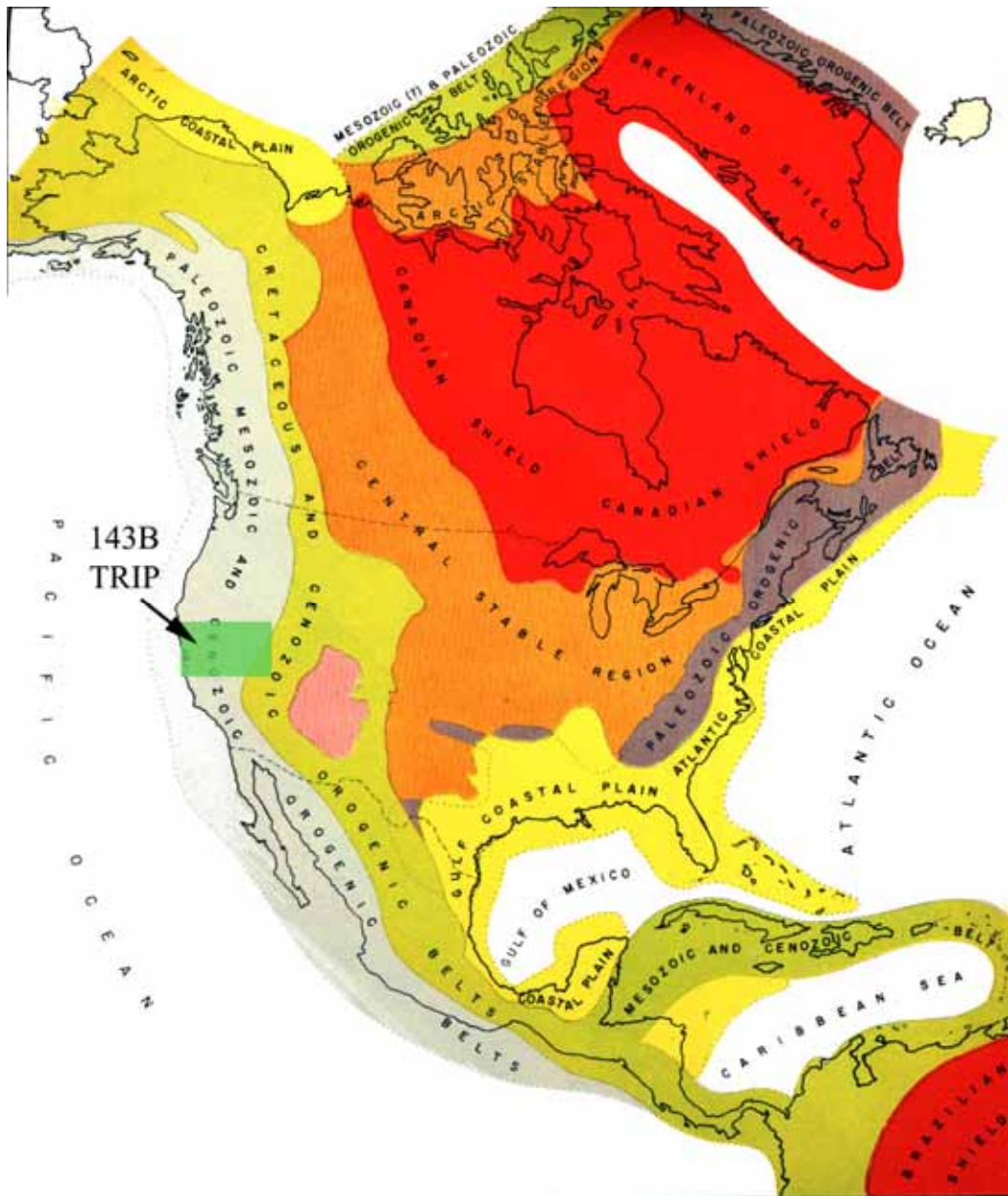# HOFSTRA UNIVERSITY
FIELD TRIP GUIDEBOOK

GEOLOGY 143B – Geology of Central California

Summary Session One – 24 May - 02 June 2004

Eardley (1951)

Field Trip Led by Dr. Charles Merguerian
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Hofstra University Geology 143B
Field Geology of Central California, May/June 2004

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Charles Merguerian

Introduction

This guidebook has been provided to discuss some of the geological background needed to enhance your experience on the Geology 143B field trip to Central California and the Sierra Nevada (Snowy Range). Our itinerary will be found after some general discussion of the history, physiography, general geology and tectonics of the state of California. As I envision it, our field trip is divided into four major geological segments that will be described in depth in a later section. These regions include the **Coast Ranges and Great Valley** (Days 1 and 2), the **Gold Belt and Foothills of the Sierra Nevada** (Days, 3, 4, and 5), the **Sierra Nevada range** (Day 6), and **Mono-Inyo Craters** (Day 7 and 8). We will travel back toward San Francisco on Day 8 and spend Day 9 in that wonderful city to be ready for our flight back from SFO on Day 10. Many features of cultural and historic interest will be encountered during our intrastate journey and although not the central focus of our trip, whenever possible, time will be allocated.

The choice of these four regions was made to best exemplify the geology of central California and to develop a transect view of the geology for students to better understand the plate tectonic assembly of the various terranes that, over geologic time, have created the state. This guidebook provides the essential background information you will need to fully understand the rock exposures that we will visit during our trip. Each day we will examine natural rock exposures in the field, employing and learning the methods of field geologic science. Use of the guidebook in the field is essential as discussions will be based upon the maps and diagrams that I have reproduced for you, under the threat of copyright arrest and intellectual torture (drive-by insults).

California harbors a rich though recent history by comparison to areas of the east coast of the United States. According to Chamberlain (1977), the conquests of Commodore Robert A. Stockton and Colonel John C. Frémont were paramount in signing over the land of California to the American Republic on 02 February 1848, thus ending Mexican rule. The Spanish and Mexican domination that lasted centuries had come to a halt that day in Hidalgo, Mexico with the slash of a pen. Many Americans feared that the land would be uninhabited. The gold rush changed all that and by 1850 nearly 100,000 people had arrived there. Physical barriers to the conquest of the gold seekers (Argonauts) came in the form of snow-covered high Sierran passes for access, steep canyons that to be crossed and controlled, and lack of food and supplies.

Stretching 800 miles in long dimension and up to 375 miles wide, California covers an area of 158,693 mi^2 and is the second largest state (Texas, of course being #1). Elevations in the Sierra Nevada range peak at 14,495' (Mt. Whitney) yet those in the Death Valley are the lowest in North America at -281.9' (below sea level, in fact, way below sea level). Now you can see why it's a **great relief** for me to be back in California! Let's learn something about the geology.

Geology of California

The Cordillera of the western United States is a 1,000-mile wide zone of mountain building that records the results of over 350 Ma of continual plate tectonic activity along the embryonic western margin of North America. Older geologic activity is not recorded in the area of our trip. Yet, Proterozoic and older rocks are exposed in southern California and in the southern Coast Range where they have been splintered and transported NW along the San Andreas fault system and form a component of the Salinian Block to the south of Monterey. These older rocks, such as those found to occupy the inner gorge of the Grand Canyon, are associated with NE-trending Proterozoic and older Archean rocks exposed in Arizona and adjacent areas (Figure 1). The Cordillera (Figure 2) consists of a vast zone of imbricated and in some cases far-traveled terranes, accrued from continual Paleozoic, Mesozoic, and Cenozoic marginal plate activity. It would appear that there was always some form of active subduction zone, volcanic arc(s), shear zone, or brittle faulting taking place across California throughout that interval. The active mobile belts of the Indonesian region come to mind when attempting to derive an analog to the paleogeography of the active California margin (Hamilton 1978).
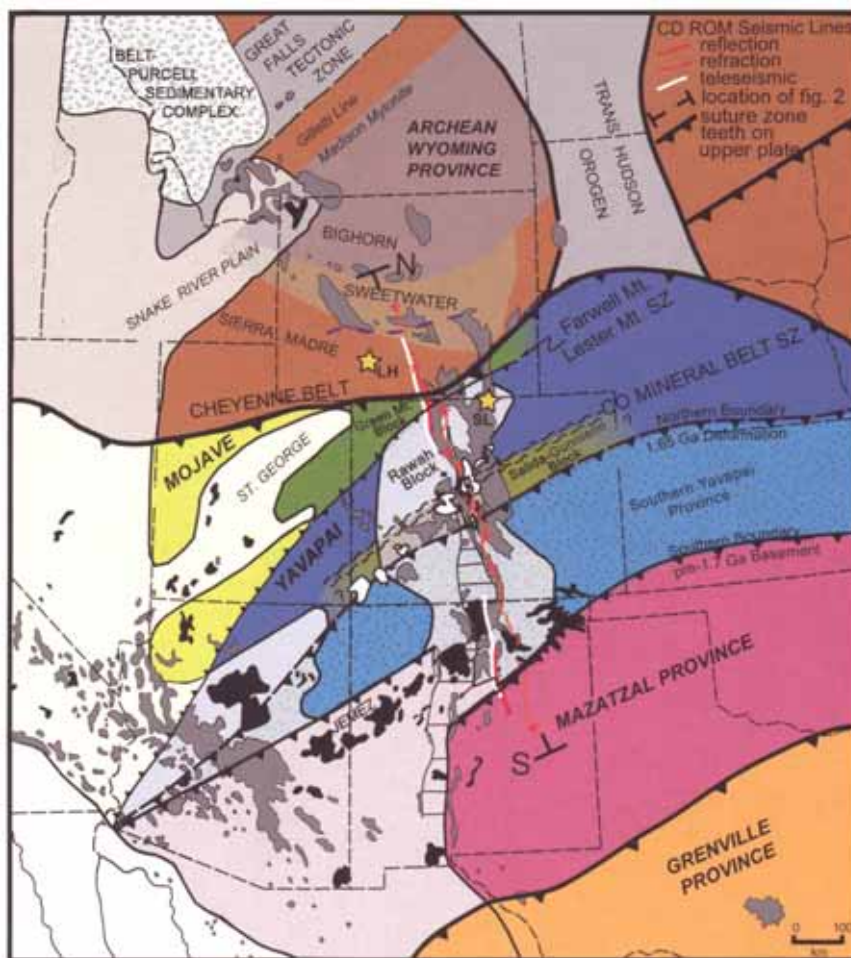
Figure 1 – Terrane map of the SW Cordillera showing the convergence of the Mohave, Yavapai, and Mazatzal provinces and their extension into southern California. (From CD-ROM Working Group, 2002.)

Figure 2 – Index map of the western United States showing the broad area underlain by the Cordilleran mountain range. Elements of this 1,000-mile wide mountainous region extend from California eastward to New Mexico, Colorado, Wyoming, and Idaho.

Figure 3 – Shaded relief map of the same area as Figure 1 showing the topography and major drainage systems. Note that California consists of two NNW-trending mountainous regions, the Coast Range on the west and Sierra Nevada Range on the east. The ranges, key targets of our Geology 143B trip, are geologically different and separated by a broad sediment-filled flat valley known as the Great Valley.

A shaded relief map of the Cordillera (Figure 3) shows a rugged juvenile terrain dissected by major drainages that flow predominately toward the Pacific Ocean. Indeed, the Continental Divide is located near the eastern edge of the Cordillera, extending through western Wyoming near Yellowstone Park southward through Colorado, and New Mexico. We plan to visit Yellowstone National Park (home of Yogi Bear), Craters of the Moon in Idaho, and Glacier National Park in Montana during the Summer of 2005 (Geology 143C). Water falling to the east of the Continental Divide flows ultimately into the Atlantic Ocean. Note the broad sediment fans (Figure 3) that cover the boundary between the Rocky Mountain Division and the Piedmont and High Plains of the central United States. Physiographic subdivisions of the Cordillera are shown in Figure 4. Our Geology 143A trip to the Intermontane Division of the Cordillera during the summer of 2002 was to central and northern Arizona to examine the Grand Canyon of the Colorado River Plateau. This year's trip to California will concentrate on the Coast Ranges of the Pacific Mountain Division, the Central Valley, and the Sierra Nevada Range.
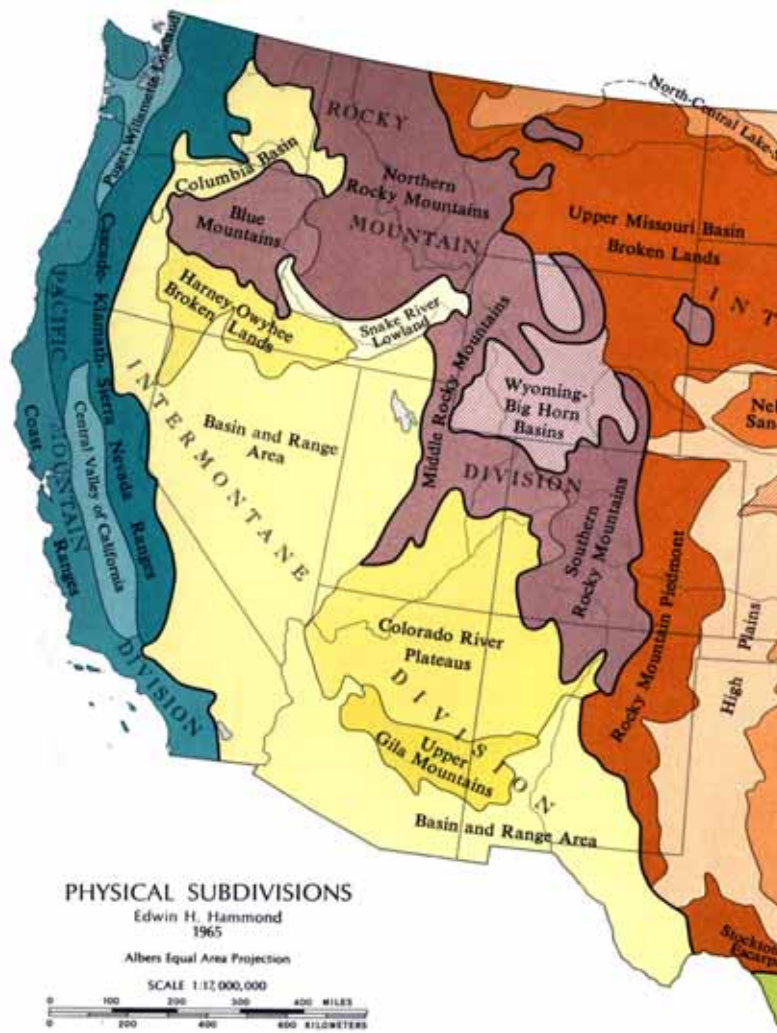
Figure 4 – Physical subdivisions of the Cordilleran belt of western North America (Hammond, 1965).

Figure 5 shows the three major NNW-trending physiographic elements of California. A physiographic diagram of California for help with place names by famed artist Erwin Raisz is reproduced as Figure 6.

The Coast Ranges

The Coast Ranges constitute a series of subdued, elongate hills consisting of highly sheared, faulted, and disarticulated Late Mesozoic to Early Tertiary oceanic rocks (mostly slate) of the Franciscan Complex. The Franciscan includes exotic blocks of lithic sandstone, chert, and eclogite (recycled mantle rocks) and show evidence for blueschist metamorphism. To the east, the Coast Ranges are in thrust fault contact with dominantly flat-lying marine and intercalated volcaniclastic strata of the Great Valley. The Great Valley of California, land of fruits and nuts, was buried by sediment during westward tilt of the Sierra Nevada block that began in earnest in Pliocene time (~2 Ma). Rapid downcutting of westward-flowing mountain streams produced steep v-shaped valleys that severely dissected the Sierran and the Foothills metamorphic terranes (Figure 7). Abundant sediment, some of it auriferous, was deposited above older volcaniclastic strata of the Great Valley, a former fore-arc basin. The Sacramento and San Joachin rivers flow from the tilted Sierra block westward across the Great Valley where they empty into San Francisco Bay, a drowned composite river mouth. A simplified geological section of the Coast Ranges is shown as Figure 8.

