex and oceanic allochthons (Roberts Mtns or Antler and Golconda or Sonoma)
Cordilleran miogeocline
Humboldt basin
King Range belt
trench-slope basin
Yager Fm (Yf)
folded strata
Cenozoic strata
Great Valley Group (GVG)
Coast Range ophiolite
Permanente terrane
Coastal Belt Franciscan (and Burnt Hills terrane)
mutual relations unexposed
m
Central Belt Franciscan
(m)
sparse fossils
Yolla Bolly belt
Snow Mtn. seamount (SM)
m
Pickett Peak and Valentine Spring belts
Franciscan Complex
Tehama-Colusa serpentinite
Kings-Kaweah belt
Smartville block-Foothills arc
Slate Creek-Lake Combie arc belt
Fiddle Creek-Tuolumne River belt
Red Ant blueschist
m
Calaveras mélange belt
northern Sierra Nevada volcanic arc (native)
Sierra Nevada batholith (color omitted from Fig. 7)
Middle Triassic Continental margin (Paleozoic Feather River peridotite)

Day 0: Caravan from Stanford to Truckee, CA



A: Start – Stanford University (leave by 2pm to avoid Sacramento traffic)

B: Stop 0.1 – Cordelia fault

C: Stop 0.2 (Optional) – Growth fault

D: Stop 0.3 – Donner Summit overview

E: Donner Memorial Campground, campsites 92, 94, 96

Continue on to Donner Memorial State Park Campground

Stop 0.1 - Cordelia Fault (Stop 29 of Moores et al., 2006)

Significance: *(Moores et al., 2006)*

This is perhaps the best exposed San Andreas–related fault zone in northern California.

Directions:

Depart from Stanford University
Turn **L** onto Palm Drive (0.7 mi)
Continue onto University Avenue (0.7 mi)
Turn **L** onto Middlefield Road (0.5 mi)
Turn **R** onto Willow Road (2.0 mi)
Turn **R** onto CA-84 E/Bayfront Expressway (8.3 mi)
Continue onto Decoto Road (0.3 mi)
Exit onto I-880N towards Oakland (25.7 mi)
Merge onto I-80 E (31.7 mi)

We cross Carquinez Bridge / Carquinez Strait, site of the former tectonic dam that allowed Lake Clyde to fill the Great Valley in the Pleistocene: 800 km north to south and ≥300 m deep. About 650,000 years ago Lake Clyde overtopped its sill, rapidly incised its outlet, and drained into San Francisco Bay, creating Carquinez Strait.

Take exit 41 and turn **L** onto Suisun Valley Road/Pittman Road (0.3 mi)
Turn **L** onto Rockville Road (1.0 mi)
Stop on right side of the road and walk to road cut (Total: 72.9 mi; ~1.5 hours)

GPS Coordinates:

38°15.196′N, 122°08.145′W

Stop Description: *(Moores et al., 2006)*

This is one of the easternmost dextral faults in the San Andreas fault system at this latitude. Some workers consider it a branch of the Green Valley fault. Here the vertical fault zone cuts Sonoma volcanics (1–6 Ma) (related to northward motion of the Mendocino Triple Junction) and exhibits a zone of ground-up rock (gouge) about a meter wide. On some fault surfaces we can see subhorizontal scratches and linear marks, known as slickensides, consistent with the strike-slip movement on the fault. This fault has been active in the late Quaternary (past 100,000 yr), and the southernmost part of the fault displays evidence of movement within the Holocene (past 10,000 yr) (Jennings, 1994). The last significant earthquake on the Green Valley Fault was the Concord 10/24/1954 magnitude 5.4 that killed one person.

Stop 0.2 (Optional) – Active folding and growth faulting (stop 8 of Moores et al., 2006)

Significance: *(Moores et al., 2006)*

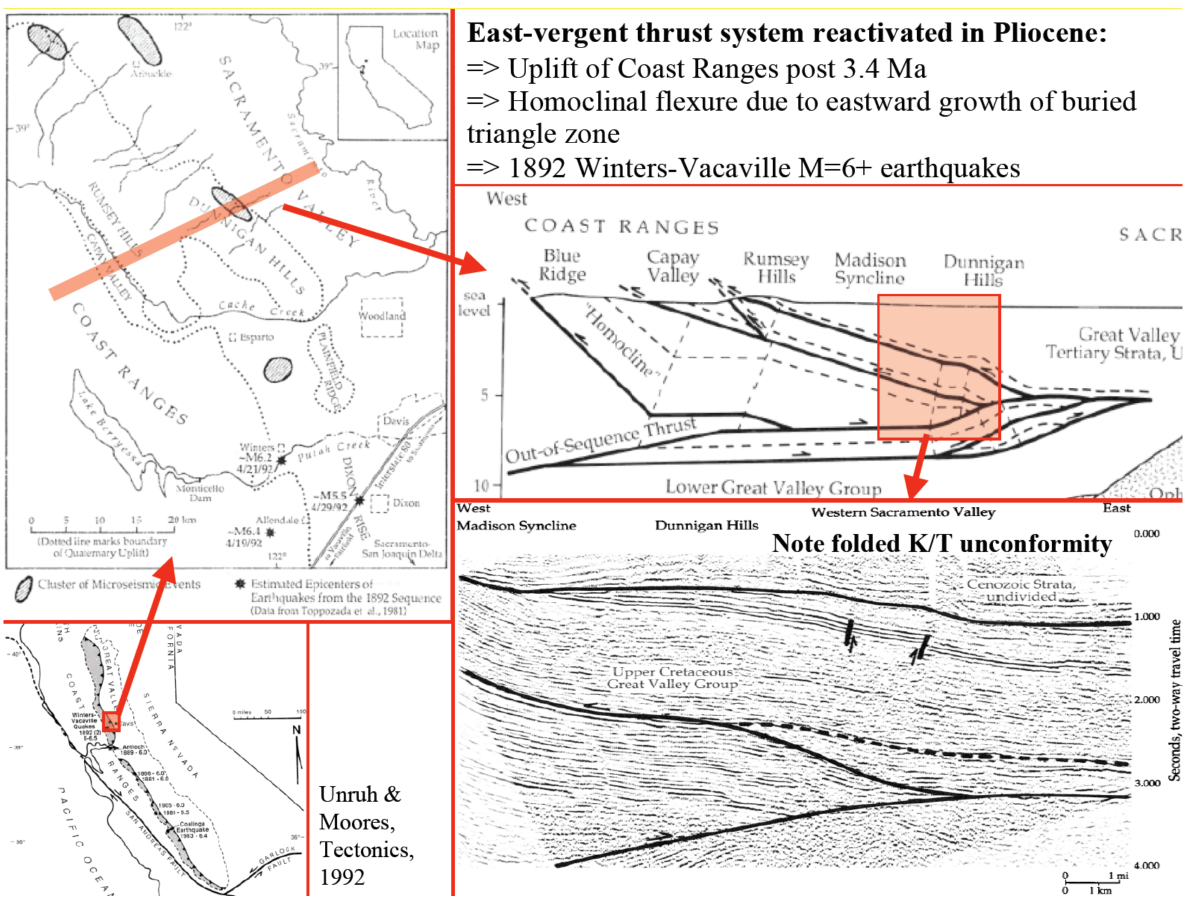
An example of the active folding that occurs along the western side of the Great Valley (the western margin of the Sierra microplate). The Great Valley is underlain by a thick sequence of oceanic crust and mantle, which in turn lies on the western margin of the continent. This dense slab of probably exotic material may account for the low-lying level of the valley, in contrast to the rapidly uplifting Coast Ranges and Sierra Nevada to the west and east, respectively.

Directions:
Depart from Stop 1.1 heading back towards I-80 (2.8 mi)
Turn **R** onto Abernathy Road (0.2 mi)
Turn **L** to stay on Abernathy Road (0.3 mi)
Turn **L** to merge onto I-80 E (11.8 mi)

California Coast Ranges; hills are on both sides of the road. Roadcuts in those hills expose Tertiary (65–1.8 Ma) clastic sediments. We continue through and past Lagoon Valley. Lagoon Valley is a tectonically ponded valley formed as a result of Quaternary (<1.8 Ma) faulting and/or folding in a region of folded Cretaceous (146–66 Ma) sandstones and shales of the Great Valley Group. Stratigraphic layering in the bedrock is evident as the grass dries in the spring (the grasses are Mediterranean invasive species, not California natives).

Take exit 56 for I-505 N/Orange Drive toward Winters/Redding/Nut Tree Road (0.7 mi)
Merge onto I-505 N (10.5 mi)
Take exit 11 for CA-128 W toward Winters/Davis (0.4 mi)
Turn **R** onto County Road 32/Russell Boulevard (6.8 mi)
Turn **L** into the school parking lot at intersection with County Road 96 (Total: 33.4 mi; 44 min)

GPS Coordinates: 38°32.857′N, 121°50.435′W



Stop Description:

This modest hill is a fold – Dixon Ridge - that resulted from movement on an active buried thrust faultthat underlies the western part of the Great Valley (Unruh and Moores, 1992). It represents part of the compressional structures along the western margin of the Sierra Nevada microplate. The east-vergent Coast Range Thrust system was reactivated in Pliocene, leading to uplift of the Coast Ranges post 3.4 Ma, homoclinal flexure due to eastward growth of a buried triangle zone, and occasional significant earthquakes (locally, the 1892 Winters-Vacaville M=6+; further south Coalinga 1983 M 6.4 caused 0.5m uplift with no surface faulting).

Stop 0.3 – Brief stop at Donner summit overview

Significance:

Gorgeous views if we arrive in daylight! See Stop 1.1 for geologic details.

Directions:

Depart Stop 0.2 heading west on County Road 32 (3.8mi)
Turn **R** to merge onto CA-113 S (1.0 mi)
Take exist 26B to merge onto I-80 E toward Sacramento (104 mi)
Take exit 174 toward Soda Springs/Norden ((0.2 mi)
Turn **L** onto Donner Pass Road (0.1 mi) (Total: 109 mi; ~2 hours)

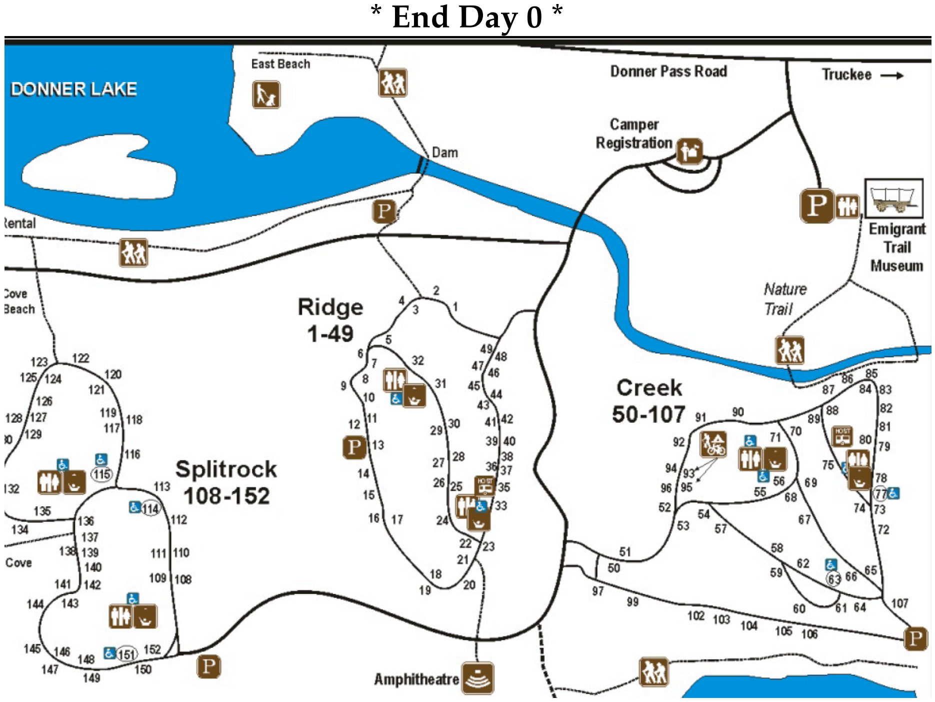
GPS Coordinates: 39°19.561′N, 120°23.593′W.

Continue to Donner Memorial State Park Campground. Dinner, campfire, and camping.

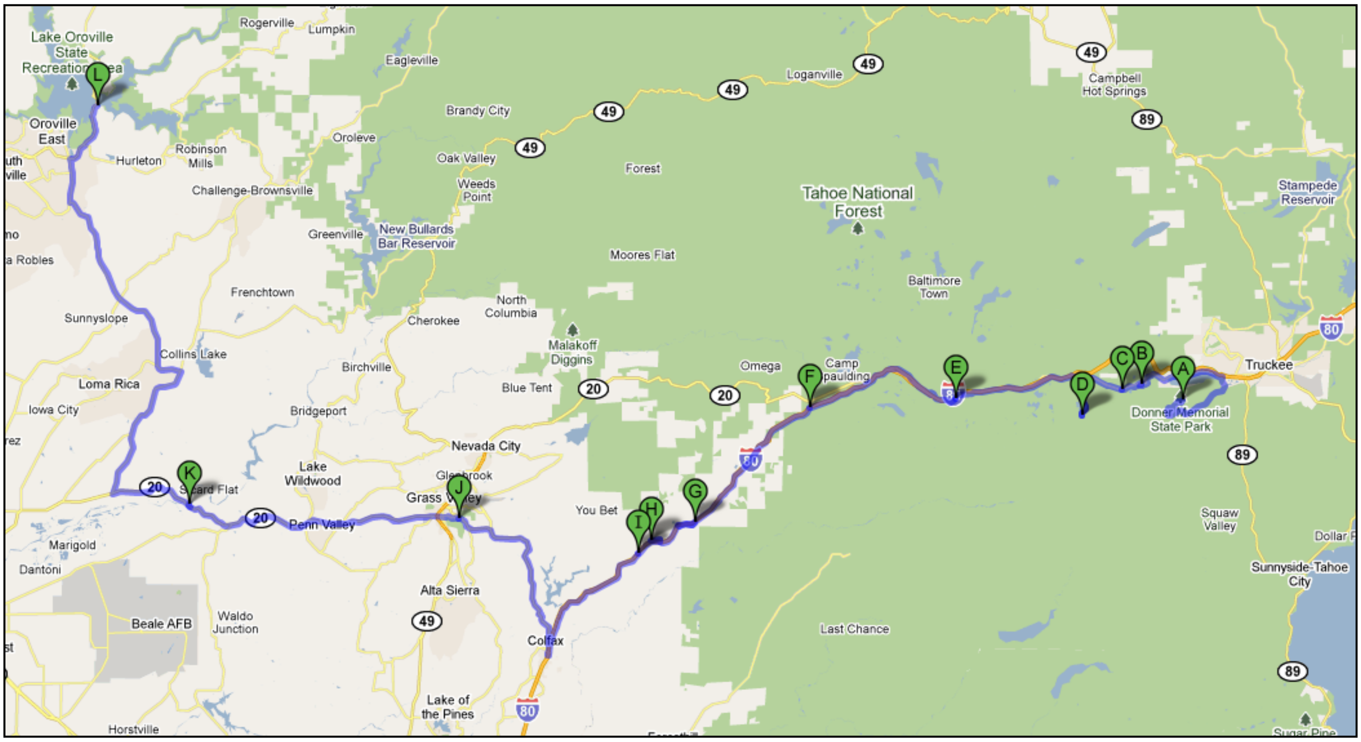
Directions:

Merge onto I-80 E towards Reno (9.9 mi)
Take exit 184 for Donner Pass Road (0.1 mi)
Slight **L** onto Cold Stream Road (4.3 mi)
Enter Donner Memorial State Park (Total: 17 mi; 34 min)

*** End Day 0 ***



Day 1: Sierran batholith and accreted terranes



A: Start – Donner Memorial State Park

B: Stop 1.1 – Magma Mingling & Batholith Geology (Donner Lake Overlook)

C: Stop 1.2 – Miocene Volcanics & Debris Avalanche

D: Stop 1.3 – Oligocene Ignimbrites

E: Stop 1.4 – Shoo Fly Metamorphic Complex

F: Stop 1.5 – Emigrant Gap: Paleovalleys and Paleorelief

G: Stop 1.6 – Melones Serpentinized Fault Zone

H: Stop 1.7 – Eocene auriferous gravels and hydraulic mining

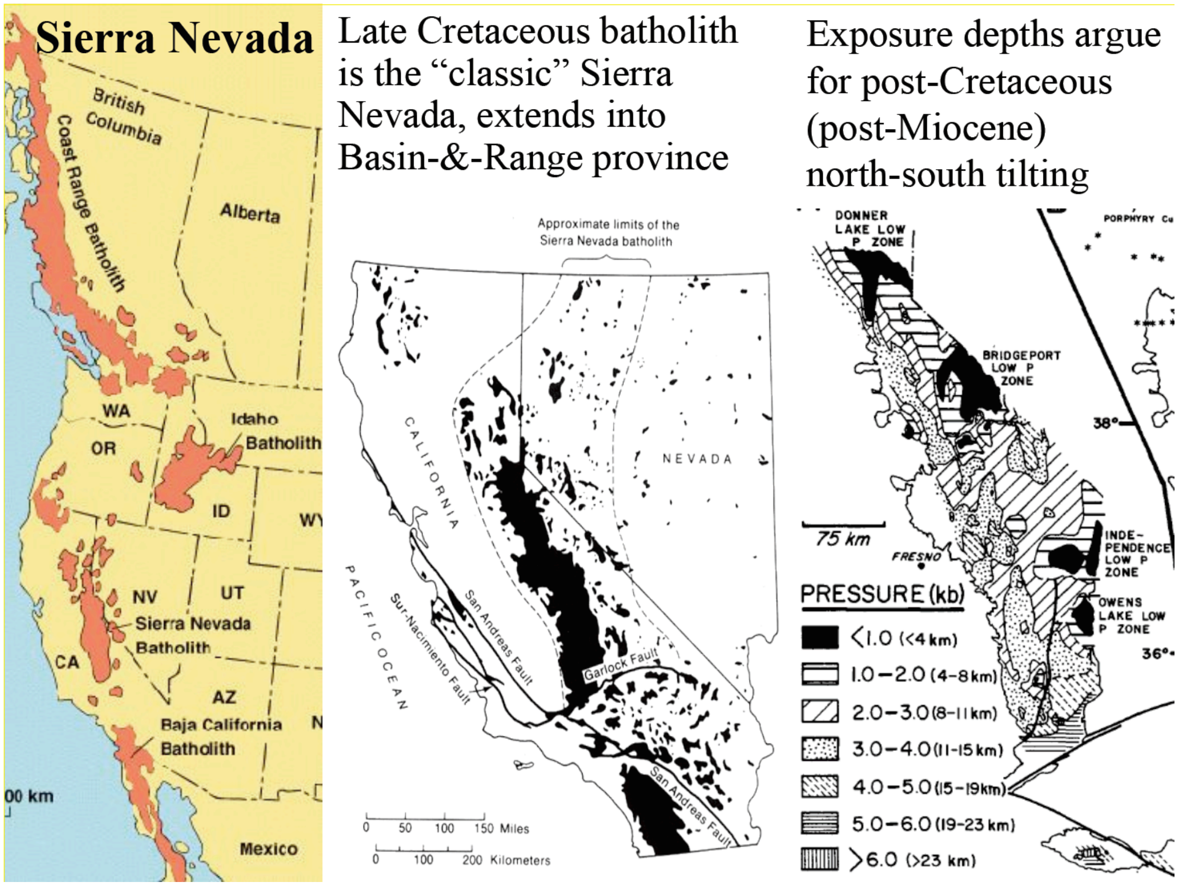
I: Stop 1.8 – Gold Run: Eocene auriferous gravels and hydraulic mining

J: Optional Stop – Empire State Mine in Grass Valley

K: Stop 1.9 – Smartville Complex Pillow Basalts

L: Stop 1.10 – Sheeted Dikes and Pillows, Lake Oroville Campground

Return to Lake Oroville Campground, Group Site GGRE (in the Loafer Creek loop--southeasternmost of the 3 camping areas)



Stop 1.1 - Magma Mingling & Batholith Geology (Donner Lake overview; Stop #2 of Ingersoll et al., 1981; Stop #23 of Moores et al., 2006)

Significance: *(from Moores et al., 2006)*

This site displays a good exposure of the younger granitic rocks of the Sierra Nevada, as well as a view eastward into the Basin and Range Province, the eastern boundary of the Sierran Microplate, and the location of the dramatic story of the Donner Party (1846). (*Donner Pass had only first been traversed in 1844 but already by 1869 completion of the transcontinental railroad removed the challenge.)*

The western boundary of the Basin and Range province consists of one or more major east-dipping normal faults that create the impressive topographic escarpment along the eastern front of the Sierra Nevada. This topographic escarpment is in part a function of this faulting and the westward tilting of the Sierra Nevada block, and in part related to the fact that the thickness of the crust changes from ~40 km beneath the Sierra Nevada to 28-30 km beneath the Basin and Range province.

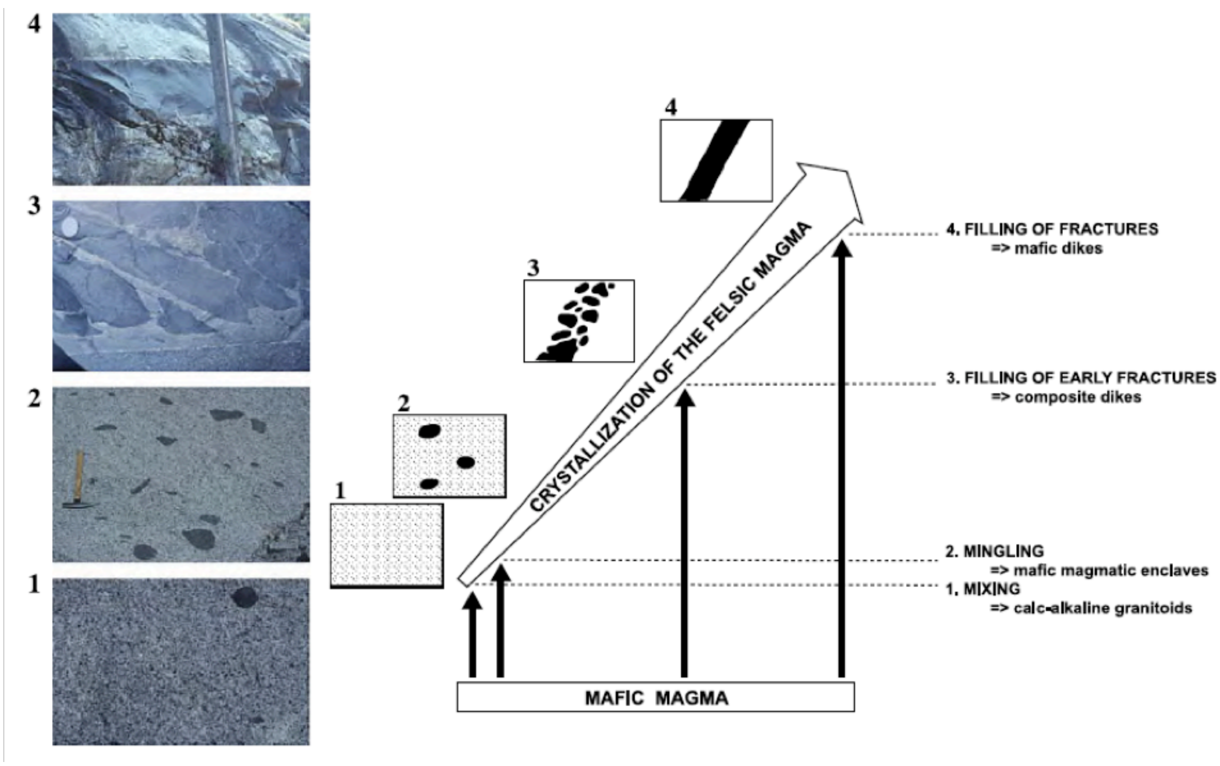
Donner Lake is a typical glacially formed lake. It was carved out approximately 12-16,000 years ago during the Tioga glaciation. The terminal moraine of the former glacier forms a dam of sorts at the lake's east end.

Directions:
Depart from Donner Memorial State Park
Turn **L** onto **Cold Stream Road** (1.2 mi)
Turn **L** to stay on **Cold Stream Road** (3.0 mi)
Turn **L** to stay on **Cold Stream Road** (0.5 mi)
Turn **R** onto **South Shore Drive** (456 ft)
Turn **L** onto **Donner Pass Road** (5.9 mi)
Destination (Donner Lake Overlook) on **R**
(Total: 13.9 mi; ~35 min)

GPS Coordinates:
39°19'7.50"N, 120°19'8.42"W

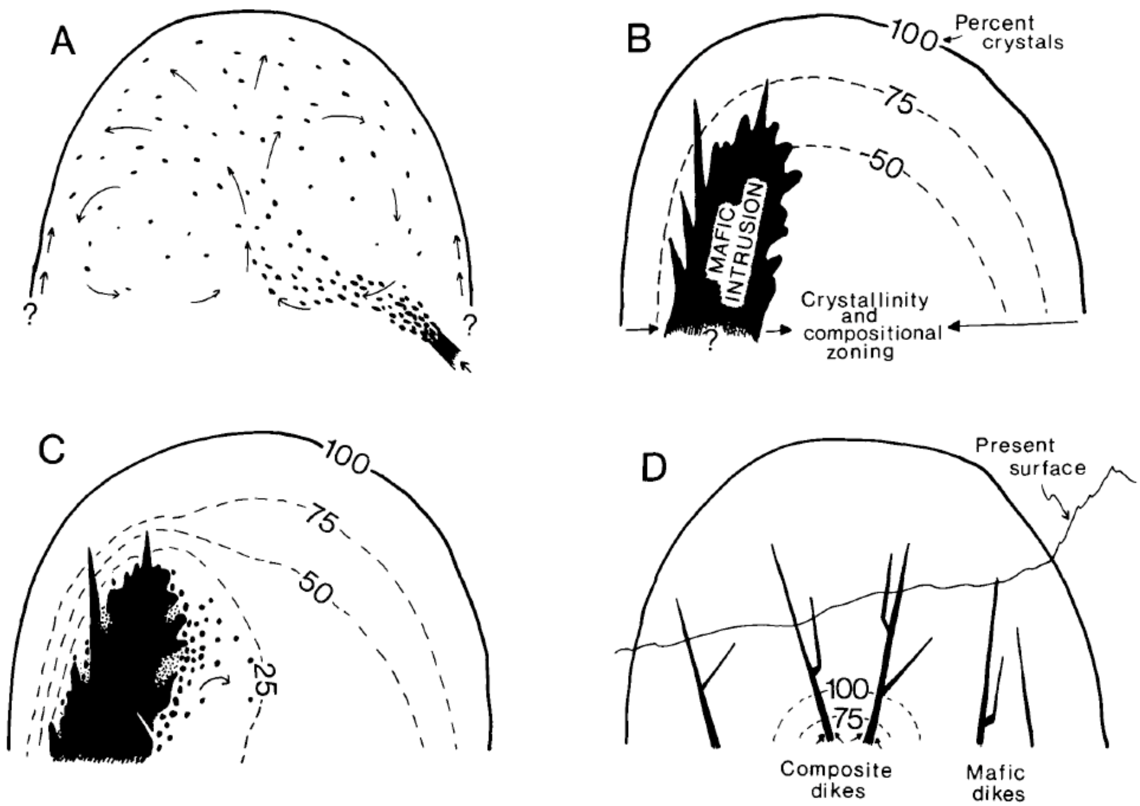
Stop Description: *(modified from Ingersoll et al., 1984; Moores et al., 2006)*

Clamber around the turn-out to find good exposures of the Cretaceous Donner Summit pluton that has yielded a K-Ar biotite age of 97 Ma (Everden and Kistler, 1970). This is a favorite stop to look at relations bearing on the origin of mafic enclaves that are so common in many of the plutons of the Sierra Nevada. The outcrop contains large masses of enclave-rich granodiorite intruded or surrounded by a more enclave-poor granodiorite.



Origin of mafic magmatic enclaves: Sketch showing the various types of hybridization processes resulting from injection of mafic magma into a felsic magma at different stages of crystallization of the felsic magma, illustrated with cases from the Dinkey Creek pluton (Barbarin, 2005)

Enclaves are diorite porphyry with phenocrysts of hornblende and plagioclase and some finer-grained dioritic rocks. Many different origins have been proposed for these mafic inclusions. These include (1) the possibility that the enclaves represent fragments of mafic dikes, disseminated and incorporated into the granodiorite before it had completely solidified, (2) possibly pieces of slightly more mafic, previously crystallized magma entrained and carried upward within the ascending magma, and (3) that they represent blobs of co-existing but immiscible magma. At this stop all rock types are cut by more felsic, aplitic dikes.



Mafic-felsic magma interaction: Vertical section cartoons showing types of magma interaction throughout crystallization of Lamarck Granodiorite. (A) Enclave formation by mingling of small amounts of high-alumina basalt magma with granodiorite magma early in its crystallization. Mechanism shown is highly speculative. (B) Intrusion of mafic magma across compositionally zoned, partially crystallized pluton that contains early, widely distributed mafic enclaves (not shown). Crystallinity of host decreases toward core due to heat loss to margins and roof as well as decrease in liquidus of magma due to compositional zonation. (C) Differing styles of interaction around margin of intrusion depending upon each magma's initial composition, temperature, crystal and water content, and volume over which they interact. Partial hybridization dominates where initial compositional and crystallinity contrasts are small and local mass fraction of mafic magma is large. Quenching of mafic intrusion with incorporation of newly formed enclaves in the host dominates where compositional and crystallinity contrasts are initially high (although melting of felsic host occurs adjacent to intrusion). Reintrusion of mafic rock by remobilized granodiorite occurs locally. (D) Late mafic dikes intrude nearly solidified felsic pluton, remobilizing and incorporating intersitial magma of granite-minimum composition near core of pluton (Frost and Mahood, 1987).

The emplacement of the Sierra Nevada batholith was a consequence of magmatic activity associated with east-dipping Franciscan subduction. In this area, the granitic rocks are discordantly (unconformably) overlain by Oligocene rhyolites of the Valley Springs Formation that are in turn overlain by Miocene Mehrten Formation andesites. Eocene auriferous gravels locally underlie Valley Springs and Mehrten rocks in other areas of the Sierra, including near the crest. Collectively these relationships suggest negligible stream incision from Eocene to Miocene time in the Sierra. Had the stream incision been significant, the older deposits would cap higher elevations than the younger ones (because the younger ones would fill channels cut into the bedrock below the older ones). Significant channel cutting (incision) is present within volcanic deposits of the Sierra Nevada. Some channels are eroded through basement rocks, but successively younger channels do not cut below the level of previous volcanic deposits (Bateman and Wahrhaftig, 1966; Huber, 1990; Rood et al. 2004). However, the later fact suggests that the incision is a consequence of clogging of drainages by eruption of volcanic rocks rather than being caused by uplift or climate change (Huber, 1990).

The faulting along the eastern margin of the Sierra migrated westward in Recent geologic time (Henry and Perkins, 2001). Some faulting actually took place in the Sierran crestal region before 10 Ma (Rood et al. 2004). This faulting must not have resulted in rock and surface uplift until sometime after ca. 5 Ma, because no stream incision resulted until then (Wakabayashi and Sawyer, 2001). The earlier Basin and Range faulting simply downdropped blocks to the east relative to sea level without uplifting the footwalls of the normal faults. Faulting of the Sierra produced footwall uplift.