Figure 5 – Physiographic relief map of California showing, from west to east, the Coast Ranges, the Great Valley and the Sierra Nevada Range.
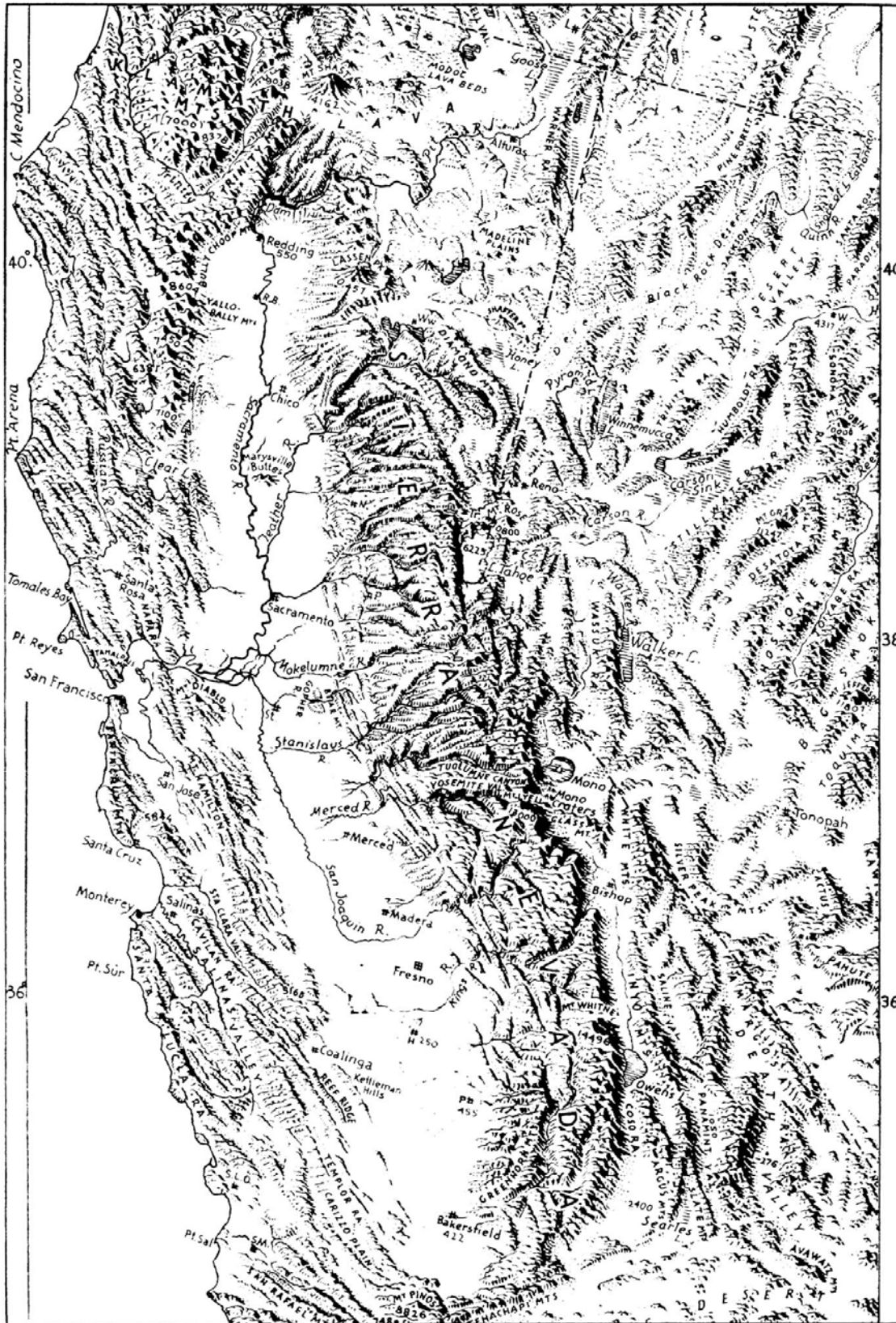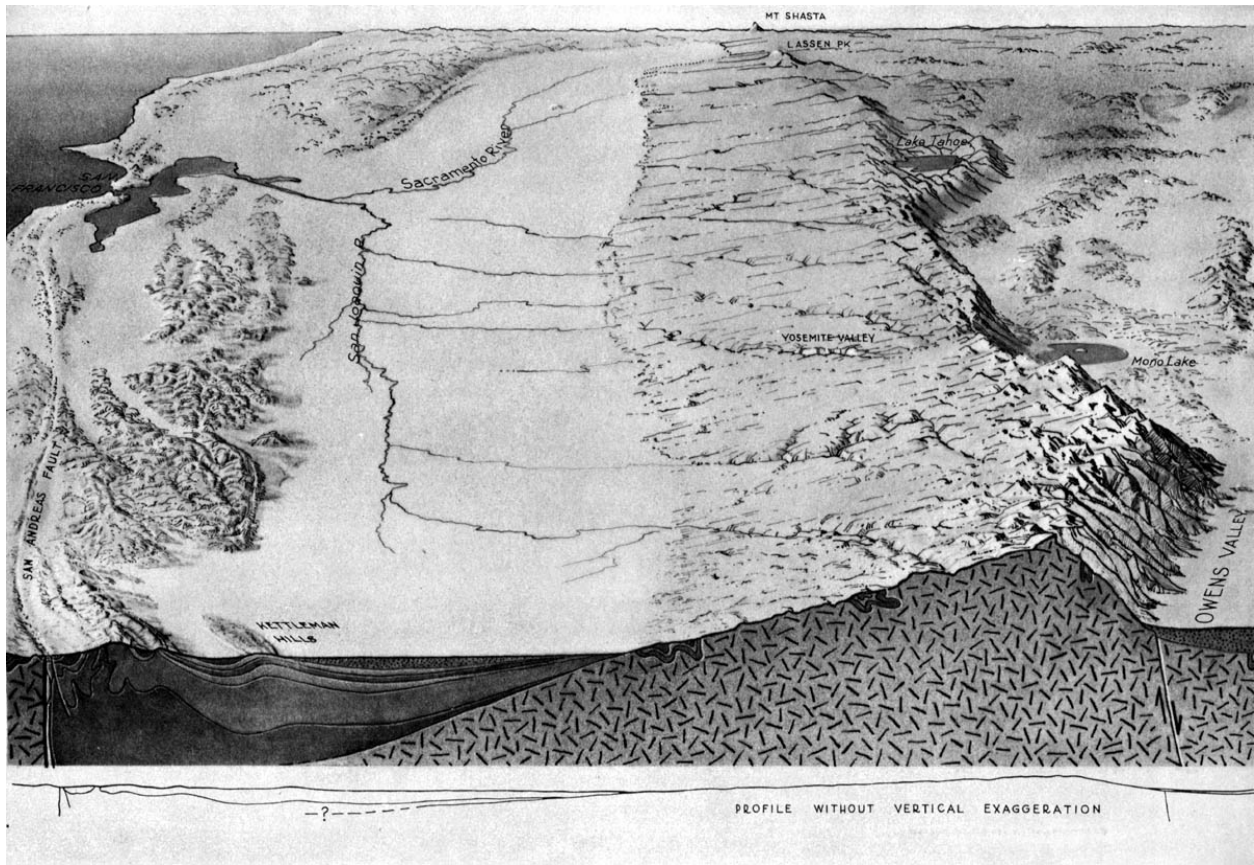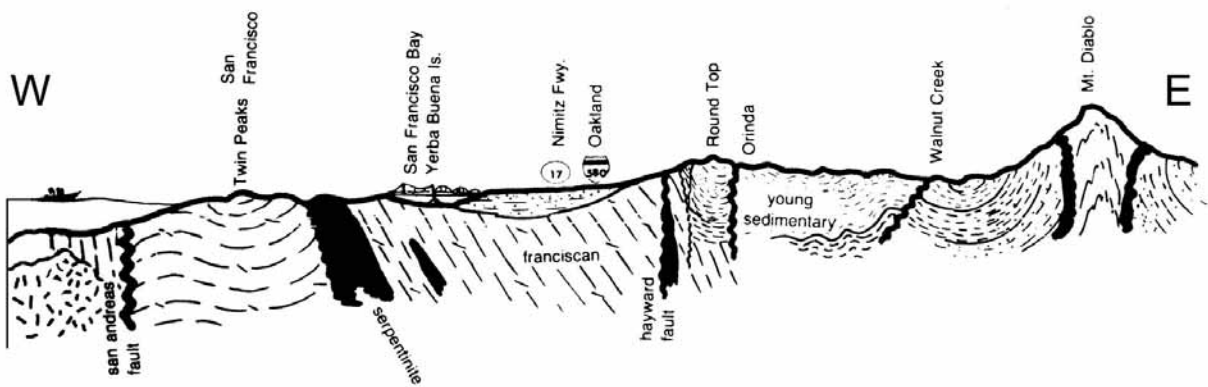
**Figure 6** – Physiographic map of California by Erwin Raisz.

Figure 7 – Drawing from Shelton (1966) showing the westward tilt of the Sierra Nevada block that began in earnest in Pliocene time (~2 Ma). Rapid downcutting of westward-flowing streams produced steep v-shaped valleys that severely dissected the Sierra and Foothills metamorphic belts.


Figure 8 – Geologic section across the eastern part of the Coast Range at the latitude of our trip routes showing the effects of the San Andreas fault zone and internal structure of the Franciscan Complex. (From Alt and Hyndman, 1975, p. 27.)

Great Valley Sequence

Along its western boundary, the Great Valley Sequence is highly deformed and overthrust above the Franciscan of the Coast Range along a zone of broken serpentinite that delineates the Coast Range thrust (Figure 9). To the east, the Great Valley strata unconformably overlie the Sierra Nevada Range – a complex metamorphic and igneous complex of variable age, lithology, and former tectonic setting. The former tectonic setting of the Great Valley was that of a forearc basin (marked v in Figure 10), situated between the trench complex on the west (Franciscan Complex) and the volcanic arc (now eroded away from the uplifted Sierran block except for a few remnant stringers of lava and deposits of lahar and ash that survived the erosion and weathering dilemma). As discussed earlier, the younger strata of the Great Valley are derived from weathering and erosion of the arc complex and its apron that were formerly situated above the present Sierra Nevada, the eroded plutonic roots of that arc.
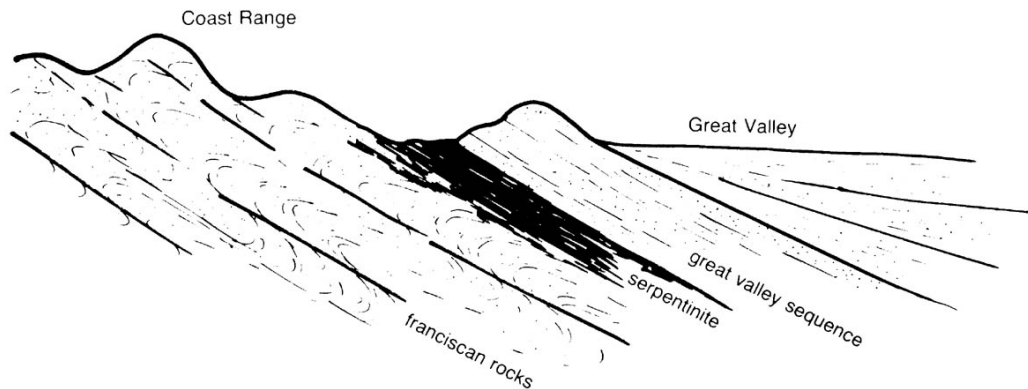
Figure 9 – Cross section showing the Coast Range thrust fault, a major fault that separates the Coast Ranges on the west from the Great Valley Sequence on the east.
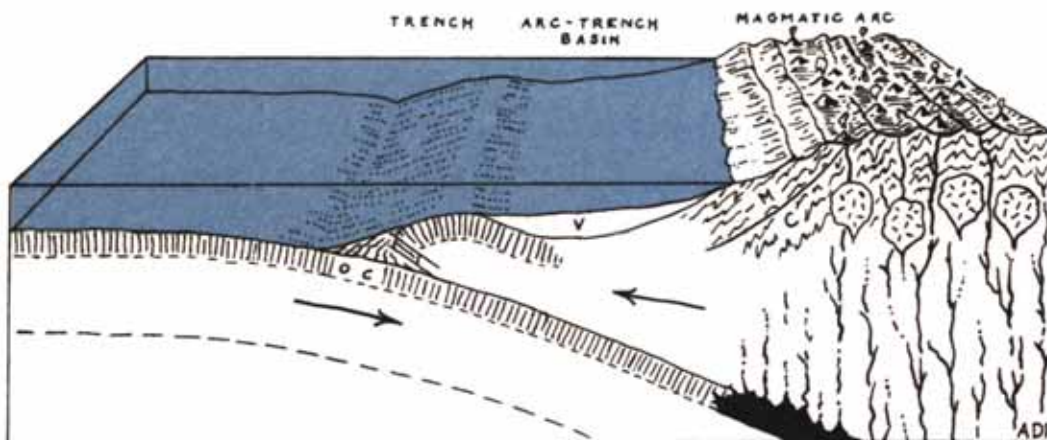
Figure 10 – Block diagram showing a typical Andean arc-trench basin, an analog for the Coast Ranges, Great Valley, and Sierra Nevada of California. Landward of the trench a broad zone of highly sheared oceanic strata or outer non-volcanic high gives way to predominately volcaniclastic strata of the Great Valley. Note that the forearc basin strata overlap the arc basement to the right of the diagram. (From Howard, 1979, Fig. 7, p. 29.)

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Foothills Metamorphic Belt

The western metamorphic belt of the Sierra Nevada range (Clark, 1964, 1976) is roughly 350 km long, 60 km wide and extends from lat. 40°15'N south-southeasterly to lat. 37°N. It is overlain by Cretaceous to Cenozoic rocks of the Great Valley sequence to the west and is intruded by the Sierra Nevada batholith to the east (Figure 11). South of lat. 39°N it is composed of three ductile-fault bounded tectonostratigraphic units known as the Jurassic belt, the Calaveras Complex, and the Shoo Fly Complex. These contiguous belts show an eastward increase in age, metamorphic grade, and structural complexity with abrupt lithologic, structural, and metamorphic truncations occurring at the Melones, Sonora, and Calaveras-Shoo Fly faults (Merguerian 1985a,b; Schweickert, Merguerian and Bogen, 1988).
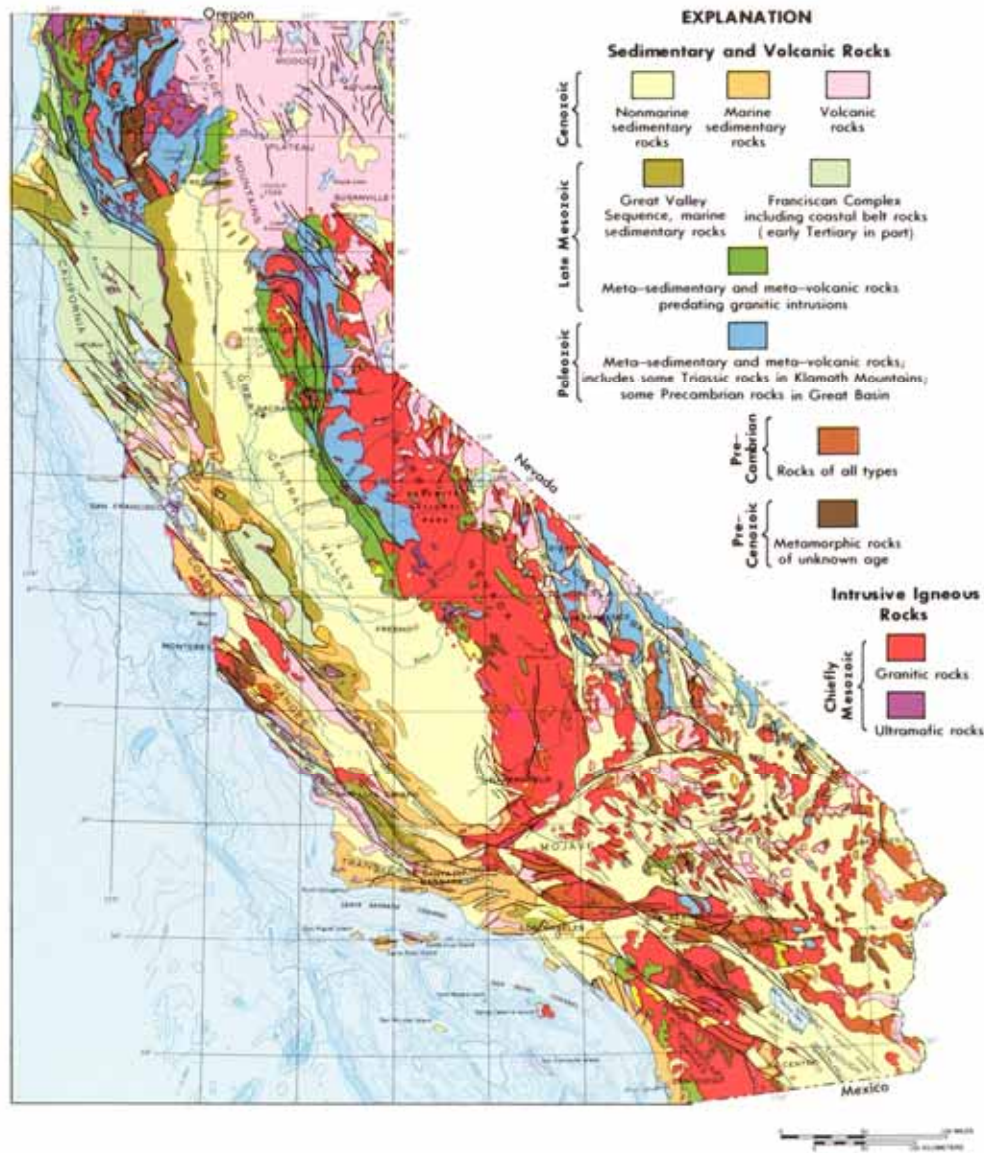
Figure 11 – Simplified geological map of California. (California Division of Mines and Geology, Centennial Map, 1980.)

The lower Paleozoic **Shoo Fly Complex** of Unit 1 underlies a terrane 330 km in length and 6-20 km wide which terminates southward near lat. 37°30'N in Mariposa County (Merguerian, 1981) where batholithic rocks cut across trend (Figure 12). Along its strike the Shoo Fly Complex shows a marked southward increase in structural complexity and metamorphic grade. North of lat. 39°N it consists of weakly metamorphosed quartzose sandstone, graywacke, slate, chert and limestone (Clark, 1976). South of lat. 38°05'N (Figure 13) it is a multiply deformed (seven superposed phases of deformation) and sheared assemblage of quartzite, quartzofeldspathic gneiss, granite-, syenite-,and gabbroic augen gneiss, garnet schist, calc-silicate rock, marble, and rare amphibolite (Merguerian, 1985a, b).

The Shoo Fly is in ductile fault contact with the Permo-Triassic **Calaveras Complex** (Unit 2) along a 1-2 km wide zone of mylonite, intense flattening, imbricated rock units and transposition with overprinting metamorphism of older fabric elements (Merguerian, 1983). The Calaveras, which forms the lower plate of' the east-dipping thrust, is a chaotic assemblage of massive argillite and siltstone, marble, massive and rhythmicallybedded-chert, talc-schist, basalt, and rare sandstone layers. The age of the Calaveras remains uncertain, but Permo-Carboniferous fossils from limestone olistoliths (Turner, 1894; Schweickert and others, 1977) indicate a minimum late Paleozoic age for the sequence. Descriptions of the Calaveras in this region can be found in Schweickert and Wright (1975), and Wright and Schweickert (1977), and Schweickert and others (1977).

Dominated by Jurassic island arc volcanic and volcaniclastic strata and deep-water flysch-type sediment, the **Jurassic Belt** (Unit 3) has been well studied. Cropping out east of the Great Valley where flat-lying strata predominate, tilted and cleaved metasedimentary and metavolcanic rocks of Jurassic age form an impressive former volcanic arc terrane now exposed in dissected low rolling hills that reflect the trend of the lithologic units and bounding faults (Figure 12). These rocks were isoclinally folded and cleaved under chlorite to greenschist grade metamorphic conditions in contrast to the blueschist metamorphism found in the Coast Range (Figure 13).

Cut by major faults in the vicinity of Jamestown, where slivers of serpentinite exhibit shearing and multiple offsets, the Jurassic Belt is in fault contact with deformed Permo-Triassic marble and chaotic argillite of the Calaveras Formation along the Melones or Sonora faults (Figure 12). The Calaveras, in turn, is in ductile fault contact with the lower Paleozoic Shoo Fly Complex along the Calaveras-Shoo Fly thrust (Figure 13). Thus, in cross sectional view the foothills metamorphic belt consists of a sequence of fault steeply dipping fault bounded terranes of increasing age, metamorphic grade, and structural complexity from west to east (Figure 14).