From Schweikert, R.A., 2009:

Criteria for recognition of beheaded rivers

Some of the most important characteristics of the west-flowing Sierran rivers are their wide, deep canyons with relatively gentle gradients. These contrast with streams east of the crest which are characterized by short, steep canyons with vigorous erosion in their headwaters. A beheaded west-flowing drainage should therefore show a number of the following characteristics:

(1) broad U or V-shaped cross section at the range crest;
(2) deep, wide valley/canyon near range crest;
(3) underfit stream within wide canyon;
(4) low, nearly flat drainage divide;
(5) unusually low stream gradient at summit;
(6) major pass at summit is unrelated to incision by east-flowing drainages;
(7) anomalous notches, wind gaps, and water gaps in long, high ridges and
(8) contrasts in scale of canyon with neighbouring drainages.

South Yuba River drainage and Donner Pass

The South Yuba has a variety of anomalous features that suggest that it was beheaded by normal faults along and near the Sierra crest (Tahoe-Sierra Fronatl Fault Zone). The river has a smooth, gentle gradient (~30 m/km) as far east as Soda Springs, at which point it branches upstream into two broad, open valleys that extend eastwards to the Sierra crest. Boreal Ridge and Beacon Peak occupy parts of the drainage divide between the two branches. The south branch extends upstream through Summit Valley, a 1 km-wide, flat valley (21 m/km) in which the South Yuba is an underfit stream originating at Donner Pass (elevation 2151 m). The north branch runs through a smaller valley, Uhlen Valley, which is about 0.5 km wide, has a gentle gradient (32 m/km), and ends at Euer Saddle (elevation

2190 m). Castle Creek is an underfit stream within this valley. Immediately east of Donner Pass and Euer Saddle are several branches of the TSFFZ which abruptly truncate both branches of the South Yuba. Steep, east flowing glaciated creeks originate east of Euer Saddle and Donner Pass, respectively, and drain into Donner Lake. The combination of broad, open, nearly flat-bottomed valleys of the South Yuba as it originates at the modern

From Schweikert, R.A., 2009, Beheaded west-flowing drainages in the Lake Tahoe region, northern Sierra Nevada: implications for timing and rates of normal faulting, landscape evolution and mechanism of Sierran uplift, International Geology Review, 51, 994–1033.

crest makes a strong case for tectonic beheading of this west-flowing drainage, and former headwaters in areas now east of the present Sierra crest. If the beheaded South Yuba drainage was initiated around 3 Ma like the other westflowing rivers in the Lake Tahoe region, relations at Donner Pass provide strong evidence against significant normal faulting in that area at 12 Ma, an interpretation by Henry and Perkins (2001). Evidence presented here indicates that deformation of Martis Valley and beheading of the South Yuba drainage must be largely post-3 Ma.

Stop 1.2 – Miocene Volcanics & Debris Avalanche (Schweickert & Graham, 1981)

Significance:

This is a brief stop to familiarize ourselves with the types of andesitic volcanic and volcaniclastic rocks that occur along and near our route.

Directions:

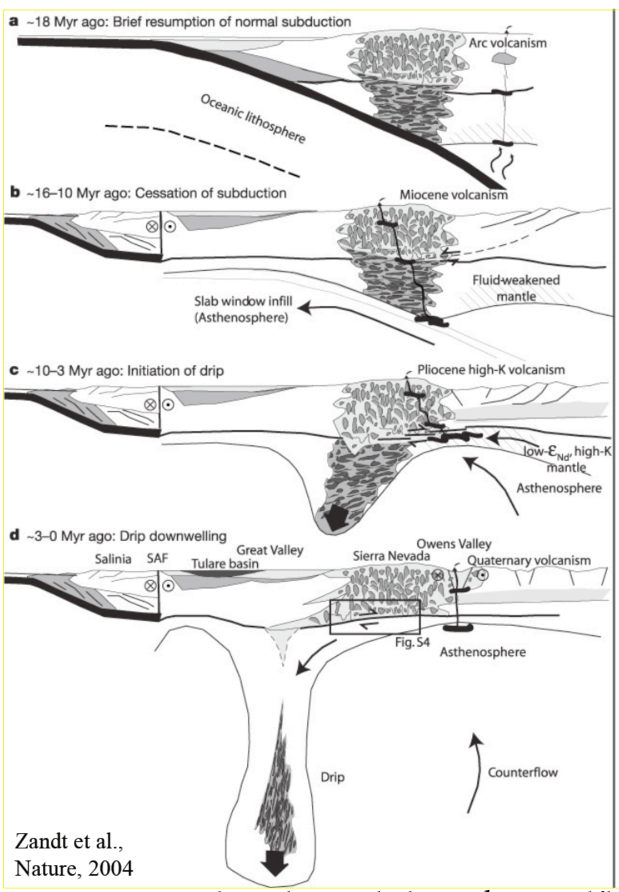
Depart from Stop 1.1
Continue **W** on **Donner Pass Road** (1.4 mi)
Destination (freeway pull-off) on **R**. (Total: 1.5 mi; ~5 min)

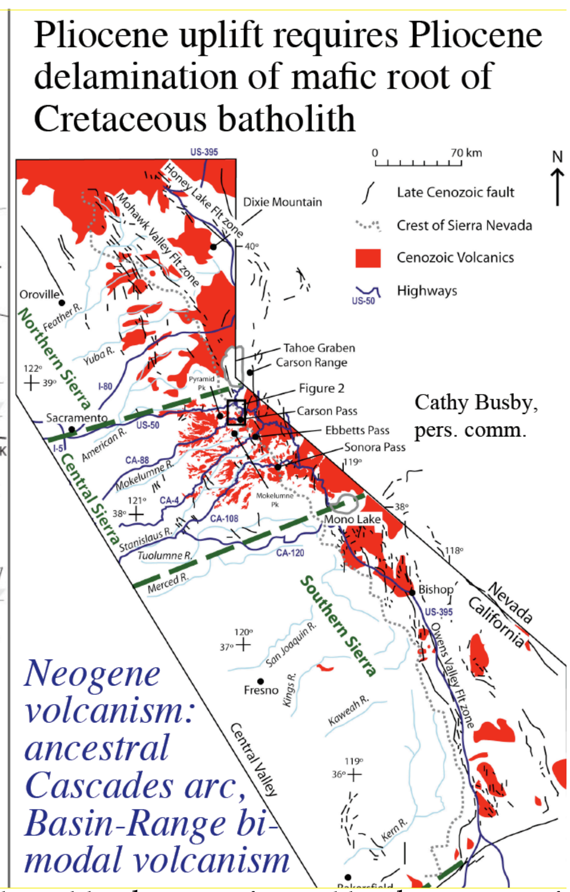
GPS Coordinates:

39°18'50.34"N, 120°20'22.69"W

Stop Description: *(modified from Schweickert and Graham, 1981)*

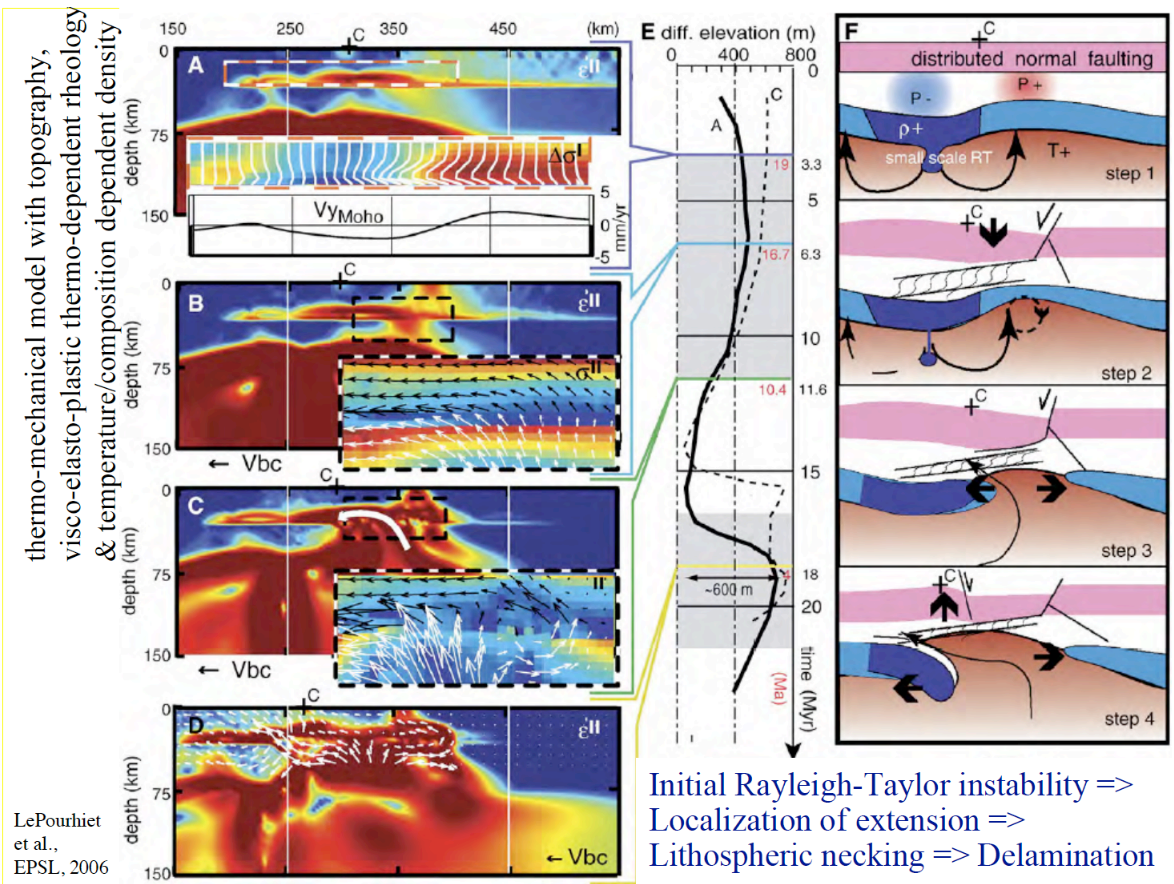
These rocks are regarded as part of the upper Miocene Kate Peak Formation by Birkeland (1966). The rocks are andesitic mudflow breccias, or lahars, which here are distinctly stratified. Clasts are primarily plagioclase- and hornblende-andesites with some reddish, oxidized scoriaceous material.





Many volcanologists believe that mudflows like these are formed by the mixing of water from rivers, lakes, and melting ice and snow with hot pyroclastic flows or with debris avalanching off the flanks of andesitic stratovolcanoes. Subsequent downhill transport of the mud/debris flows may result in stratification and internal sedimentary features including slurry flow-like structures and inverse grading.

Although the above hypothesis may account for the origin of most laharic mudflow breccias, some intrusive pipes and dikes of similar appearance clearly require an alternative explanation. According to Durrell (1966), such bodies probably result from brecciation related to eruption and escape of volatiles, which alters fragments to clay and forms a muddy matrix.



Stop 1.3 – Oligocene Ignimbrites

Significance:

This stop displays typical Oligocene ignimbrites that flowed westward across the Sierra Nevada from an eruptive centers in central Nevada, funneled along paleovalleys incised into the ancestral Sierran complex by Eocene river systems. Hence during the Oligocene the region of the modern Sierra Nevada included valleys lower than the region of the modern Basin-&-Range province (though both may already have been at high elevation – the "Nevadaplano" hypothesis).

Directions:

Depart Stop 1.2.

Continue **W** on **Donner Pass Road** (2.3 mi)

Turn **L** on **Soda Springs Road** (2.3 mi)
Destination (road cut) will be on **R**.

GPS Coordinates:
39°18.50′N, 120°20.22′W

Stop Description:

The timing and mechanism of uplift of the Sierra Nevada remains controversial. A sequence of Oligocene ignimbrites is preserved along the western slopes of the Sierra, extending eastward across the range into western Nevada. These ignimbrites preserve isotopic compositions of meteoric waters incorporated soon after emplacement, which indicate how paleotopography may have influenced precipitation (Cassel et al., 2009).

Oligocene rhyolitic ignimbrites, tuffaceous paleosol horizons, and volcaniclastic fluvial sandstones overlie Eocene gold-bearing gravels (*see Stop 1.7, this volume)* in westward-oriented paleovalley tracts (Cassel et al., 2009). Ignimbrites traveled from their source calderas in central Nevada across what is now the crest of the range, indicating that the Oligocene drainage divide must have been much farther east than it is today (Cassel et al., 2009). Volcanic glass samples analyzed from these volcaniclastic strata indicate that the northern Sierra Nevada was an area of high topography in the Oligocene, comparable to that of today (Cassel et al., 2009). These results are also comparable with similar studies of Eocene (Mulch et al., 2006) and Miocene (e.g., Chamberlain and Poage, 2000; Crowley et al., 2008; Mulch et al., 2008) strata, suggesting that the Sierra constituted a significant paleotopographic high throughout Cenozoic time (Cassel et al., 2009).

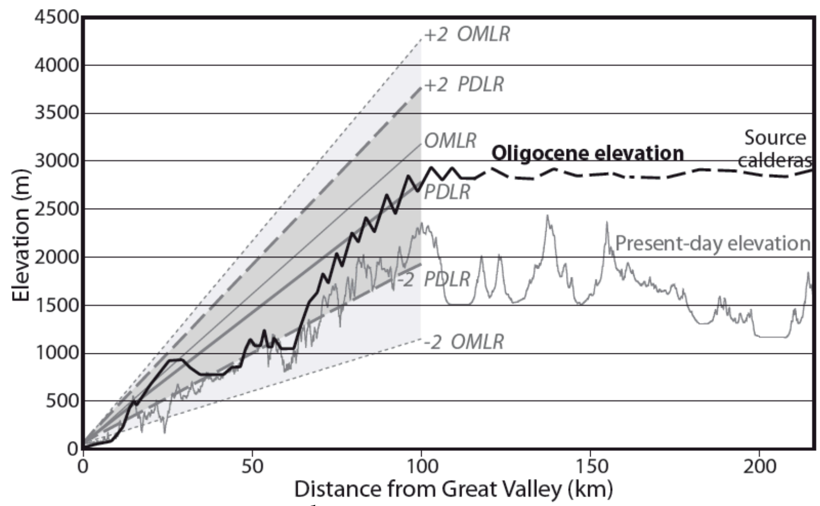


Figure 1.1: Topographic profile comparison of present-day and Oligocene elevations along the Yuba River drainage based on stable isotope paleoaltimetry (Cassel et al., 2009).

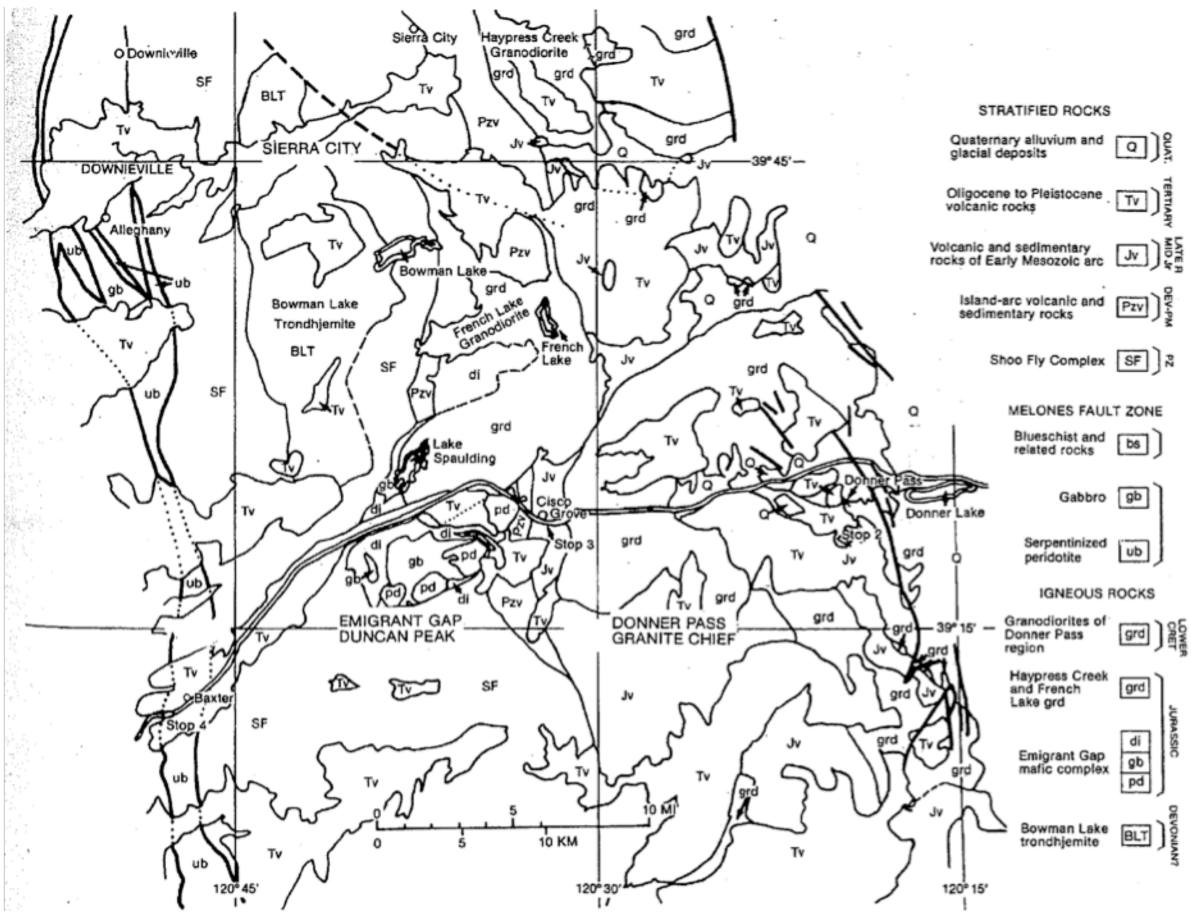
Stop 1.4A – Contact: Sierra Nevada batholith and metamorphosed Jurassic volcanics

(Stop #24 of Moores et al., 2006; see also Schweikert & Graham stop 3)

Significance and Description: *(from Moores et al., 2006, and Schweikert & Graham, 1981)*

This is an exemplary exposure of a contact between the main portion of the Sierra Nevada batholith and metamorphosed Jurassic volcanic rocks of the Eastern Belt. This is the Lower to Middle Jurasic Sailor Canyon formation, part of a north-trending Andean-type magmatic arc (exposed in roof pendants as far east as Reno) that was isoclinally folded during the Nevadan orogeny, prior to the emplacement of the Sierra Nevada batholith. This arc, together with a Permo-Triassic intra-oceanic arc and the Devonian-Mississippian Sierra Buttes intra-oceanic arc, discordantly overlies the lower-Paleozoic Shoo Fly Complex (Stop 1.4B).

The metavolcanics are rich in metal sulphides that stain cliff faces with striking colors. Stream-polished exposures show thinly-laminated, graded silicified ash fall tuffs and mudstones, occasionally with delicate grading and possible slump folds. All rocks have been contact metamorphosed and are now hornfelses. Bedding and cleavage are approximately N003°E / 85°E.



Map of Donner Memorial Park from Schweikert and Graham, 1981; their Figure 5. Their stop 2 =our Stop 1.1; Stop 3 is just west of our Stop 1.4A; Stop 4 is our Stop 1.6

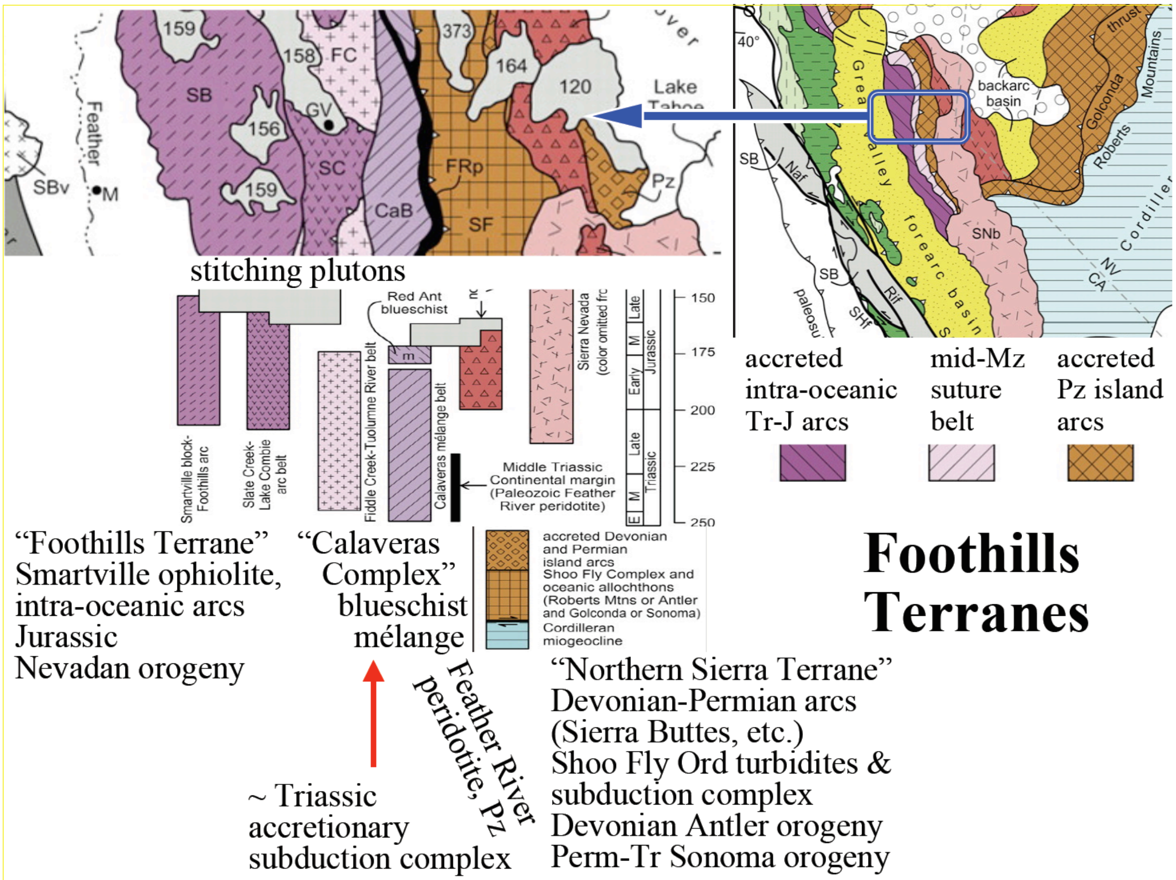
Directions:

Depart Stop 1.3.
Backtrack **N** on **Soda Springs Road** (2.3 mi)
Turn **L** onto **Donner Pass Road** (0.8 mi)
Turn **L** to merge onto **I-80 W** toward Sacramento (5.8 mi)
Take **Exit 168** toward Big Bend/Rainbow Road (0.1 mi)
Turn **L** onto **Lincoln Highway** (0.1 mi)
Take slight **R** onto **Hampshire Rocks Road** (1.1 mi)
Destination (road cut) will be along the road.

GPS Coordinates:

39°18.382′N, 120°31.056′W

(outcrop is "slightly west of the Big Bend Visitor Center" and markers for the old Lincoln Highway, the first continuous automobile road across the United States in 1915)



Stop 1.4B – Contact: Sierra Nevada batholith and Shoo Fly Metamorphic Complex
(Stop #4 of Ingersoll et al., 1984)

Directions:

Continue S/W on **Hampshire Rocks Road** (1.6 mi)

Turn L / S on **Cisco Road** and R/E to merge onto **I-80 W**

(after crossing S. Fork of the Yuba River, we pass through the Emigrant Gap mafic/ultramafic complex, and roadcuts of olivine pyroxenites, probably Jurassic. These are not ophiolites, but appear to be derived from a single gabbroic parent by crustal fractionation, and may represent magma chambers beneath andesitic stratovolcanoes. Along the road this is succeeded by a younger (Upper Jurassic?) biotite-hornblende granodiorite (Schweikert & Graham, 1981).)

Continue 3.7 mi to **exit 161, CA-20 W** toward Nevada City/Grass Valley

After 0.4 mi stay R on CA-20 W

Continue 3.8 mi; at 3.5 mi watch for aqueduct carrying water from Spaulding Lake to Drum powerhouse on Bear River
Turn sharp R /N on **Bowman Lake Road**.
After 0.6 mi cross Bear River on a narrow bridge; after 0.4 mi cross ditch and park on left.

GPS Coordinates:
39°18'22.92"N, 120°31'3.36"W

Stop Description: *(modified from Ingersoll et al., 1984)*
Walk north onto the glaciated exposures to view lithologic and structural features of the Lower Paleozoic Shoo Fly complex. These are among the oldest rocks of the Sierra Nevada region (lower Paleozoic), and form the basement to the Eastern Belt of the Foothills Terranes. No fossils have come from these metasedimentary rocks, but they predate the 370 Ma Bowman Lake batholith, which forms the light-colored outcrops in the canyon of the South Yuba River to the north of here. Sparse remains of recrystallized radiolarians suggest that these rocks are Cambrian or younger. Elsewhere the Shoo Fly contains fault-bounded slices of quartz-rich turbidites, mafic volcanics, slivers of serpentinite, and a mélange containing blocks of chert and Ordovican limestone.

These outcrops are part of the structurally lowest part of the Shoo Fly Complex, here called the Lang sequence. They consist of highly deformed quartzite and schist cut by foliated dikes of white, fine-grained, quartz porphyry and dikes of coarse plagioclase porphyry. The quartz-bearing dikes are probably related to the Bowman Lake batholith, and indicate that strong deformation here postdates the batholith; the plagioclase porphyry dikes are probably Jurassic, so the deformation may have been late Jurassic. However, the metasedimentary rocks also contain penetrative structures that predate the dikes, indicating a complicated structural history. Intrafolial isoclinal folds within the foliation have axial surfaces oriented N20°E, 89°NW. Note also that the darker rocks contain andalusite spots formed as contact metamorphic minerals by intrusion of the Emigrant Gap pluton.

The Shoo Fly, with its pre-late Devonian structures, forms the basement of a major Paleozoic island arc that may have been accreted to North America in early Triassic time. Its origin and affinity prior to the early Triassic are still enigmatic.

Note excellent glacial striations on the surface and erratics of diorite.

Stop 1.5 – Emigrant Gap: Paleovalleys and paleorelief (Stop #25 of Moores et al., 2006)

Significance: *(modified from Moores et al., 2006)*
This site provides a good example of paleorelief of Sierra Nevada paleogeography that existed during deposition of the most recent volcanic rocks in the area (the 5 Ma Mehrten Formation).

Directions:
Depart Stop 1.4B
Return S on **Bowman Lake Road** (1.0 mi)
Turn **L/E** onto **CA-20 E** (0.4 mi)
Turn **R/SW** on **Bear Valley Road** (1.2 mi)

Turn **R** to merge onto **I-80 W** (0.6 mi)
Take exit for **highway pull-off/rest area** before Emigrant Gap exit.
Destination will be on the **N** side of the parking area.

GPS Coordinates:
39°17'57.48"N, 120°40'22.32"W

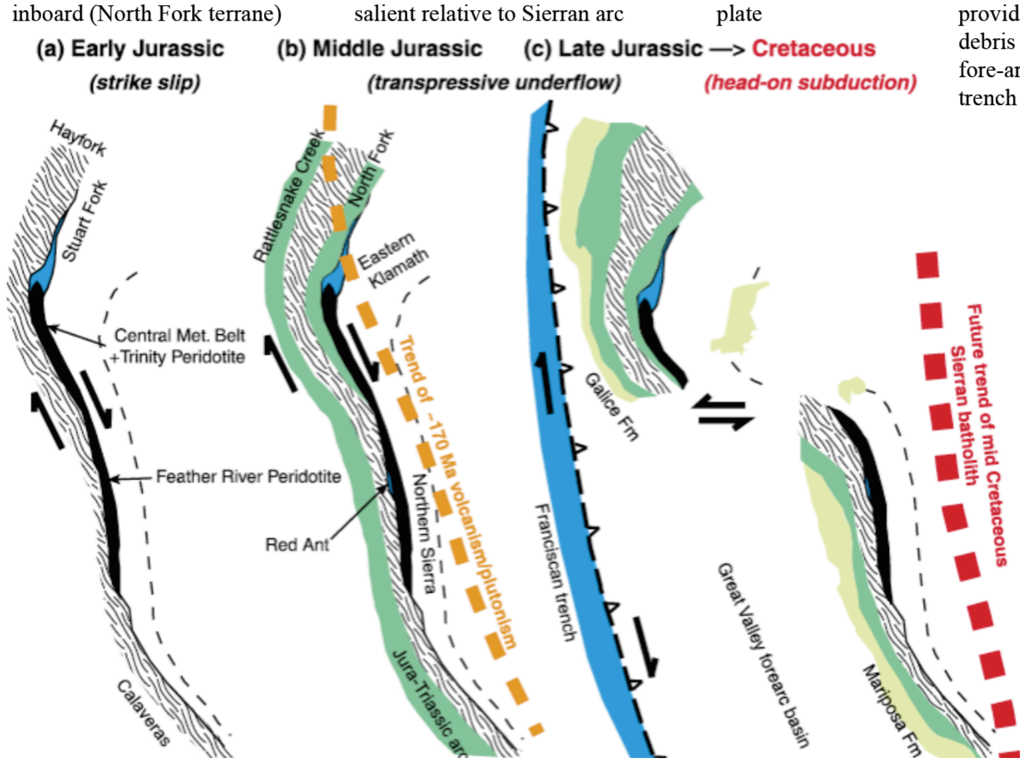
Stop Description: *(from Moores et al., 2006)*
From this stop, we look northward into and across the Yuba River drainage. The western part of the vista is dominated by a gently sloping ridge top that is capped by late Miocene Mehrten Formation andesites. The gentle westward slope shows the post-Miocene tilt of the Sierra Nevada – stop 2.1 will look at the similar tilt of the 15 Ma Lovejoy basalt. Similar volcanic rocks blanketed much of the Sierra north of Sonora Pass, leaving only a few basement highs sticking out above the surface. The youngest volcanic rocks associated with this outpouring are ca. 5 Ma. Thus, the modern-day canyons have been cut since 5 Ma. The canyon depth beneath the Mehrten records incision and relief produced during this time. If we look a bit farther east of this Mehrten-capped ridge, we see that the tilt projects below the tops of some peaks. These peaks are composed of basement rocks, and they are higher than the tops (let alone the bottoms) of the late Cenozoic deposits in the area: at 5 Ma they would have been low hills rising above the volcanic plain. Some of them rise over 600 m above the base of the adjacent late Cenozoic paleochannels. These are examples of the paleorelief in this part of the Sierra.
Emigrant Gap is so named because it was a low gap on a ridge where the emigrants wagons crossed from the American River drainage to the Bear River drainage – despite cliffs so steep that the pioneers had to disassemble and lower their wagon on ropes!