In the period 1978-1980, CM was a part of a huge NSF-funded research effort to better understand the intricacies and structural sequence across the Foothills Metamorphic belt in the vicinity of Sonora, California. In the summer of 1981, CM mapped at 1:24,000 scale, ten 7.5-minute quadrangles south of the Sonora-Twain Harte area for the California Division of Mines and Geology (Merguerian, 1981). Along with graduate advisor Dr. Richard A. Schweickert and fellow Columbia University graduate student Nicholas Bogen, focused study and integration of results from the Shoo Fly, Calaveras, and the Jurassic belt along the same general latitude resulted in new geological data and interpretation. The combined results of those studies can be

found in papers by Bogen (1983, 1984a, b), Merguerian (1981, 1985a, b), Schweickert and others (1984), Merguerian and Schweickert (1987), Schweickert and Bogen (1983), and Schweickert, Merguerian, and Bogen (1988) and in new maps of the region published by the California Division of Mines and Geology (Wagner and others, 1981, 1990). During our field trip we will study the various components of the Foothills metamorphic belt and examine the terrane bounding fault zones and try to find some mistakes that CM made the first time.
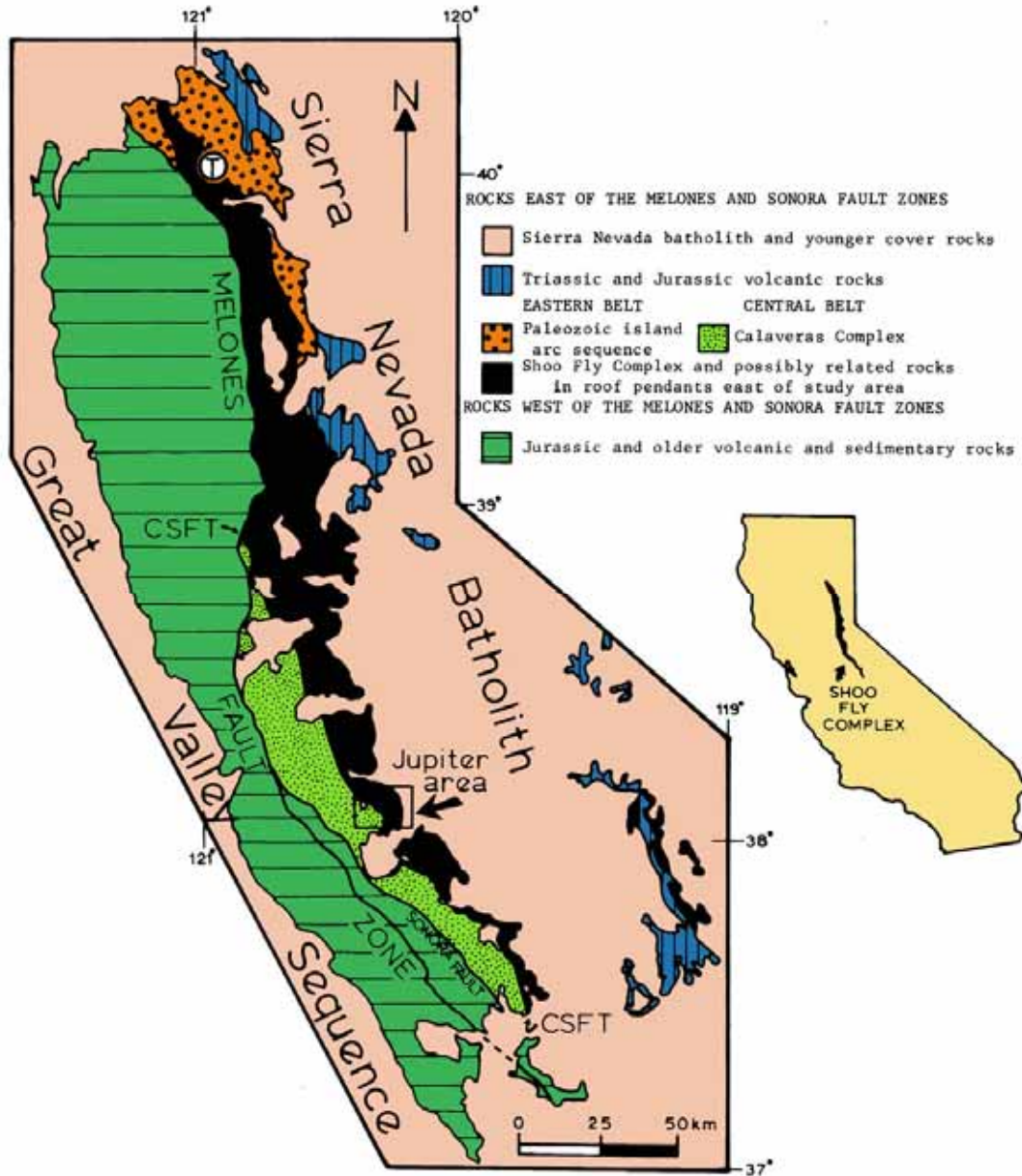
Figure 12 – Geologic map showing the components of the Foothills Metamorphic belt of the Sierra Nevada. The area underlain by the Lower Paleozoic Shoo Fly Complex is shown in black on map and inset. (From Merguerian, 1985.)

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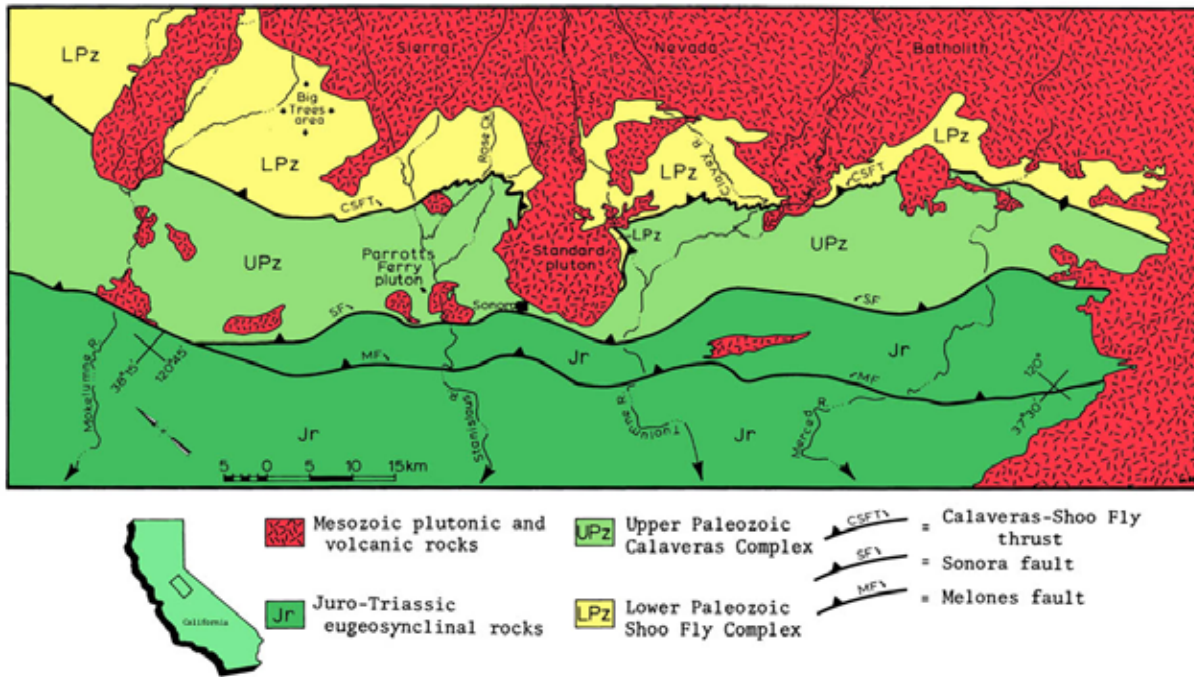
Figure 13 – Geologic map of the southern part of the Foothills Metamorphic belt of the Sieerra Nevada showing the Melones and Sonora faults and the Calaveras-Shoo Fly thrust. These major tectonic boundaries separate Juro-Triassic arc strata (Unit 3), from the Calaveras Complex (Unit 2), from the older Shoo Fly Complex (Unit 1). (From Merguerian, 1985.)
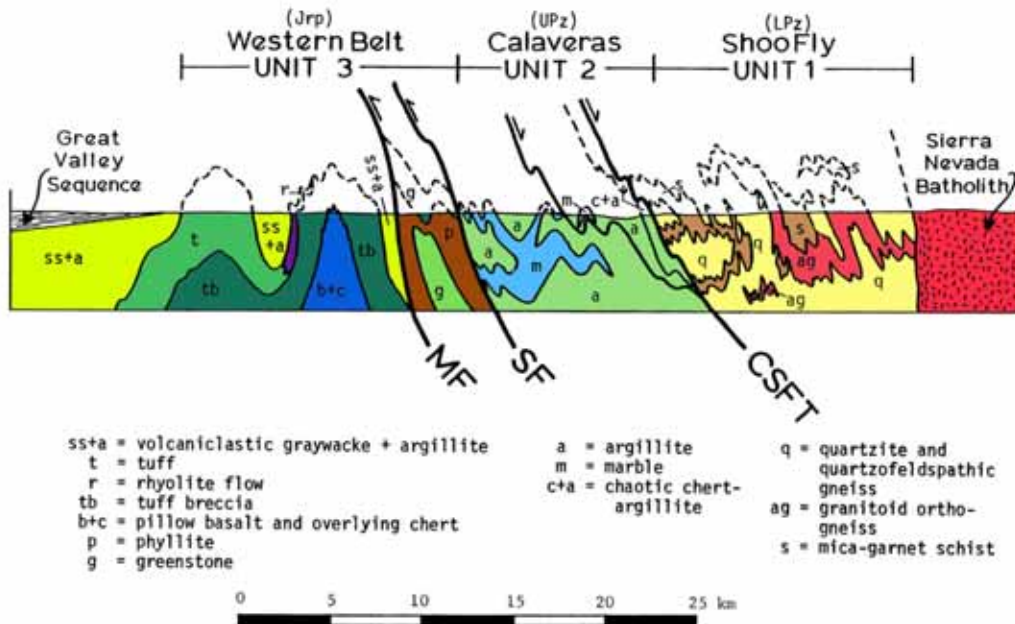
Figure 14 – Geologic section of the foothills metamorphic belt showing the across strike internal structure and stratigraphy. (From Merguerian, 1985.)

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The Sierra Nevada Batholith

The Foothills Metamorphic belt is truncated by plutonic rocks of the Sierra Nevada batholith. (See Figure 13.) The foothills belt was intruded by a number of isolated middle Jurassic plutons that were early harbingers of the massive intrusive series that was to follow in late Jurassic through Cretaceous time. The Sierran granites dominate the landscape of California forming imposing mountains of eroded granitoid rock sculpted by rapid uplift and subsequent glaciation. During this interval the Tuolumne Intrusive series and related rocks were emplaced as a series of coalescent plutons the invaded an area over 40 miles in width in our field trip transect (Figure 16). The coarse-grained igneous rocks include granite and granodiorite mostly but also include intermediate, mafic, and ultramafic phases (listed in order of decreasing abundance). Uplift and erosion of the arc sequence of the Sierra Nevada, a former Andean or marginal volcanic arc has exposed the plutonic roots of that arc (Figure 17). The details of the geology of this sequence will be developed below in the actual trip description section.
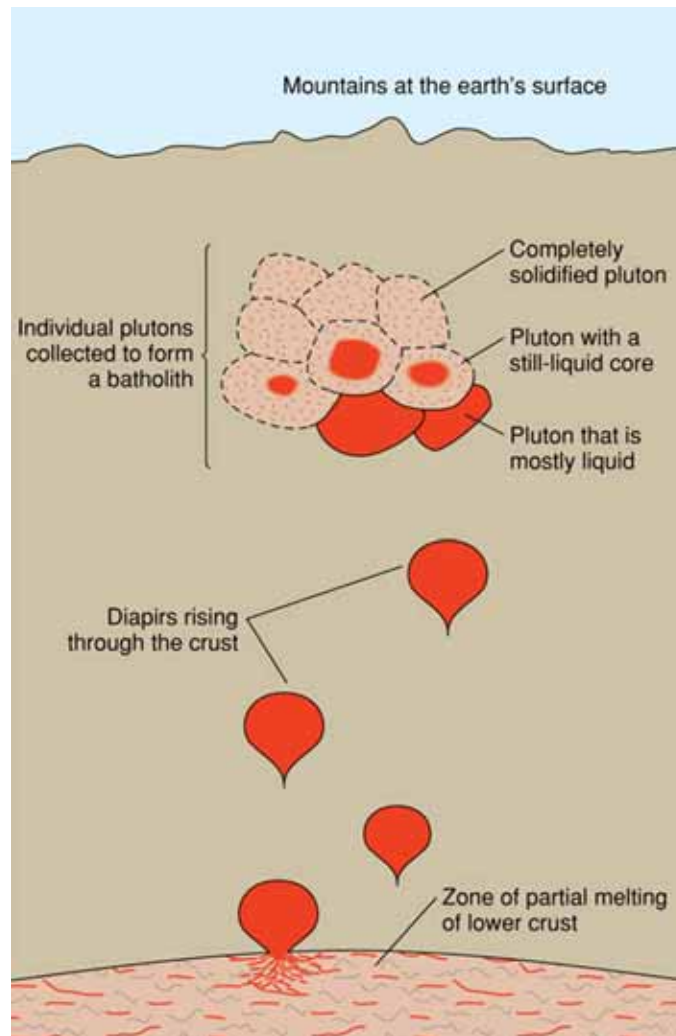
Figure 16 – Development of a batholith in the lithosphere, the result of coalesced diapers of magma that rise from the lower crust and solidify in the upper crust. (From Plummer and McGeary, 2002.)
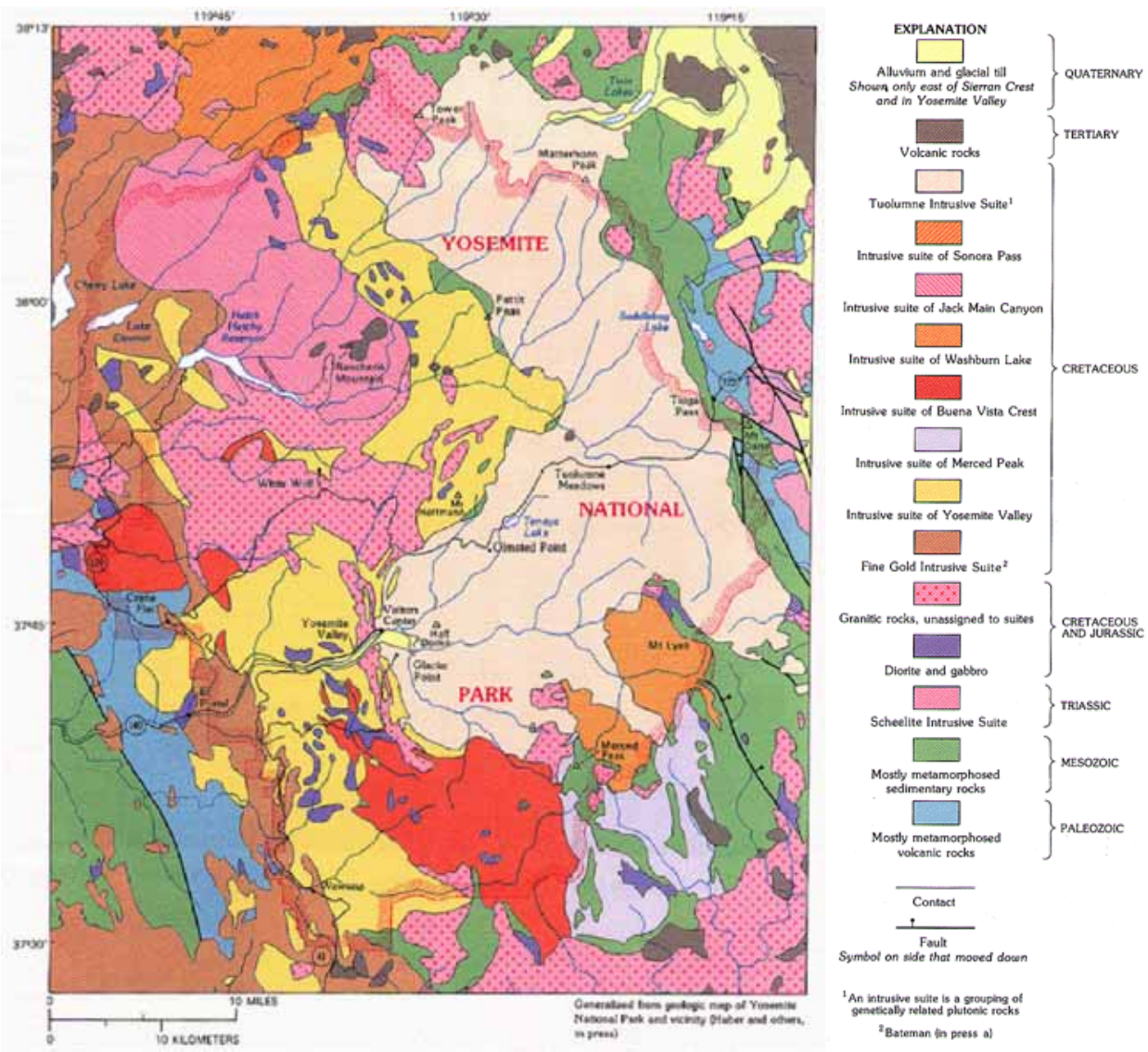
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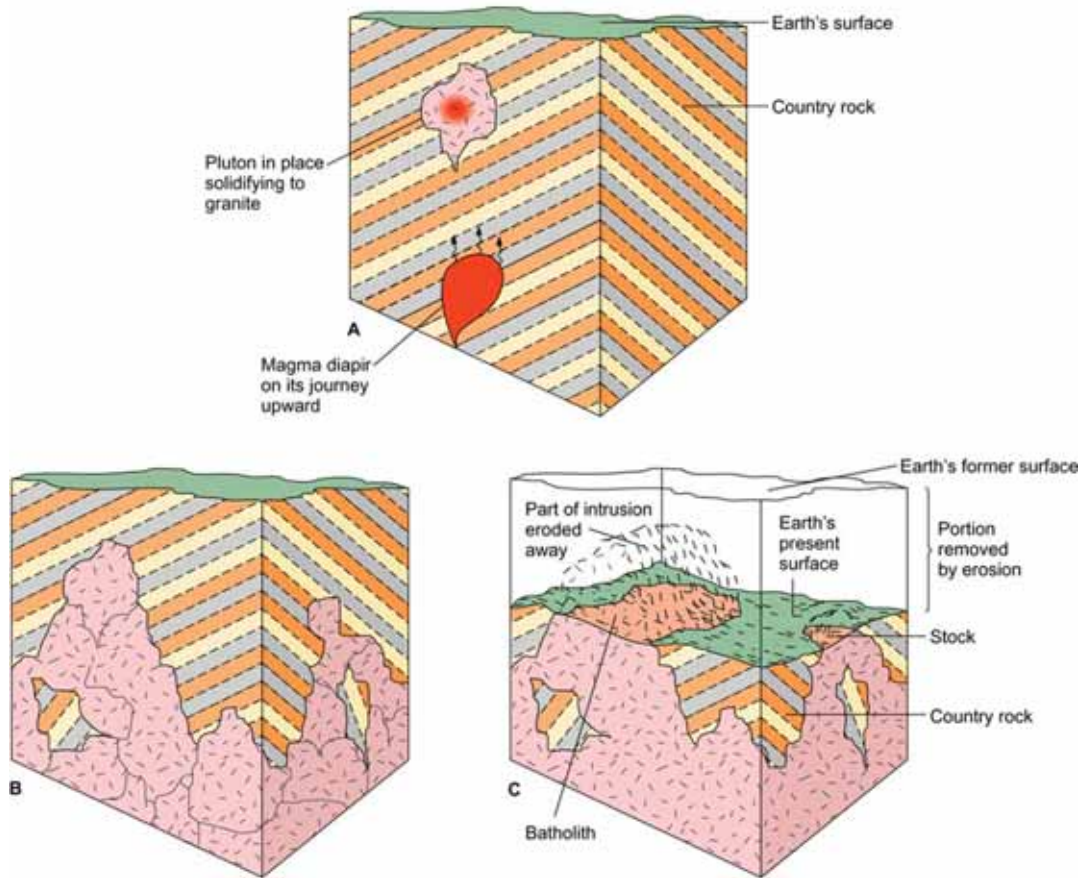
Figure 17 – Composite diagram showing (A) an early stage of intrusion of numerous plutons into the country rock, (B) an intermediate stage where other magma diapers have intruded, coalesced, and crystallized into a solid mass of plutonic rock. After uplift and erosion, the surface expression of batholiths, stocks, roof pendants, screens, and xenoliths results. (From Plummer and McGeary, 2002.)

A geological map of the high Sierra in the vicinity of Yosemite National Park is reproduced as Figure 18. Note the pattern of individual plutons showing cross-cutting relationships and the presence of roof pendants in the central portion of the range. Detailed mapping to establish crosscutting relationships and targeted age dating has resulted in definition of the intrusive pulses of magma that formed the Sierra Nevada batholith in the 32 Ma interval 116 to 84 Ma (Table 1). Middle Jurassic plutonism at roughly 170 Ma (Standard pluton) marks an early stage in the eventual development of the batholithic series to the east.

As we cross over the Sierra at Tioga Pass (Elev. 9,941') we cross over the drainage divide of the Sierra with water falling west of there going to the Pacific. To the east, water enters the Great Basin, the fourth major geological area of our trip route where Cenozoic and Recent tectonics have dominated the geology. Because this creates unusually stark landscapes, we are blessed to have the opportunity to visit this area.

EXPLANATION

Alluvium and glacial till
Shown only east of Sierran Crest and in Yosemite Valley — QUATERNARY

Volcanic rocks — TERTIARY

Tuolumne Intrusive Suite[1]

Intrusive suite of Sonora Pass

Intrusive suite of Jack Main Canyon

Intrusive suite of Washburn Lake

Intrusive suite of Buena Vista Crest — CRETACEOUS

Intrusive suite of Merced Peak

Intrusive suite of Yosemite Valley

Fine Gold Intrusive Suite[2]

Granitic rocks, unassigned to suites — CRETACEOUS AND JURASSIC

Diorite and gabbro

Scheelite Intrusive Suite — TRIASSIC

Mostly metamorphosed sedimentary rocks — MESOZOIC

Mostly metamorphosed volcanic rocks — PALEOZOIC

Contact

Fault
Symbol on side that moved down

[1] An intrusive suite is a grouping of genetically related plutonic rocks

[2] Bateman (in press a)

Generalized from geologic map of Yosemite National Park and vicinity (Huber and others, in press)

Figure 18 – Geologic map and explanation of Yosemite National Park and vicinity showing the broad zone of intrusive activity and the minor amount of metasediment (green) and volcanic rocks (brown) still preserved as pendants and erosional remnants.

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Table 1 - PLUTONIC ROCK UNITS OF YOSEMITE REGION

Tuolumne Intrusive Suite

JOHNSON GRANITE PORPHYRY- 84 Ma? Fine-grained, equigranular granite, locally contains sparse K-feldspar phenocrysts, miarolitic cavities.

CATHEDRAL PEAK GRANODIORITE - 86 - 88 Ma. Medium-grained biotite granodiorite, conspicuous blocky K-feldspar megacrysts - poikilitic.

HALF DOME GRANODIORITE - 88 - 90 Ma. Medium-grained biotite-hornblende granodiorite. Equigranular facies- large euhedral hornblende and biotite, abundant sphene. Porphyritic facies- conspicuous K-feldspar phenocrysts - poikilitic, large euhedral hornblende, seriate texture, abundant sphene.

TONALITE OF GLEN AULIN - 90 - 91 Ma. Dark-gray, variable composition. Fine-grained quartz diorite (west) to medium-grained granodiorite (east).

TONALITE OF GLACIER POINT - 90 - 91 Ma. Medium- to dark-gray, medium-grained, hornblende-biotite tonalite. Conspicuous, medium- to coarse-grained biotite, minor sphene.

GRANODIORITE OF GRAYLING LAKE - 90 - 91 Ma. Fine- to medium-grained, biotite-hornblende granodiorite, abundant sphene, well-foliated.

GRANODIORITE OF KITNA CREST - 90 - 91 Ma. Medium- to dark-gray, medium-grained, hornblende-biotite granodiorite/quartz monzodiorite.

Outboard of Tuolumne Intrusive Suite, but possibly related

SENTINEL GRANODIORITE - 96 Ma. Light- to medium-gray, medium-grained, biotite-hornblende granodiorite, euhedral hornblende, abundant sphene, equigranular to seriate.

GRANODIORTTE OF YOSEMITE CREEK - ? Ma. Dark-gray, medium- to coarse-grained, hornblende-biotite granodiorite to tonalite, locally contains plagioclase phenocrysts.

Intrusive Suite of Buena Vista Crest

BRIDALVEIL GRANODIORITE - ? Ma. Medium-gray, fine-grained, hornblende-biotite granodiorite, granular, `salt and pepper' appearance.

LEANING TOWER GRANITE - 100 Ma. Medium-gray, medium-grained, hornblende-biotite granite, granular, small (<1 cm) clusters of hornblende and biotite -'speckled' appearance.

Intrusive Suite of Yosemite Valley

NORTH AMERICA DIORITE - 103 Ma. Dark-gray, Fine-grained biotite-hornblende quartz diorite. Rich in hornblende.

TAFT GRANITE - 103 Ma. Very light-gray to white, fine- to medium grained, biotite granite to granodiorite. ~quartz – plagioclase - K-feldspar. Biotite scarce. Locally coarse-grained and porphyritic - K-feldspar.

DIORITE OF THE ROCKSLIDES - 104 Ma. Very dark-gray, fine- to medium-grained, biotite-hornblende gabbro to diorite, weakly porphyritic, and coarse-grained, equigranular, hornblende-biotite quartz diorite to tonalite. Conspicuous hornblende.

EL CAPITAN GRANITE - 104 Ma. Light-gray to white, medium- to coarse-grained, equigranular, biotite granite to granodiorite. Locally porphyritic - blocky K-feldspar, conspicuous quartz.

Finegold Intrusive Suite

BASS LAKE TONALITE/ TONALITE OF THE GATEWAY - 114 Ma. Dark-gray, medium-grained, biotite-hornblende tonalite. Locally varies to granodiorite and quartz diorite.

GRANODIORITE OF ARCH ROCK - 116 Ma. Medium- to light gray, medium-grained, biotite granodiorite. Poikilitic K-feldspar.

From Bateman et al. (1983), Bateman (1992), Calkins et al. (1985), Huber et al. (1989), Kistler (1973), Peck (1980), and Ratajeski et al. (2001). Ages are U-Pb ages from zircon and sphere. Ages from Bateman (1992), Coleman and Glazner (1997), Huber et al. (1989), Ratajeski et al. (2001), and Stern et al. (1981).

Mono Basin and Inyo Craters

        The final phase of our trip (which we may visit before the Sierran segment for logistical reasons) is to visit the Mono Basin volcanic district on the east side of the Sierra block. Recent seismicity along the Sierra Nevada – Great Basin Boundary Zone indicate the youthful tectonics of this region where significant right-lateral offset has been demonstrated. Clearly, the effects of right lateral shear of the San Andreas system are not restricted to the area immediately surrounding the fault. Locked transform-type tectonic boundaries, such as the San Andreas, form deep-seated lithospheric boundaries that distribute strain over a broad area. As such, right-lateral and resultant extensional forces are at play here, as is typical of the Basin and Range province of Nevada and southern Arizona. The heat derived from the subducted East Pacific Rise and lithospheric fracturing and extension write a sweet recipe for active volcanism. The area of Mono and Inyo Craters is the place to see it (Figure 19).

Figure 19 – Location map of the Mono-Inyo Craters area. From: *quake.wr.usgs.gov/VOLCANOES/LongValley/*.

Over the past 5,000 years, volcanic eruptions of small to moderate size have been reported from the area of Mammoth Mountain and the Mono Basin (Figure 20). Volcanic activity repeats every 250-700 years in that interval from sites along the Mono-Inyo craters volcanic chain. Steam blasts are responsible for large pits or craters and explosive eruptions typically spread hot ash as pyroclastic flows. These events are usually followed by lava doming and at other times lava flows. Of all of the areas we shall visit on our trip route, (with a runners up award given to San Francisco), this is the most geologically active.
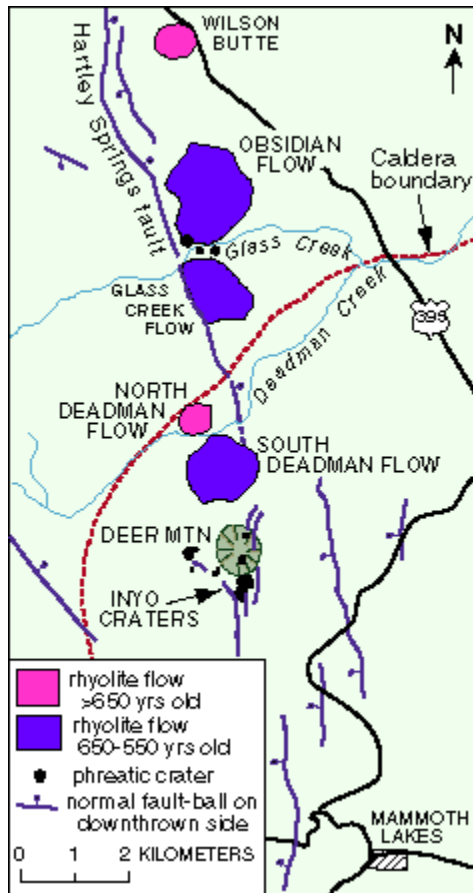
Figure 20 – Geological map of the Inyo Craters area showing the extent and ages of volcanism and fault zones. From: *quake.wr.usgs.gov/VOLCANOES/LongValley/.*

Phanerozoic Tectonic History of California

The modern plate tectonic setting of California is depicted in Figure 21 in the glorious physiographic map produced by Tharp (1969). In this view the cause for the broad zone of Cordilleran deformation is clearly evident. Subduction of most of the east half of the Pacific Ocean plate along the California margin has created it all. Today, with the development of a triple junction in Baja California, the subduction has converted to strike-slip motion along most of the western margin of North America and certainly along the south half of California. Basin and Range extension concentrated in areas of eastern California, Arizona, and Nevada and extending all the way to west Texas (the Rio Grande Rift) are the extensional lithospheric response to subduction of the spreading East Pacific Rise. To the north of the Mendicino fracture zone, Andean subduction is responsible for the Cascade volcanic district which includes Mt. Shasta and Lassen in California.

Figure 21 – Physiographic relief map of the Pacific ocean showing the modern plate tectonic configuration of North America. Note the obvious subduction of the East Pacific Rise beneath the Rocky Mountain range of the western Cordillera. In addition note that the rise separates Baja California from the mainland – a place where the east Pacific Rise changes from an extensional boundary to a transform fault known as the san Andsreas Fault. (From Tharp, 1969.)

All of the elements of the modern tectonic setting of California have occurred in the past. Indeed the assembly of California requires a rich history of continuous active margin plate tectonic activity since the early Paleozoic Era. To best explain the ins and outs of our modern ideas on the tectonics of California, I will explain things geologically – that is, from the bottom up. So, bottoms up! Here we go.

In the blink of a geological eye we draw your attention to the time scale below (Figure 22) that is specific to California. The time scale indicates the era, period, and epoch subdivisions. The geologic development of California spans at least a half a billion years (0.5 Ga) and elements of great age are caught up in the highly faulted terranes of southern California where they have been slivered off and transported northward. (See Figure 11.) To simplify a complex story, I have taken the liberty of subdividing the geologic history of California into major Phanerozoic orogenies. In much the same way that a layer cake is made, we start with the older events and move upwards in time and stratigraphy to the present. The details of the ingredients of each layer are described individually below where many stratigraphic charts and tables are provided for use in the field.

Figure 22 – Geological timescale. Geological Society of America, 1999.

You've heard of Tora! Tora! Tora! Well, Subduction!, Subduction!, Subduction! That would be the easiest way to describe the Phanerozoic tectonics of the western Cordillera. Throughout the early Paleozoic, development of an open-ocean passive margin formed an extensive open ocean miogeosynclinal and deep-water eugeosynclinal couple formed adjacent to embryonic western North America (Figure 23). Although facing in the opposite direction, the plate tectonic setting of the Cordillera was a mirror image of the developing Appalachian passive margin throughout the early Paleozoic.
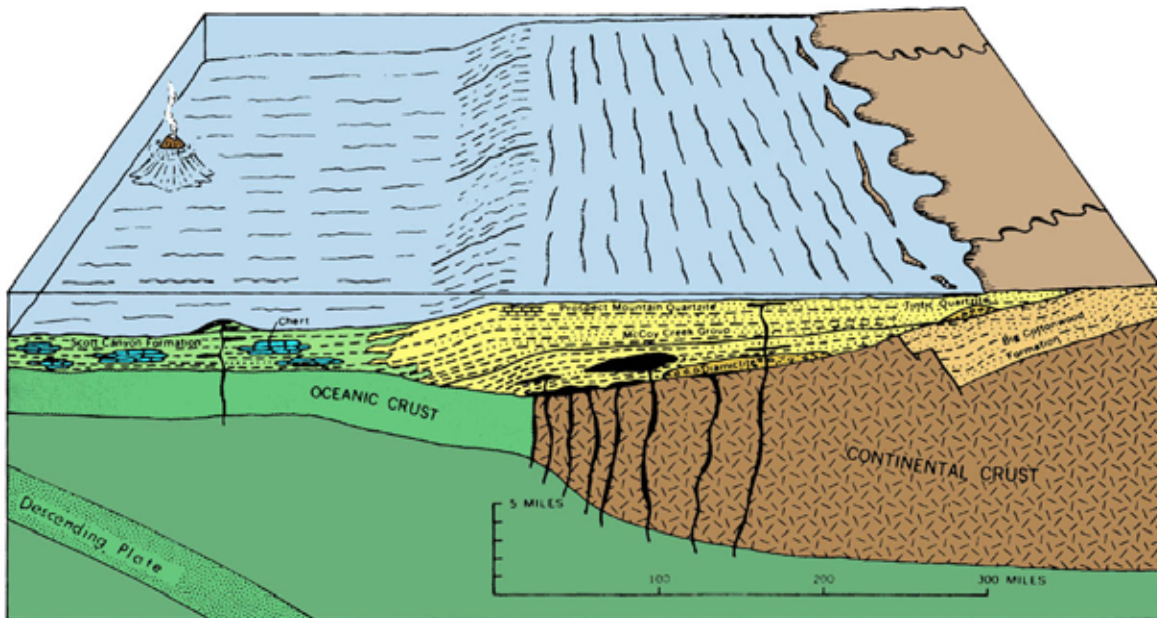
Figure 23 – Pre-Antler open ocean view of the passive Cordilleran margin during early Paleozoic time. The eventual position of California is somewhere near the middle of this diagram.

Pre-Antler

Roughly 550 Ma, with formation of an open ocean to the west, Cambrian clastics spread out over the edge of North America under shallow water conditions. Directly analogous to the transgressive lower Paleozoic facies of the Appalachian belt, with rising sea level, subsiding continental edge, or both, the Cambrian shoreline migrated eastward to sweep across areas as far as Arizona. As time passed, the offshore depositional environments shifted continentward along with the Cambrian trangression of the seas. This resulted in a fining upward sequence of strata where Cambrian sands (Tapeats Sandstone) were overlain by shale (Bright Angel Shale), then by carbonate (Muav Limestone) of the Tonto Group as shown in Figure 24. A regionally impressive Cambrian to early Ordovician transgression is also recorded in the Appalachian belt.
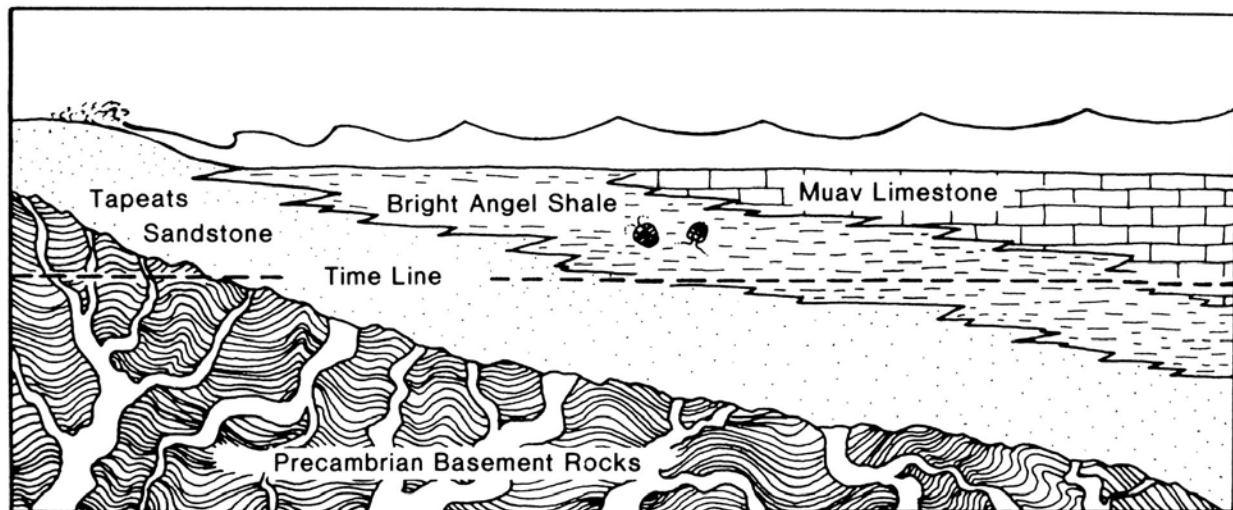
Figure 24 – Southward view along a profile section showing the discordant relationship between time lines and formational contacts in a transgressive environment. (Nations and Stump, 1981, p. 19.)