(1) 205–190 Ma dextral(?) suturing of Calaveras; (2) 190–170 Ma oceanic crust produced or inserted outboard ("Smartville") and inboard (North Fork terrane)

(3) 170–150 Ma transpressive plate underflow => calc-alkaline arc ± blueschists; (4) 150–140 Ma 200 km left-lateral motion of Klamath salient relative to Sierran arc

(5) 125–120 Ma nearly orthogonal convergence during reversal in tangential motion of the Pacific plate

(6) after 120 Ma, head-on subduction + minor dextral transpression => voluminous Sierran arc, providing erosional debris to Great Valley fore-arc and Franciscan trench



Ernst, Saleeby, Snow, JGR, 2009

Stop 1.6 – Melones Serpentinized Fault Zone (Stop #4 of Schweickert & Graham, 1981)

Significance:

This site provides a view of oceanic crustal rocks caught up in the Melones fault zone, which possibly mark the zone of early Mesozoic subduction/arc-continent collision.

Directions:

Depart Stop 1.5
Continue **W** on **I-80 W** (10.4 mi)
Take **Exit 146** toward **Alta** (0.2 mi)
Turn **L** onto **Alta Bonnynook Road** (413 ft)
Cross beneath freeway and turn **L/E** onto **Casa Loma Road** (1.0 mi)
Destination (road cut) on **R**

According to Schweikert & Graham: "park just before the SPRR overpass and walk up to RR cuts beneath and north of freeway"

Beware of trains – this is an active railroad

GPS Coordinates:

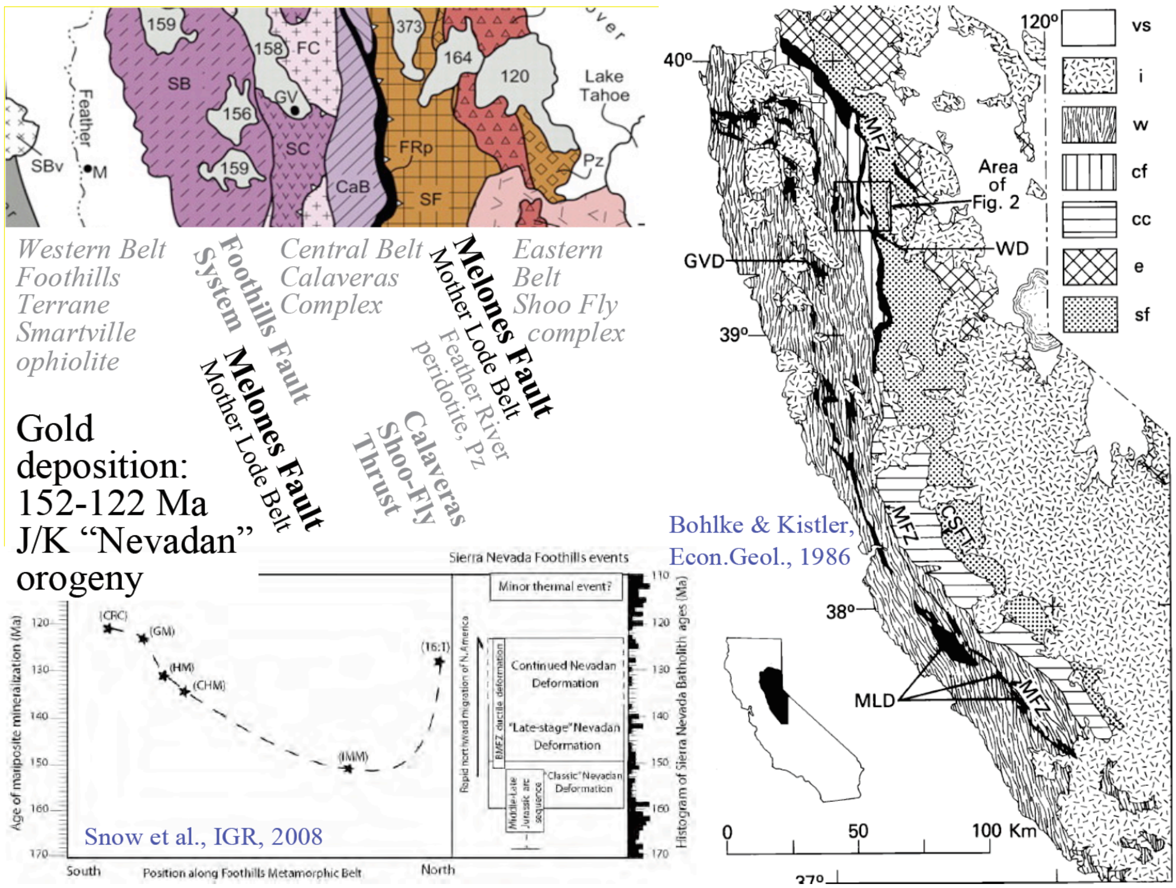
39°12'15.40"N, 120°47'40.29"W

Stop Description: *(modified from Schweickert & Graham, 1981)*

The Melones fault zone likely represents a deep crustal fault, and possibly marks the site of an early Mesozoic subduction zone. Lawsonite blueschists occur with serpentinites and metabasalts on the North Fork Yuba River, 25 miles north of here, and have yielded K/Ar ages suggesting mid-Jurassic or older blueschist metamorphism (Schweickert et al., 1980). The Melones fault zone is currently active and displaces overlying Mio-Pliocene volcanics a few to a few hundred feet, east side down. Magnitude ~5.0 and ~5.5 earthquakes occurred 13 miles north in 1909.

Here we will examine exposures of ultramafic rocks which mark the position of the Melones fault zone. These rocks extend discontinuously 70 miles to the north, before they disappear beneath Pliocene andesites near Lake Almanor. Plagiogranite from the peridotite along the Feather River yielded 275-320 m.y. U-Pb zircon ages (Saleeby and Moores, 1979), suggesting Pennsylvanian-Permian igneous ages. Many people regard these rocks as the basal part of a slice of oceanic crust, which was stripped of its volcanic cover during tectonic emplacement.

The rocks here are massive, serpentinized peridotite (harzburgite?) cut by occasional shear zones. Ave Lallement (1979) suggested structures such as these may be related to the period of formation of the ophiolite. Late Nevadan (?) spaced cleavage and shears oriented N10-20°E and dipping 80°SE locally cut the foliation. There is very little direct evidence here of any fault fabric that could be considered related to the Melones fault zone.



Stop 1.7 – Eocene auriferous gravels and hydraulic mining (Stop #26 of Moores et al., 2006)

Significance: *(modified from Moores et al., 2006)*

This is an excellent location from which to view the evidence of hydraulic mining that occurred between 1860 and 1884 in this area.

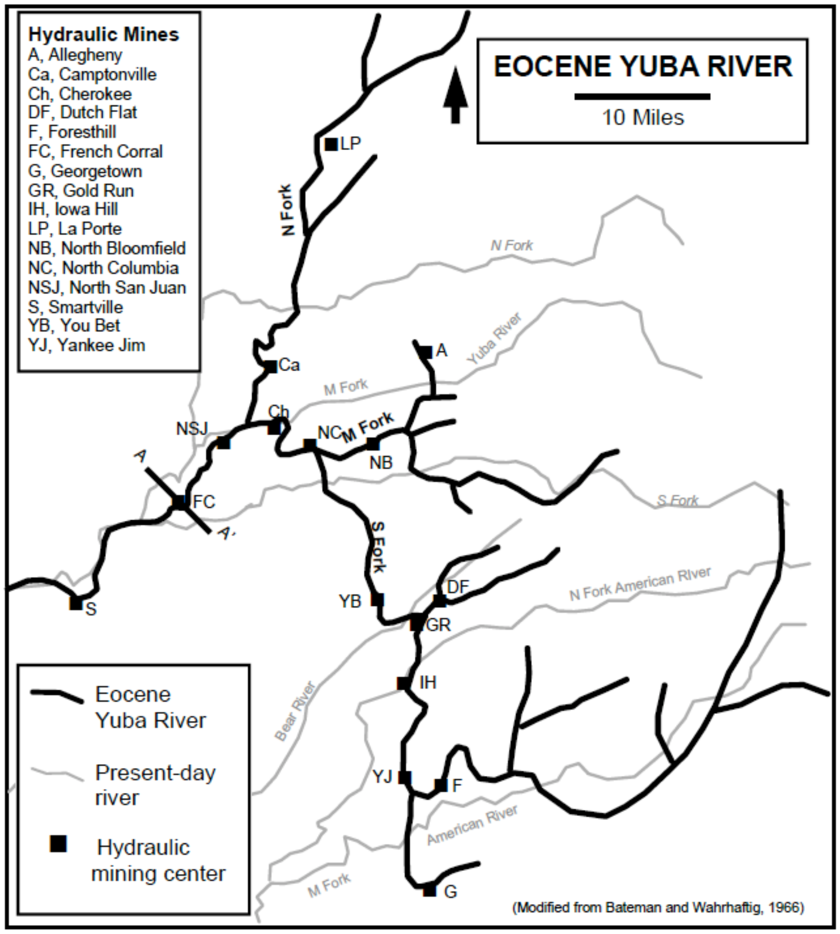
Directions:

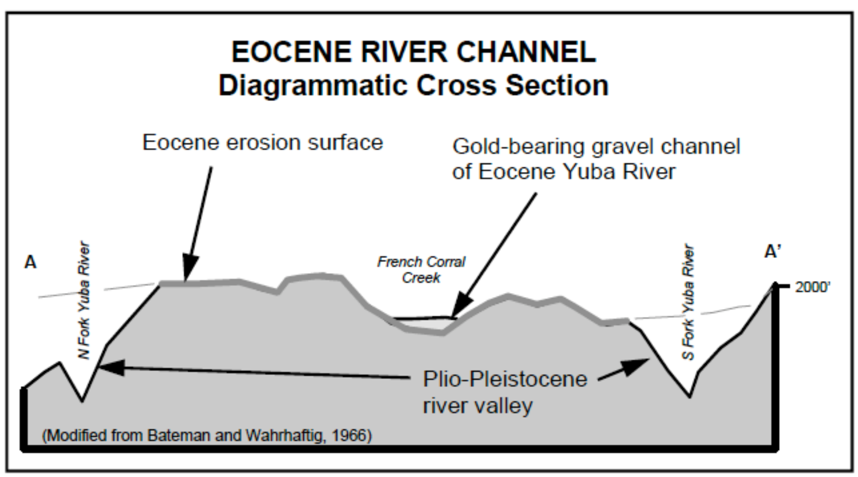
Depart Stop 1.6
Backtrack **W** on **Casa Loma Road** (1.0 mi)
Turn **R** onto **Morton Road** (95 ft)
Continue onto **Alta Bonnynook Road** (318 ft)
Cross beneath freeway and turn **L** to merge onto **I-80W** toward Sacramento (1.4 mi)
Take **Exit 145** toward **Dutch Flat** (0.1 mi)
Turn **R** onto **Ridge Road** (0.1 mi)
Turn **L** onto **Gold Run School Road**. Cross SPRR tracks after 0.2 mi.
Road continues as **Lincoln Road** (0.7 mi)
Stop along the road near the RR tracks.
Beware of trains – this is an active railroad

GPS Coordinates:
39°11'21.33"N, 120°50'28.31"W

Stop Description: *(modified from Moores et al., 2006)*

We are on a ridge formed of auriferous (gold-bearing) gravels, and Eocene (~50 Ma) river deposit that possibly originated in a Tibet-like highland in central Nevada. The deposit has been removed to the north and south. Legend has it that the miners tried to buy the land from the railroad, but the Southern Pacific Railroad Company refused to sell. Thus, only this narrow ridge has been preserved. The scale of hydraulic mining can be estimated by looking at the area that has been denuded. Also, the small pine trees in the mined area attest to the slow rate of landscape recovery following the hydraulic that covers the ground in sterile silt. A legal decision in 1884 banned discharge into the rivers, and largely halted this style of mining.





(Koniesmark, 2002)

Stop 1.8 – Gold Run: Eocene auriferous gravels and hydraulic mining (Stop #5 of Schweickert & Graham, 1981; #27 of Moores et al., 2006)

Significance:

This site displays remnants of Eocene gold-bearing gravels that filled west-trending paleovalleys incised into the Sierra Nevada. These gravels were extensively mined for detrital gold in the late 1800s. Overlying late Miocene (5 Ma) Mehrten andesites are visible in the upper part of the cliff.

Directions:

Depart Stop 1.7
Backtrack **E** on **Gold Run School Road** (0.9 mi)
Turn **R** onto **Ridge Road** (0.1 mi)
Turn **R** to merge onto **I-80 W** toward Sacramento (1.3 mi)
Take the **exit** toward **Rest Area** (0.2 mi)
Turn **R** to Destination (Rest Area). Restrooms available.

GPS Coordinates:

39°10'43.65"N, 120°51'20.14"W

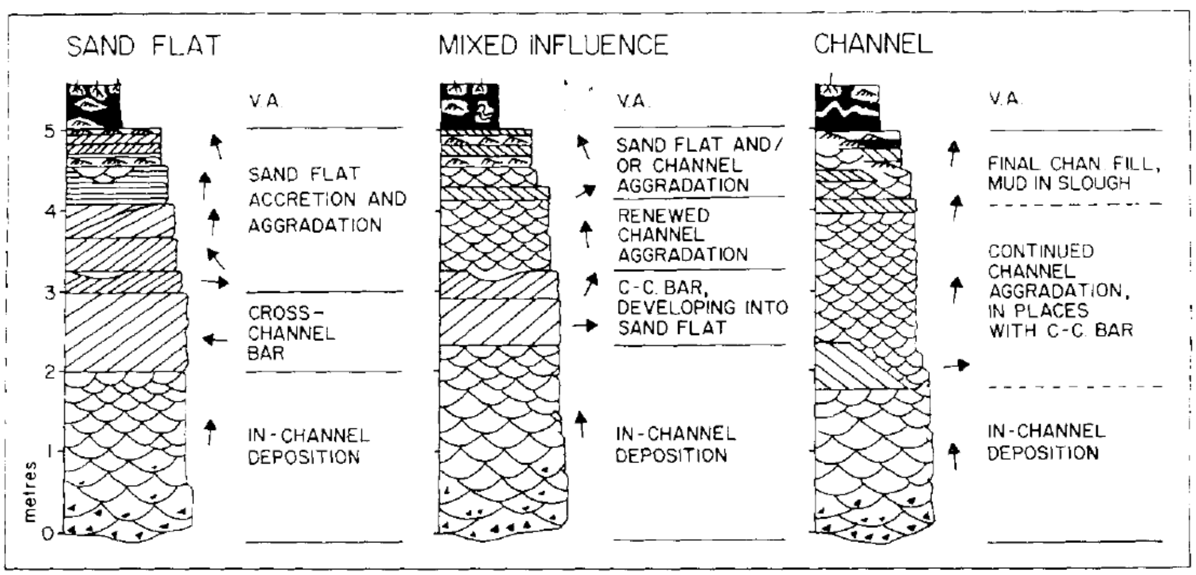


Figure 1.2: Summary stratigraphic successions for areas dominated by sand flat development, channel aggradation, and a mixture of the two in a braided river system (Cant and Walker, 1978). Highly migratory bars and channels result in very complex cut-and-fill features and high degrees of amalgamation.

Stop Description: *(modified from Schweickert & Graham, 1981)*

The cliff faces of weakly indurated gravel are part of the abandoned Indiana Hill hydraulic pit gold mine.

Extensive weathering and erosion stripped upper levels of the northern Sierran arc complex from the late Cretaceous to early Tertiary, during a time of igneous quiescence (a “magmatic null”). An integrated drainage system connected the Sierran region to the westward-located forearc basin during this time, as is reflected by Eocene gravels such as those seen here. Recent renewed incision by the modern Sierran drainage system has exposed Eocene river gravels on the relict erosional surface.

The age of these gravels is not tightly constrained, but they are known to grade laterally in the lower Sierran foothills into lower Eocene marginal marine deposits of the Ione Formation (Bateman and Wahrhaftig, 1966). Upper parts of the gravels have produced plant fossils yielding early Eocene ages, but their lower age limit remains uncertain. The upper age limit is constrained by overlying volcanics, the oldest of which yield ages of ~33 Ma (Yeend, 1974). Thus, the gravels could span the Eocene, and possibly parts of the Paleocene.

Eocene gravels occur as fill of paleovalleys incised into Sierran bedrock. Here at gold Run we see the fill of the south fork of the Tertiary Yuba River (Lindgren, 1911), the best preserved of the Tertiary Sierran rivers. The gravel fill of these valleys, ranging from minimal thickness to ~150m, occurs in two modes: (1) coarse, polymictic (with variations based on local changes in basement lithology), lower or “blue” gravels that occur chiefly in the central incised paleovalley thalwegs; and (2) finer, quartzose, upper gravels (“white” or “bench” gravels) that occur chiefly along the valley flanks and in upper parts of paleovalley fills. Upper gravels often have a matrix dominantly composed of kaolinite. Compositional differences between the upper and lower gravels allow two interpretations: (1) the lower gravels are less weathered due to preservation in central channels below the Paleogene water table; or (2) the upper gravels reflect more intense weathering related to progressively warmer and wetter climatic conditions throughout the Paleogene. Large clast sizes imply steep river gradients.

As a fossil placer, detrital gold is concentrated in the basal parts of the lower gravel (in the paleo-thalweg). Upper gravels are notably poorer in gold. At Gold Run, 555 acres of gravel, approximately 75 feet thick, were removed, and only the outermost gravels of the western paleovalley flank remain.

Although only minor valley flank gravels remain unmined at Gold Run, extensive lengths of the rich central channel remain unmined, especially beneath volcanic cover. A court ruling in 1884, recognizing the deleterious impact of hydraulic mining on streams of the Sacramento Valley, ended the otherwise cost-effective practice of hydraulic mining.

Optional Stop – Empire State Mine in Grass Valley

Significance:

This stop provides a historical view into the Californian gold mining culture that persisted from the late 1800s to the early 1900s.

Directions:

Depart Stop 1.8
Continue **W** on **I-80 W** (8.3 mi)
Take **Exit 135** toward **Colfax/Grass Valley/ CA-174 W** (0.1 mi)
Merge onto **South Auburn Street** (0.1 mi)
Turn **R** onto **CA-174 W/Central Street**, follow CA 174-W (1.5 mi)
Turn **L** to stay on **CA-174 W** (10.2 mi)
Turn **L** onto **East Empire Street** (0.2 mi)
Destination will be on **L**

GPS Coordinates:

39°12'21.33"N, 121° 2'43.26"W

Stop Description: *(modified from Empire Mine, 2011)*

The Empire Mine is the site of the oldest, largest, and richest gold mine in California. From 1850 to its closing in 1956, it produced 5.8 million ounces of gold. It is estimated that this represented only 20% of the available gold... suggesting that 80% remains. The Park contains many of the original mine buildings, the owner's cottage and the restored gardens and grounds as well as the entrance to 367 miles of abandoned and flooded shafts and tunnels.

Stop 1.9 – Smartville Complex Pillow Basalts

Significance:

This stop displays pillow lavas associated with the late Jurassic (?) Smartville ophiolite complex, along the Yuba River, part of the Western Belt or Foothills Terrane, accreted during the Nevadan orogeny.

Directions: *(about 50 mins from Stop 1.8)*

If leaving from Empire State Mine, Continue W on CA-174 to Grass Valley
If leaving from Stop 1.8, continue W on I-80 W (8.3 mi)
Take **Exit 135** toward **Colfax/Grass Valley/ CA-174 W** (0.1 mi)
Merge onto **South Auburn Street** (0.1 mi)
Turn **R** onto **CA-174 W/Central Street**, follow CA 174-W (1.5 mi)
Turn **L** to stay on **CA-174 W** (11.5 mi)
In Grass Valley, take ramp onto **CA-20 W/CA-49 S** (0.3 mi)
Take the **CA-20/Empire Street exit** toward **Marysville Street** (0.3 mi)
Turn **R** onto **CA-20 W/West Empire Street**, follow **CA-20 W** (15.4 mi)
Turn **L** onto **Old Bonanza Ranch Road/Timbuctoo Road** (0.2 mi)
Cross back N underneath CA-20, and after 50 m park on left just east of the Yuba River bridge.
Outcrop is on the Yuba River, 50 m N of the parking area

GPS Coordinates:

39°13'11.39"N, 121°19'59.78"W

Stop Description:

Menzies et al. (1977) subdivide the Smartville ophiolite complex (159-175 Ma; Saleeby and Moores, 1979) into four major stratigraphic units: (1) an upper volcanic unit of volcanic-derived sedimentary rocks containing mafic and siliceous quartz-bearing clasts interbedded with differentiated flows (Xenophontos and Bond, 1978); (2) a lower volcanic unit of pillowed and brecciated extrusives with minor sedimentary horizons; (3) a dike complex containing diabasic, andesitic, and dacitic intrusives in the northeastern portion and quartz porphyries in the southeastern portion; and (4) a plutonic suite of trondjhemite, diorite, homogeneous gabbro, and layered anorthosite-gabbro-pyroxenite.

At this location, we see an excellent example of pillow basalts (unit 2). This unit is characterized by a predominance of pillowed lavas, massive flows, flow breccias, and cross-cutting intrusives (Menzies et al., 1980). Intercalations of chert,

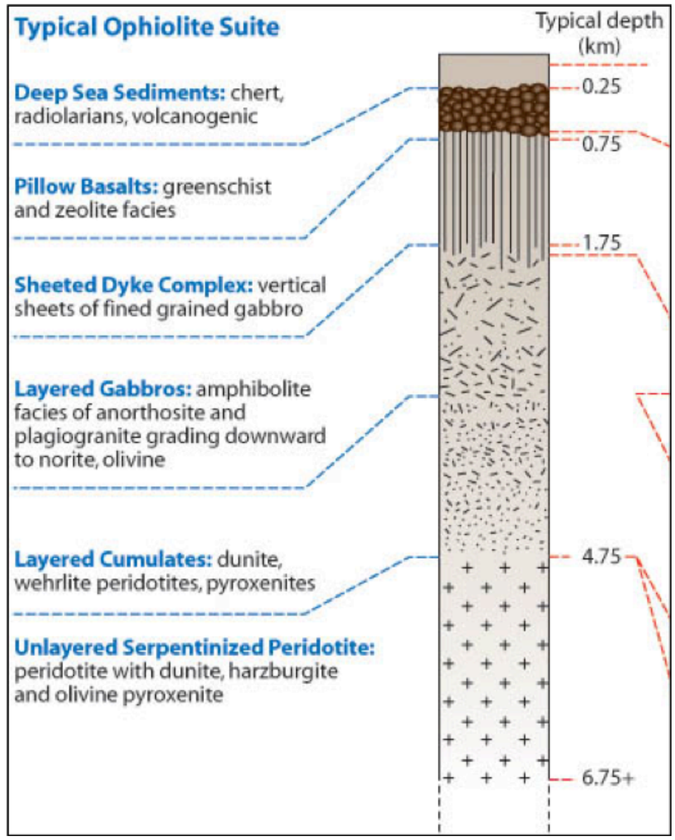


Figure 1.3: Schematic section of an idealized ophiolite suite. http://members.shaw.ca/ph-design/BettsCove/index.html

(photo credit: Todd Greene, Chico State) coarse clastic horizons, fine sand, and silt occur between the pillows and massive flows (Menzies et al., 1980). However, these are volumetrically insignificant.

Stop 1.10 – Sheeted Dikes and Pillows, Lake Oroville Campground

Significance:

This site displays sheeted dikes and pillow basalts of the Smartville ophiolite complex (*e.g., Stop 1.9, this volume*) along the shores of Lake Oroville.

Directions: *(about 55 minutes)*

Depart from Stop 1.9
Backtrack along **Old Bonanza Ranch Road** toward **CA-20 W** (0.2 mi)
Turn **L/W** onto **CA-20 W** (5.0 mi)
Turn **R/N** onto **Marysville Road** (8.8 mi)
Turn **L** onto **Loma Rica Road** (1.4 mi)
Turn **R** onto **Los Verjeles Road** (5.0 mi)
Continue onto **Oro Bangor Highway** (6.6 mi)
Turn **R** onto **Miners Ranch Road** (2.5 mi)
Turn **R** onto **CA-162 E** (3.8 mi) (note entrance to Loafer Creek Recreation Area and campground after 1.6 mi)
Destination (**pillow basalts**) will be on **R**
Continue across Bridge (0.6 mi)
Destination (**sheeted dikes**) will be on **R**

GPS Coordinates:

39°33'10.72"N, 121°25'47.97"W; 39°32'42.68"N, 121°26'0.15"W (respectively)

Stop Description:

At this location, we can see examples of pillow basalts and sheeted dikes (units 2 and 3, respectively, of Menzies et al., 1980) associated with the Smartville ophiolite complex. As noted at *Stop 1.9*, pillow basalt horizons may include massive flows, flow breccias, and cross-cutting intrusives, as well as volumetrically minor chert, coarse clastics, fine sand, and silt (Menzies et al., 1980).

The sheeted dike unit contains dikes and sills of variable composition, ranging from diabases and quartz porphyries to pyroxenites (Day, 1977). Some of the porphyritic dikes also occur in the uppermost volcanic unit (unit 1 of Menzies et al., 1980), and may be associated with highly differentiated extrusive rocks. Contacts between the dike complex (unit 3) and overlying pillow basalts (unit 2) are gradational, displaying an upward-increase in inter-dike pillow basalts (Menzies et al., 1980). Saleeby and Moores (1979) reported 159-175 Ma U-Pb zircon ages from plagiogranite in a sheeted dike complex in the Smartville ophiolite, suggesting that the ophiolite is mid- to late-Jurassic in age.

Return to Campsite for dinner, campfire and camping

Campground has restrooms, coin-operated showers, designated swimming area.

Directions:

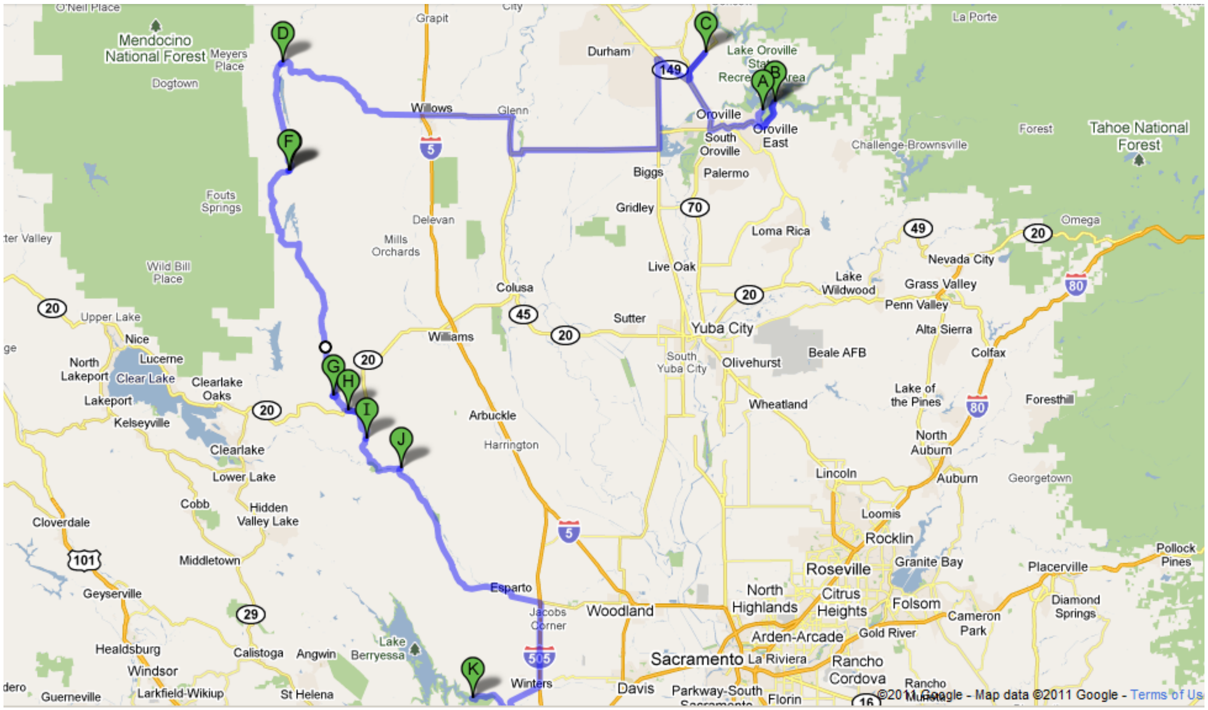
Return 1.6 miles south on CA-162 to Lake Oroville Loafer Creek Recreation Area and campground;
Turn R/N and drive 1 mile into park.

Lake Oroville is a reservoir on the Feather River, former home to the Maidu tribe. The lake drowns several mining villages, and was created in when Oroville Dam, at 770 ft the highest earthen dam in the USA, was built in 1967.

*** End Day 1 ***

Stops 1.9, 1.10, and campground – we have Group Site GGRE (in the Loafer Creek loop--southeasternmost of the 3 camping areas)

Day 2: Great Valley Group: The forearc basin between the Sierran basement and accretionary complex



A: Start – Lake Oroville Campground

B: Stop 2.1 – Miocene Lovejoy Basalt (Table Mountain)

C: Stop 2.2 – Great Valley Group on Sierran basement

D: Stop 2.3 – Bidwell Point Conglomerate

E: Stop 2.4a – Gravelly Ridge Conglomerate

F: Stop 2.4b – Basaltic Sandstone

G: Stop 2.5 – Wilbur Springs pillow basalts and overlying Great Valley Sequence

H: Stop 2.6 - Serpentinite intrusion and chemofossils

I: Stop 2.7 - Cache Creek (Salt Creek Sequence Boundary)

J: Stop 2.8 – Cache Creek (Sites locality)

Stop 2.8a – Drive-by: Putah Tuff (not on map)

Stop 2.8b – Drive-by: Blackrocks (Putnam Peak Basalt) (not on map)

K: Stop 2.9 – Monticello Dam

Stop 2.9a – GVG (Knoxville), volcanic breccias, Stony Creek Fm. (not on map)

Stop 2.10 – SW Lake Berryessa: Sedimentary serpentinite w/in GV group (southern edge of lake)

Bothe-Napa Valley State Pk, 3801 Saint Helena Hwy, Calistoga, CA - sites 23, 24, 26

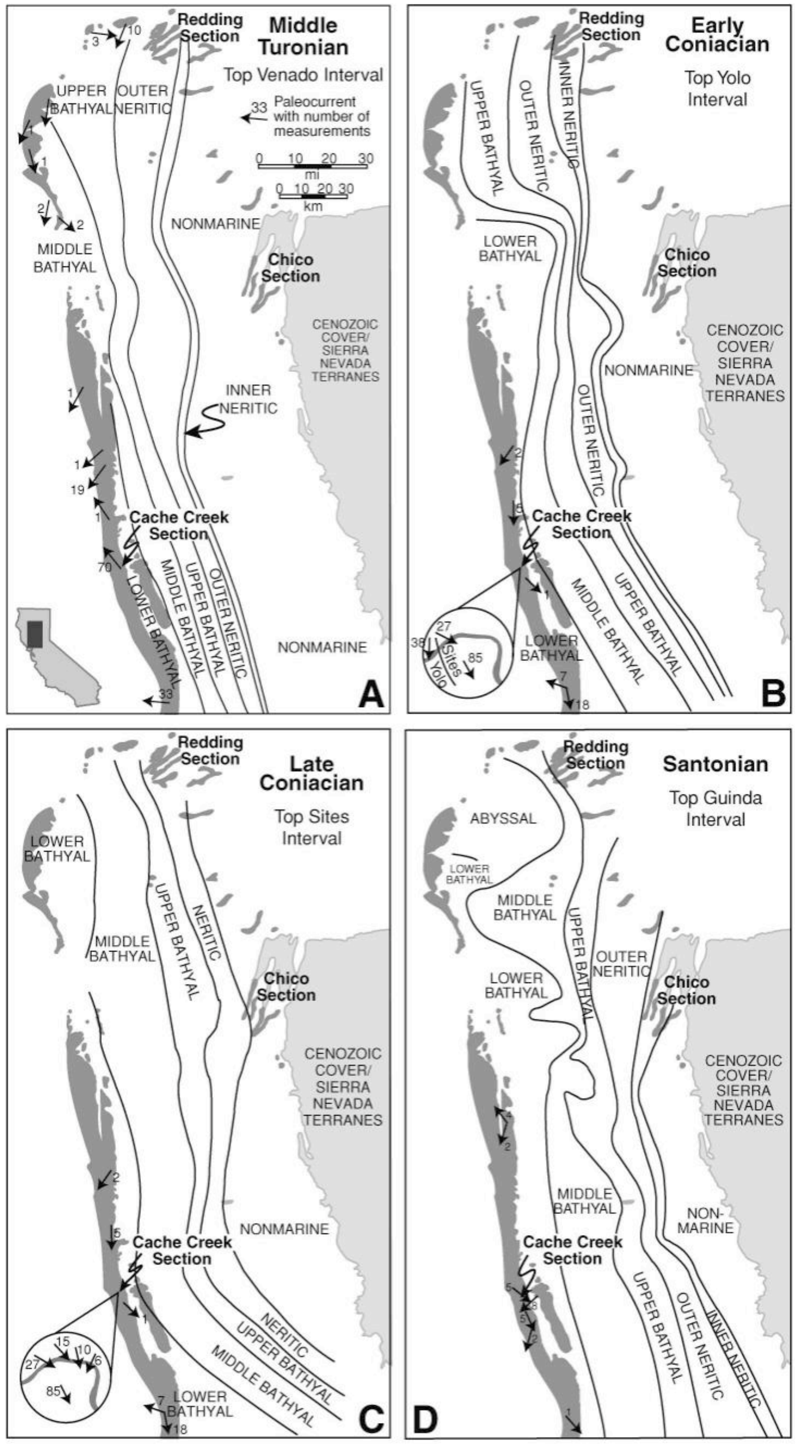


Figure 2.3: Maps (A–D) showing paleocurrent directions and the development of paleobathymetry in the Sacramento Valley during the Late Cretaceous. Outcrop distribution of Great Valley strata is shown in dark gray, and Cenozoic cover/Sierra terranes are shown in light gray. The three sections sampled for detrital zircon analysis are the Cache Creek section, Redding section, and Chico section. All paleocurrentdata from Ingersoll (1979); paleobathymetric contours from Williams (1997).