Antler Orogeny

Starting with the **Antler orogeny** in late Devonian – early Mississipian time, a series of convergent margin events affected the western Cordillera. An arc-continent collision was responsible for the Antler orogeny (Figure 25). The Roberts Mountain Allochthon places deep-water facies atop coeval miogeoclinal rocks through central Nevada along east-directed overthrusts. Such overthrusts were produced within the walls of an accretionary prism that collided with the passive margin of North America. Seek geologic timescale (Table 2). In the area of our trip, the Shoo Fly Complex records the effects of Antler orogenesis superimposed on the lower Paleozoic passive margin sequence.
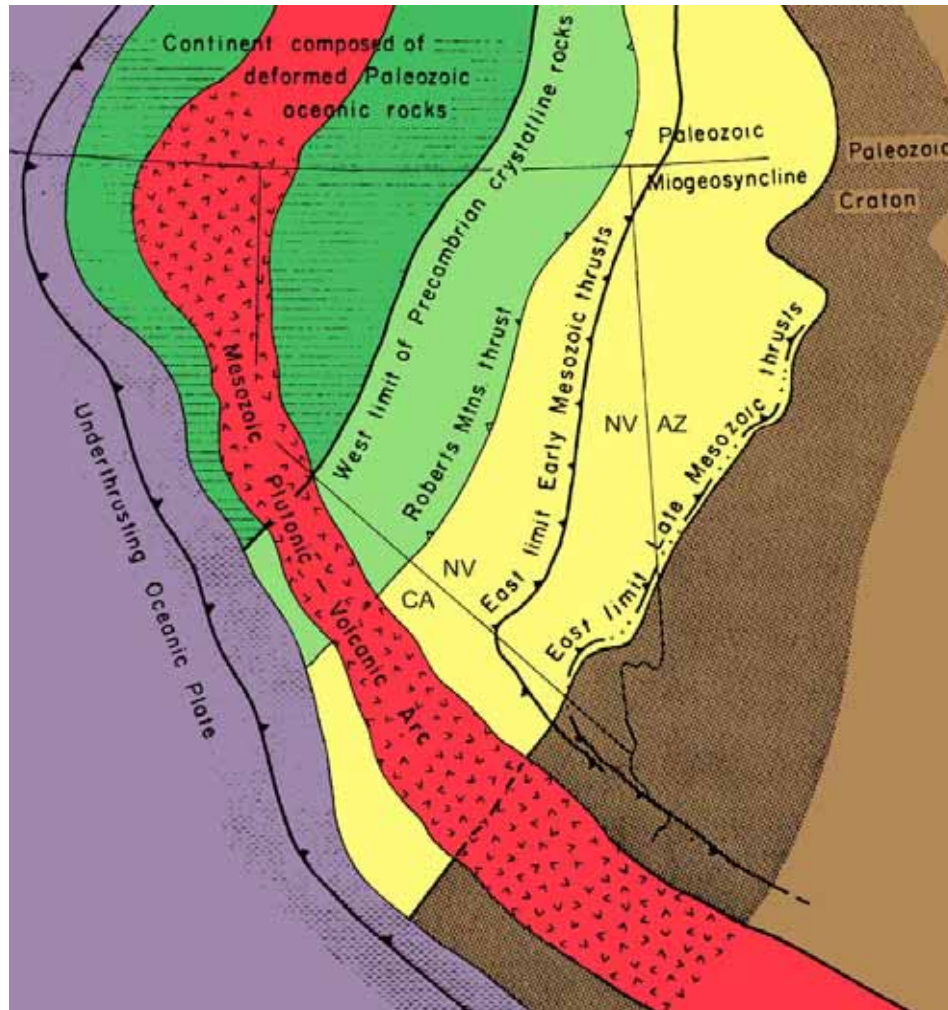
Sonoman Orogeny

After a period of uplift, erosion and extension, a marginal basin formed that filled with Pennsylvanian and Permian sediment. A piece of the late Devonian Antler volcanic arc that had already collided rifted away from the suture zone, leaving a small oceanic "marginal" basin behind. Closure of that marginal basin along a west-dipping subduction zone resulted in a collision with the old Antler arc that had rifted away earlier. The **Sonoman orogeny** (late Permian - early Triassic) produced a collision that resulted from the composite arc that formed in the upper plate of the new subduction zone. Figure 26 shows, in green, the trend and position of both the Antler (Roberts Mountain) and Sonoman (Golconda allochthon) belts in Nevada and their presumed extension into California. Note the high-angle truncation of the older Antler and Sonoman tectonic trend with the late Triassic and younger NW trend.
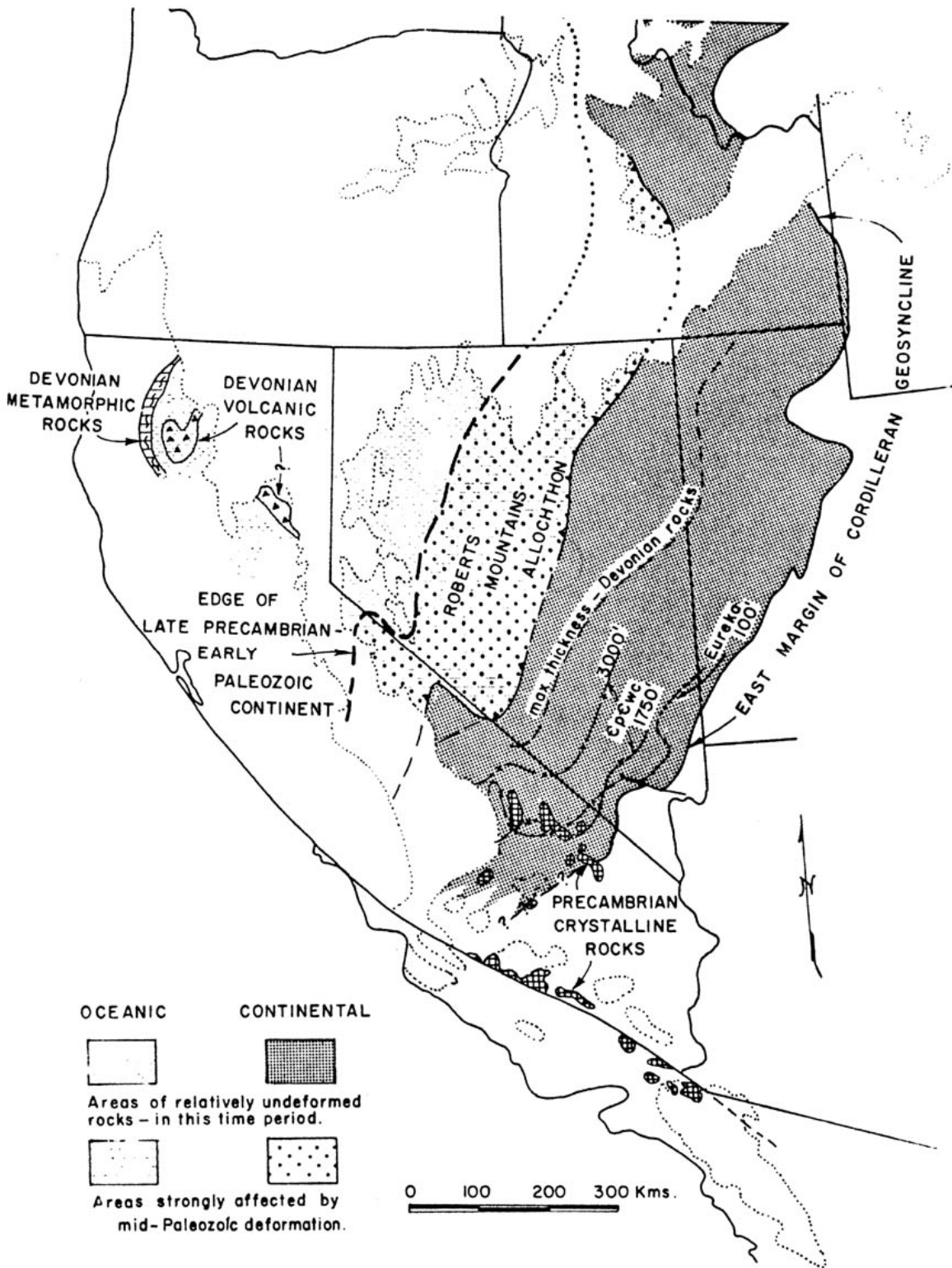
Figure 25 – Map showing Late Proterozoic to Devonian isopachs and position of Roberts Mountain allochthon.

Figure 26 – Geologic sketchmap showing the truncation of Antler, Sonoman, and Sevier thrusts. (Burchfiel and Davis, 1972, Fig. 7.)

Nevadan Orogeny

By the late Triassic, after some significant shifts in polar wander paths (indicating rapid plate reorganizations), the SW Cordillera looked quite different. Development of a NW-trending megashear zone cut across the Antler and Sonoma trends and prepared the newly arranged margin for an unprecedented epoch (Jurassic to present) of continuous continentward subduction. During the middle Jurassic **Nevadan orogeny**, island arcs were swept into the Cordilleran margin and subduction flips were common (Figure 27). The scattered volcanic island arcs of the SW Pacific may offer a modern analog to the conditions that must have prevailed along the active edge of the western Cordillera throughout the Mesozoic (Figure 28).
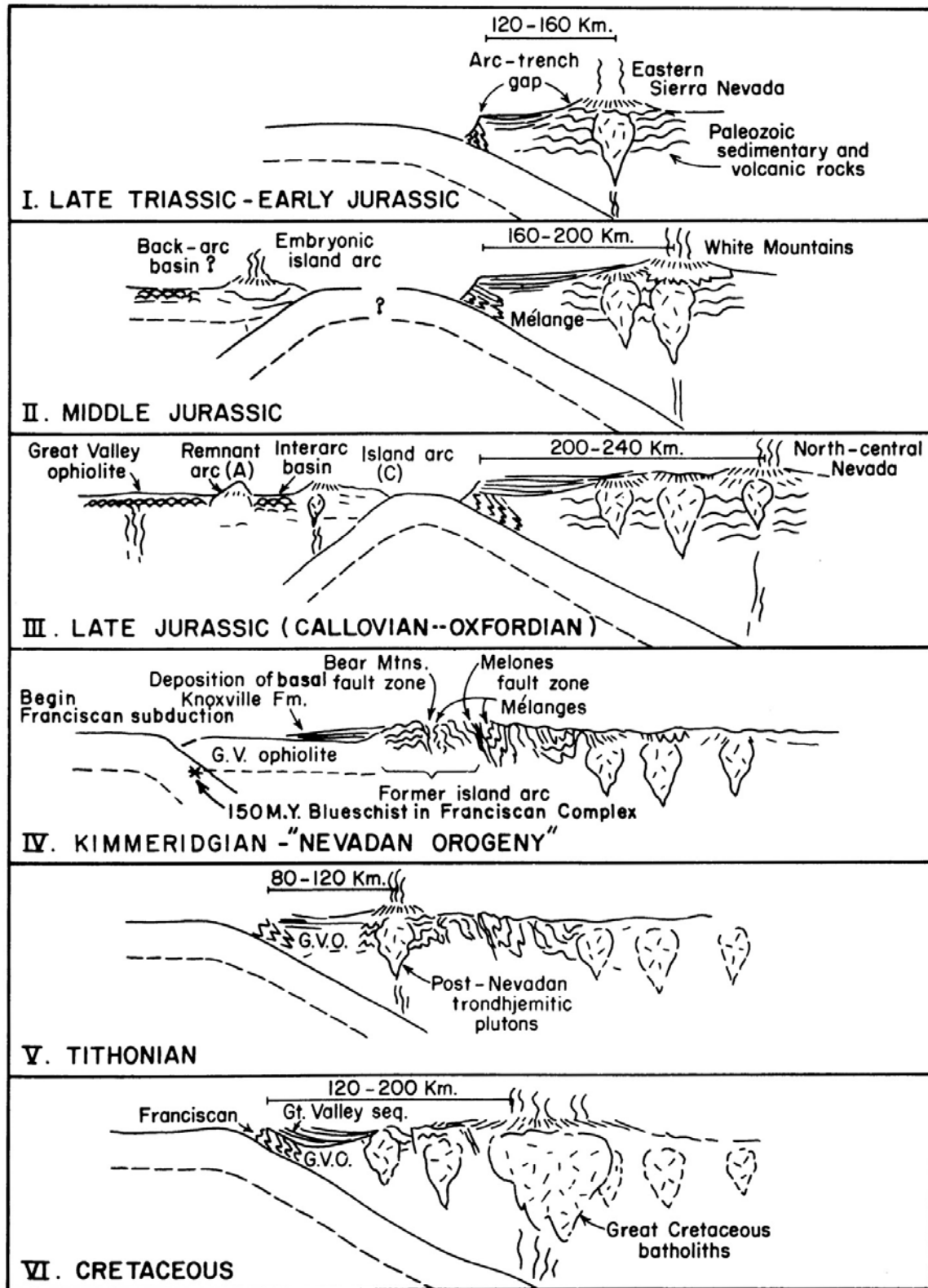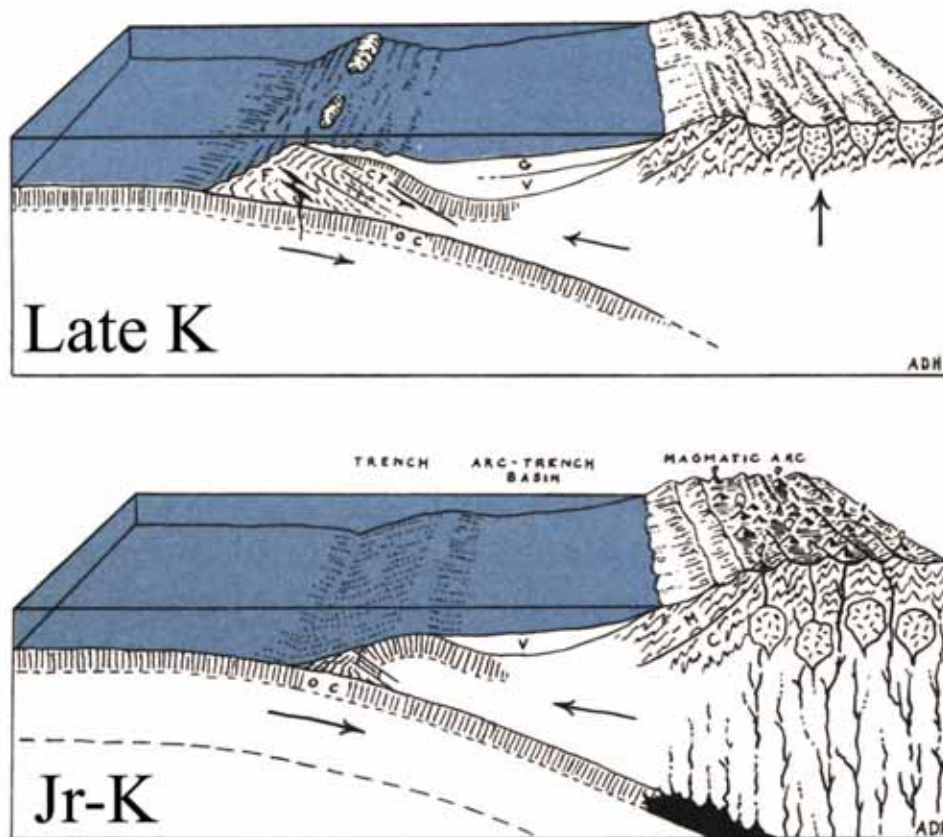
Figure 27 – Plate models to explain Mesozoic tectonics of the SW Cordillera. (Schweickert and Cowan, 1975.)

27

Figure 28 – Block diagrams depicting the growth and evolution of an Andean arc-trench system during Mesozoic time. (Composite diagram adapted from Howard, 1979.)

As we had mentioned earlier, the Mesozoic was a period of continuous subduction but many changes in tectonic plate subduction. For example, between the late Triassic to Cretaceous rapid tectonic suturing of exotic terranes and development of a broad tectonic welt occurred in the SW Cordillera. Thus, starting in Kimmeridgian (middle Jurassic) time and extending through the Cretaceous to present, continentward subduction has resulted in the truncation of all older geologic trends including Antler (Roberts Mountain) and Sonoman overthrusts. (See Figure 27.) The Cenozoic geology California is the product of continuous subduction against a complexly deformed Phanerozoic mobile belt and eventual changeover to a San Andreas type margin, the product of interaction with a subducted spreading ridge (Figure 29).

Laramide Orogeny and Beyond

The Laramide orogeny affected the SW Cordillera between late Cretaceous and Eocene time. Arizona was tectonically active with upwarps and downwarps of the region controlling sediment patterns. That instability was followed by intermediate to silicic eruptive volcanism in response to continuous subduction along the active Andean margin to the west. Lithospheric softening and NE-directed compression resulted in thermal collapse of internal core zones of the

Laramide overthrusts where ductile thrusts show maximum offset of 100 km. Known as metamorphic core complexes to some, these areas exhibit mobilized amphibolite facies gneiss in massive overthrust sheets. In addition, large Cenozoic plutons invaded portions of southern Arizona but Basin and Range faulting has obscured many of the geologic relationships.
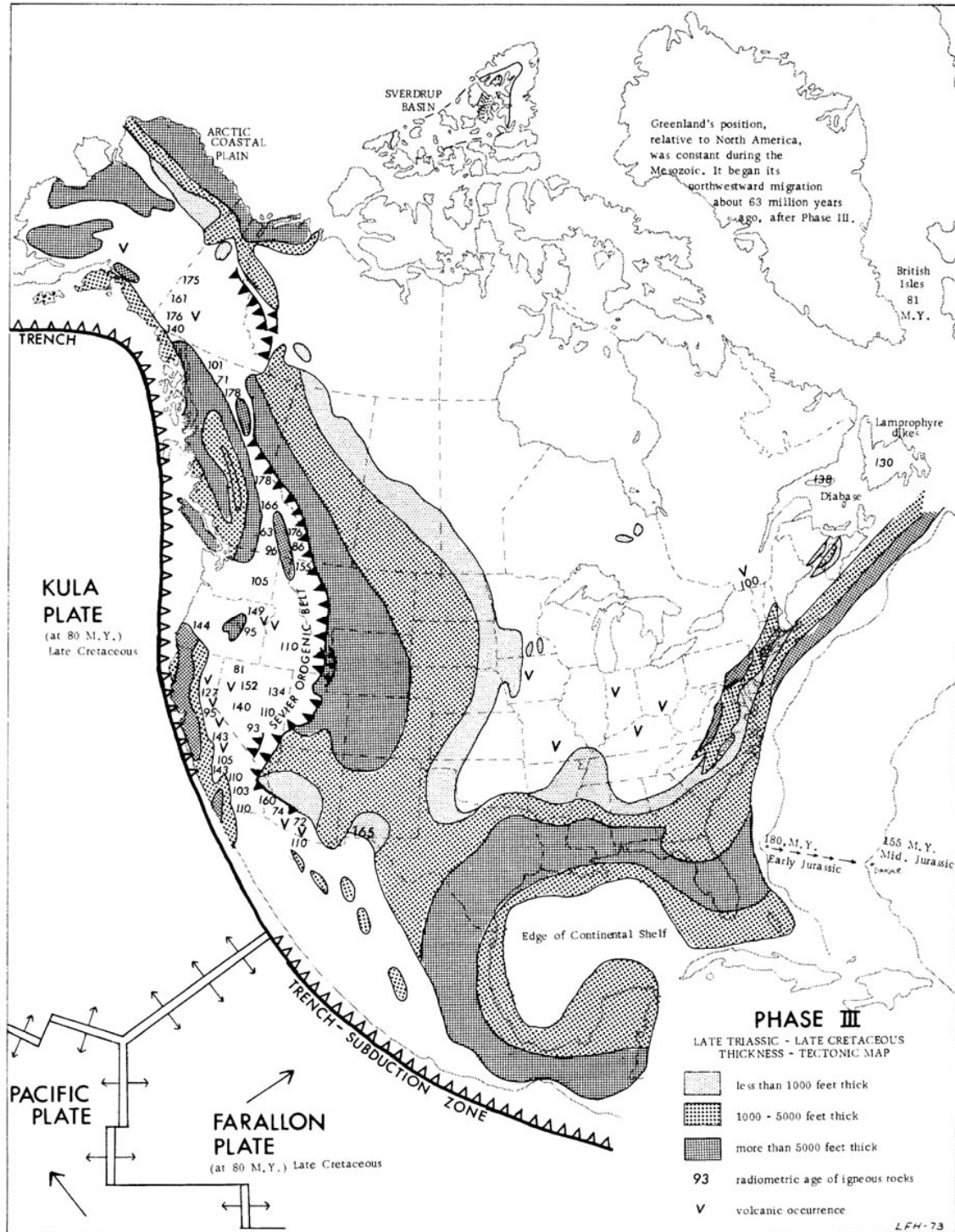
Figure 29 – Paleotectonic map of the Cordillera from Late Triassic to Early Cretaceous time.