Stop 2.1 - Miocene Lovejoy Basalt (Table Mountain) (Stop #10 of Moores et al., 2006)

Significance:

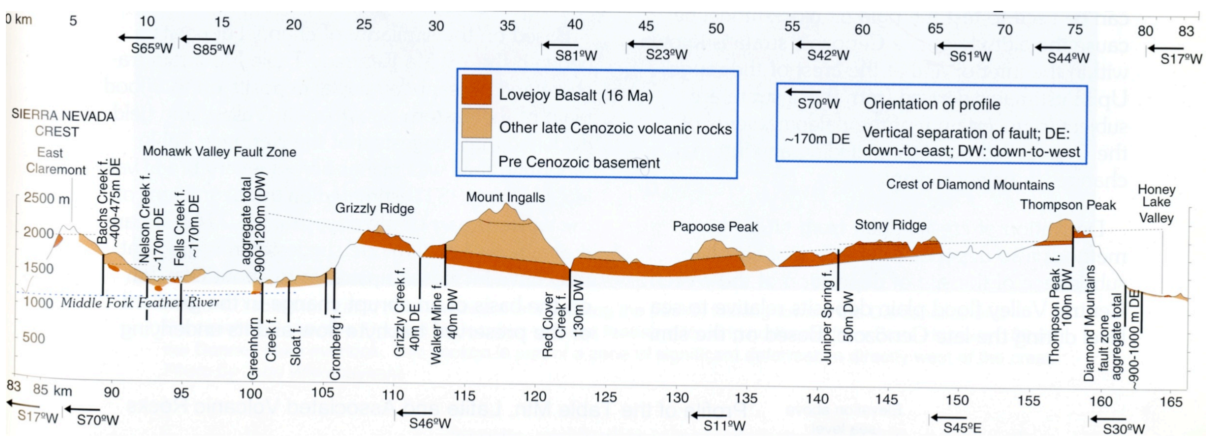
This is an excellent location to view the 15 Ma Lovejoy basalt, of which the age and chemistry indicate a genetic affinity with the Columbia River Flood Basalts and associated mantle plume activity (Garrison et al., 2007) and the tilted surface of the Sierra Nevada.

GPS Coordinates:

39°27'38.16"N, 121°34'55.08"W

Directions:

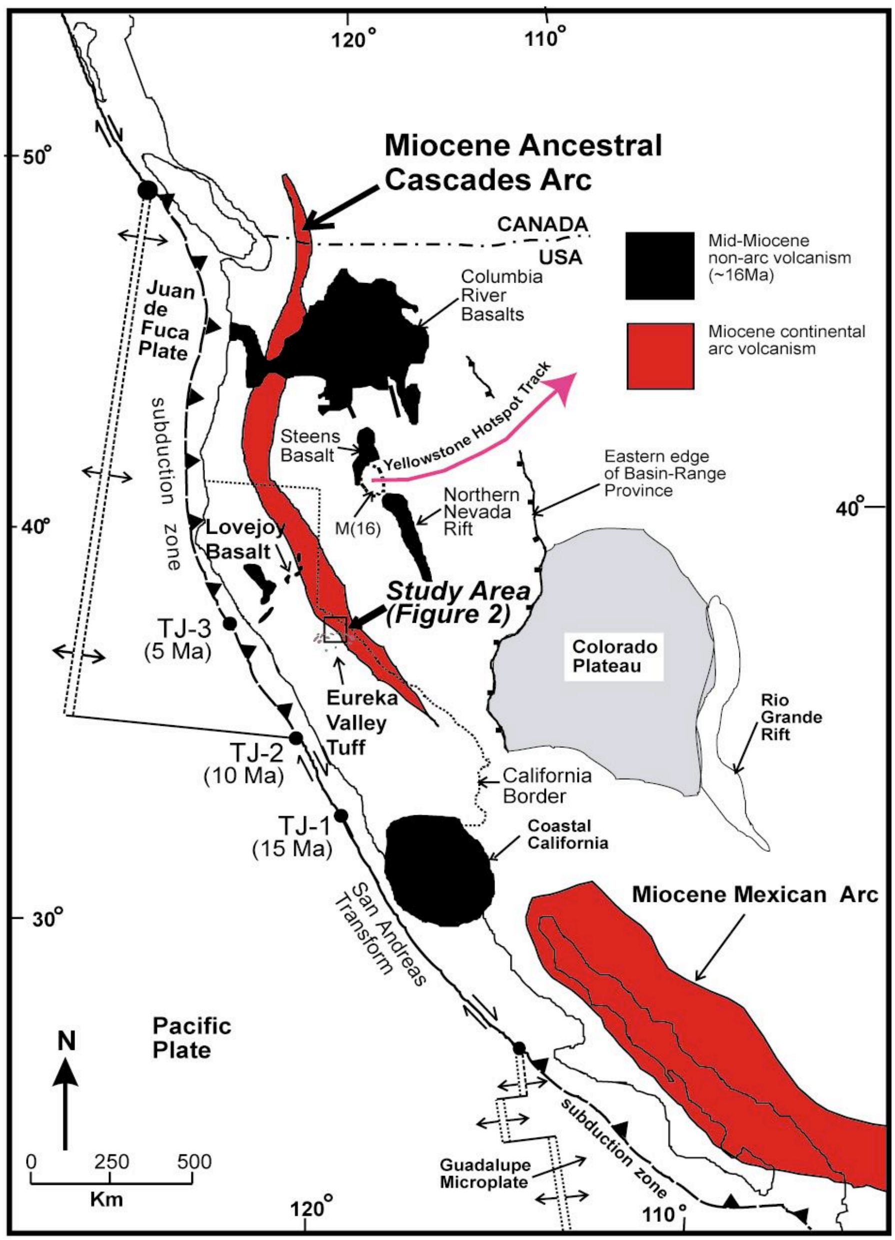
Depart Lake Oroville Campground
Head **SW** on **CA-162 W** toward **Marina Vista** (8.7 mi)
Turn **L** onto **CA-162 W/Oroville Dam Blvd E** (1.7 mi)
Turn **L** to merge onto **CA-70 S/State Hwy 70 S** (2.7 mi)
Destination will be on the **L**



(Wakabayashi and Sowier, 2000)

Stop Description: *(from Moores et al., 2006)*

Here, gentle westward slope of Lovejoy basalt shows the tectonic tilt of the Sierra Nevada. The Lovejoy basalt caps ridges today, but at 16 Ma it flowed down a sediment-covered valley in a low relief landscape. Some of this old landscape is preserved as low hills (of pre-Cenozoic basement rocks) that are topographically higher than the Lovejoy basalt. The paleo-relief, defined as the difference in elevation between the base of Cenozoic channels and the highest basement adjacent to them, is 100 m or less near the crest of the range in the Feather River watershed, although a few ridges exceed 300 m or so in the lower part of the drainage (Wakabayashi and Sawyer, 2001). Some of the "paleohills" may be visible from this viewpoint as the rounded hills that appear higher than the flat-topped ridges capped by Lovejoy basalt. In general, the northern Sierran landscape at the time of the eruption of the Lovejoy basalt was a very gentle and comparatively featureless surface with a few isolated hills and ridges.



(Garrison et al., 2007)

The Lovejoy basalt also provides a means of estimating late Cenozoic rock uplift of the Sierra Nevada, because the unit spans the range. The reconstruction of the Lovejoy basalt across the Sierra Nevada yields a minimum rock uplift estimate of 1,710–1,860 m for the crest of the Sierra in the Feather River drainage (Wakabayashi and Sawyer, 2001; Small et al., 1997; Unruh, 1991).

Minor internal deformation of the Sierra is distributed fairly evenly in across the range. There is no preferential concentration of deformation through the metamorphic belts (Wakabayashi and Sawyer, 2001). Although the internal faults have low slip rates (generally hundredths of a mm/yr or slower) and long recurrence intervals between earthquakes (commonly tens of thousands of years or more), these faults are nevertheless a concern for seismic safety of certain critical facilities, such as dams and power plants. The 1975 Richter magnitude 5.7 Oroville earthquake (Hart and Rapp, 1975) alerted the geologic and engineering community to the potential hazard posed by the internal faults.

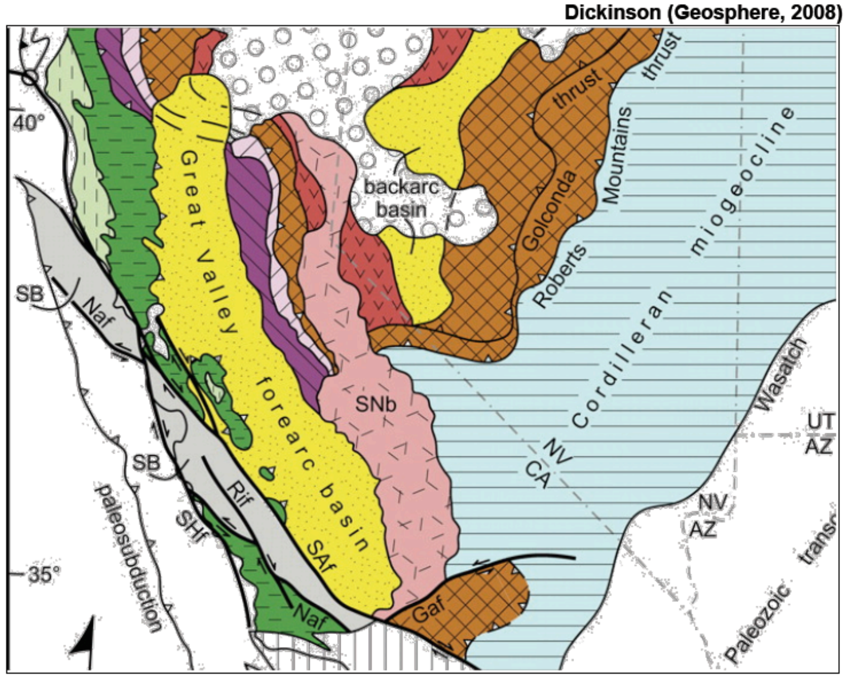
Great Valley Forearc Basin

Dickinson (Geosphere, 2008)

Great Valley Group: ~150–65 Ma; >10 km succession of turbidites

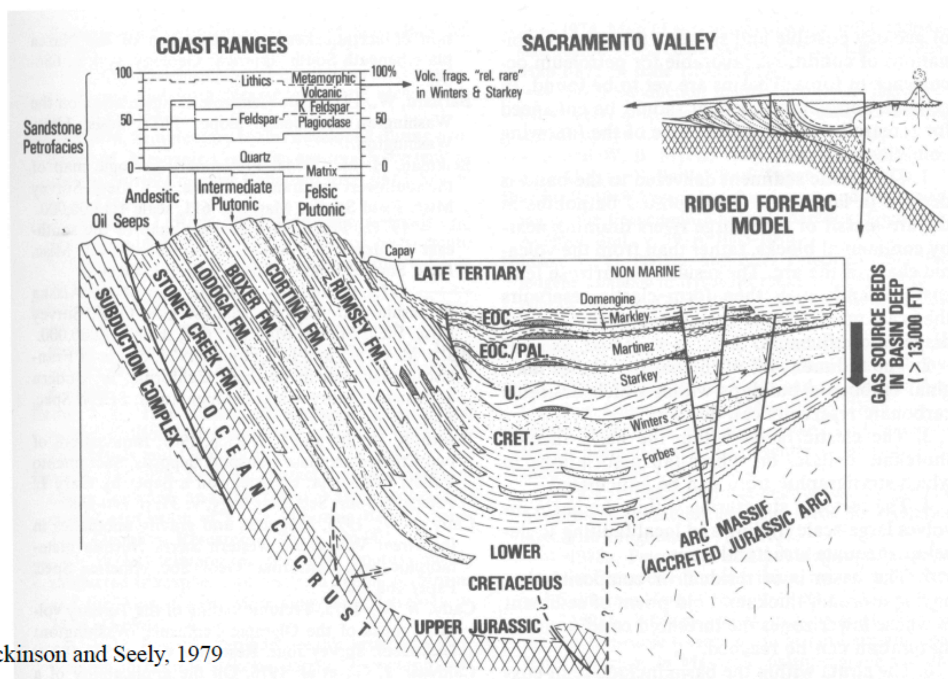
Coast Range Thrust: east-vergent thrust formed major unconformity in GVG; created the GV monocline; exhumed Franciscan from ≥25 km to ≤15 km, ~ 80–65 Ma

GVG overlain by Cenozoic sandstones, shales, volcanics, and poorly consolidated sediments overlie GVG



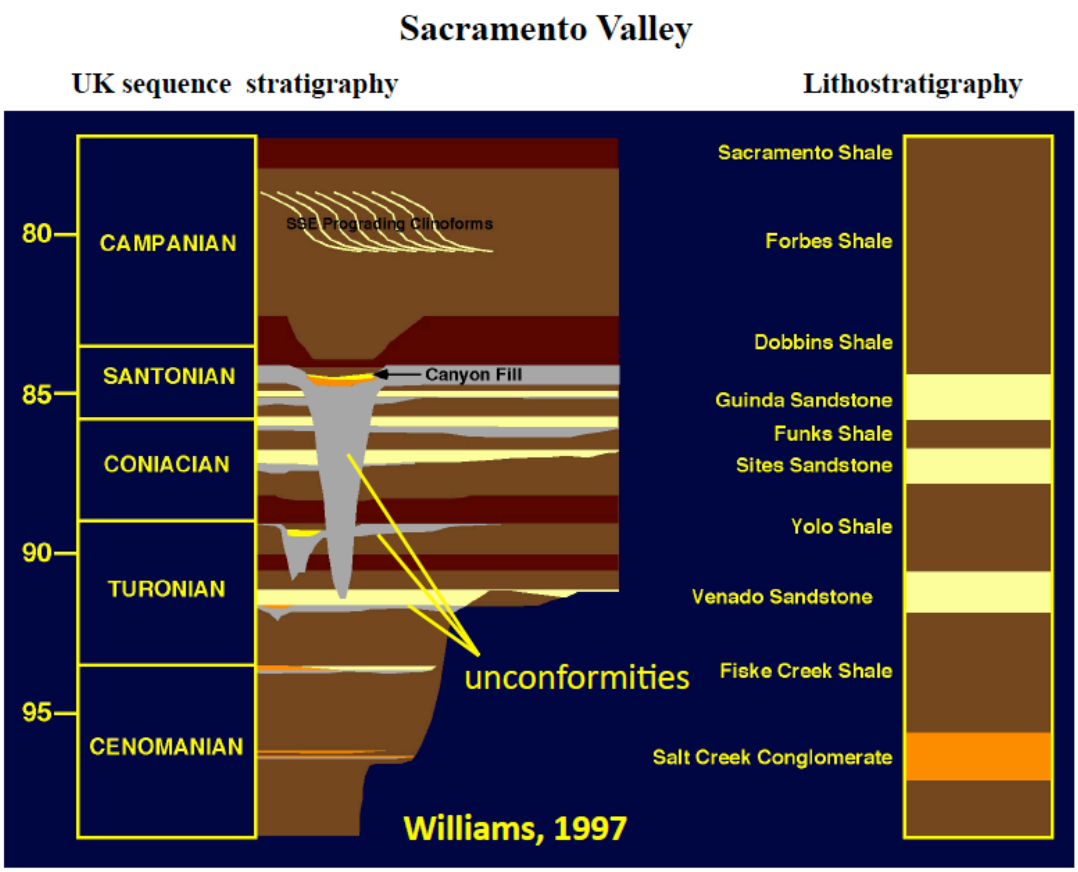
Great Valley Forearc Basin

West

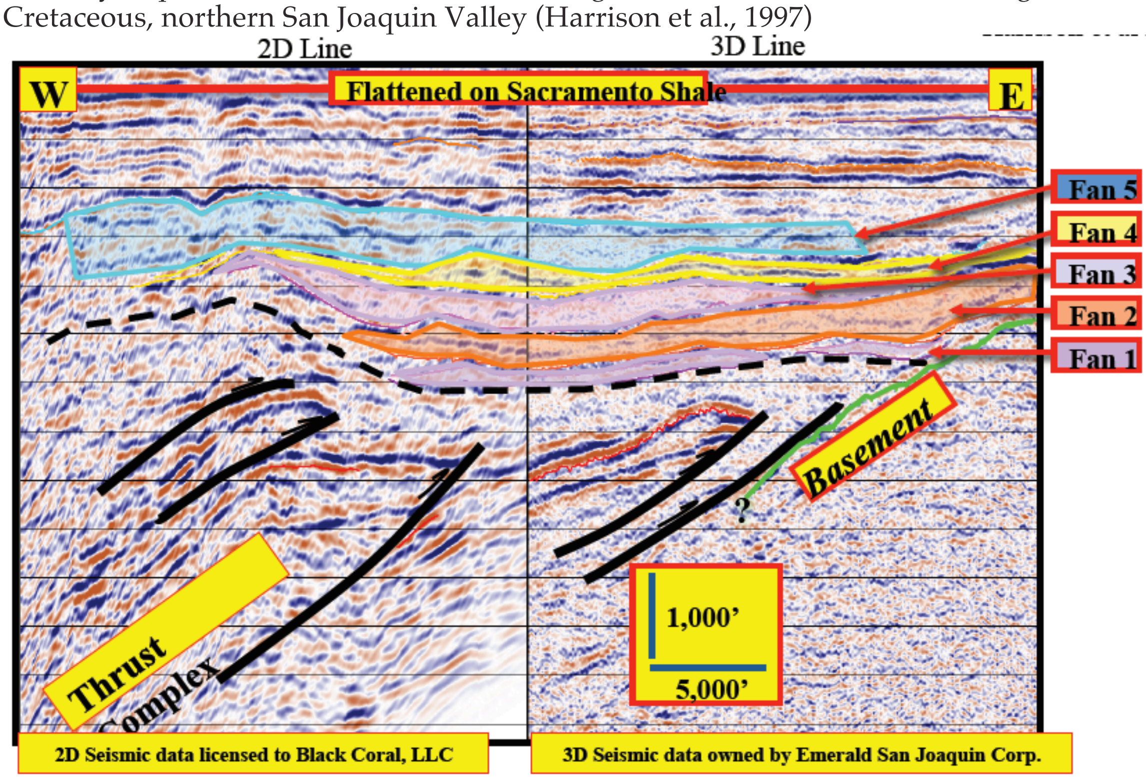


East

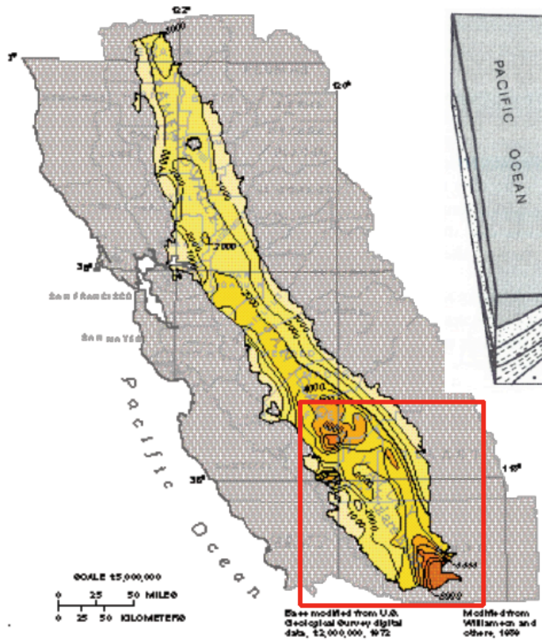
Dickinson and Seely, 1979



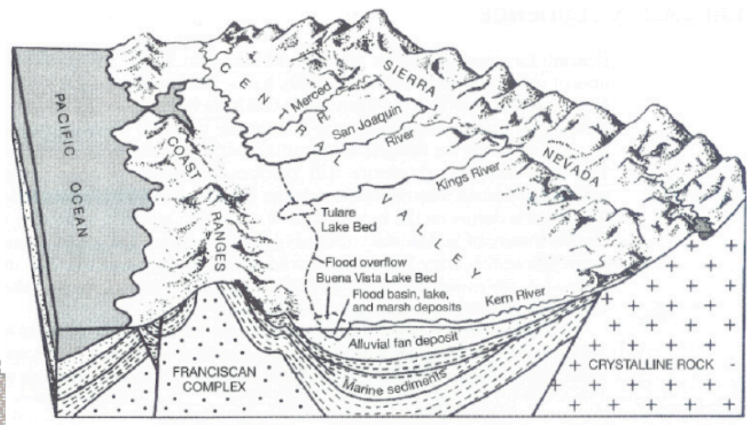
Recently acquired seismic-reflection data image arcward thrusts formed during the Late Cretaceous, northern San Joaquin Valley (Harrison et al., 1997)



Great Valley Forearc Basin



Williamson et al., 1989



Continental Sediments in the Great Valley

Average 2400 ft;
> 9000 ft in Tulare Basin

Stop 2.2 – Great Valley Group atop Sierran basement (near Stop #11 of Moores et al., 2006)

Significance:

At this locality we can see Cretaceous forearc basin deposits of the Great Valley Group resting unconformably on Sierran basement.

GPS Coordinates:

39°38'11.30"N, 121°34'47.40"W

Directions:

Depart Stop 2.2
Head **NE** on **CA-70 N** toward **Ophir Rd** (9.1 mi)
Slight **R** to stay on **CA-70 N** (4.8 mi)
Destination (road-cut) will be on **R** and/or **L**

Stop Description: *(modified from DeGraaff-Surpless et al., 2002; Moores et al., 2006)*

Following initiation of subduction under western North America in Late Jurassic time (Schweickert and Cowan, 1975; Saleeby, 1981; Ingersoll and Schweickert, 1986), the Great Valley forearc basin widened and filled through Cretaceous time, due to westward and upward growth of the Franciscan accretionary prism, coupled with eastward migration of the Sierra Nevada magmatic arc (Evernden and Kistler, 1970; Dickinson and Rich, 1972; Dickinson and Seely, 1979; Ingersoll, 1979; Graham and Ingersoll, 1981). Sedimentation in the Great Valley basin first occurred in a slope setting that developed by the Early

Cretaceous into a broad bathyal forearc basin with an extensive system of submarine fans (Ingersoll, 1979, 1982; Suchecki, 1984; Linn et al., 1992).

The Great Valley Group forearc basin-fill strata crop out in a homocline along the western margin of California's Central Valley (divided into a northern Sacramento Valley segment and a southern San Joaquin Valley segment) and locally in stream valleys in the northeast corner of the Central Valley. The forearc strata are underlain by the Great Valley ophiolite and Sierran basement terranes (Harwood and Helley, 1987; Godfrey et al., 1997) and are covered by Cenozoic sedimentary and volcanic rocks. The Great Valley Group unconformably rests on the Eastern Klamath terrane in the north and Sierran arc and associated foothills terranes in the east; the Group is in fault contact with the Franciscan accretionary complex to the west (Ingersoll, 1979; Irwin, 1981).

In the Sacramento Valley, sediment dispersal directions changed from primarily southward in the Late Jurassic to southward and westward in the Cretaceous, suggesting a shift from primarily Klamath to Sierran sources (Ojakangas, 1968; Ingersoll, 1979).

Paleobathymetric maps constructed by Williams (1997) for the Sacramento Valley document the evolution of the forearc basin from a narrow trough with a steep slope in late Cenomanian time to a broader basin with a wider shelf in Santonian time. The development of localized areas of subsidence and uplift in the basin in Santonian time complicated the formerly simple pattern of axial transport with transverse input of sediment from the Sierran arc.

We see the first exposures of Sierran metamorphic basement. These rocks have been mapped as Jurassic metasediments. Mid-late Jurassic (176–146 Ma) fossils were found 2–5 km north of here in the metamorphosed "Pentz" sandstone. (Moores et al., 2006).

Drive west across Central Valley toward town of Willows. Scenic drive through coast range hills

Stop 2.3 – Bidwell Point Conglomerate (Stop #1.1 of Shervais et al., 2010)

Significance:

This stop displays chert-rich conglomerate deposited during the early phase of the forearc basin, with abundant *Buchia rugosa* fossils.

GPS Coordinates:

39°36'44.69"N, 122°31'41.62"W

Directions:

Head **SW** on **CA-70 W** toward **Messilla Valley Rd/Wheelock Rd** (4.1 mi)
Take the **ramp** onto **CA-149 N** (4.4 mi)
Keep **R** at the fork, follow signs for CA-99 and merge onto **CA-99 S** (11.3 mi)
Turn **R** onto **CA-162 W/Butte City Hwy**
Continue on **CA-162 W** (17.9 mi)
Turn **R** onto **CA-162 W/CA-45 N** (4.5 mi)
Turn **L** onto **CA-162 W** (31.0 mi)
Turn **R** onto **CA-162 W/Rd 306** (0.1 mi)
Destination (outcrop) will be on **R**

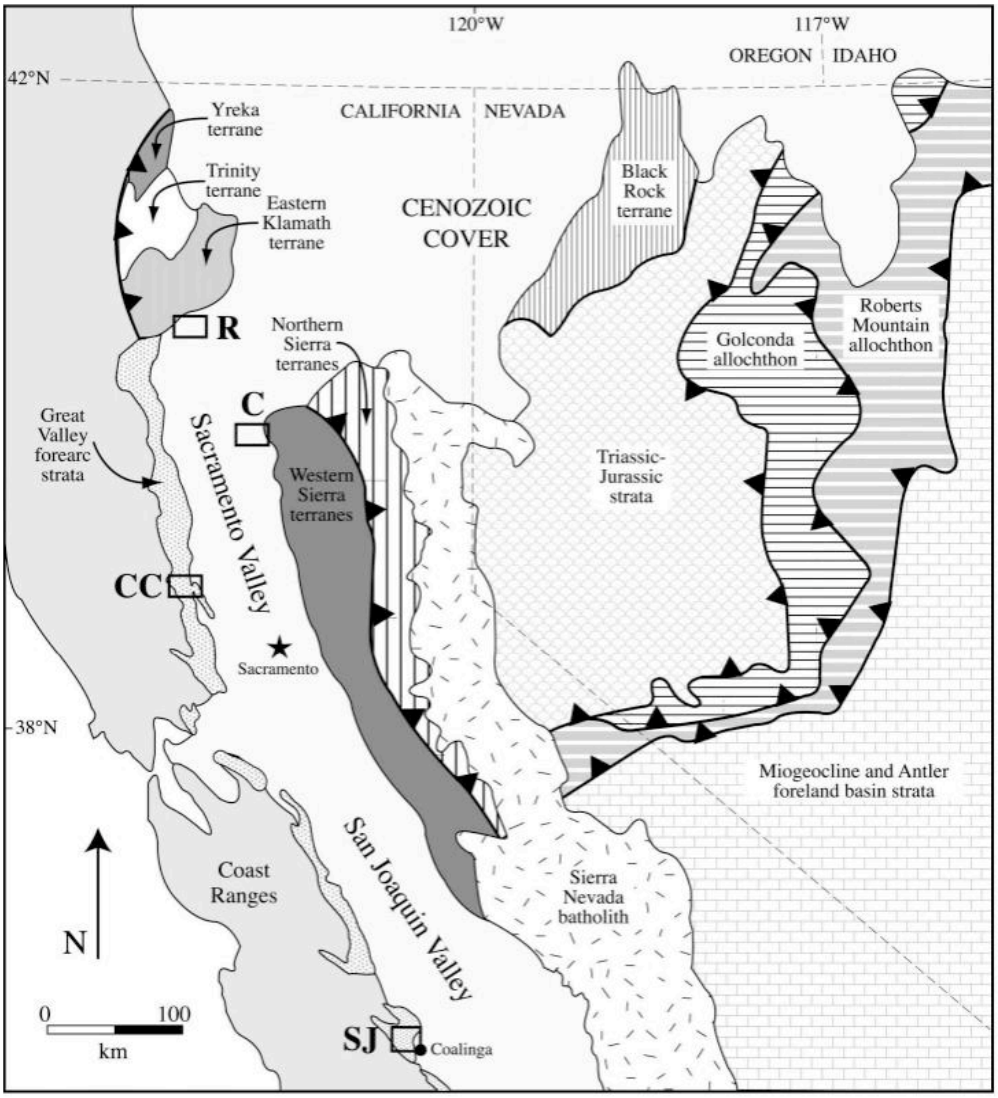


Figure 2.1: Geologic map showing Great Valley forearc basin-fill outcrops as well as terranes and assemblages (with their bounding faults) in California and Nevada (map modified from Gehrels and Miller (2000); adapted from Kistler and Peterman (1973); Oldow (1984); Silberling et al. (1987); Kistler et al. (1991); and Silberling (1991). Small boxes indicate Great Valley sampling locations: CC—Cache Creek section, C—Chico section, R—Redding section, and SJ—San Joaquin section; star indicates location of Sacramento. Widespread Cretaceous and younger rocks shown in shades of gray; Cretaceous and younger structures omitted to emphasize pre-Cretaceous configuration.

Stop Description: *(modified from Shervais et al., 2010)*

Here we see chert-rich conglomerate with abundant *Buchia rugosa* fossils. The deep-water facies exposed at Stony Creek is part of a series of Upper Jurassic conglomeratic lenses that can be traced laterally for 70 km along the western GVG outcrop belt; individual lenses are continuous for up to 10 km (Bertucci, 1983). They were deposited during the early phase of the forearc basin when the basin was a narrow, elongate trough. The conglomerates are often dominated by Klamath-derived chert, have southerly paleocurrents, and probably represent reworking of river gravel braid plains deposited on a narrow shelf during sea-level lowstands. As sea level rose, failures along the shelf edge could have triggered powerful sediment gravity flows that transported the large clasts down submarine channels. The deep-water facies exposed at the Elk Creek bridge are in stark contrast to the Sites (*Stop*

2.6, this volume) and Salt Creek (*Stop 2.5, this volume*) facies. The conglomerate at the Elk Creek bridge was named the Bidwell Point Lens by Bertucci (1983), and it is a ridge-forming conglomerate continuous for up to 7 km along strike. The entire Bidwell Point lens is over 100 m thick and the conglomerate portion contains rounded clasts and boulders up to 50 cm in diameter. The conglomerate overlies muddy turbidites and has a very sharp base. The conglomerate lens grades upward into interbedded sands and muds with abundant fossils.

Stop 2.4 – Gravelly Ridge Conglomerate and basaltic sandstone (Stop #1.2 of Shervais et al., 2010)

Significance:

Here we will see Great Valley Series, including at least five stacked channel complexes separated by mudstone intervals.

GPS Coordinates:

Gravelly Ridge Conglomerate: 39°25'39.60"N, 122°30'42.82"W
Basaltic Sandstone: 39°25'35.63"N, 122°30'52.27"W

Directions:

Gravelly Ridge Cgl:
Depart Stop 2.3
Backtrack **SW** on **Rd 306 (**0.5 mi)
Continue onto Co **Rd 306** (13.2 mi)
Destination (stream cut) will be on **L**
Basaltic Ss:
Continue **SW** on **Co Rd 306** (0.2 mi)
Destination (stream cut) will be on **L**

Stop Description: *(modified from Shervais et al., 2010)*

The Great Valley Series (GVS) here is a homoclinally folded sequence of mudstone/argillite with minor intercalated greywacke and micritic limestone overlain by a coarse basaltic sandstone and the chert-rich Gravelly Ridge conglomerate. The contact between the GVS and the serpentinite-matrix mélange is a high-angle reverse fault which dips steeply to the west, and places serpentinite over sediments of the GVS. High-angle faults within the GVS which trend NW and W are probably tear-faults related to earlier west-vergent thrusting of the GVS (e.g., Wentworth et al., 1984; Glen, 1990). The Gravelly Ridge Lens is a laterally extensive conglomeratic ridge, slightly older than the Bidwell Point lens, containing at least five stacked channel complexes separated by mudstone intervals (Campion et al., 2000). Each channel complex is between 0.5-1.6 km wide, 60-100 m thick, and extends at least 12 km in a down-dip direction. Campion et al. (2000) interpreted these conglomerates as fill of sinuous deep-water channels.

Stop 2.5 – Wilbur Springs pillow basalts and overlying Great Valley Sequence

GPS Coordinates:

38°0'45.67"N, 122°23'1.29"W

Directions:

Continue **SW** on **Co Rd 306** toward Forest Route 18N38 (4.1 mi; about 17 min)

Continue onto **Lodoga Stonyford Rd** (0.6 mi; about 1 min)
Continue onto **Market St** (0.3 mi)
Turn **R** onto **3rd St/Lodoga Stonyford Road** (7.7 mi; about 14 min)
Turn **R** onto **Leesville Lodoga Rd** (9 mi; about 16 min)
Turn **R** onto **Bear Valley Rd** (12.1 mi; about 33 min)
Turn **R** onto **Wilbur Springs Rd** (0.6 mi; about 2 min)

Stop 2.6 – Serpentinite intrusion and chemofossils

GPS Coordinates:
38°2'16.12"N, 122°24'58.17"W

Directions:
Head East on **Wilbur Springs Road** toward Bear Valley Road (0.6 mi; about 2 min)
Turn **R** onto **Bear Valley Rd** (3.9 mi; ~10 min)
Turn **R** onto **CA-20 W** (5.8 mi; ~2 min)

Stop 2.7 – Cache Creek (Salt Creek Sequence Boundary) (Stop #2 of Shervais et al., 2010)

Significance:
Here we will see the Salt Creek Sequence Boundary.

GPS Coordinates:
38°57'52.61"N, 122°20'29.81"W

Directions:
Depart Stop 2.6
Head east on **CA-20 E** toward Bear Valley Road (1.4 mi; ~1 min)
Turn **R** onto **CA-16 E** (3.9 mi; about 5 min)
Destination (road-cut) will be on **R**

Stop Description: (*modified from Lowe, 2004; Shervais et al., 2010)*
Here, Cache Creek cuts across outcrops of the Great Valley Group. Exposed Upper Cretaceous units include the Fiske Creek Shale, Venado Sandstone, Yolo Shale, and the Sites Sandstone. Several of these units represent more distal submarine fan facies than any seen thus far.

The base of the Salt Creek Member is widely regarded as a major sequence boundary that marks the cessation of large-scale coarse-sediment influx into the forearc basin. The basin remained coarse-sediment-starved throughout the Cenomanian (Fiske Creek Shale), although there was clearly an enormous amount of mud and very fine sand available during this interval.

The overlying Salt Creek Member of the Boxer Formation consists of 9 meters of medium- to fine-grained sandstone containing lenses of conglomerate. Along Hwy 16, there is a lower conglomerate composed of small intrabasinal clasts, mostly mudstone, and an upper conglomerate that includes intrabasinal and extrabasinal material. Where the Salt Creek Member crosses Bear Creek, below the road, it consists of about 12 meters of sandstone with <50 cm of granule-conglomerate near the top. In both sections, the base of the Member shows a spectacular development of flute casts.

The Salt Creek Sequence Boundary was used by one of the original proponents of sequence stratigraphy to show how the lowering of base level creates sharp-based sandstone in the deep-water environment many 10's of km down-dip of the coeval delta. However, later work confirmed the actual sequence boundary occurred within deepwater shales, and had little to do with the sharp-based sandstone. Note the curious features on the base of the lowermost sandstone. These flute casts provide paleocurrent indicators for the turbidity currents. Also note the highly deformed mud-sand package stratigraphically above the lowermost sand.

Stop 2.8 – Cache Creek (Sites locality) (Stop #4 of Shervais et al., 2010)

Significance:

Here we will see a type section for a progradational outer lobe within a submarine fan.

GPS Coordinates:

38°54'42.55"N, 122°15'53.50"W

Directions:

Continue **SE** on **CA-16 E** toward **Rd 40/Rayhouse Rd** (8.1 mi)
Destination (stream cut) will be on **L**

Stop Description: *(modified from Shervais et al., 2010)*
The Sites Sandstone was used as a type section for prograding outer lobe within a submarine fan. The Sites Sandstone sections along Cache Creek were measured in detail by Ingersoll (1981). His interpretation became the classic model for outer fan lobe deposits in a deep-water submarine fan. He produced a schematic stratigraphic section consisting of three upward-thickening sequences overlain by one upward-thinning sequence which he interpreted to be three depositional lobes followed by an overriding channel. Many of the top deep-water researchers came from far and wide to witness the classic prograding lobe succession. However, in the 1990's, a Stanford group measured the Sites Sandstone (500 meters at cm scale) to statistically define any real thickening or thinning trends (Chester, 1994). After using every appropriate statistical measure, the results showed some thickening-upward, some thinning-upward, and some bundling. In general, no overall thickening-upward trend was recognized for the Sites Sandstone (Murray et al., 1996). The Sites Sandstone contains numerous high density turbidites with massive bedding, amalgamated beds, dewatering features, and injected sand dikes. Lowe (2004) interpreted these sands to be deposited on a submarine sandy braid plain.

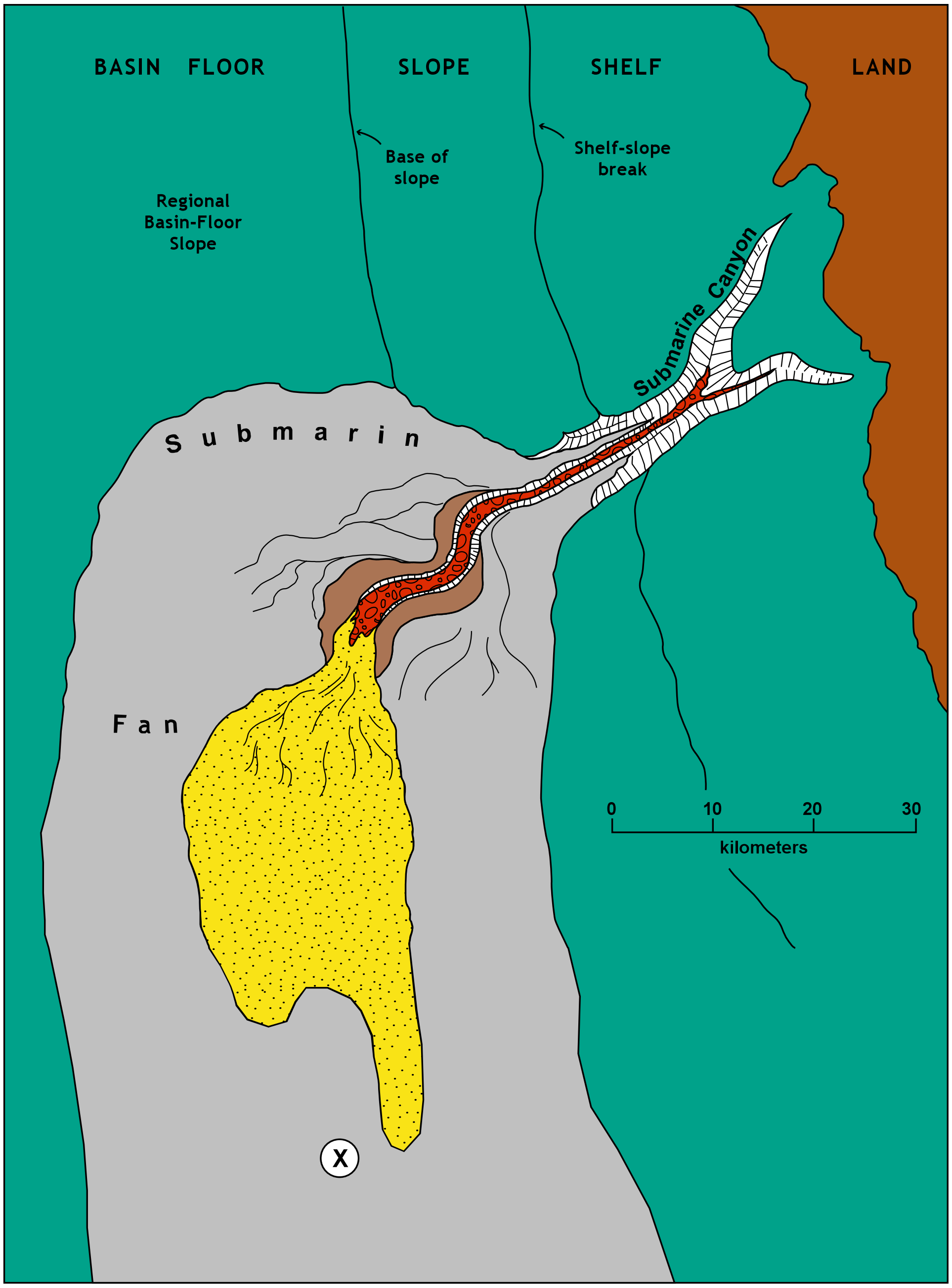


Figure 2.5: General depositional setting of the lower Fiske Creek Shale. It accumulated mainly as thin rhythmic, fine-grained beds from low-density turbidity currents on a low-relief, poorly-channelized, muddy outer-fan apron and basin plain (X). Such deposits formed around the fringes and downslope from sandy lobe and channel mouth deposits when the sandy fan was active and often backstepped upslope over older sandy deposits during periods of little coarse-sediment influx.

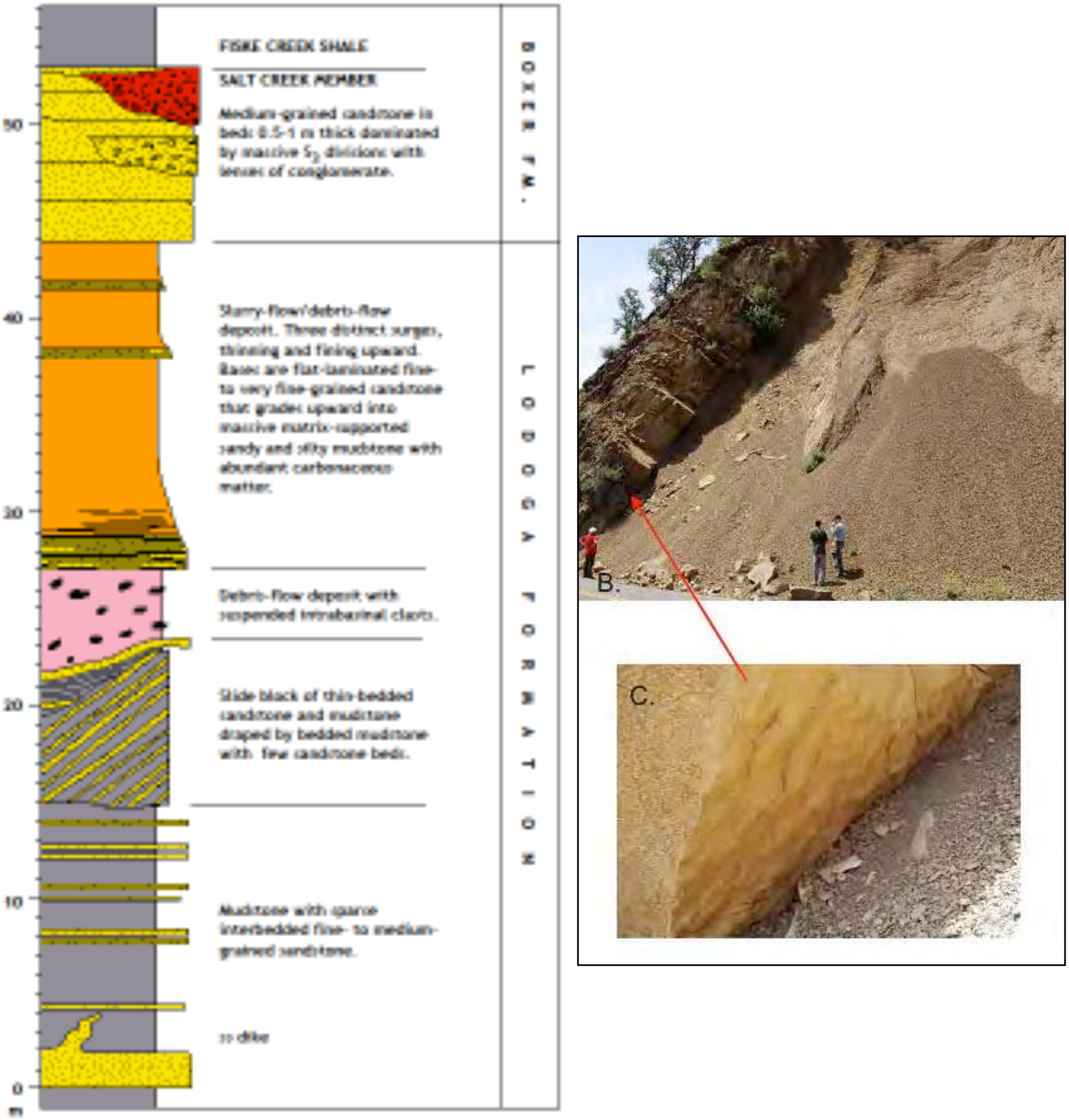


Figure 2.4: Stop 2.7 - Salt Creek Member of the Boxer and Lodoga Fms. A) stratigraphic section (taken from Lowe, 2004), B) photo of upper Salt Creek Member, and C) flute casts at base of upper sandy section

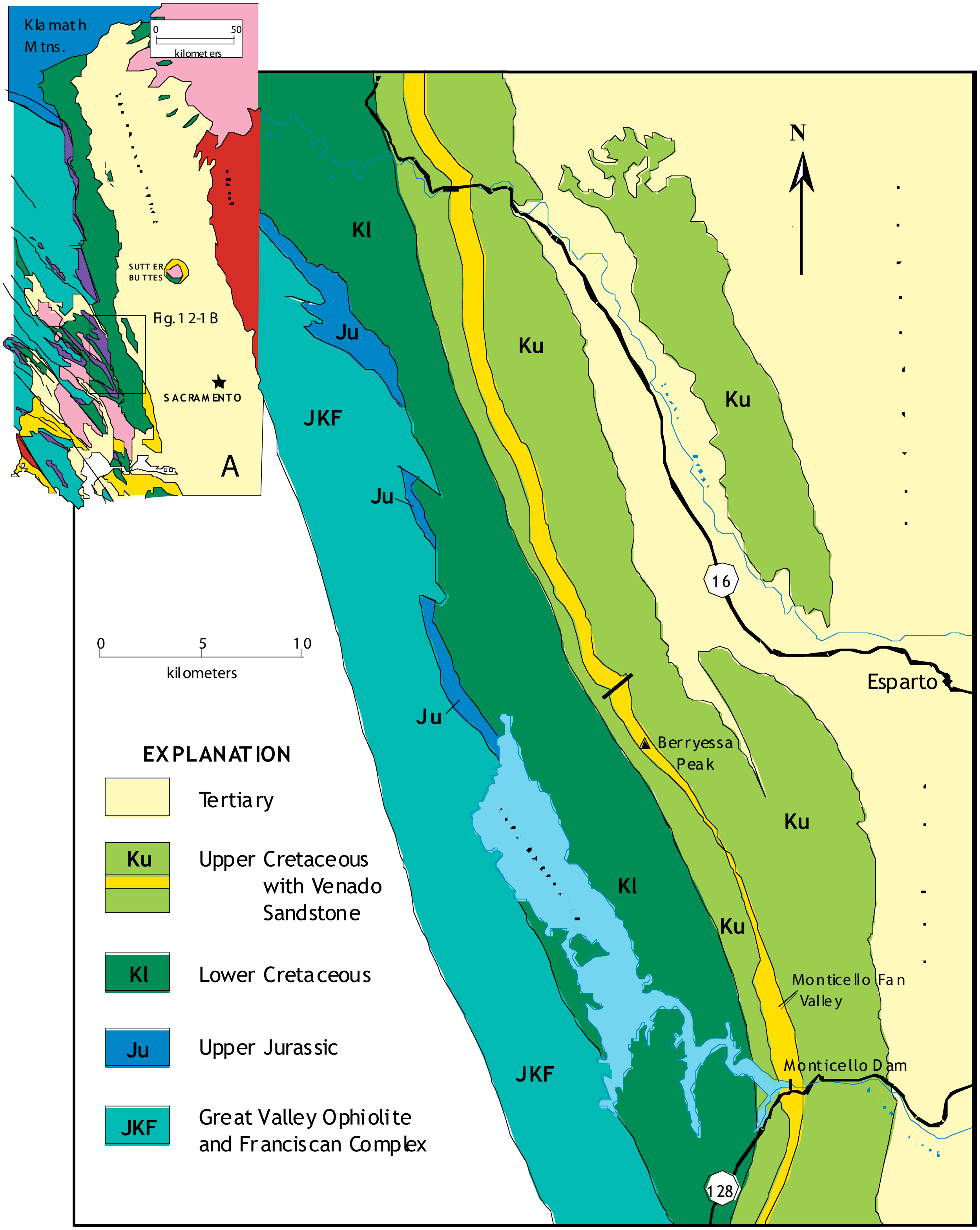


Figure 2.2: Location map for geology along Cache Creek. (Taken from Lowe, 2004.)

Stop 2.8a - Drive-by: Putah Tuff

Significance:

This site provides an excellent exposure of a young (1.8 Ma) rhyolitic tuff.

GPS Coordinates:

38°29'41.10"N, 122° 1'16.36"W

Directions:

Depart Stop 2.8
Continue **SE** on **CA-16 E** toward **Rumsey Canyon Rd** (23.1 mi)
Turn **R** onto **Yolo Ave** (0.5 mi)
Turn **L** onto **CA-16 E** (3.5 mi)
Turn **R** to merge onto **I-505 S** toward **Sacramento** (10.0 mi)
Take **Exit 11** toward **Winters** (0.4 mi)
Merge onto **CA-128 W/E Grant Ave**
Continue to follow **CA-128 W** (4.7 mi)
Destination will be on the **L**

Description:* (modified from Moores et al., 2006)*

[We will pass roadcuts in the Tehama gravel. These Pleistocene to Recent gravels contain clasts of Great Valley and Franciscan rocks, indicating that they were derived principally from source areas to the west. This is the youngest recognized unit of this region. The gravels underlie much of the western part of the Great Valley and probably form the principal aquifers of the western Great Valley.]

The 1.8 Ma Putah rhyolitic tuff is probably derived from a volcanic center in northern Napa valley. The tuff (a product of explosive volcanism) is interlayered with the Tehama gravels and shows evidence of having been reworked by stream action.

Stop 2.8b - Drive-by*:* Blackrocks (Putnam Peak Basalt)

Significance:

This site provides a good exposure of columnar jointed landslide blocks of a mid-Tertiary basalt flow that originated NE of the Sierra Nevada.

GPS Coordinates:

38°31'2.52"N, 122° 3'21.66"W

Directions:

Depart Stop 2.8a
Continue **SW** on **CA-128 W** toward **Pleasant View Rd** (2.6 mi)
Destination (stream cut) will be on the **L**

Description:* (modified from Moores et al., 2006)*

Here we see slide blocks of 15 Ma basalt that are derived from the Lovejoy basalt. The Lovejoy basalt erupted from east of the present Sierra Nevada crest near Honey Lake and flowed westward across what later became the Sierra and the Sacramento Valley (Durrell, 1959). The basalt here is called the Putnam Peak basalt and has been correlated with the Lovejoy on the basis of its estimated age and its composition (Siegel, 1988). Recently, detailed measurements of the magnetic properties of these rocks by Coe et al. (2005) also strongly suggest that the Putnam Peak basalt is equivalent to the Lovejoy basalt and that 90% of the Lovejoy basalt erupted within a geologically short period of time, probably a few hundred to a few thousand years. The Lovejoy basalt and other remnants of basalt in the Sierra Nevada have yielded 16 Ma Ar/Ar ages (Page et al. 1995; Garrison, 2004). The Lovejoy basalt is apparently buried beneath post-16 Ma sediments in the Sacramento Valley, whereas in the northern Sierra Nevada it is a ridge-former. The position of the Lovejoy (Putnam Peak basalt) in these hills along the eastern margin of the Coast Ranges is a product of uplift associated with fold and thrust fault development along the eastern Coast Ranges range front (Unruh et al., 1995). Massive landslides were reported from this area during the 1896 Winters-Vacaville earthquakes.

Stop 2.9 - Monticello Dam (Stop #1 of Ingersoll & Graham, 1984; Stop #5 of Moores et al., 2006)

Significance:

This is an excellent and world-famous exposure of the deep-sea fan deposits that characterize the Great Valley Group of the California Coast Ranges.

GPS Coordinates:

38°30'45.36"N, 122° 6'11.16"W

Directions:

Depart Stop 2.8b
Continue **W** on **CA-128 W** (3.1 mi)
Destination (road-cut and stream cut) will be on the **R** and **L**

Stop Description: *(modified from Ingersoll et al., 1984; Moores et al., 2006; Shervais et al., 2010)*

One of the more prominent ridge formers exposed along the eastern Coast Ranges intersects Lake Berryessa's Monticello Dam. This succession contains Late Cretaceous (Turonian) aged debris-flow deposits, channel conglomerate and sandstone, and overbank mudstone. The base of the Venado Sandstone can be traced in the subsurface over large areas of the GVG (Williams, 1997).

Deposition here was concurrent with transgression eastward onto the Sierran arc. Paleocurrent studies have shown that sediment was deposited by generally westward flowing currents at this time. As a result, the Venado shows a retreat of fan facies from bottom to top. Slope facies of the Boxer Formation underlie the Venado, and the base of the Venado consists of chaotic slump and channel-fill deposits. The Ladoga Formation is predominantly continuous, thin-bedded to laminated mudstone and sandstone, typical of deposition in a basin-plain environment.

At the dam, the Venado Sandstone is 375 meters thick, and displays excellent incision surfaces, braid-plain valley fill, and channel-levee architecture. Although the outcrop has been extensively studied, interpretations vary from a low-stand basin floor fan to mid-fan channel-levee complexes (Ingersoll, 1978, 1981), to a large submarine fan valley fill eroded into the underlying Fiske Creek Shale (Lowe, 2004).

The massive sandstones on the abutments of Monticello dam form the base of the Upper Cretaceous part of the Great Valley Group. The Upper Cretaceous section presents the most voluminous part of the Great Valley Group; this part of the forearc basin strata represents the highest rate of deposition and subsidence (Moxon, 1988). The rapid subsidence that marks this part of the Great Valley Group coincides with the main stage of exhumation of the coherent blueschist facies rocks of the Franciscan Complex. This deposition may have been associated with downward movement on the fault that separated the upper plate of the trench-forearc system (Coast Range ophiolite and Great Valley

Group) from the underplated and off-scraped Franciscan Complex structurally beneath it (Wakabayashi and Unruh, 1995).

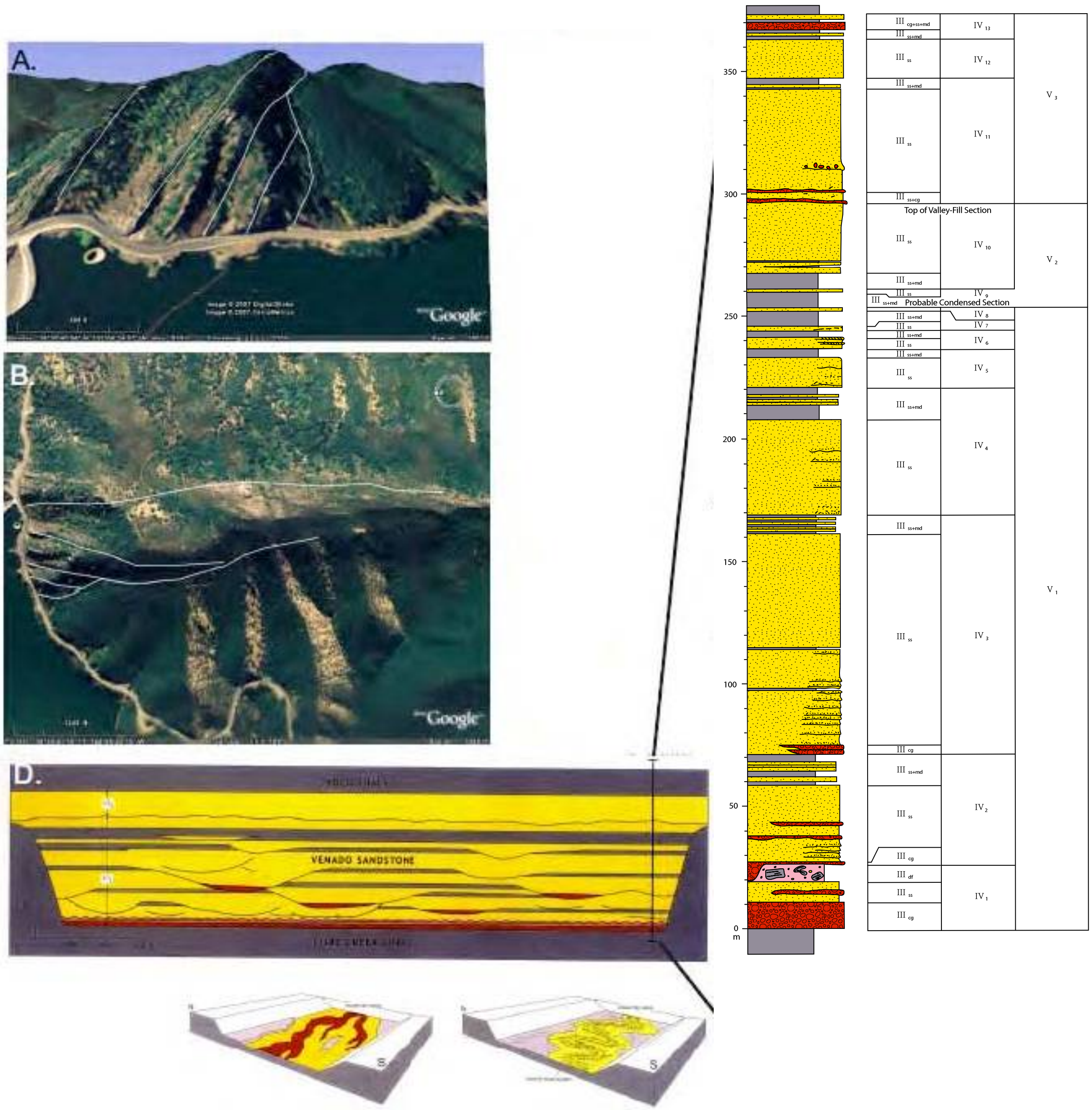
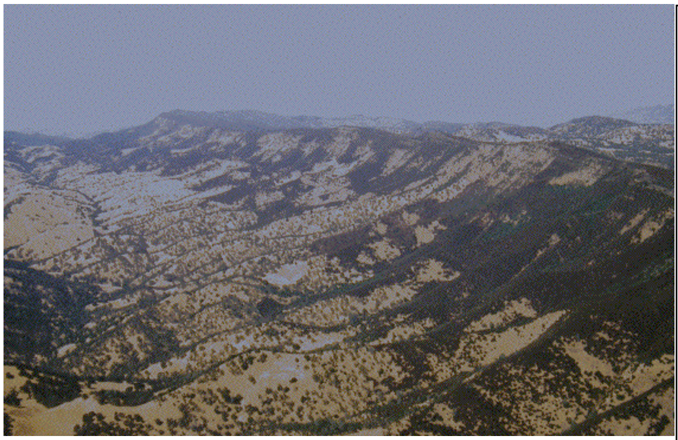


Figure 2.6: Stop 2.9 - Monticello Dam, Lake Berryessa. A) Google Earth perspective view map of the Venado Sandstone showing the incision surface and valley fill. Stratigraphicup is to the left. B) Map view of outcrop in Part A. Stratigraphicup is toward the top. C) Stratigraphic section of Monticello Dam outcrop (taken from Lowe, 2004). D) Schematic crosssection and map views of the Venado Sandstone deepwater depositional setting (taken from Lowe, 2004).