Far as California goes, by early Cenozoic time subduction was in an Andean setting with development of an elongate volcano-plutonic complex parallel to the present coastline. With flattening of subduction angles in the Cenozoic, volcanogenesis broadened to include the Great Basin. Starting at about 30 Ma, destruction of the Farallon plate and development of the San Andreas plate boundary has dominated the tectonics of the region (Figure 30).
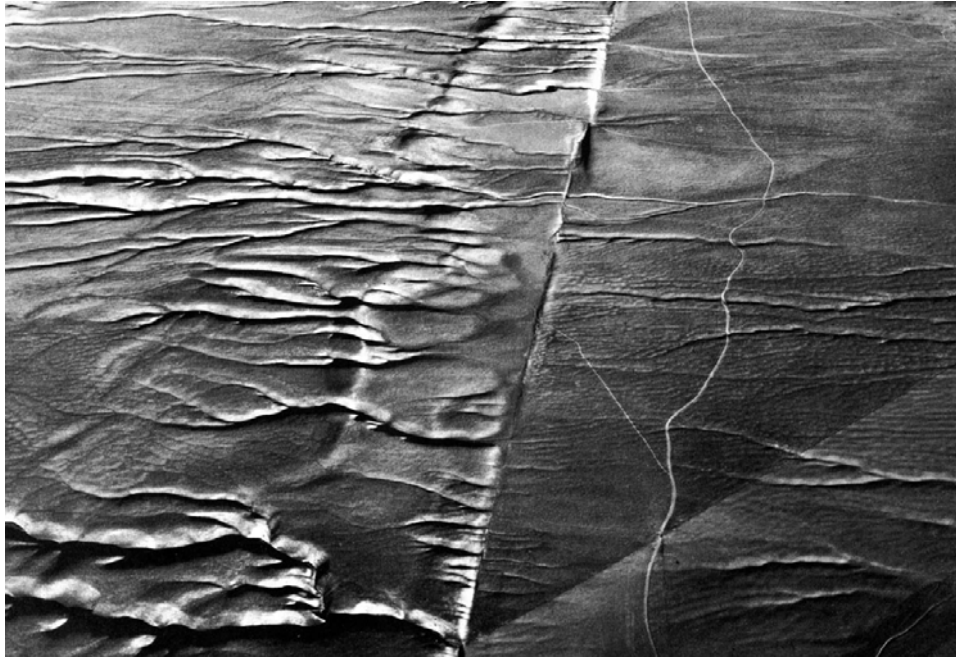

Figure 30 – Aerial view of the San Andreas fault. (From Shelton, 1966.)

A view of the Cenozoic tectonics of the region helps to understand the products of Cenozoic geologic development of California. Subduction of the east half of the Pacific Ocean plate during the Mesozoic and Cenozoic resulted in the formation of the western Cordillera of the United States. Subduction of the Farallon plate and parts of the East Pacific Rise began during the later part of the Cenozoic Era. By the Eocene (roughly 50 Ma) the plate configuration involved subduction of an offset ridge crest that ultimately resulted in fragmentation of North American crust and development of the right-lateral San Andreas fault system (Figure 31). By 30 Ma, the NE-corner of the transform-ridge Farallon segment had collided with northern Mexico and from that noble area subduction of western half of the Pacific Ocean plate officially began. Parades, celebrations, and parties were held throughout the western Cordillera.

By 15 Ma the partying had faded as the consequence of the subduction of an active ridge crest had become obvious – decreased volcanicity at first then continuous volumes of lava and explosive volcaniclastic debris all in the midst of active seismicity. Indeed, the result of subduction of the Pacific Ridge had far-reaching geological consequences. High heat flow and resulting volcanicity, extensional faulting, uplift, and seismicity can all be attributed to the consequences of subduction and active ridge crest. The development of Cenozoic metamorphic core complexes, with low-angle ductile normal faulting, were formed by thermal weakening produced by the same mechanism.

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Starting about 5 Ma in Baja California our present plate configuration has produced a sliver of North America (the Salinian block) that moves northwestward along the Cordilleran margin. As demonstrated by studies of the western Canadian Rockies, this scenario has played out many times in the past. Much of the western Canadian Rockies form a collage of accreted terranes that are linked to the SW Cordillera of the United States and Mexico. The Cenozoic dislocation and drift of the Salinian block provides a candidate for the next accreted terrane when the future tectonics change to convergence. A summary diagram is provided as Figure 32.

The San Andreas system continues to evolve along the SW Cordillera. Because of the relative motion of the Pacific Ocean plate, the extension produced by the spreading of the subducted Pacific Ridge has resulted in an overall pattern of seismicity (Figure 33).
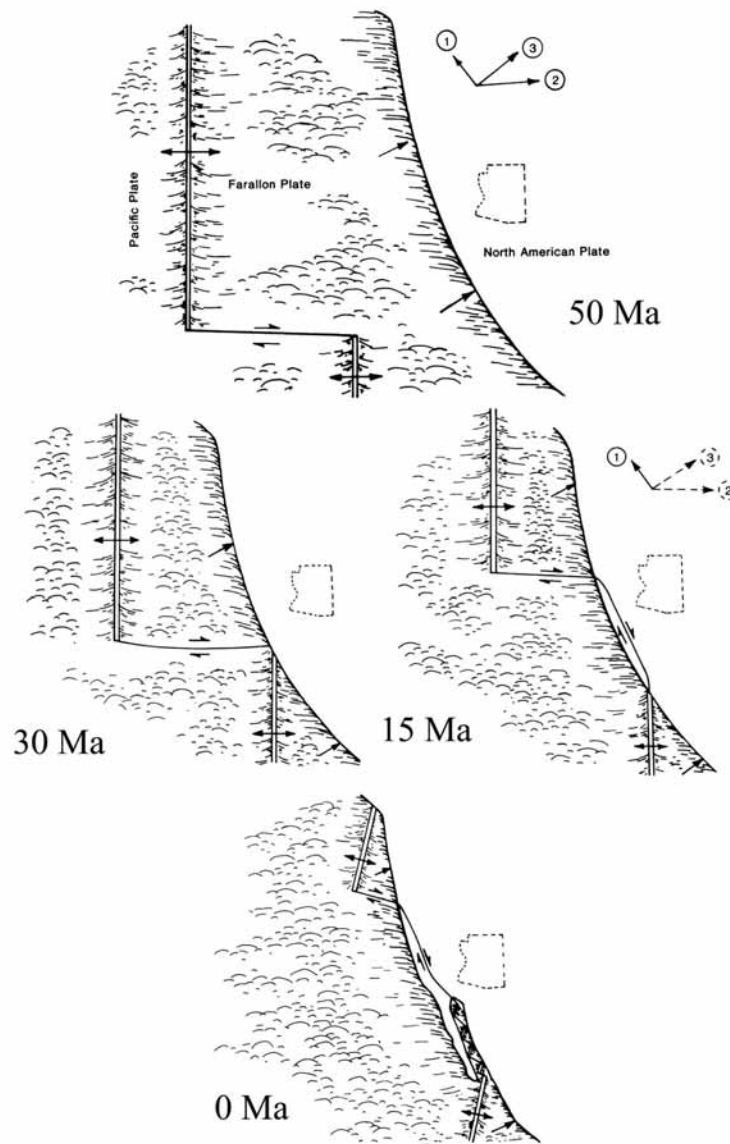

Figure 31 – Four views of the post-Eocene plate tectonic evolution of the SW Cordillera. The position of Arizona is shown as a dotted outline. (Adapted from Nations and Stump, 1981, Figure 7-6, p. 75-77.)

31
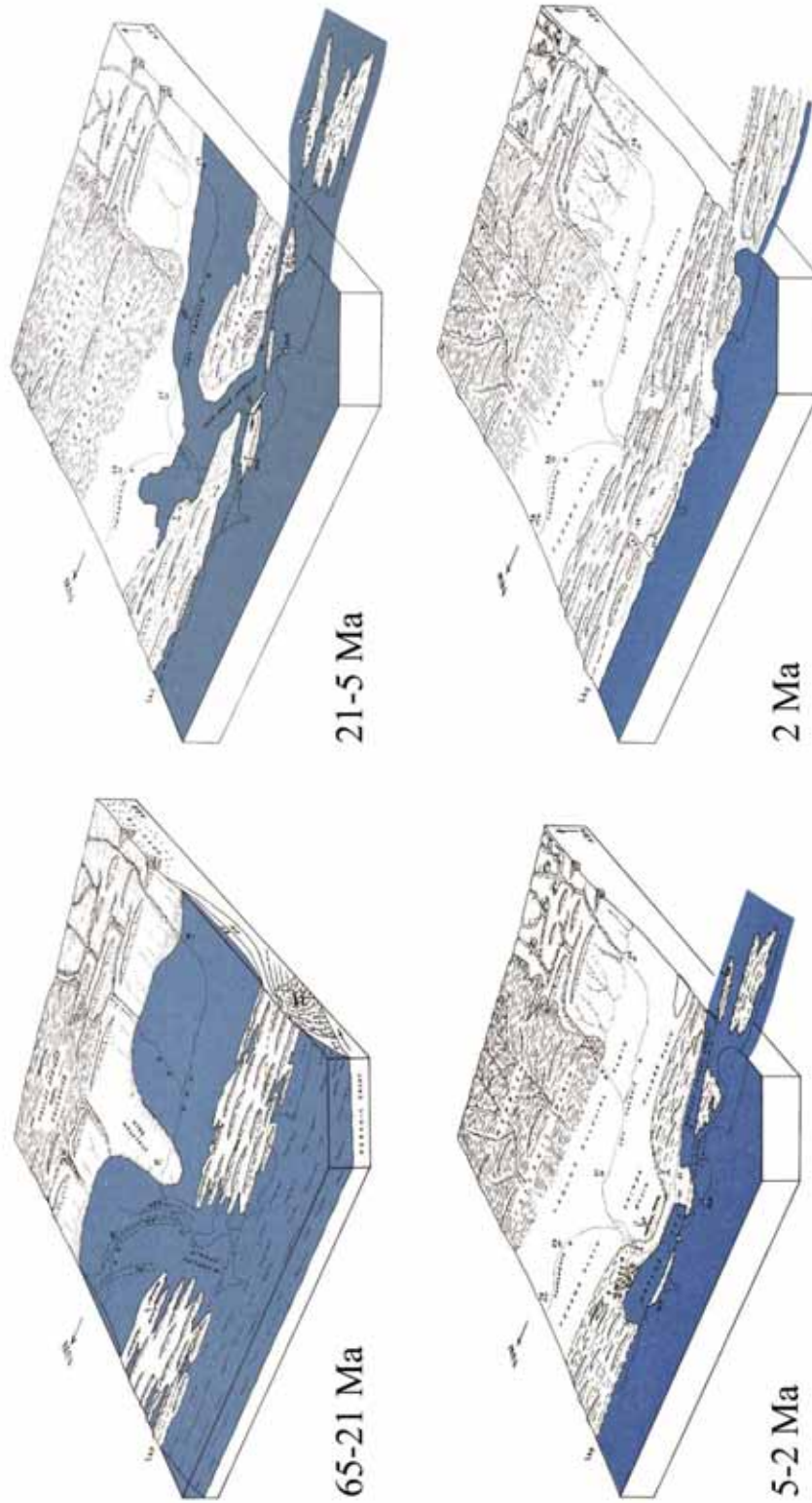
Figure 32 – Block diagrams showing the NW migration of the Salinian block and physiographic changes taking place during the last 65 Ma. (Composite diagram adapted from Howard, 1979.)
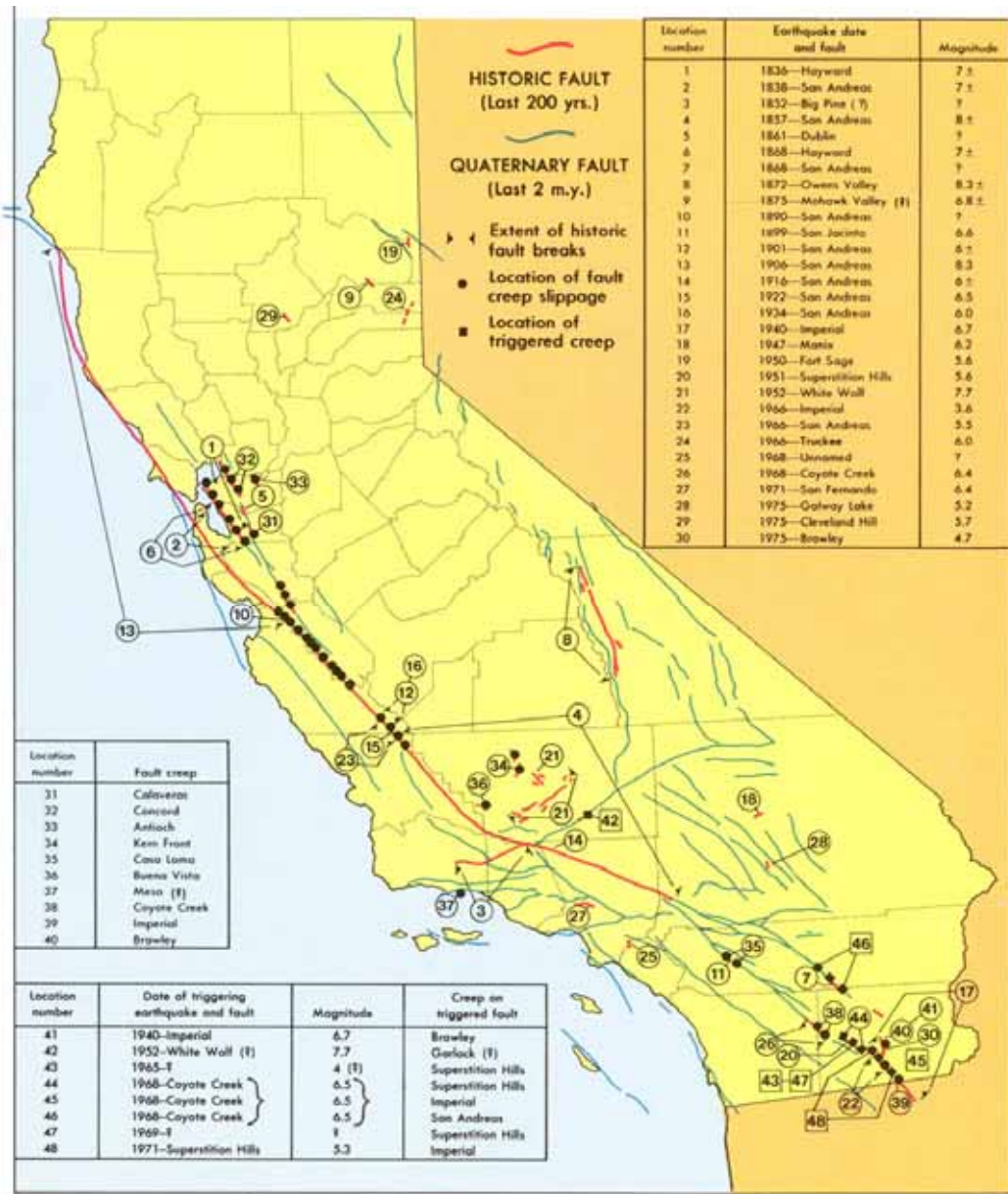
Figure 33 – Fault map of California showing the locations of major faults and a listing of major events. (From California Division of Mines and Geology, 1980.)

Thus, we end the description of the geological background and tectonics of California and we can look over the itinerary (below), then move on to the day by day details of the geology and history of the four segments of our trip across California. Described separately below in the appropriate section, the Coast Range and Great Valley, Foothills Metamorphic Belt, Sierra Nevada, and Mono-Inyo Basin form the four geological segments of our 10-day excursion. Appendix A includes a Geological Primer. Reading the primer will help you brush up on the terminology and major concepts of geology that we need to apply to our outcrop scale study of this impressive terrane.

Trip Itinerary

We will make every attempt to go to as many places listed in the itinerary as possible and will certainly stop at other places along the way if deemed necessary to develop the field trip message. Detailed geologic descriptions of the four trip segments follow. The following pages will be referred to often in the field during our trip. The index map below (Figure 34) covers our entire trip route.

Figure 34 – Road map of the field trip route from San Francisco northeast to Placerville, down the foothills metamorphic belt then across the Sierra Nevada along the Merced River to Mono Craters.

Itinerary for Geology 143B – Field Course in Central California

Day 1 (Monday, 24 May)

American Airlines Flight 15 from JFK to SFO

Arrive SFO at 2:54 PM and secure van. Drive N and visit Marin lookout then continue N to Mt. Tamalpais area to see sheared oceanic rocks of the Franciscan complex. At Stinson Beach one can see dark-colored Fransiscan rocks consisting of thinly bedded chert surrounded by muddy sandstones. Drive N along the coast road (California State Route 1) which follows along the east side of Bolinas Lagoon. According to Alt and Hyndman (1975), the lagoon is a drowned valley developed along the San Andreas fault. Optional visit to Muir Redwoods area. Continue

N to Point Reyes National Seashore area and plan to stay at Olema Ranch Campground for the night. Visit Point Reyes after setting up camp. Enjoy the geology, the lighthouse, the whales (if we get lucky) and the sunset if CM can get the timing right.

Olema Ranch Campground
10155 Hwy 1
Olema, CA 94950
(800 655-2267)

Speak with Ed. $23/night for 2 people + $3/night/each add'l person + $2/vehicle = $39 total.

Day 2 (Tuesday, 25 May)

Visit Stinson Beach and Point Reyes.   At Stinson Beach, Franciscan mélange is exposed. Backtrack to Point Reyes and walk to coast to examine granites of the Salinian block, to the west of the San Andreas fault. Between the coast road and the seashore, you have walked across the San Andreas fault - you have passed from the North American plate to the Pacific plate.

Head north from Point Reyes past Bodega Bay toward Jenner along State Route 1. Along this tract of the coast road the San Andreas fault is to our west, buried beneath Tomales Bay. As we drive north we will try to stop to examine exposures of Franciscan and work our way eventually to Jenner at the mouth of the Russian River. At Shell Beach, roughly 2-3 miles before Jenner, a picnic area exhibits mélange. After crossing Route 116 and the Russian River the first headland that juts out exposes knockers within the Franciscan. At the first turn-out N of the river eclogite is exposed. Here we plan to hike up to see the exposed knockers, recognizing that we are in a former subduction complex where significant shearing and intercalation of rock units has taken place. What types of rocks can we find in these exotic blocks swimming in a shaly matrix.