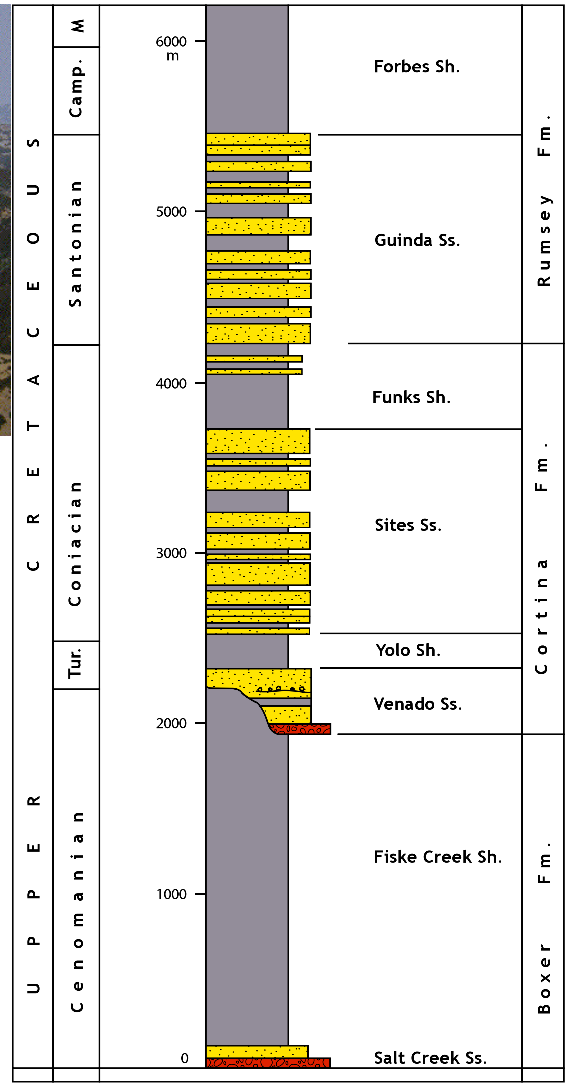


Figure 2.7: A View of the prominent north-south ridge formed by the resistant Venado Sandstone between Monticello Dam and Cache Creek. The low slopes in the foreground and to the left (west) are underlain by non-resistant mudstones of the Fiske Creek Shale. The upper half of the ridge consists of thick-bedded sandstones of the Venado Formation striking roughly north-south and dipping to the east (right). B Stratigraphy of Upper Cretaceous rocks of the Great Valley Group along the west side of the Sacramento Valley. The formations represent petrofacies and are defined and identified based on QFL compositions (from Lowe, 2004).

Stop 2.9a – Basal Great Valley unit (Knoxville), volcanic breccias, Stony Creek Fm.

GPS Coordinates:

38°26'44.23"N, 122°11'47.47"W

Directions:

Depart Stop 2.9
Continue **W** on **CA-128 W** toward **Lake Berryessa Exd** (10.3 mi)
Destination (road-cut) will be on **R**

Stop Description: *(modified from Ingersoll et al., 1984)*

Rocks exposed in the road cut are near the base of the Great Valley Group and are part of the Stony Creek Formation. The exposed sandstone beds contain high percentages of basaltic and/or andesitic volcanic lithic fragments. Bedding characteristics suggest deposition as outer fan depositional lobes. The beds are overturned and constitute three negative cycles.

Stop 2.10 – SW Lake Berryessa: sedimentary serpentinite within basal GV group

(Stop #4 of Moores et al., 2006)

Significance:

Here we see the basal contact of a sedimentary serpentinite unit of the northern Great Valley Group, the Mysterious Valley Formation.

GPS Coordinates:

38°30'29.10"N, 122°12'35.10"W

Directions:

Depart Stop 2.9a
Continue **W** on **CA-128 W** toward **Lake Berryessa Exd** (10.4 mi)
Turn **R** onto **CA-128 W/Capell Valley Rd** (4.8 mi)
Turn **R** onto **Berryessa Knoxville Rd/Knoxville Rd** (3.0 mi)
Destination (road cut) will be on **L** past parking area

Stop Description: *(modified from Moores et al., 2006).*

Here we will view the basal contact of a sedimentary serpentinite unit of the northern Great Valley Group, the Mysterious Valley Formation of Phipps (1984). On the north side of the road (across from the parking area) serpentinite is exposed, some of which is not in place because it has been transported by landslides, such as the landslide on which an electric substation visible to the NE was built. This serpentinite appears somewhat disaggregated, although the slope movement probably influences the appearance of the rock here. We will walk NE along the road for a few hundred feet. The road-cut exposes a contact of serpentinite over shales of the Great Valley Group. The base of the serpentinite unit is marked by a conglomerate that contains gabbro and other mafic clasts. This contact indicates that this serpentinite is sedimentary in nature. The sedimentary serpentinite may have originated as serpentinite mud volcano deposits similar to those found in the forearc of the Marianas, overlying an active intra-oceanic subduction zone (Fryer et al., 2000).

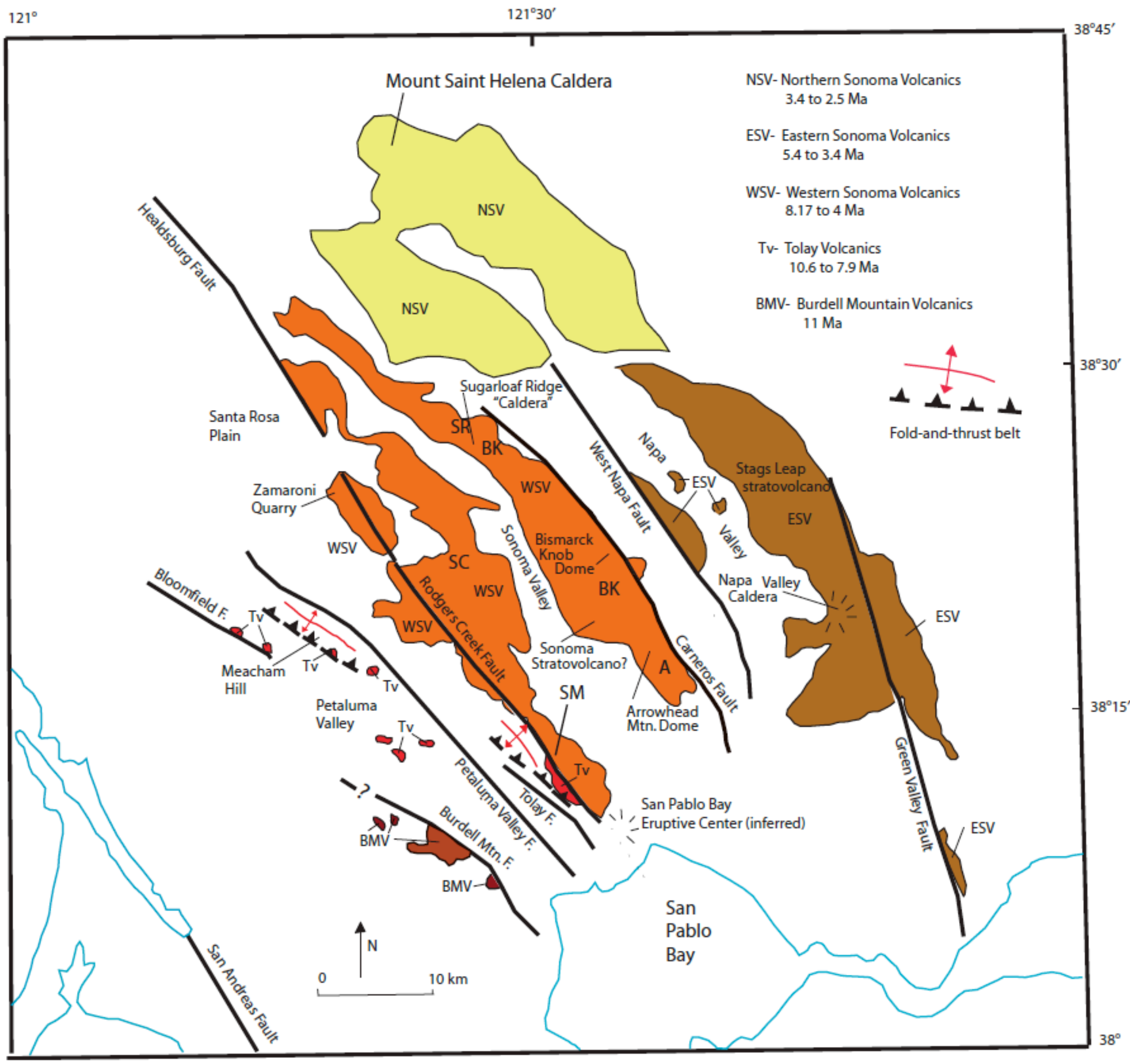
Continue on to Bothe Campground in Napa County. Dinner and campfire (…and wine?).

Directions: *(approx. 35 mins)*

Depart Stop 2.10; return to CA-128
Turn **R/W** on **CA-128 W (Sage Canyon Rd)** toward St. Helena (11.2 mi)

After 7.5 im, optional Stop 2.8 ***Lake Hennessey Dam.*** *Multiple exposures of Franciscan serpentinite mélange can be seen along the side of the road.*

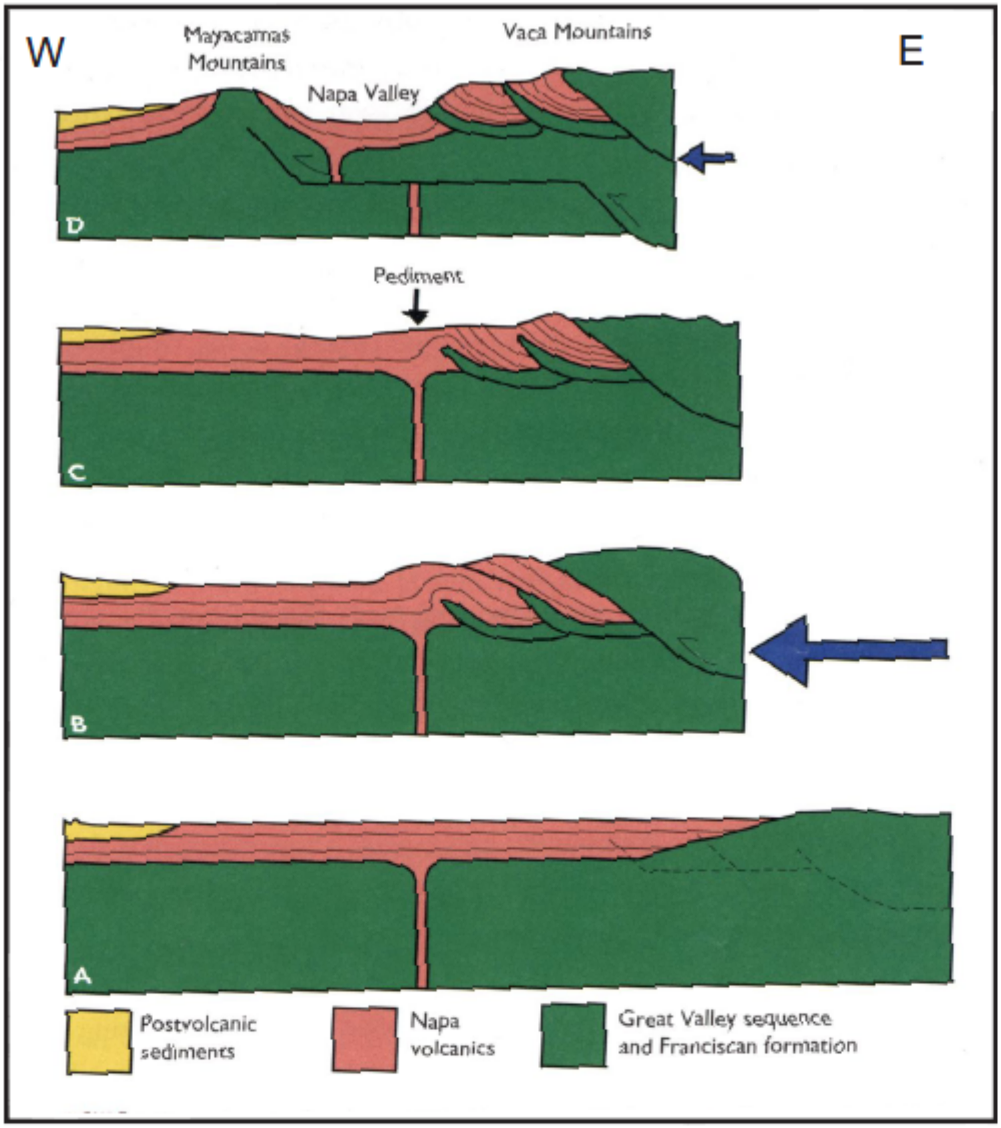
Turn **R /NW** onto **CA-128 E/Silverado Trail S** (1.3 mi)
Turn **L/SW** onto **Zinfandel Lane** (1.4 mi)
Turn **R/NW** onto **CA-128 W CA-29 N/St Helena Hwy** (6.9 mi through St. Helena)
Turn **L/S** into Bothe State Park, and double back to E 0.3 mi to Park HQ
Turn **R** to Ritchey Creek Campground (0.4 mi)



Volcanic fields, eruptive centers, and major faults (Wagner et al., Geosphere, 2011).

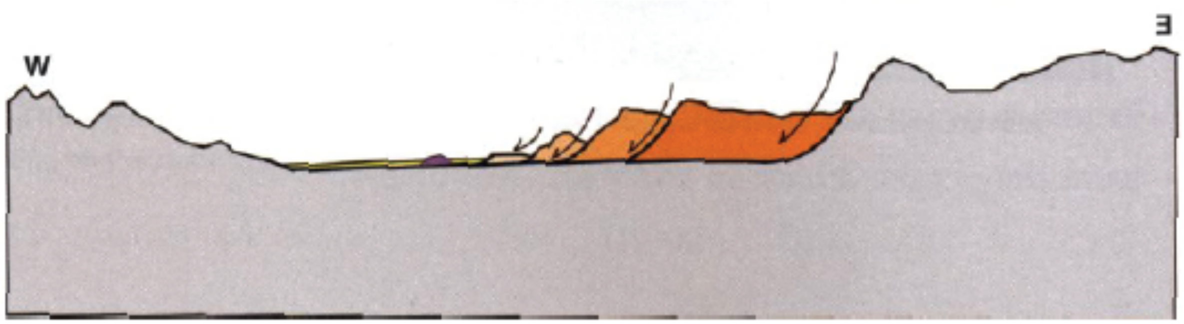
Geologic notes while driving:

When we crosses the dam/spillway of Lake Hennessey on CA128, we are crossing into the Sonoma Volcanics of the Stag's Leap stratovolcano , then out of the Vaca Mountains into Napa Valley. Not long after and during the Sonoma Volcanics were laid down, an interpreted restraining bend of the San Andreas Fault produced uplift in this part of the Coast Ranges causing the Vaca Mountains to uplift, erode a pediment surface, and uplift again many times. The degree of deformation increased from east to west causing much more complexity in the Vaca Mountains than the Mayacamas Mountains. Consequently there are preserved pediment surfaces in the Vaca Mountains now occupied by vineyards (Swinchatt & Howell, 2004). We drive north up Napa Valley (bounded to the west by West Napa Fault that terminates near St. Helena, and camp on Northern Sonoma volcanics.

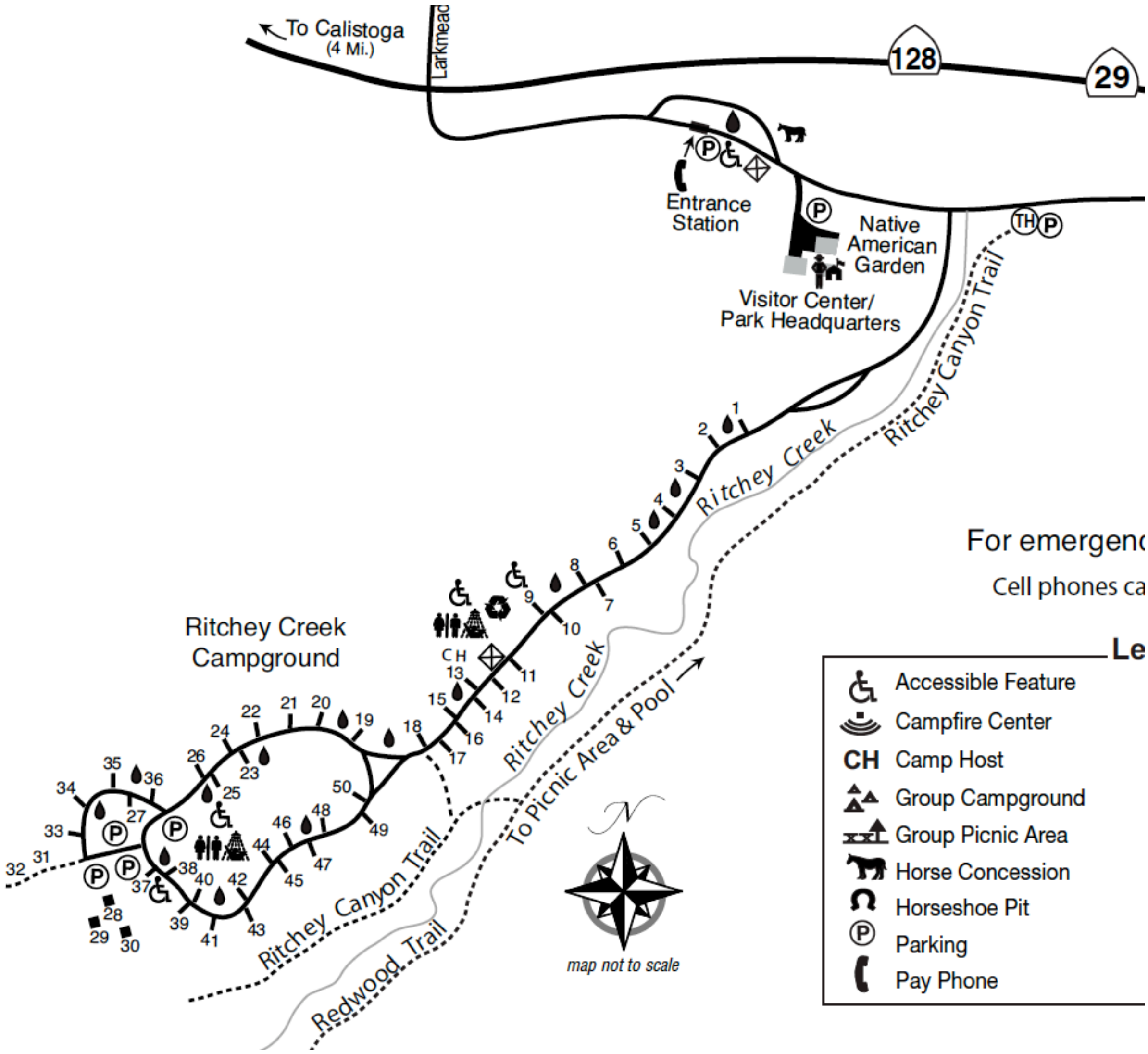


Schematic cross-sections through Napa Valley showing progressive east-to-west compression causing uplift and pediment surface formation in the Vaca Mountains (Swinchatt and Howell, 2004).

Following uplift of the Vaca and Mayacamas Mountains, a releasing bend of the San Andreas Fault induced a pull-apart basin that is now the physiographic expression of the Napa Valley. As the basin filled, gravitational sliding of massive blocks from the Vaca Mountains ensued (figure). The blocks were diverse in origin containing pieces of disrupted Fanciscan, ophiolite, GVG rocks, and volcanics. Many tips of these slide blocks are still visible in the middle of Napa Valley. In fact, most of the topography in the middle of the valley are exposed tips of buried slide blocks (Swinchatt and Howell, 2004).



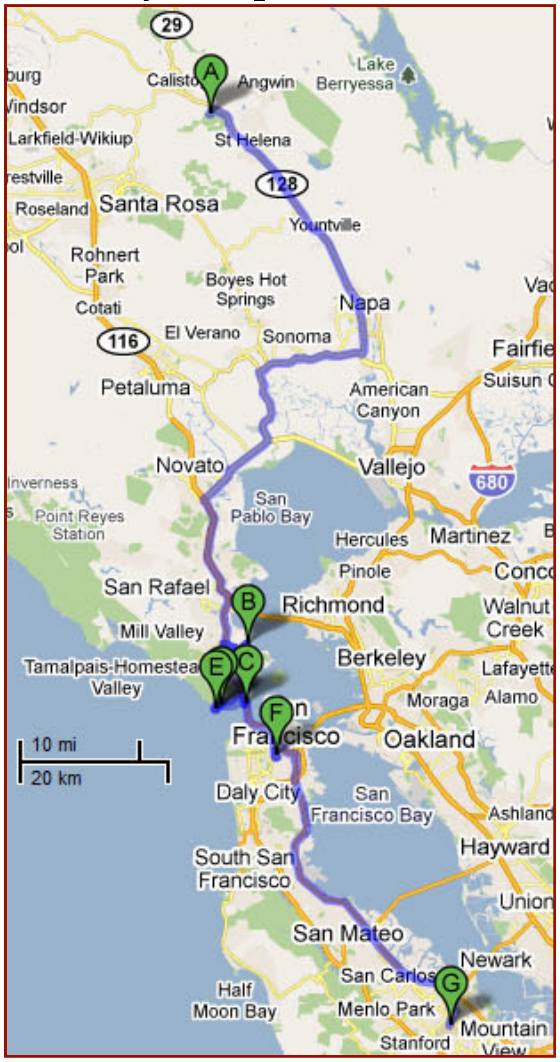
Once the gravitational sliding slowed, alluvial fans began to fill the basin. Depending on the point source of the alluvial fan, the composition of each fan was unique. In addition, facies variations in alluvial fan produced a variety of sedimentary textures: axial channels, overbank to channels, debris flow deposits, etc. Therefore, the end product of the soils - and the terroirs that produce the Napa Valley wines - is a combination of the rock type that sourced the alluvial fan as well as the alluvial fan facies (Swinchatt and Howell, 2004).



Map of Ritchey Creek Campground

*** End Day 2 ***

Day 3: Franciscan Accretionary Complex and the San Andreas Fault



A: Start – Bothe Campground in Napa County

B: Stop 3.1 – Ring Mountain

C: Stop 3.2 – Marin Headlands

E: Stop 3.3 – Point Bonita Lighthouse

F: Stop 3.4 – Corona Heights Fault in San Francisco

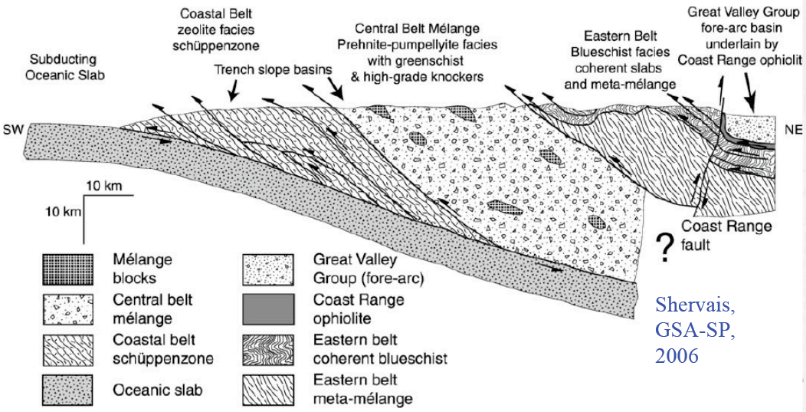
G: Stanford University

Continue on to Stanford University and Conclude the Field Trip

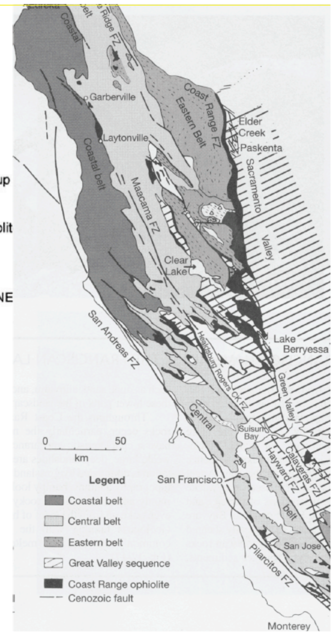
On the morning of Day 3 we will drive west across the Northern Sonoma volcanics of the Mayacamas Mountains, the southern tip of the Maacama Fault, the Western Sonoma Volcanics, and cross the Healdsburg (Rodgers Creek) Fault to join 101 at Santa Rosa.

Franciscan Terranes:

Progressive accretion (outward growth) by underthrusting:
oldest accreted rocks at **top** of wedge; &
oldest rocks on **inboard** (arc) side of wedge



Shervais, GSA-SP, 2006



Coastal
•coherent imbricates & "broken formation"
•zeolite facies

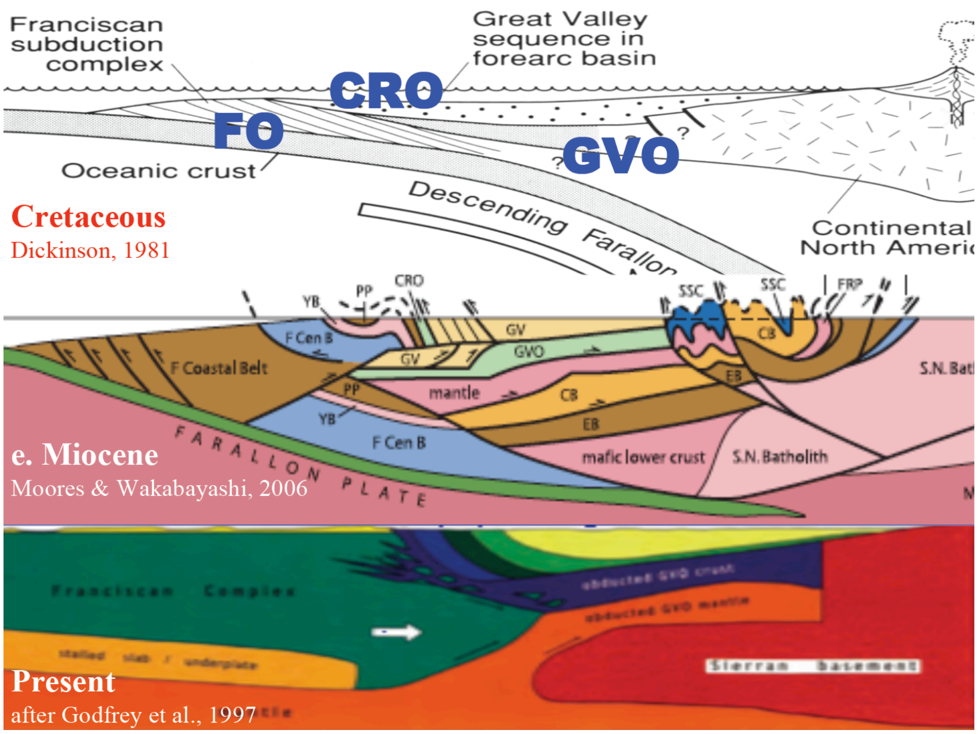
•greywacke-argillite

Central
•classic mélange knockers in scaly clay
•pp-blueschist-eclogite
•greywacke, basalt, diabase, peridotite, serpentinite, chert, lst

Eastern
•schistose coherent thrust sheets
•blueschist

•greywacke, basalt

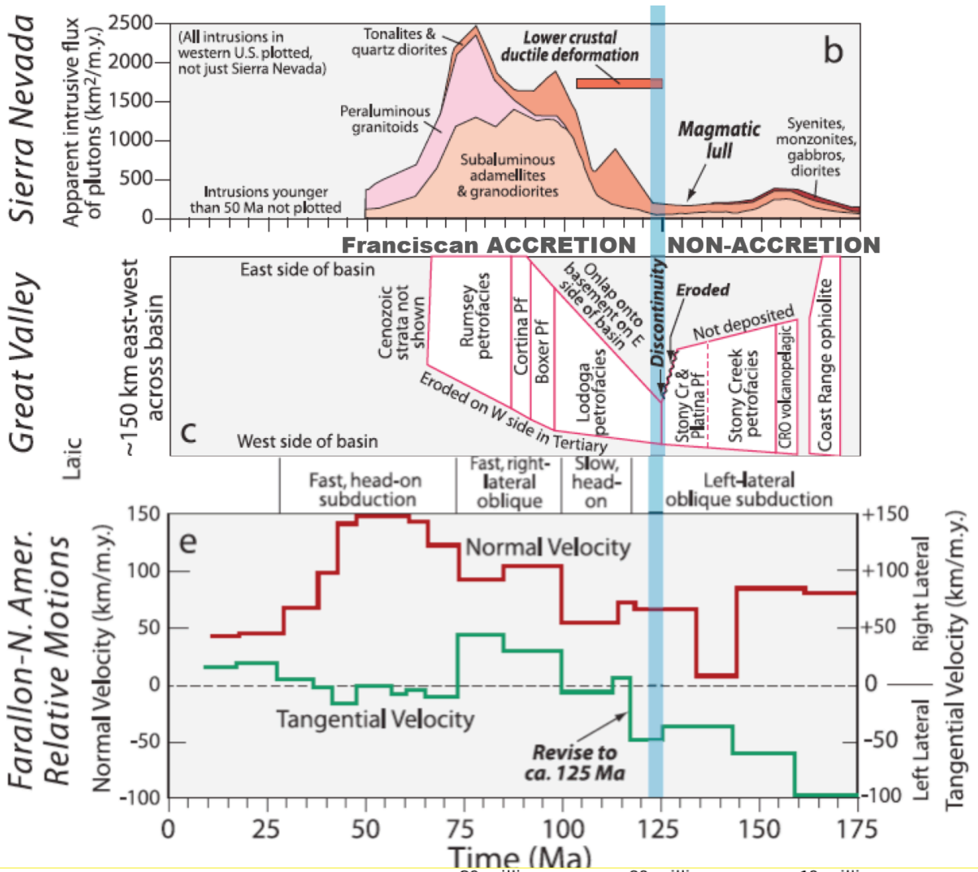
Post-accretion (San Andreas) deformation folded the fault contacts: outcrop patterns become more complex southward



Cretaceous
Dickinson, 1981

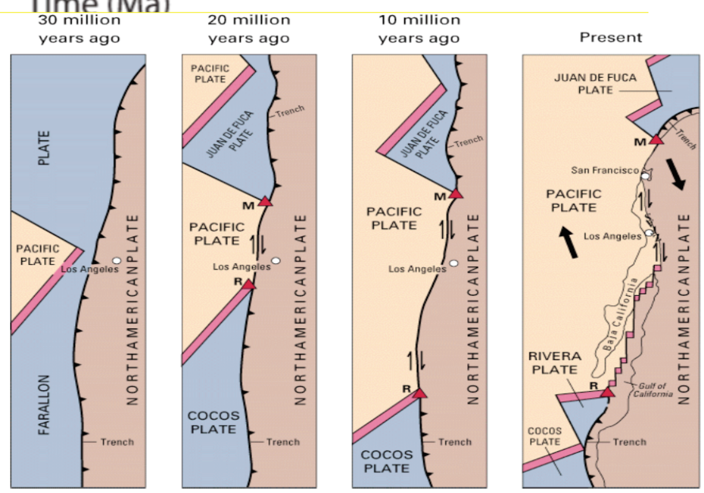
e. Miocene
Moores & Wakabayashi, 2006

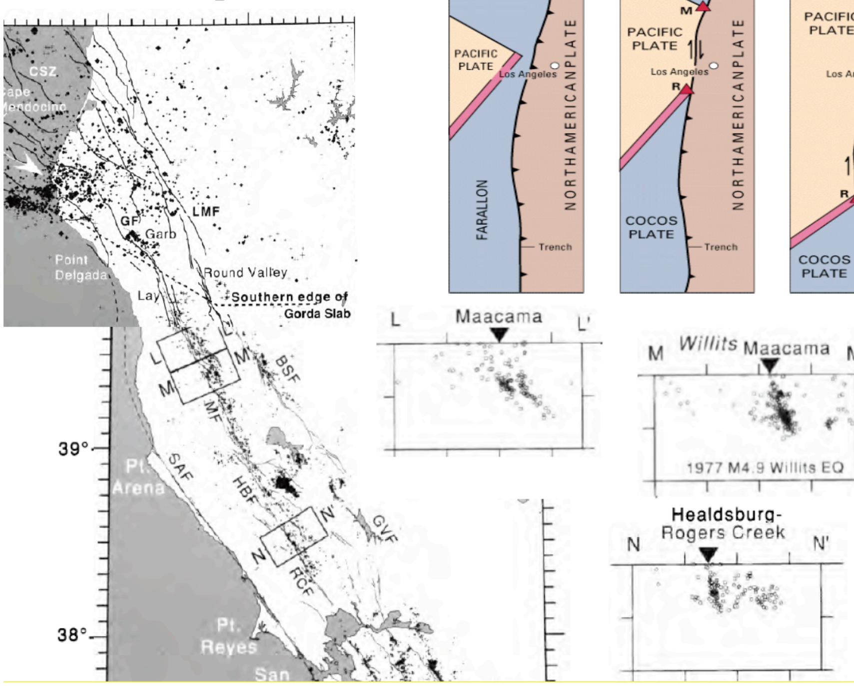
Present
after Godfrey et al., 1997



Dumitru et al., Tectonics, 2010

Formation of "Slap Gap", lengthening of San Andreas fault, and northward migration of Mendocino Triple Junction





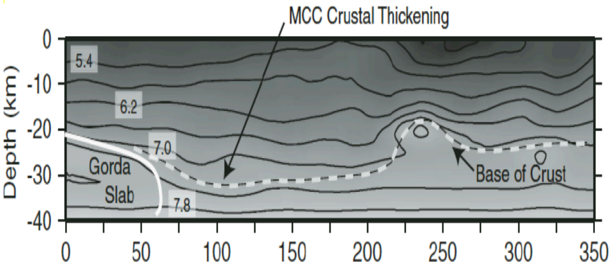
Individual strands of San Andreas may initiate on dipping subduction thrusts, then gradually rotate to vertical, and organise into a single SAF

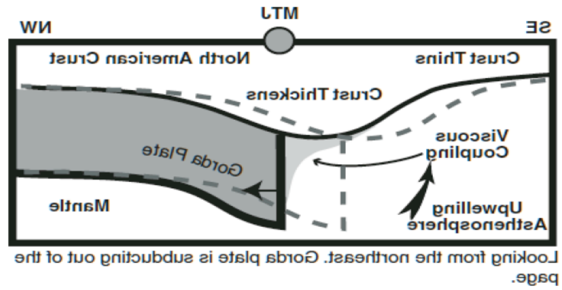
Castillo & Ellsworth, JGR, 1993

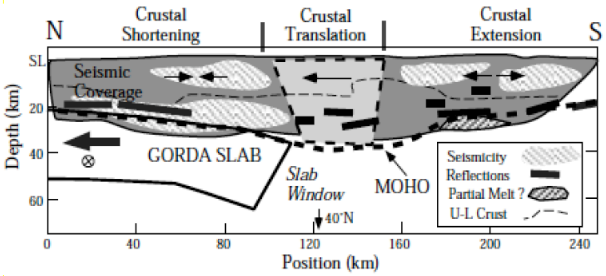
"Mendocino Crustal Conveyor"

Furlong & Govers, Geology, 1999

North American crust is ephemerally thickened then thinned over a few hundred km (≤ 5 m.y.), due to viscous coupling between north-migrating Gorda slab and the base of North America south of the MTJ





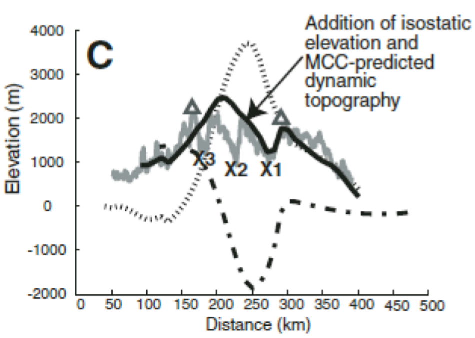


Lock et al., GSAB, 2006

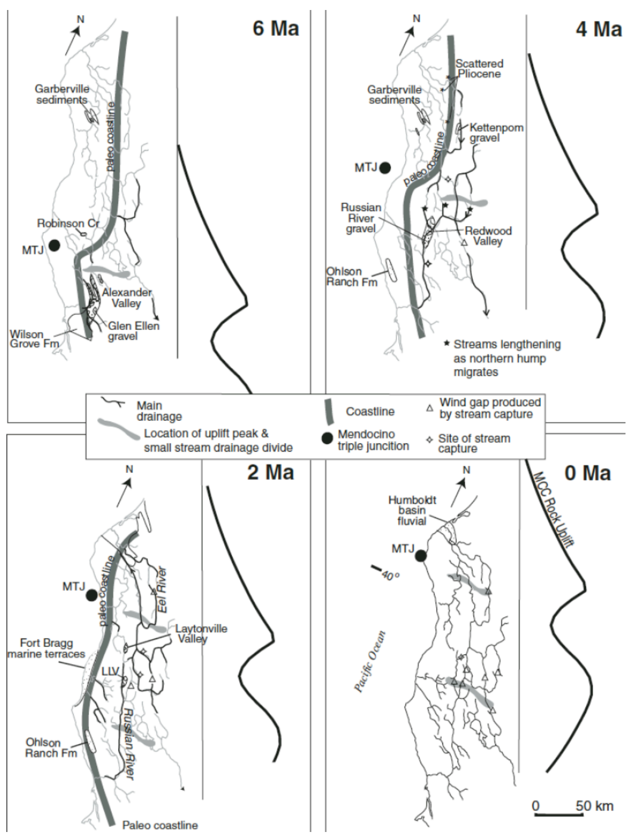
1/ Sub-horizontal flow induced in the slab window by migration of the Gorda plate produces "low pressure" and downward flexure (≤ -2 km; λ ~100 km) centered on the southern edge of the slab.

2/ Asthenospheric flow into slab window gives surface uplift ~100–150 km south of slab edge (≤ 1 km; λ ≥100 km)

Mendocino Crustal Conveyor predicts northward migration of shoreline and sedimentary facies; anomalous coast-parallel drainage systems (Russian River); northward migration of drainage divides



Triangles: two main drainage divides,
cf. two peaks of MCC-predicted uplift
X1, X2, X3: E-W trending cross streams of the Eel River.



Lock et al., GSAB, 2006

Stop 3.1 - Ring Mountain (Stop 2 Moores et al., 2006)

Significance:

This site provides an excellent exposure of Franciscan high-grade tectonic blocks in a disordered unit (mélange) in the highest structural horizon of the Franciscan Complex in the San Francisco Bay Area.

Directions: *(about 90 minutes)*

Depart Bothe Campground in Napa County

Turn **L/NW** onto **CA-128 W / CA-29 N / St Helena Highway** (4.4 mi)

Pass through Calistoga, home of "Old Faithful" geyser that erupts every 30 mins, and may (Paul Silver) or may not (Michael Manga) have exhibited precursory interval lengthening 2.5 days prior to the Loma Prieta earthquake. Fluids have high B/Cl ratios, indicating a mixture of meteoric and connate water from Cretaceous marine sedimentary rocks: can Great Valley sequence be present beneath the Sonoma volcanics? (Stevens & Cooper, SEPM, 2005)

Turn **L/W** on **Petrified Forest Road** (4.4 mi)

Petrified Forest is a private attraction in which numerous large silicified Sequia langsdorfii (also avocado and oak)were felled by a lateral blast and/or ash-flow from the NNE (Mt St. Helena – the presumed caldera source of the eruption), buried and petrified by the Tuff of the Petrified Forest between 3.34 and 3.19 Ma (Stevens & Cooper, SEPM, 2005). Trees are up to 8ft in diameter, up to 100 ft in length.

($5 to tour the Main Trail (1/2 mile, 15 mins around the Petrified Tree exhibits; or free entry to the Store to buy your own piece of petrified wood …)

Continue onto Calistoga Rd (5.3 mi)

Crossing (poorly to un-exposed) sheared mélange and serpentinite of Franciscan Central Belt, then the southern tip of the Maacama Fault Zone into (poorly to un-exposed) basalts of Western Sonoma Volcanics

Turn L/S to stay on Calistoga Rd (1.8 mi)

Entering Rincon Valley and the Santa Rosa pull-apart basin associated with the right step from the Rodgers Creek-Healdsburg fault zone to the Bennett Valley-Maacama fault zone

Turn R/W on CA-12 (2.4 mi)

Turn L/S onto Farmers Lane (0.9 mi)

Farmers Lane runs over the buried connection between the Rodgers Creek Fault (to the south) and the Healdsburg Fault (to the north) location of M 5.6 and 5.7 earthquakes in October 1969.

Merge right onto CA12W (1.7 mi)

Santa Rosa Plain

Merge onto **US 101 S** to San Francisco (39.8 mi)
Take exit 449A for Tamalpais Dr toward Paradise Drive
Keep **right** at the fork, follow signs for Corte Madera/Larkspur (0.1 mi)
Turn **L/E** onto **Tamalpais Dr** (0.2 mi)
Slight **R** to stay on **Tamalpais Dr** (443 ft)
Slight **R** onto **San Clemente Dr** (0.5 mi)
Continue onto Paradise Dr (1.6 mi)
Turn **R/S** onto **Taylor Rd**, continue to parking lot (0.7 mi)

GPS Coordinates:
37°54.181′N, 122°28.925′W

Stop Description: *(Moores et al., 2006; Konigsmark, 2006; Shervais et al., 2010)*

Even the non-geologist finds the high-grade metamorphic blocks of Ring Mountain on Tiburon Peninsula exceptionally interesting (these high-grade blocks are coarsely crystalline metamorphic rocks whose minerals indicate high-pressure–low-temperature recrystallization in a subduction zone). **Rockhounds take heed:** This stop is entirely on a protected natural preserve— collecting of rocks is prohibited (one can gawk but not bash or take).

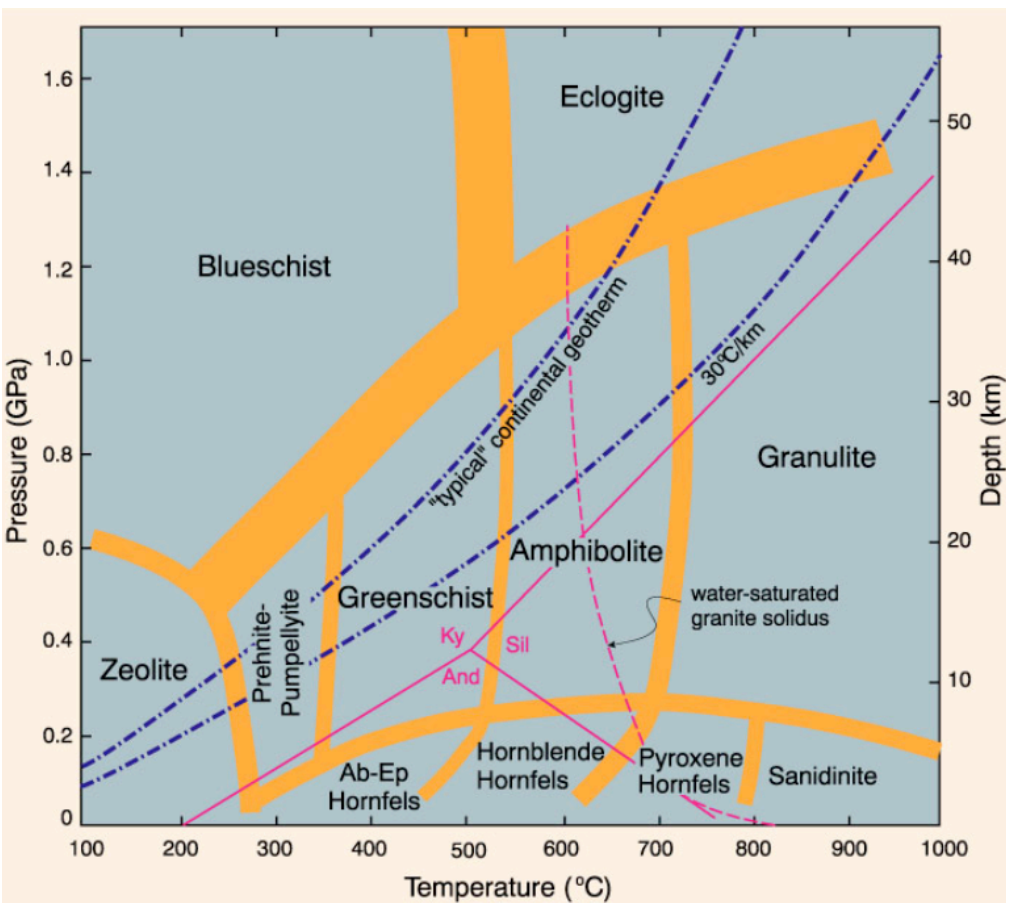
Ring Mountain is probably the best place in the Franciscan Complex to examine high-grade tectonic blocks because of the tremendous variety and number of mineral assemblages. The rocks appear in a serpentinite-matrix mélange that is structurally beneath a sheet of serpentinite (Bero, 2003) and structurally above a stack of coherent Franciscan thrust units or nappes (Blake et al., 1974; Wakabayashi, 1992). Landslides have displaced many of the blocks downslope.

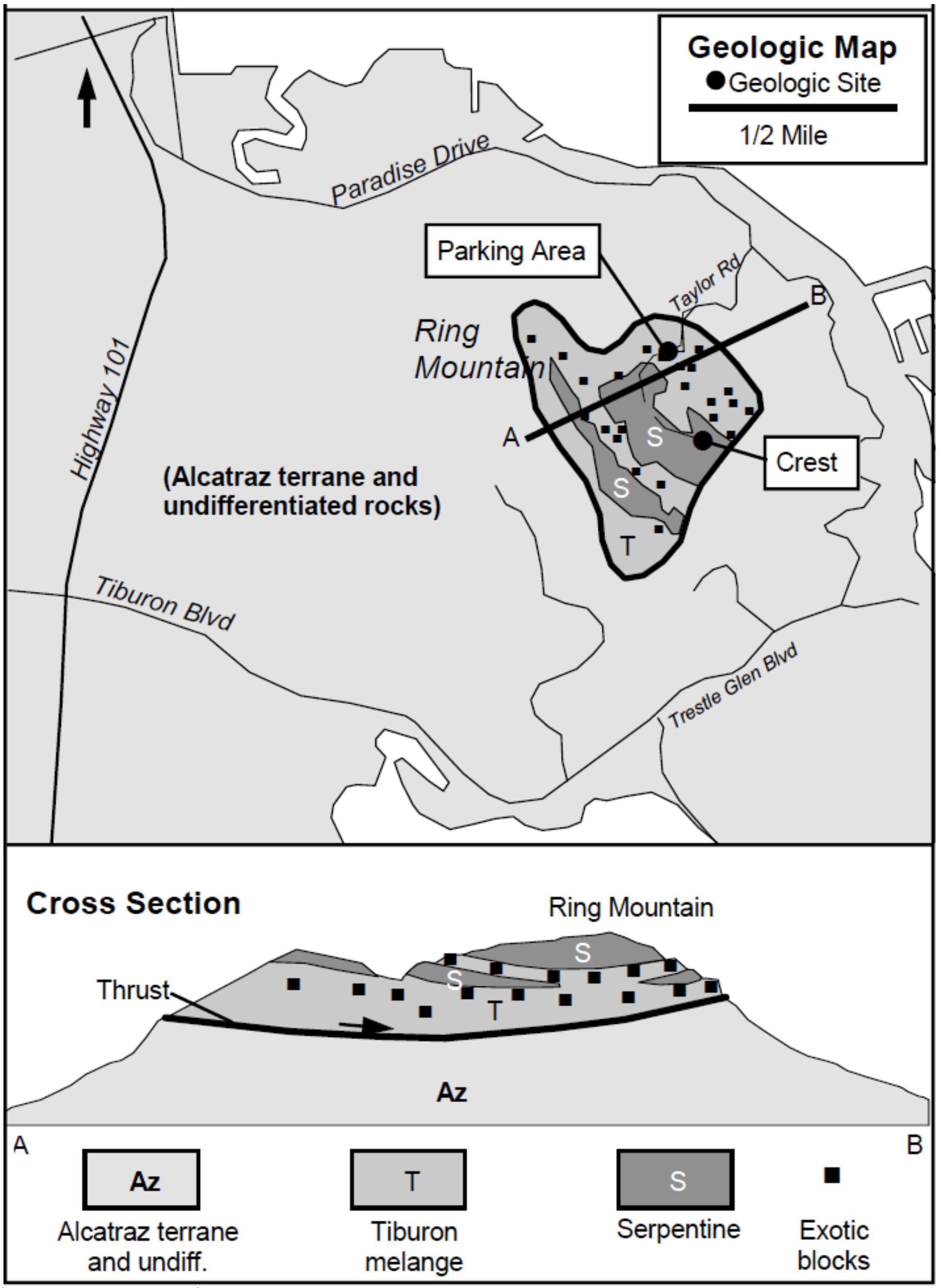
In and adjacent to the parking area are a number of large isolated boulders of varying size - exotic blocks or knockers in the Tiburon mélange from which the soft clay has been washed away. Some blocks have a rind of chlorite or talc, and almost all are schistose. Some of the more common metamorphic rocks include amphibolites, eclogites, and blueschists. The amphibolites have dark elongated crystals, sometimes up to two inches long. The blueschists appear as very dark blue layers within the schists. The eclogites have small red crystals of garnet. Glaucophane and lawsonite formed under these low temperature-high pressure conditions from original amphiboles and feldspars.

Continue on the path to the crest of Ring Mountain, formed from two thick sub-horizontal layers of light yellow-brown serpentine. These layers represent coherent pieces of the ocean crust of the Farallon plate that were incorporated into the Tiburon melange. The serpentine on the crest of Ring Mountain resists weathering and forms hard blocky outcrops. On fresh exposures, the rock is pale green, sometimes with dark specks, remnants of pyroxene crystals that have been altered to serpentine. In places, some large blocks of this serpentine have broken off and are slowly sliding down the side of the mountain, lubricated by the soft and slippery clay of the underlying Tiburon melange. Soils formed from serpentine (iron and magnesium silicate) are characterized by anomalous plant life - there is almost no aluminum, so no clay soil is formed and the soil is thin and gravelly. The serpentine also has toxic amounts of magnesium, nickel, chromium and cobalt, and is low in plant nutrients such as potassium, sodium, calcium, and phosphorus. Some of the unusual plants at Ring Mountain include Tiburon Indian paintbrush, Oakland Star tulip, and the very rare Tiburon Mariposa lily, whose only natural occurrence is at Ring Mountain, found especially among the blocky serpentine boulders and outcrops where there are springs and where the lily is protected from grazing. The plant is about two feet high and blooms in May and June with cinnamon-and-yellow flowers.

The high-grade blocks display metamorphic minerals of several millimeters to several centimeters in size. They include amphibolites (composed of amphibole and other minerals), eclogites (composed of garnet and Na-rich pyroxene, called omphacite), and blueschists (characterized by blue amphibole minerals) that exhibit the oldest ages of metamorphism of any rocks in the Franciscan Complex (Coleman and Lanphere, 1971). Most blocks exhibit an earlier higher temperature (amphibolite grade) metamorphism (Blake et al., 1984; Moore and Blake, 1989). These high-grade blocks constitute but a tiny fraction of Franciscan metamorphic rocks, but they are arresting in appearance. They also record an interesting tectonic history involving high temperature recrystallization (500–700 °C) followed by deep burial in the Franciscan subduction zone. The eclogite-facies assemblage comprises garnet + omphacite + epidote ± hornblende. The blueschist-facies assemblage comprises chlorite + titanite + glaucophane + epidote ±albite ± phengite. New P-T calculations by Tsujimori et al. (2006) yield T~550-620ºC and P~22-25 Kb for peak eclogite conditions and a tight counter-clockwise P-T-t path that implies metamorphism of a relatively cold subducting slab. Wakabayashi and Dumitru (2007) have documented metamorphic ages in high-grade Franciscan rocks that range from ~120 Ma to ~160 Ma – a span of some 40 Ma. The high-grade assemblages in most blocks have oceanic island basalt chemistry. More widespread sheets of Franciscan metamorphic rocks, which are generally much finer grained (minerals generally tenths of millimeters and smaller) and of lower metamorphic grade, are commonly referred to as coherent blueschists (because of the presence of blue-colored metamorphic minerals) or coherent metamorphic rocks. These blueschists make up a significant part of the Franciscan Complex. Because of their fine grain size, however, they are visually rather disappointing.

Be on the lookout for Native American petroglyphs carved into chlorite schists, a soft but weather resistant rock.





(Konigsmark, 2006)

Stop 3.2 - Marin Headlands, Battery 129 (Elder, 2001; Konigsmark, 1998; see also (Stop 1 Moores et al., 2006)

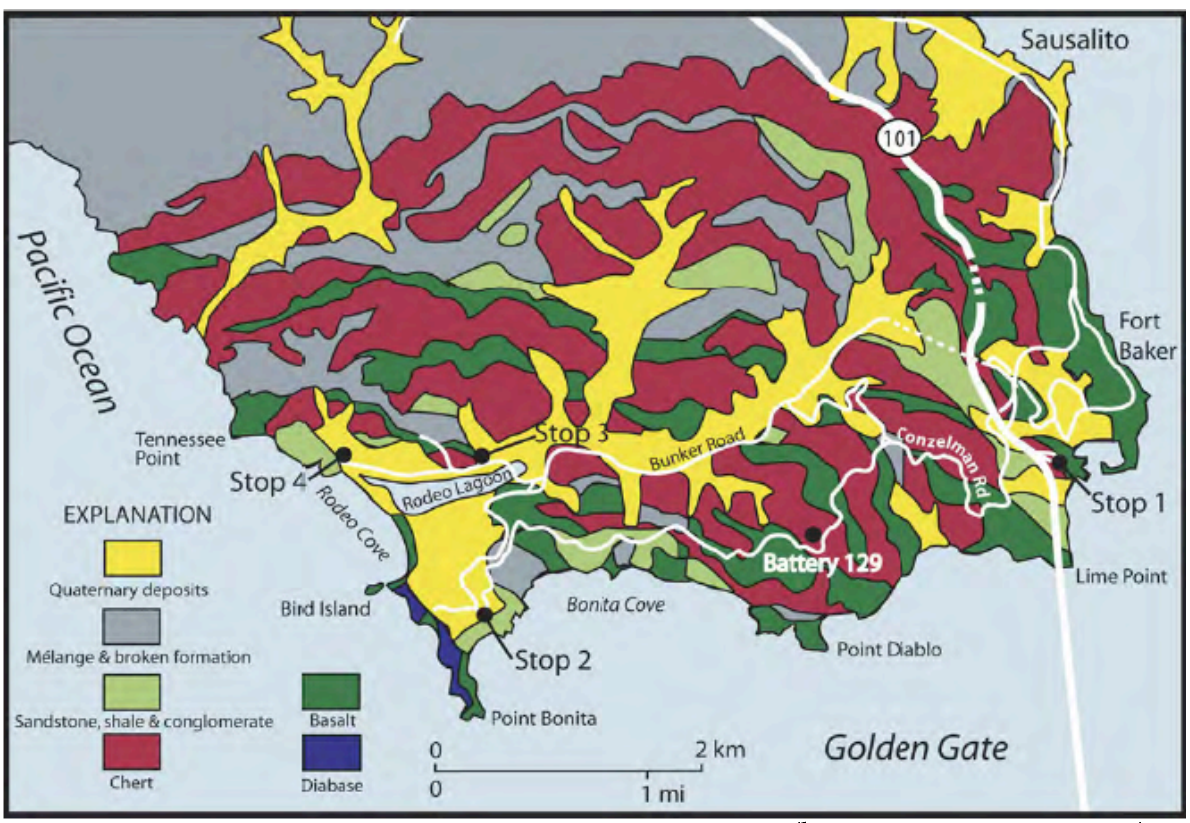
Significance: *(Moores et al., 2006)*

This site displays an excellent exposure of oceanic basalt and red chert of the Marin Headlands terrane in the Franciscan Complex.

GPS Coordinates: 37°54.79"N 122° 29.21'W

Directions: (about 25 mins)

Depart Stop 3.1
Return N on Taylor Rd (0.7 mi)
Turn R/SE onto Paradise Dr (0.1 mi)
Turn L to stay on Paradise Dr (1.3 mi)
Turn **L/W** onto **Trestle Glen Boulevard** (0.6 mi)
Turn **R/W** onto **CA-131 W / Tiburon Boulevard** (1.8 mi)
Merge onto **US-101 S** via the ramp to San Francisco (5.6 mi)
Take exit **442** toward Sausalito (300 ft)
Turn R onto **Alexander Ave** and loop back N under the freeway (0.3 mi)
Half L/NW onto Danes Dr (0.1 mi)
Continue straight onto Bunker Rd, through one-lane tunnel (5 min traffic light) (1.1 mi)
L onto McCullough Rd (0.9 mi)
At the traffic circle, take the 2nd exit (S)onto Upper **Conzelman Road** (0.7 mi)
Pull into the parking area at Battery 129, north side of road.



Elder, 2001. Battery 129 is our Stop 3.2; Stop 2 is our Stop 3.3 (hike towards Point Bonita)

Stop Description: *(Shervais et al., 2010; Elder, 2001; Moores et al., 2006)*

The Marin Headlands terrane represents an oceanic plateau that now forms an enormous discrete block within the Franciscan Central Belt mélange. The Marin Headlands itself is the northern buttress of the Golden Gate, with spectacular cliffs that anchor the northern rampart of the Golden Gate Bridge.

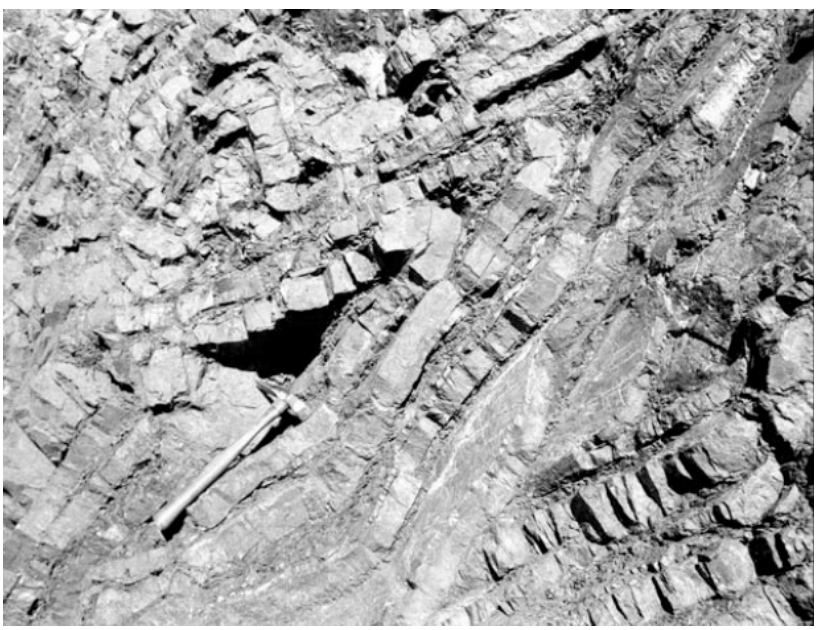
The Marin Headlands terrane comprises an enormous pile of pillow lava overlain by thick sections of classic red ribbon chert that ranges in age from late Pliensbachian (early Jurassic c. 200 Ma) to early Cenomanian (middle Cretaceous c. 100 Ma) – a span of some 100 Ma (Murchey 1984). Approximately 95 Ma, deposition of the dirty sandstone ("greywacke") on top of the chert occurred as this piece of ocean floor neared the Franciscan trench and was incorporated into the Franciscan Complex (Wahrhaftig, 1984). Based on studies of the radiolarian fossils (radiolaria are unicellular floating plants that produce a siliceous shell) in the cherts and on paleomagnetic studies, the 80-m-thick chert section was deposited near the paleo-equator and drifted northwards prior to emplacement (Hagstrum and Murchey, 1993). One can see the radiolaria in the rock (best on a freshly broken, wet surface) with a hand lens. These appear as round, somewhat darker dots, set in the dark red-brown matrix of the chert.

Elder, 2001. Ribbon chert in depositional contact with pillow basalt at Battery 129.

The pillow lava-chert sections have been repeated by thrust faulting along a series of WNW-trending thrust faults (current orientation) that have deformed the pillows and folded the cherts into a series of open chevron folds. Basalts of the Marin Headlands terrane are oceanic tholeiites suggesting its formation at an oceanic spreading center (Shervais, 1989). Based on their geochemistry and local field relations, most volcanic rocks within the Franciscan Complex appear to have formed at spreading ridges or were away from the spreading ridge on seamounts or thick volcanic accumulations called oceanic plateaus (Shervais, 1990). Pillow lavas dominate, but sheet flows and diabase dikes are also found.

As with other tectonic units within the Franciscan Complex, in this region, the terranes are actually tabular rock units that may represent thrust sheets, or nappes. In many places, the chert is faulted against basalt, but locally its original depositional contact on basalt is preserved. Elsewhere in the Marin Headlands, dirty brown-gray sandstone and shale depositionally overly the chert. Metamorphism of these rocks is minor, and igneous and sedimentary features are well preserved (Swanson and Schiffman, 1979; Blake et al., 1984). These rocks probably were buried to a depth of less than 15 km during subduction.

Battery 129 is on a hill that of red chert of the Marin Headlands terrane. This hill is a classic viewpoint for Golden Gate Bridge. In September and October, thousands of migrating birds of prey concentrate at this hill, called Hawk Hill, before crossing the Golden Gate. At the north end of the parking area the chert rests in depositional contact on the pillow basalt. This red chert is also referred to as ribbon chert for its characteristic alternating layers of hard red chert and soft red shale. The chert layers are about two inches thick, and the red shale layers are ususally less than one-half inch thick. Radiolaria commonly make up from 10% to 50% of the chert. The red shale between the chert layers is fine mineral dust from the atmosphere that fell into the ocean and accumulated in the silica gel on the sea floor. The red color indicates the oxidized state of the iron in this siliceous rock. Light green to white chert beds also are present, but are much less common and occur in the mid to upper parts of the section. Chert lying near the basalt contact has a silvery gray to black manganese-oxide staining. This manganese is probably related to both hydrothermal and hydrogenous Mn associated with the spreading ridge (Karl, 1984). In general, the bedding thickness decreases and the shale content increases upsection. The observed upsection decrease in bedding thickness is consistent with a depositional site that was moving northward, out of the equatorial high-productivity zone, thus resulting in progressively thinner bedding cycles (Karl, 1984). The general lack of terrigenous, continental-derived sediments throughout the sequence implies that it was deposited far offshore, probably more than 1,000 km (600 miles), if there was no topographic barrier to impede continental sediment supply (Karl, 1984).



(Konigsmark, 1998). Bedding rhythms developed in ribbon chert along Conzelman Road. Diagenetic transfer of silica has enhanced the bedding. The chert has been bent into a small fold along the axis of the hammer.