The second part of today's excursion includes a traverse through the wine country of the Napa and Sonoma valleys. We will backtrack to Route 116 and head inland along the north side of the Russian River and across the strike of the Coast Range. Follow Route 116 past Guerneville and Forestville and at Sousa Corners head due east along the Guerneville Road (Route 12) to U.S. Route 101. Take Route 101 northward to Fulton and turn R along Mark West Springs Road to, guess where?? – Mark West Springs. From there follow Porter Creek Road to the Petrified Forest Road onward to Canistoga. The Napa Valley lies before us! Time permitting we may stop to see what the Petrified Forest is all about.

Turn R out of Canistoga onto Routes 29 and 128 into the Napa Valley and then turn L at Rutherford onto Route 128 past Lake Hennessey and turn L at the end of the lake to follow Chiles Pope Valley Road down to Chiles Valley. Turn L and follow along until turn off to R where Pope Canyon Road takes off and wind your way northward to the west side of Lake Berryessa. We may opt to pass through Santa Rosa, Napa and Sonoma and stop for lunch. All along the way we will travel across the geologic grain or strike of the Franciscan strata before crossing the Coast Range thrust and passing into the Great Valley Sequence. Camping is available at Lake Berryessa Resort (707 966-2161) and Spanish Flat (707 966-7700). We will

stay at Spanish Flat for the evening by continuing east along the southwest shore of Lake Berryessa along the Berryessa-Knoxville Road to Spanish Flat.

Spanish Flat Resort
4290 Knoxville Road
Napa, CA 94558
(707 966-7700)

Note: Lake Berryessa Resort wanted two nights stay but speak with Sharon (Manager) at Spanish Flat and get one-day rate for student trip at Lower Trout Point (secluded area).

Day 3 (Wednesday, 26 May)

To start the day we will backtrack along the southwest shore of Lake Berryessa along the Berryessa-Knoxville Road where serpentinites related to the Coast Range thrust are found all chopped up. After we are done exploring, travel back along the Berryessa-Knoxville Road through Spanish Flat and follow along to the junction with State Road 128. Turn L and follow 128 to examine dipping strata of the great Valley Sequence at the Monticello Dam area on the east end Lake Berryessa. We will spend a few hours at this locality examining the volcaniclastic turbidites.

After this morning activity, take Route 128 east to pass beneath I-505 and follow 128 east through Davis where we will turn R onto State Road 113. Follow 113 south to I-80 and follow the interstate into West Sacramento. Pick up State Route 50 and follow it into Placerville at the intersection with CA Gold Route (49). We plan to camp overnight along gold trail near Coloma. If time is available we will drive northward to see the American River.

Camp Lotus
PO Box 578
Lotus, CA 95651
(530) 622-8672

Speak with Margaret. Cost is $7/person/night = $42.00

Day 4 (Thursday, 27 May)

Begin gold trail in Placerville and head south toward Sonora (~70 mi). Stop at the major gold camps along the way. Coloma is where gold was discovered in 1848 by James W. Marshall at John A. Sutter's Mill. At the Cosumnes River (~15 miles S of Placerville) stop and hike downstream on N side of river to see Jurassic volcanic rocks west of the Melones fault zone. Continue S on Route 49 to Angels Camp and look at the Jurassic volcanic rocks exposed there if time permits. Stop at S side of bridge over the Middle Fork of the Stanislaus River to examine exposures of greenish phyllite of the Jurassic belt. Columbia, Sonora, and Jamestown are next and plan to hang there for the evening. Many old mines spot the countryside and their history is

summarized below as Segment 2. Rich placers above the Columbia Marble saw the use of hydraulic mining and in 1954 the site was preserved as a State Historic Park. We will spend some time in this old gold town, then make our way to Jamestown to camp for the evening.

Lake Tulloch RV Campground
14448 Tulloch Road
Jamestown, CA 95327
(209) 881-0107

Speak with Jane (12 years on premises) who says to just come on in and pick out a campground. Site is 12 miles from Jamestown and the place should be empty – just show up (no reservation needed). Water, Picnic Tables, Fireplaces, Showers.

Day 5 (Friday, 28 May)

      Drive eastward toward Jamestown and take the Rawhide Road NW from Jamestown, perhaps stopping to see the train yard. Rawhide road cuts through Table Mountain which is the type locality for latite. Find some slickensided serpentinite exposures along the Melones fault zone and spend the morning examining the Jurassic Belt following the trip guide produced by Schweickert and Bogen (1983).

      Backtrack to Columbia and Sonora and take back roads into the Camp 9 Powerhouse area to see the Calaveras, the Calaveras-Shoo Fly thrust and then some of the Shoo Fly Complex in Jupiter, the area of CM's Ph.D. thesis research in the interval 1978-80. The powerhouse is built on the Confluence pluton, one of the many orthogneiss bodies in the Shoo Fly Complex (Merguerian and Schweickert, 1985). This will take about an hour in and an hour out on dirt roads – we will spend the rest of the time looking at rocks and awesome vistas. Continue on Camp 9 road to the Jupiter area and look at good exposures in Deer Creek, Knight Creek, and Rose Creek where river-polished exposures reveal the effects of ductile polydeformation. Walk upstream at Knight Creek to see exposures of intercalated rocks. Get out of the forest through Twain Harte and stay in Sonora for night – this time in a motel/cabin.

Best Western Sonora Oaks
19551 Hess Avenue
Sonora, CA 95370
(209) 533-4400
Confirmation # 174358

Speak with Brenda who offers a two-room suite at $159 for the night. Fee includes Continental Breakfast, Jacuzzi, Pool, and Internet access.

Day 6 (Saturday, 29 May)

Head south and stay on Route 49 past Jamestown, Chinese Camp, and Moccasin where the road cuts through the Penon Blanco ridge. At Hatch Creek, take Marshes Flat road to see Jasper Point cherts and exposed pillow lavas of Jurassic sea floor. Go west around Lake Don Pedro for some swimming. Get back to Route 49 and drive toward Coulterville, Bagby, Bear Valley, and eventually Mariposa where we will try to find the type locality for *mariposite* (west a short ways along 140, I think), a chromian mica more formally known as *fuchsite*.

Out of Mariposa take Route 140 eastward up the south side of the Merced River drainage, the scenic route into Yosemite, stopping to see geology and awesome scenery along the way. Camp somewhere upslope but before Yosemite (El Portal?). If running short of time take Route 120 into the Sierra before Moccasin. Private campsites are found along 140 and State Forest campgrounds are scattered too. Alternate plans include visits to Hetch Hetchy Reservoir and the wild, wild Clavey River. As of now, we will plan to stay at the Indian Flat RV Park.

Indian Flat RV Park
PO Box 356
El Portal, CA 95319
(209) 379-2339

Day 7 (Sunday 30 May)

Yosemite (half day or more) then head out toward the High Sierra. Cut up Canyon Road and take Big Oak Flat Road to Crane Flat then E to Tioga Pass Road. It's about 50 miles from Yosemite to Tioga Pass. Stop and camp (?) at Yosemite Creek – High Country scenery and scenery. Drive to Olmstead Point for view back at Yosemite Half Dome granodiorite and view the effects of glaciers. We are in freeform mode for the rest of the trip as it is too hard to plan accurately so far in advance when we are living the life of traveler/vagabonds and because of the unpleasant increase in people the result of Memorial Day weekend. We will use a guidebook by Schweickert (2003) as a guide to this part of our journey. Plan to camp for the evening in the high Sierra in federal park lands along Route 120.

Day 8 (Monday, 31 May)

About 1-2 miles east of Olmstead Point, Tenaya Lake (a Sierran mountain lake) can be found and swimming is called for. The contact is exposed between the Half Dome Granodiorite and the Cathedral Peak granite (w/ large K-spar). At Tioga Pass we are in the Saddlebag Lake roof pendant. At Tioga Pass take road N from highway to Saddle Bag Lake. Glacial features are visible to the west as well as an angular unconformity and Triassic Caldera (Schweickert and Lahren, 1999). The caldera is exposed along the highway near Tioga Lake. Plan to do some hiking in areas to the east side of Tioga Pass. About 9 miles E of Tioga Pass we get to Lee Vining Canyon (before the town of Lee Vining).

The Mono-Inyo Craters are east of Lee Vining. In Lee Vining we may visit the Mono Craters Committee, a grass roots effort to preserve the craters and the lake shore. The higher parts of Mono craters are difficult to reach and we will rely on a guide by Tierney, (1995). On the South shore is Panum crater a 600-700 year old obsidian dome and tuff ring. Continue south out of the Mono Lake area to Mammoth to see a 30-mile to long caldera valley, roughly 780,000 years old. The Bishop Tuff is exposed there. Spend the day here and begin drive back to San Francisco across the same terrain and get back to Sonora by the evening. Perhaps we will retake our Sonora Best Western hotel room or simply head back to San Francisco.

Day 9 (Tuesday, 01 June)

Spend the day in San Francisco sightseeing and examing rocks along the west shore of the San Francisco Peninsula. Group dinner at night. We will stay at the Sheraton Hotel at Fishermans Wharf.

Two double rooms booked for $159/room + 14% Room Tax. Deadline is up to 5/31. Confirmation# C747304455. Speak with Evelyn.

Day 10 (Wednesday, 02 June)

American Airlines Flight 16 from SFO back to JFK.

Field Trip Descriptions

Segment 1
The Coast Range and Great Valley

As planned, our geological field course will be held in Central California, a part of the Pacific Mountain Division of the SW Cordillera of the United States. (See Figure 4.) The landscape varies greatly in relief and climate from desert in the south and central valley to gentle coastal and rugged interior mountains where elevations exceed 16,000'. (See Figures 5, 6).

San Francisco was the main entry point for gold seekers during the California gold rush of the mid 1800s (Figure 35). The city of San Francisco thrived during this period, seeing development of a commercial port, major city, and industries to support the gold effort. The argonauts came from all over the world to seek their fortunes in the golden hills of California. The international flavor and pioneer spirit of the old west is still evident, even to the most casual of observers.

Figure 35 – Painting of the port city of San Francisco, home port for many of the argonauts.

We plan to take the coast road north from San Francisco to Point Reyes National Seashore for the first leg of our trip (Figures 36, 37). Our stay in the Coast Ranges will enable us to view the stratigraphy and structural geology of the Franciscan subduction complex and allow examination of exotic blocks or "knockers" in the Franciscan. We will discuss the geology of the San Andreas fault (Figures 38, 39) and the geology of the Salinian block (Figure 40), crossing over the major boundary from time to time during our investigations (Figures 41-43).

Figure 36 – Road map of the San Francisco Bay area showing San Francisco International Airport, our entry point to California.

Figure 37 – Index map for Segment 1 of our trip.
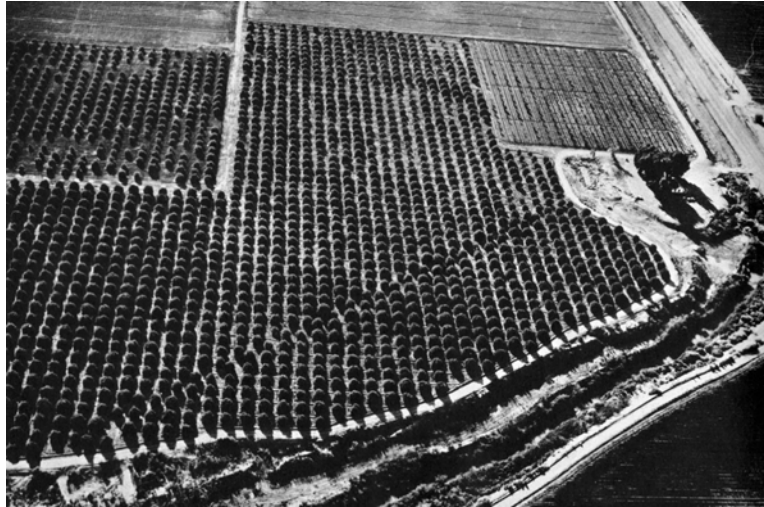
Figure 38 – Aerial view of an orange grove showing offset, the result of creep along the San Andreas fault system. (From Shelton, 1966.)

Figure 39 – Satellite image of the San FranciscoBay area showing refraction and internal waves produced by strong currents that buffet the west coast of North America in the vicinity of San Francisco. The San Andreas fault is the linear feature that trends NNW along the western California coast. Note the sediment plumes related to the Sacramento and San Joachin rivers. Clearly the satellite image indicates that the San Francisco Bay area is a drowned river mouth.
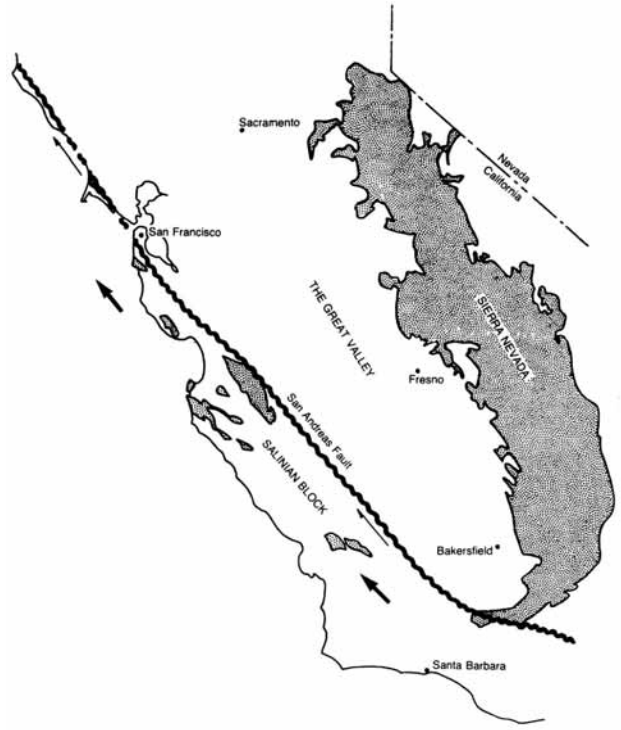
Figure 40 – Geologic sketchmap showing the dislocation of the Salinian block along the San Andreas fault system of California. (Adapted from Alt and Hyndman, 1975, p. 8.)
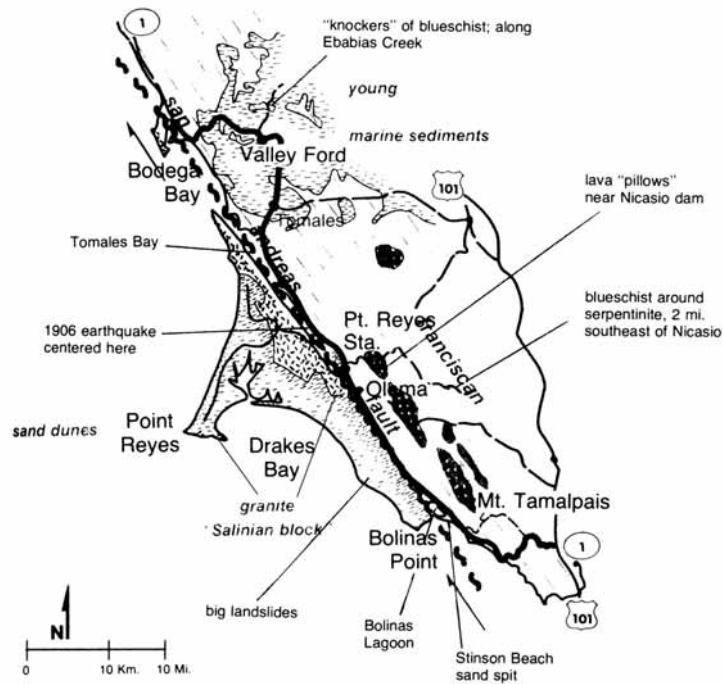
Figure 41 – Geologic map in the vicinity of Drakes Bay and Point Reyes National Seashore. (Adapted from Alt and Hyndman, 1975, p. 37.)
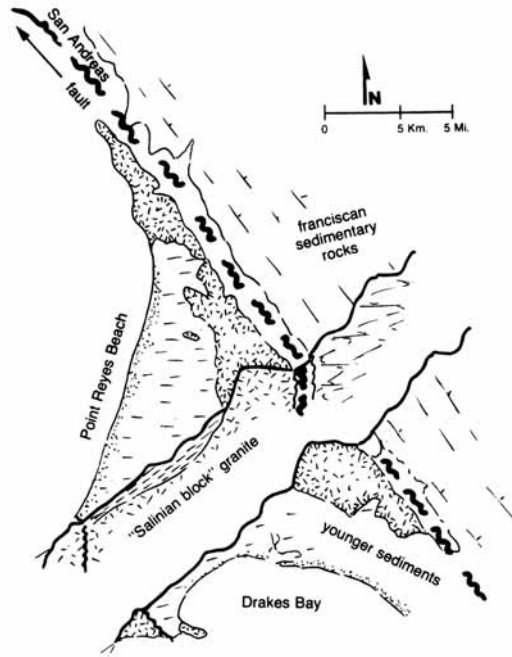
Figure 42 – Geologic map of the Salinian block and Franciscan along the San Andreas fault at Point Reyes. (Adapted from Alt and Hyndman, 1975, p. 42.)
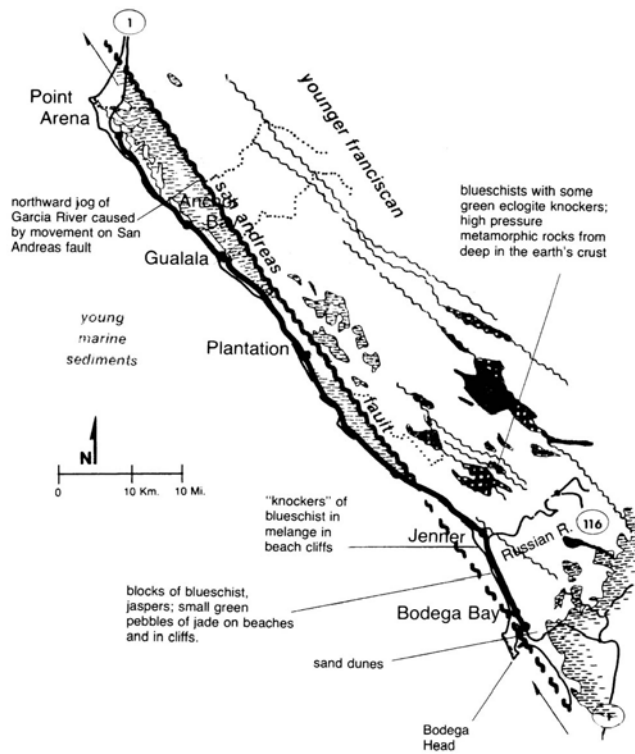
Figure 43 – Geologic map of the San Andreas fault north of Bodega Bay. (Adapted from Alt and Hyndman, 1975, p. 48.)