Because of the prominent thin bedding, these rocks are commonly called ribbon chert. The prominent rhythmic bedding of the cherts is one of their most distinguishing features (fig. 3.11). The contrast between the hard chert beds and the intervening shale beds has been magnified by diagenesis following deposition. Subtle original compositional differences would have been enhanced as silica moved from the less silica-rich zones to the more silica-rich beds during diagenesis, in which opal-A silica from radiolarian shells was transformed into opal-CT silica, and ultimately to quartz (Tada, 1991). However, the origin of the primary compositional differences is debatable. Karl (1984) concluded that the bedding was produced by periodic submarine landslides (dilute turbidity currents) that occurred on the flank of the mid-ocean ridge. Predominately lenticular bedding and some internal sedimentary features are consistent with this origin. Alternatively, the rhythmic bedding may represent periodic changes in oceanic upwelling and siliceous productivity, possibly developed in response to the Earth's orbital cycles (Decker, 1991). A growing body of literature indicates that the Earth's 21,000, 41,000 and 100,000 year orbital cycles, as well as others, are reflected in biogenic sedimentary sequences (Fischer, 1991). In any case, diagenesis would have enhanced the cycles produced by either turbidite or productivity mechanisms.

Locally, the chert is intensely folded, forming complex sharp-crested chevron and isoclinal folds. Such folding is well exposed along Conzelman Road. Most likely, the folding occurred when the Marin Headlands terrane was wedged against the continental margin and subsequently faulted to its present position. However, abrupt changes from only slightly deformed sequences to highly folded areas, and unbroken sharply folded beds, have led to speculation that some of the contorted folding reflects submarine slumping on the flank of the mid-ocean ridge prior to final hardening of the layers (Bailey and others, 1964; Wahrhaftig, 1984a).

Near Battery 129, cream to pink pelagic limestone also is present. The occurrence of these relatively slowly deposited sedimentary rocks indicates periods of volcanic quiescence between pillow lava flows. In addition, the presence of limestone between the pillows demonstrates that the mid-ocean ridge crest was above carbonate compensation depth (CCD), which in today's oceans is typically around 4 km depth, allowing carbonate to be preserved. The lack of limestone in the immediately overlying chert sequence shows that the cooling oceanic plate descended below CCD shortly after it moved away from the ridge crest.

Stop 3.3 - Point Bonita Lighthouse (Stop 3.5 Shervais et al., 2010)

Significance: *(Elder, 2001; Konigsmark, 1998; Shervais et al., 2010)*

Another opportunity to see basaltic pillow lava and intercalated carbonate sediment. Excellent views of the Marin Headlands area, the Golden Gate Bridge, and San Francisco.

GPS Coordinates:

37°48.950′N, 122°31.717′W (approx.)

Directions: (about 5 mins unless there are construction delays)

Depart Stop 3.2
Continue W on Upper Conzelman Road (2.1 mi)
Turn L/S on Fort Barry, passing the Point Bonita parking lot and trailhead (0.3 mi)
Park at Lookout Vista.
From this point we can see Bird Island (covered with white guano), Point Bonita Lighthouse, basalt seacliffs and gun emplacements from the early 20th century.
Return on Fort Barry to the Point Bonita parking lot and trailhead (0.3 mi)
Park and walk the 0.5-mile trail towards the lighthouse: the tunnel and suspension bridge will be closed when we are there.

Stop Description: *(Elder, 2001; Shervais et al., 2010)*

Bonita Point is a small sub-terrane that consists of alkali basalt pillow lava suggesting a seamount or oceanic island site of eruption, although a mid-ocean ridge site near a hot spot is also possible, with intercalated chert and carbonate sediment. This sub-terrane contrasts sharply with the more common tholeiitic pillow lavas and chert of the main Marin Headlands terrane.

This stop will be focused on the pillow basalts (now altered to greenstone) of the Point Bonita block. Alteration of Franciscan Complex basalt, presumably by hot seawater circulating through it at the mid-ocean ridge, has resulted in low-grade metamorphism and the development of the minerals chlorite and pumpellyite. These minerals give the basalt a dark green color and hence its common name, *greenstone*. Basalt in the Marin Headlands is typically deeply weathered, forming a zone of orange-brown clays and iron oxides that extends to depths of 5 to 10 m (15 to 30 feet). Most roadcuts do not penetrate this weathered zone to expose fresh rock. When subjected to constant wave action, however, the basalt forms hard, erosion-resistant black to dark green seacliffs like those seen at the Point Bonita. On the way down the trail, the first outcrop seen to your right is graywacke sandstone. A prominent fault and sheared zone can then be seen separating the graywacke from greenstone. Greenstone is the predominate rock the rest of the way to the tunnel, except for a small interval of serpentinite and shale just beyond the fault. Near the tunnel entrance, well-developed pillows are seen in the basalt of the cliff face. Pods of red chert, altered to jasper, are present between some pillows. The chert was deposited during periods between eruptions. Locally, in the Marin Headlands terrane, interpillow limestone pods also are found, indicating that the sea floor was above calcium carbonate compensation depth (CCD) for at least a short time after forming. The best pillows are seen near the water line below Point Bonita lighthouse, where the waves have beautifully exposed them.

Views to the south of the Golden Gate and San Francisco. The red-looking growth covering the basalt by the tunnel entrance is a type of cyanobacteria (Trentepohlia). Feral cabbage, escaped from the lighthouse keeper's garden, is a common plant here, as well as a many native species, such as cobweb thistle and blue-dicks. The lighthouse was completed in 1855, but was placed on a ridge 300ft above sea level, so that fog frequently obscured the light! The upper half of the old lighthouse was moved to the present site in 1877. Similarly the warning cannon used in fog proved ineffective; was replaced by a fog bell, then a steam siren in 1874, and today an electric fog horn triggered automatically by a fog sensor.

Stop 3.4 - Corona Heights Fault in San Francisco (Christie Rowe and Jamie Kirkpatrick, UC Santa Cruz, pers. comm.)

Significance:

This stop will provide an opportunity to observe an excellently preserved and exposed fault surface within the Franciscan Complex.

GPS Coordinates:

37°45.923′N, 122°26.236′W (approx.)

Directions: (about 30 mins)

Depart Stop 3.3, NE on Fort Barry (0.8 mi)
Continue straight on Field Road (0.3 mi)
Continue on Bunker Road and Danes Drive (2.7 mi) includes one-lane tunnel
Slight **R** onto Alexander Avenue (0.3 mi)
Merge onto US-101 S via ramp to San Francisco (4.0 mi) TOLL road across Golden Gate Bridge. 101 becomes Doyle Drive, Richardson Ave., Lombard St.
Turn **R/S** onto Divisadero Street (1.9 mi)

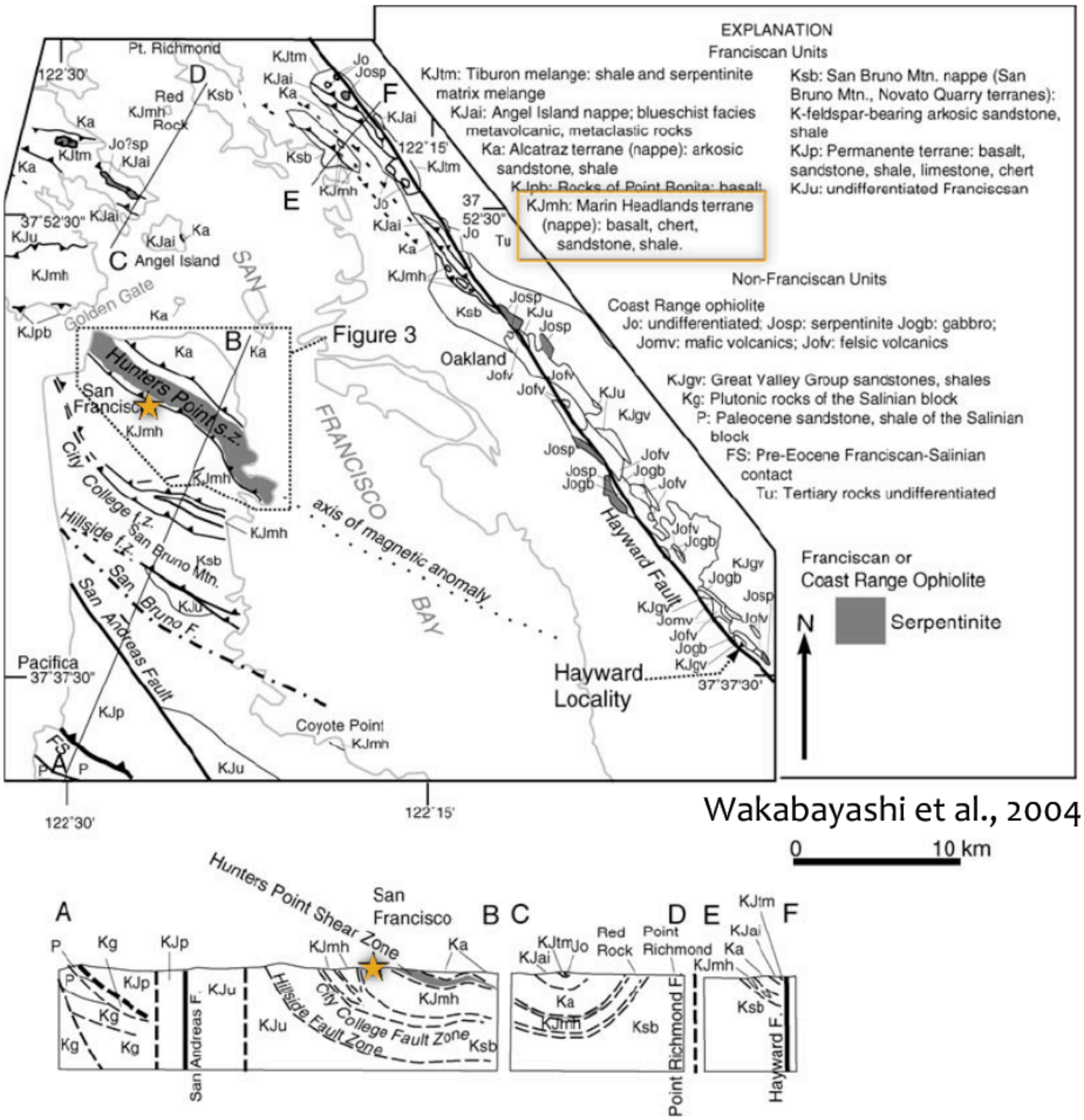
Turn **R/W** onto Haight Street (0.2 mi)
Take the 2nd L/S onto Buena Vista Avenue E (0.3 mi)
Turn **L/S** onto Park Hill Avenue (0.1 mi)
Cross Roosevelt Way, with slight L/SE on 15th St (one way street) (0.1 mi)
Either park on R/S at the tennis courts between Rocky Mt Preschool or Peixotto Playground; or take 1st R/SE on Beaver St to park.

Stop Description:

The Corona Heights fault occurs in cherts of the Marine Headlands Formation (Franciscan Complex) and offers an opportunity to observe features associated with brittle deformation in outcrop (Karplus, class presentation). Especially well preserved are slickenlines (striations produced by fault movement) that reveal the slip trajectories of the fault. Slickenside – polished fault surface, striated by frictional wear, often associated with the principal slip zone within the fault core. A mirror-like polish can be formed by surface melting (< 1 mm) producing a glass-bonded gouge layer.

Return to Stanford

Directions: (about 50 mins)
Depart Stop 3.4
Either continue E on 15th St; or return N on Beaver and R/E on 15th (0.6 mi)
Turn R/S on Dolores St. (1.8 mi)
Continue on San Jose Ave (0.8 mi)
Merge onto I-280 S via ramp to Daly City (28.8 mi)
Exit 24, Sand Hill Rd, direction Menlo Park


EXPLANATION
Franciscan Units
KJtm: Tiburon melange: shale and serpentinite matrix melange
KJai: Angel Island nappe; blueschist facies metavolcanic, metaclastic rocks
Ka: Alcatraz terrane (nappe): arkosic sandstone, shale
KJpb: Rocks of Point Bonita: basalt
KJmh: Marin Headlands terrane (nappe): basalt, chert, sandstone, shale.
Ksb: San Bruno Mtn. nappe (San Bruno Mtn., Novato Quarry terranes): K-feldspar-bearing arkosic sandstone, shale
KJp: Permanente terrane: basalt, sandstone, shale, limestone, chert
KJu: undifferentiated Franciscan
Non-Franciscan Units
Coast Range ophiolite
Jo: undifferentiated; Josp: serpentinite Jogb: gabbro; Jomv: mafic volcanics; Jofv: felsic volcanics
KJgv: Great Valley Group sandstones, shales
Kg: Plutonic rocks of the Salinian block
P: Paleocene sandstone, shale of the Salinian block
FS: Pre-Eocene Franciscan-Salinian contact
Tu: Tertiary rocks undifferentiated
Franciscan or Coast Range Ophiolite
Serpentinite
N
Figure 3
Pt. Richmond
Red Rock
Angel Island
Golden Gate
San Francisco
Hunters Point s.z.
City College f.z.
Hillside f.z.
San Bruno Mtn.
San Bruno F.
San Andreas Fault
Pacifica
Coyote Point
Oakland
Hayward Fault
Hayward Locality
SAN FRANCISCO BAY
axis of magnetic anomaly
122°30'
122°15'
37°52'30"
37°37'30"
Wakabayashi et al., 2004
0 10 km
Hunters Point Shear Zone
City College Fault Zone
Hillside Fault Zone
San Andreas F.
Point Richmond F.
Hayward F.

*** End Day 3 ***

References:

Ave Lallement, H.G., 1979, Structural evolution of the northern part of the Melones fault zone and adjacent areas in California (abs.): GSA Abstracts with Programs, v. 11, p. 67.

Bateman, P.C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada, *in* Bailey, E.H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin, v. 190, p. 107-172.

Bero, D.A., 2003, Geology of the Tiburon Peninsula, Marin County, California: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 640.

Bertucci, P. F., 1983, Petrology and provenance of the Stony Creek Formation, northwestern Sacramento Valley, California, in Bertucci, P. F., and Ingersoll, R. V., eds., Guidebook to the Stony Creek Formation, Great Valley Group, Sacramento Valley, California; Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 1 - 16.

Birkeland, P.W., 1966, Tertiary and Quaternary geology along the Truckee River with emphasis on the correlation of Sierra Nevada glaciations with fluctuation sof Lake Lahontan: GSA Cordilleran Section Guidebook for field trip excursions, p. D1-D24.

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

Blake, M.C., Jr., Bartow, J.A., Frizzell, V.A., Jr., Schlocker, J., Sorg, D., Wentworth, C.M., and Wright, R.H., 1974, Preliminary geologic map of Marin, and San Francisco counties and parts of Alameda, Contra Costa and Sonoma Counties, California: U.S. Geological Survey Miscellaneous Field Study Map MF-574, scale 1:62,500.

Campion, K.M., Sprague, A.R., Mohrig, D., Lovell, R.W., Drzewiecki, P.A., Sullivan, M.D., Ardill, J.A., Jensen, G.N., and Sickafoose, D.K., 2000, Outcrop expression of confined channels: GCSSEPM Foundation 20th Annual Research Conference, Deep-Water Reservoirs of the World, p. 127-150.

Cant, D.J., and Walker, R.G., 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, p. 625-648.

Cassel, E.J., Graham, S.A., and Chamberlain, C.P., 2009, Cenozoic tectonic and topographic evolution of the northern Sierra Nevada, California, through stable isotope paleoaltimetry in volcanic glass: Geology, v. 37, p. 547-550.

Chamberlain, C.P., and Poage, M.A., 2000, Reconstructing the paleotopography of mountain belts from the isotopic composition of authigenic minerals: Geology, v. 28, p. 115-118.

Chester, T., 1994, Analysis of vertical cyclicity patterns in two sediment gravity flow sequences: Stanford University, M.S. thesis [unpublished], 169 p.

Coe, R.S., Stock, G.M., Lyons, J.J., Beitler, B., and Bowen, G.J., 2005, Yellowstone hotspot volcanism in California? A paleomagnetic test of the Lovejoy flood basalt hypothesis: Geology, v. 33, p. 697–700.

Coleman, R.G., and Lanphere, M.A., 1971, Distribution and age of high-grade blueschists, associated eclogites, and amphibolites from Oregon and California: Geological Society of America Bulletin, v. 82, p. 2397-2412.

Crowley, B.E., Koch, P.L., and Davis, E.B., 2008, Stable isotope constraints on the elevation history of the Sierra Nevada Mountains, California: GSA Bulletin, v. 120, p. 588-598.

Day, D., 1977, Petrology and intrusive complexities of sheeted dikes in the Smartville ophiolite, northwestern Sierra Foothills, California: GSA Abstracts with Programs, v. 9, p. 410.

DeGraaff-Surpless, K., Graham, S. A., Wooden, J. L. and McWilliams, M. O., Detrital zircon provenance analysis of the Great Valley Group, California: Evolution of an arc-forearc system, Geological Society of America Bulletin, December, 2002, v. 114, p. 1564-1580.

Dickinson, W.R., and Rich, E.I., 1972, Petrologic intervals and petrofacies in the Great Valley Sequence, Sacramento Valley, California: GSA Bulletin, v. 83, p. 3007-3024.

Dickinson, W.R., and Seely, D.R., 1979, Structure and stratigraphy of forearc regions: AAPG Bulletin, v. 63, p. 2-31.

Durrell, C., 1959, The Lovejoy Formation of northern California: California Publications in Geological Sciences, v. 34, p. 193–220.

Durrell, C., 1966, Tertiary and Quaternary geology of the northern Sierra Nevada: California Division of Mines and Geology Bulletin 190, p. 185-197.

Elder, W.P., 2001, Geology of the Golden Gate Headlands pp. 61-86 in Geology and Natural History of the San Francisco Bay Area A Field-Trip Guidebook 2001 Fall Field Conference NAGT, U.S.G.S. Bull. 2188, P.W. Stoffer ,L.C. Gordon, eds.

Empire Mine, 2011, http://www.empiremine.org/.

Evernden, J.F., and Kistler, R.W., 1970, Chronology of emplacement of Mesozoic batholith complexes in California and western Nevada: USGS Professional Paper 623, 28 p.

Fryer, P., Lockwood, J.P., Becker, N., Phipps, S., and Todd, C.S., 2000, Significance of serpentine mud volcanism in convergent margins, in Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A., eds., Ophiolites and oceanic crust: New insights from field studies and the Ocean Drilling Program: Geological Society of America Special Paper 349, p. 35–51.

Garrison, N.J., 2004, Geology, geochronology and geochemistry of the mid- Miocene Lovejoy flood basalt, northern California [M.S. thesis]: Santa Barbara, University of California, 106 p.

Ghosh, B., and Lowe, D.R., 1993, The architecture of deep - water channel complexes, Cretaceous Venado Sandstone Member, Sacramento Valley, California, in Advances in the sedimentary geology of the Great Valley Group, Sacramento Valley, Graham, S.A. and Lowe, D.R. (eds.), SEPM Pacific Section, p. 51 - 65.

Godfrey, N.J., Beaudoin, B.C., Klemperer, S.L., Levander, A.R., Lerutgert, J.H., Meltzer, A.S., Mooney, W.D., and Trehu, A.M., 1997, Ophiolitic basement to the Great Valley forearc basin, California, from seismic and gravity data: Implications for crustal growth at the North American continental margin: GSA Bulletin, v. 109, p. 1526-1562.

Graham, S.A., and Ingersoll, R.V., 1981, Field trip road log, Great Valley Group submarine fan facies and Sacramento Valley forearc gas province: Part I. Sacramento to Cache Creek and return, *in* Graham, S.A., ed., Field guide to the Mesozoic-Cenozoic convergent margin of northern California: Camarillo, California, AAPG Pacific Section, v. 50, p. 71-78.

Hart, E.W., and Rapp, J.S., 1975, Ground rupture along the Cleveland Hill fault, in Sherburne, R.W., and Hauge, C.J., eds., Oroville, California, earthquake 1 August 1975: California Division of Mines and Geology Special Report 124, p. 61–72.

Harwood, D.S., and Helley, E.J., 1987, Late Cenozoic tectonism of the Sacramento Valley, California: USGS Professional Paper 1359, 46 p.

Ingersoll, R.V., 1978, Petrofacies and petrologic evolution of the Late Cretaceous fore-arc basin, northern and central California: Journal of Geology, v. 86, p. 335-353.

Ingersoll, R.V., 1979, Evolution of the Late Cretaceous forearc basin, northern and central California: GSA Bulletin, v. 90, p. 1813-1826.

Ingersoll, R.V., 1981, Petrofacies, lithofacies, submarine fan facies of the Great Valley Group (Sequence), *in* Graham, S.A., ed., Field guide to Mesozoic-Cenozoic convergent margin of northern California: Camarillo, CA, AAPG Pacific Section, Guidebook, p. 59-69.

Ingersoll, R.V., 1982, Initiation and evolution of the Great valley forearc basin of northern and central California, USA, *in* Legett, J.K., ed., Trench-forearc geology: Sedimentation and tectonics on modern and ancient active plate margins: Geological Society [London] Special Publication 10, p. 459-467.

Ingersoll, R.V., and Schweickert, R.A., 1986, A plate-tectonic model for Late Jurassic ophiolite genesis, Nevadan orogeny and forearc initiation, Northern California: Tectonics, v. 5, p. 901-912.

Ingersoll., R.V., Schweickert, R.A., Kleist, J.R., Graham, S.A., and Cowan, D.S., 1984, Field guide to the Mesozoic-Cenozoic convergent margin of northern California: Revised Roadlogs (Field trip 16), *in* Lintz, J., Jr., ed., Western geological excursions: 1984 Annual Meetings of the Geological Society of America and Affiliated Sections, v. 4, p. 304-363.

Irwin, W.P., 1981, Tectonic accretion of the Klamath Mountains, *in* Ernst, W.G., ed., The geotectonic evolution of California (Rubey Volume I): Englewood Cliffs, New Jersey, Prentice-Hall, p. 29-49.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Division of Mines and Geology, California Geologic Map Series, Map No. 6, scale 1:750,000.

Konigsmark, T., 1998, Geologic Trips: San Francisco and the Bay Area, GeoPress, pp.175

Konigsmark, T., 2002, Geologic Trips: Sierra nevada, GeoPress, pp.319

Lindgren, W., 1911, The Tertiary gravels of the Sierra Nevada of California: USGS Professional Paper 73, 226 p.

Linn, A.M., DePaolo, D.J., and Ingersoll, R.V., 1992, Nd-Sr isotopic, geochemical, and petrographic stratigraphy and paleotectonic analysis: Mesozoic great Valley forearc sedimentary rocks of California: GSA Bulletin, v. 104, p. 1264-1279.

Lowe, D.R., 2004, Deep-water sandstones: submarine canyon to basin plain, western California: AAPG Special Publication GB 79, 79 p.

Menzies, M., Blanchard, D., and Xenophontos, C., 1980, Genesis of the Smartville arc-ophiolite, Sierra Nevada foothills, California: American Journal of Science, v. 280-A, p. 329-344.

Moore, D.E., and Blake, M.C., Jr., 1989, New evidence for polyphase metamorphism of glaucophane schist and eclogite exotic blocks in the Franciscan Complex: California and Oregon: Journal of Metamorphic Geology, v. 7, p. 211–228.

Moores, E.M., Wakamayashi, J., Unruh, J.R., and Waechter, S., 2006, A transect spanning 500 million years of active plate margin history: Outline and field trip guide, *in* Prentice, C.S., Scotchmoor, J.G., Moores, E.M., and Kiland, J.P., eds., 1906 San Francisco Earthquake Centennial Field Guides: Field trips associated with the 100th Anniversary Conference, 18-13 April 2006, San Francisco, California: GSA Field Guide 7, p. 373-413.

Moxon, I., 1988, Sequence stratigraphy of the Great Valley in the context of convergent margin tectonics, in Graham, S.A., ed., Studies of the geology of the San Joaquin Basin: Pacific Section, Society for Sedimentary Geology (SEPM), v. 60, p. 3–28.

Mulch, A., Graham, S.A., and Chamberlain, C.P., 2006, Hydrogen isotopes in Eocene river gravels and paleoelevation of the Sierra Nevada: Science, v. 313, p. 87-89.

Mulch, A., Sarna-Wojcicki, A.M., Perkins, M.E., and Chamberlain, C.P., 2008, A Miocene to Pleistocene climate and elevation record of the Sierra Nevada (California): National Academy of Sciences Proceedings, v. 105, p. 6819-6824.

Murchey, B.M., 1984, Biostratigraphy and lithostratigraphy of chert in the Franciscan Complex, Marin Headlands block, California, *in* Blake, M.C., Jr., ed., Franciscan geology of Northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 43, p. 23–30.

Murray, C.J., Lowe, D.R., Graham, S.A., et al., 1996, Statistical analysis of bed-thickness patterns in a turbidite section from the Great Valley Sequence, Cache Creek, northern California: Journal of Sedimentary Research, v. 66, p. 900-908.

Ojakangas, R.W., 1968, Cretaceous sedimentation, Sacramento Valley, California: GSA Bulletin, v. 79, p. 973-1008.

Page, W.D., Sawyer, T.L., and Renne, P.R., 1995, Tectonic deformation of the Lovejoy Basalt, a late Cenozoic strain gage across the northern Sierra Nevada and Diamond Mountains, in Page, W.D., ed., Quaternary geology along the boundary between the Modoc Plateau, southern Cascades and northern Sierra Nevada: Friends of the Pleistocene Pacific Cell Field Trip, San Francisco, 368 p.

Phipps, S.P., 1984, Ophiolitic olistostromes in the basal Great Valley sequence, Napa County, northern California Coast Ranges: Geological Society of America Special Paper 198, p. 103–125.

Saleeby, J., and Moores, E.M., 1979, Zircon ages on northern Sierra Nevada ophiolite remnants and some possible regional correlations (abs.): GSA Abstracts with Programs, v. 12, p. 125.

Schweikert, R.A., 2009, Beheaded west-flowing drainages in the Lake Tahoe region, northern Sierra Nevada: implications for timing and rates of normal faulting, landscape evolution and mechanism of Sierran uplift, International Geology Review, 51, 994–1033.

Schweickert, R.A., Armstrong, R.L., and Harakal, J.E., 1980, Lawsonite blueschist in the northern Sierra Nevada, California: Geology, v. 8, p. 27-31.

Schweickert, R.A., and Cowan, D.S., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: GSA Bulletin, v. 86, p. 1329-1336.

Schweickert, R.A., and Graham, S.A., 1981, Field Trip Road Log: Sierra Nevada arc complex, Reno to Sacramento, 14 p.

Shervais, J.V., 1989, Geochemistry of igneous rocks from Marin Headlands, *in* Wahrhaftig, C., and Sloan, D., eds., Geology of San Francisco and vicinity: Washington, D.C., American Geophysical Union, International Geological Congress Field Trip Guidebook T105, p. 40–41.

Shervais, J.W., 1990, Island arc and ocean crust ophiolites; contrasts in the petrology, geochemistry and tectonic style of ophiolite assemblages in the California Coast Ranges, *in* Malpas, J., Moores, E., Panayiotou, A., and Xenophontos, C., eds., Ophiolites oceanic crustal analogues: Proceedings of the Symposium 'Troodos 1987': Nicosia, Cyprus, Geological Survey Department, Ministry of Agriculture and Natural Resources, p. 507–520.

Shervais, J., Greene, T., Ritts, B., and Leech, M., 2010, Field Trip Guide – The Coast Range Orogen of California, 40 p. Trip associated with 25th HKT Conference, San Francisco, http://pubs.usgs.gov/of/2010/1099/

Siegel, J.H., 1988, Stratigraphy of the Putnam Peak Basalt and correlation to the Lovejoy Formation, California [M.S. thesis]: Hayward, California State University, 119 p.

Simpson Seymore, A. V., 1999, Tectonic implications of the Stony Creek basaltic sandstone, late Jurassic Great Valley Series, Stonyford, California, M.S. thesis, University of South Carolina.

Small, E.E., Anderson, R.S., Repka, J.L., and Finkel, R., 1997, Erosion rates of alpine bedrock summit surfaces deduced from in situ 10Be and 26Al: Earth and Planetary Science Letters, v. 150, p. 413–425,

Suchecki, R.K., 1984, Facies history of the Upper Jurassic-lower Cretaceous Great Valley Sequence: Response to structural development of an outer-arc basin: Journal of Sedimentary Petrology, v. 54, p. 170-191.

Swanson, S.E., and Schiffman, P., 1979, Textural evolution and metamorphism of pillow basalts from the Franciscan Complex, western Marin County, California: Contributions to Mineralogy and Petrology, v. 69, p. 291–299, doi: 10.1007/BF00372331.

Swinchatt, J., and Howell, D.G., 2004, *The Winemaker's Dance: Exploring Terroir in the Napa Valley*: University of California Press, Berkeley, 230 p.

Tsujimori, T., Matsumoto, K., Wakabayashi, J., and Liou, J.G., 2006, Franciscan eclogite revisited: Reevaluation of P-T evolution of tectonic blocks from Tiburon Peninsula, California, *in* Mogessie, A., and Proyer, A., eds., International Eclogite Conference 7th Special Volume (in press).

Unruh, J.R., 1991, The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera: Geological Society of America Bulletin, v. 103, p. 1395–1404

Unruh, J.R., Loewen, B.A., and Moores, E.M., 1995, Progressive arcward contraction of a

Mesozoic-Tertiary fore-arc basin, southwestern Sacramento Valley, California: GSA Bulletin, v. 107, p. 38-53.

Unruh, J.R., and Moores, E.M., 1992, Quaternary blind thrusting in the southwestern Sacramento Valley, California: Tectonics, v. 11, p. 192-203.

Wahrhaftig, C., 1984, Structure of the Marin Headlands block, California: A progress report, *in* Blake, M.C., ed., Franciscan Geology of Northern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 43, p. 31–50.

Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: Journal of Geology, v. 100, p. 19-40.

Wakabayashi, J., and Sawyer, T.L., 2000, Neotectonics of the Sierra Nevada and the Sierra Nevada–Basin and Range transition, California, with field trip stop descriptions for the northeastern Sierra Nevada, in Brooks, E.R., and Dida, L.T., eds., Field guide to the geology and tectonics of the northern Sierra Nevada: California Division of Mines and Geology Special Publication 122, p. 173–212.

Wakabayashi, J., and Sawyer, T.L., 2001, Stream incision, tectonics, uplift, and evolution of topography of the Sierra Nevada, California: Journal of Geology, v. 109, p. 539–562

Wakabayashi, J., and Unruh, J.R., 1995, Tectonic wedging, blueschist metamorphism, and exposure of blueschist: are they compatible?: Geology, v. 23, p. 85-88.

Williams, T.A., 1997, Basin - fill architecture and forearc tectonics: Cretaceous Great Valley Group, Sacramento basin, northern California [Ph.D. thesis]: Stanford, California, Stanford University, 412 p.

Xenophontos, C., and Bond, G.C., 1978, Petrology, sedimentation, and paleogeography of the Smartville Terrane (Jurassic) – bearing on the genesis of the Smartville ophiolite, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the western US: Society of Economy, Paleontology, and Mineralogy, Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 291-302.

Yeend, W.E., 1974, Gold-bearing gravel of the ancestral Yuba River, Sierra Nevada, California: USGS Professional Paper 772, 44 p.