Segment 2
The Mother Lode - California Gold and Gold Mining

There's "Gold in Them Thar Hills" the argonauts cried as they abandoned their old lives for the frontier. The search for gold brought the gold seekers to the region and changed everything, some good - some bad. Economic prosperity was dangled in the eyes of many who could not resist the flame of gold. The Argonauts came from land and sea routes to the gold hills of the Sierra Nevada, crossing the high Sierran passes from the east and by docking in San Fransisco and heading east by wagon. Mining towns and the infrastructure to maintain mining was "the" industry, not the gold. Common implements such as shovels, hammers, shirts, pants were sold at astronomic prices, the result of huge demand and short supply. Men came to the area in droves, each eager to stake their claim in the Mother Lode. Women were scarce and ladies were even scarcer as the rough and tumble existence of the outdoorman molded their fun. It was a time of frontier justice with murders and hangings commonplace. It was a rough and tumble time that brought experienced and inexperienced workers to the gold belt of California. Some walked away with fortunes, others with huge losses in wealth and destiny.

One component of the Geology 143B trip you are taking will bring us through the gold belt, southward from Placerville or Auburn through Coloma, Sonora, and Mariposa (Figure 44). Gold mineralization took place during the Cretaceous emplacement of the Sierra Nevada batholith. Siliceous fluids rich in gold permeated the wallrocks of the Sierra Nevada batholith including the Shoo Fly and Calaveras Complexes, and the Jurassic belt. We will spend a few days in the gold belt of the Sierra Nevada before heading eastward across the high country to ultimately examine the plutons from which gold quartz veins of the Mother Lode were produced.
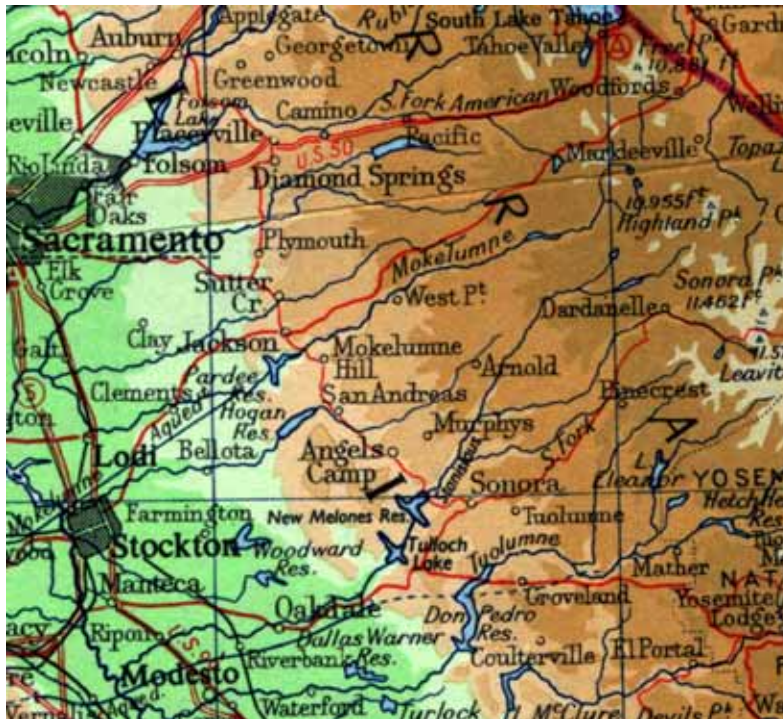

Figure 44 – Index map for Segment 2 of our trip, the Mother Lode Belt.

Figure 45 - Composite maps of the Mother Lode gold belt (California Route 49) showing the major mine towns.

Our field trip route down the "Gold Highway" or CA Route 49 (Figure 45) will take us through some of the most picturesque regions of the state. We will cross the American, Mokelumne, Stanislaus, and Tuolumne, and the Merced rivers and some of their tributaries in our traverse – a region thick with history and human endeavor. The "marks" made by the argonauts are visible almost everywhere. We plan to stop at many of the gold towns along the way from Placerville to the rich gold mining areas of Columbia and Sonora. We will camp for the evening along the shores of Lake Tulloch, west of Jamestown.

As we will be traveling through the gold belt some information on the discovery of gold would be appropriate. Thus in the interest of a break in the science stuff, here are some factoids assembled from many sources. A list of selected gold references can be found in the reference section at the end of the guide.

Some Important "Gold" History

Early 1500's – To the **early Spaniards**, California was linked to legends of fabulous golden riches yet efforts to exploit these potential riches were not explored. Indeed, the world would have been a different place had the Spanish exploited these rich deposits.

1753 – **Ponce de Leon** lands in Florida and is told of Indian tribes with much gold.

1799 – A 28-pound gold nugget was found in Reed, North Carolina, starting the first American "gold rush". **Thomas Jefferson** reported on a gold+quartz specimen found in the Rappahannock River. From 1793 to 1828, Appalachian gold mining from North Carolina produced a meager $110,000.

1825 – **Jedediah Smith** discovers gold near Mono Lake, CA while leading a trapping party for the American Fur Company. He returned with a mining party the next year (1826) but the entire party was killed by Indians. The American Fur Company stopped all mineral exploration because of this calamity.

1826 – Beginning of argonauts (adventurous trappers and frontiersmen) a thin trickle of inhabitants "discovered" California. These hardy folk included **Jedediah Smith, Joseph Walker, Sylvester Pattie, Benjamin Wilson, Peter Lassen, and Kit Carson**. Their arrival disturbed the Mexican inhabitants who thought the Sierran peaks impervious to emigration. American sovereignty was established after the Bear Flag Revolt, establishment of the short-lived California Republic, and the Mexican War.

1829 – Gold was discovered in **Virginia** and the **Belzoro mine** opened a few miles from Richmond. The mine operated for many years and after the Civil War was publicized as the site for most important mineral wealth within the country.

1829 – Gold rushes in Georgia and Alabama results in establishment of United States Mints in Charlotte (NC), Dahlonega (GA), and in New Orleans (LA). From 1804 to 1866 the Appalachian production amounted to $20,000,000, far exceeding earlier production reported

from North Carolina. Eastern miners were paramount in exporting techniques and equipment to California when gold was eventually discovered there.

1839 – **John Sutter**, a Swiss immigrant, settled in northern California and from a land grant provided by the Russians, created a small empire. He later purchased all Russian holdings at Fort Ross including ships, cattle, and farm implements and even an arsenal captured by the Russians during Naploeon's 1813 retreat from Moscow. All of these materials were moved to Sutter's Fort near Sacramento, CA.

1842 – Gold placer deposit found in San Francisquito Canyon near the San Fernando Jesuit Mission. This and earlier reports of gold to Jesuit fathers were largely ignored. This deposit was not rich enough to last beyond a few years but gold was sent to the Philadelphia Mint for coinage purposes. The American government did not publicize the discovery as anticipation of a change of ownership of the region was planned. When the region became American, the discovery was announced to assist in populating the area.

1844 – John Bidwell (an employee of John A. Marshall) lost his chance at fame when a Mexican worker informed him that gold was to be found in the Sierra Nevada. Mexicans came from Sonora in Old Mexico, a region with a deep mining history. The worker asked for a "batea" in order to prove the richness of California gold but Bidwell thought he required an exotic implement of some kind. Thus, the worker's request for a batea (a wooden bowl) was overlooked and faded into insignificance when James W. Marshall "discovered" gold in Coloma, CA in 1848.

~19 January 1848 – Four or five pieces of gold found in tail race of John A. Sutter's sawmill in Coloma, CA on the south fork of the American River by **James W. Marshall** (Figure 46). Marshall was building a water-powered sawmill for Sutter and found a small flake that he flattened with a hammer to prove its composition. That original piece resides in the Smithsonian Institute. Days later, a few ounces of gold were delivered to John Sutter whereupon the discovery was acknowledged and announced on 24 January 1848. Despite earlier indications of gold, this discovery initiated the California gold rush and opened the west. The minor incursion of argonauts transformed into a flood of adventurers (Figure 47) after this important discovery. The famous Oregon- and Humboldt trails became useful routes to the eastern foothills of the Sierra. Spring weather permitting, settlers crossed the high Sierra into the gold region through the Donner and Carson passes. Other overland routes brought miner/settlers southward through the south across Owens Valley, crossing the Sierra via Walker Pass east of what is now Bakersfield, CA. Other overland routes southward from Salt Lake City and through Texas along the U.S.-Mexican border brought settlers into the region. Some came in from the north working their ways southward from the Oregon Trail on the Columbia River. By sea, the argonauts traveled "around the horn" of South America or across the thin strip of land in Panama where, after a treacherous overland crossing, Pacific ships would take passengers northward to California.
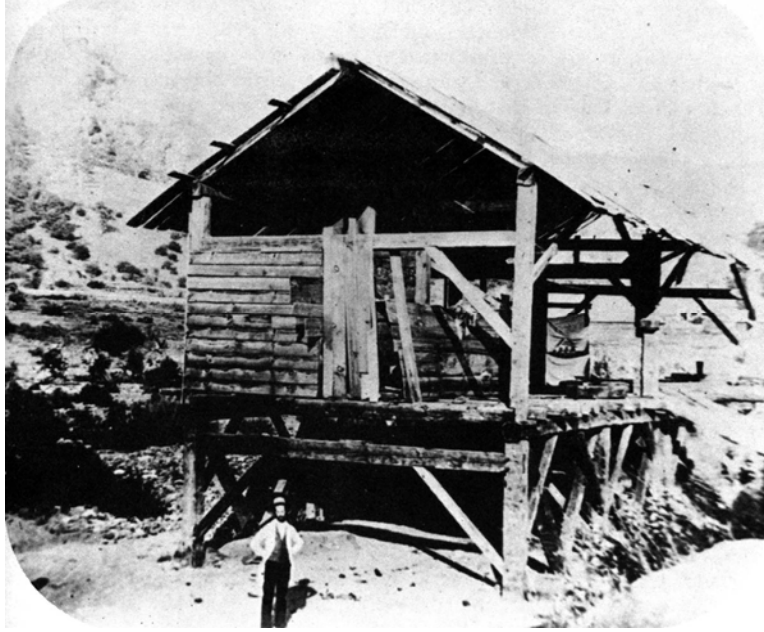
Figure 46 – A view of Sutter's Mill, the place where gold was first found and publicized to the point of sparking a gold rush. (Daguerrotype from the early 1850s.)
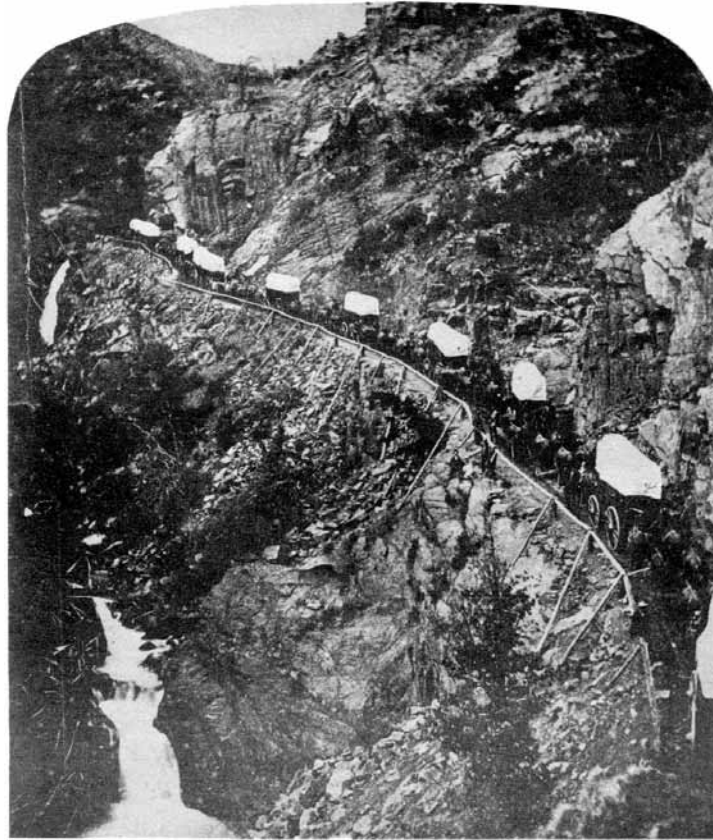
Figure 47 – The argonauts were frontiersmen and trapper-adventurers who came to California in search of their fortunes in gold.

Miners from Europe joined the fray early on with Englishmen, Frenchmen, Germans, Cornishmen, Welshmen, Italians, and many others (Figure 48). Mexicans pushed northward from Mexico to join their countrymen already in California and miners from Peru, Chile, and Bolivia joined the argonauts in search of gold. Men from Australia came across the Pacific as did hoards of Chinese. Many Americans from the east brought their slaves and they were commonly freed by their masters or permitted to earn their freedom in the mines. Thus, the "call of gold" allowed rapid and multicultural settling of the gold region. Highway 49 was the main connecting link for the southern and northern gold mines and gold towns sprung up all over the countryside. Many of the towns no longer exist, the result of commonplace fires and destruction the result of mining. A plethora of small adits, mine tunnels, and shafts spot the foothills countryside today.

Figure 48 – Typical view of the attire of the times during what appears to be a day off at the Central Mines. (Photo from 1856.)

Some Famous Names from the Mother Lode

Mark Twain (writer, visited mines)
Bret Harte (writer, visited mines)
Darius Ogden Mills (co-founder Bank of California)
George Hearst (father of William Randolph Hearst; Senator 1886-1893; purchased San Francisco Examiner)
John C. Fremont (soldier, explorer, first CA senator, Presidential nominee in 1856)
John B. Stetson (store operator)
J. M. Studebaker (blacksmith who manufactured wheelbarrows, then wagons and carriages in Placerville, then cars back east)
Lola Montez (actress, dancer, and mistress to King of Bavaria)
Lotta Crabtree (protégé of Montez, successful actress, "darling" of the mines)
Joaquin Murietta and **Three-Fingered Jack** (bandits preying on innocent miners)

Famous Gold Towns of Route 49

The towns along CA Route 49 all have stories to tell related to the influx of gold miners during the gold rush. (Refer to Figure 45.) Starting in the north, **Auburn** is known as the place where Claude Chana, an employee of John A. Sutter, discovered gold in a ravine in May of 1848, starting a mini gold rush in that area. Soon after John S. Wood, a member of Stevenson's Regiment in the Mexican War, recognized the wealth of the area and assembled military companions that resulted in a large community. Originally known as North Fork Dry Diggings then Wood's Dry Diggings, by 1849 the name was changed to Auburn when civil government was installed. Disastrous fires in 1854 and 1859 destroyed many of the older structures but the "old town" still can be found in the ravine of its origin. $75M in gold was discovered there.

As described above, gold was discovered by James W. Marshall in **Coloma** in January 1848 on the south fork of the American River. Marshall is buried on a nearby hilltop and is marked by a large standing statue and monument. His finger points to the spot where gold was discovered. Although not now a shadow of its former used to be, all visitors to the region should stop to experience the history and peaceful beauty.

Placerville is at the junction with CA Route 50 and originated in the summer of 1848. Overrun with the flood of miners finding their way to Coloma, a rich find was made in what is now known as Weber Creek. Word spread and a town was built up that changed in name from Dry Diggings, Old Dry Diggings, Ravine City, and finally, Hangtown. The last name was in honor of the approach by law abiding citizens to the criminality in the region. Ultimately, the bad guys just stayed away. The name Placerville was adopted by 1850 as the crime rate dropped. Rich gravels in creeks and ravines produced large amounts of gold but Placerville became a place of business for the mining endeavors. Wheelwright John Studebaker arrived in 1853 and set up a blacksmith shop specializing in wheelbarrows that were prized throughout the district for their sturdy construction. Later he would head east and be a part of the motor car industry.

Areas off of Route 49 also drew participants in the gold rush. Places such as **Fiddletown**, **Michigan Bar**, **Volcano** and many others sprang up and many produced gold in large amounts. Fiddletown inspired the Bret Harte story "An Episode of Fiddletown". In 1849 Fiddletown was named for the many musicians that "hung out" there. The name was changed to Oleta in 1879 but then changed back to Fiddletown shortly thereafter. Volcano boasted 8000 inhabitants at the height of the gold rush and although off the beaten path, it still preserves many original structures including the St. George Hotel, once the pride of the Mother Lode. $90M in gold was extracted from this area during the gold rush.

The wildest town in the gold belt is known as **Mokelumne Hill** – a site of rich diggings and multinational inhabitants. The town began in the Fall of 1848 as a store and as word of rich diggings spread the town developed into a large size. The I.O.O.F. building, a veritable three-story skyscraper in its day, is still there as are the remnants of their Chinatown.

Site of the Chilean war of 1849 between American and Chilean miners, the town of **Chile Gulch** is next on our route, just a short distance south of "Mok Hill". Famed bandit Joachin Murietta was known to inhabit the area with his band of merry men.

In **San Andreas**, the notorious Black Bart was brought to justice. He was sentenced to prison for his string of 27 stage robberies over a seven year period. Today, he would host a reality TV show. His downfall occurred near Copperopolis (to the south) while attempting another robbery, this time the Milton-Sonora stage. He fled after a small boy startled him leaving behind evidence that traced him to San Francisco where he was arrested, playing his dual role as a respected mining man who traveled to his mine properties. Only trouble was his mines had wheels, possibly made by Studebaker!

Angel's Camp boasts fame because of the story by Samuel L. Clemens (Mark Twain) titled "The Celebrated Jumping Frog of Calaveras County" (Figure 49). The town was founded by James H. Carson and Henry Angel in 1848 after discovery of a placer gold deposit of great richness in a ravine that became the center of town. The area was so rich that when claims produced less than two ounces of gold per day ($16/ounce in those days) they were abandoned. One claim ten feet square produced $9,000 in gold alone and when the surface material was removed to bedrock, a gold ore vein was discovered. Talk about a glory hole!
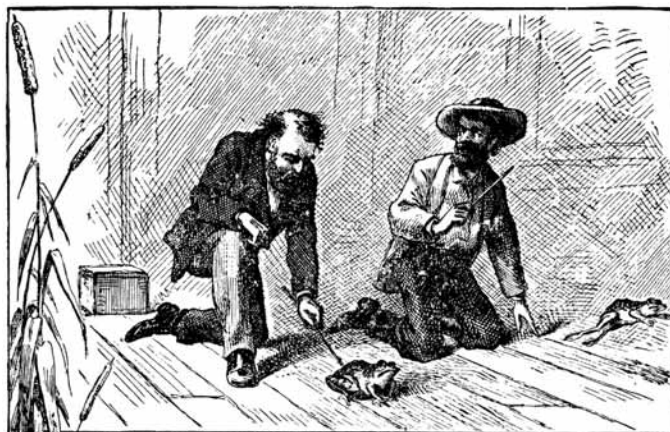
Figure 49 – Engraving from Samuel Clemens' "Celebrated Jumping Frog of Calaveras County".

With this discovery, Angel's Camp saw huge growth as it became one of the largest of the southern mines. Always up for a good time, miners from this area concocted the famous "Pliocene Skull" hoax that puzzled researchers for years and provided grist for a poem by Bret Harte. A few of the old building still are preserved in this picturesque mining town that still holds and annual jumping frog contest in honor of their history.

Our next stop is **Columbia**, the so-called "Queen of the Southern Mines" (Figure 50) where extremely rich placer deposits of gold were found lying above the Calaveras Marble. The spirit and structure of the gold town was preserved in 1954 as a State Park and evidence of the hard rock and hydraulic methods of mining are on display. We will stop in Columbia CA for a few hours to see the geology and the museums.
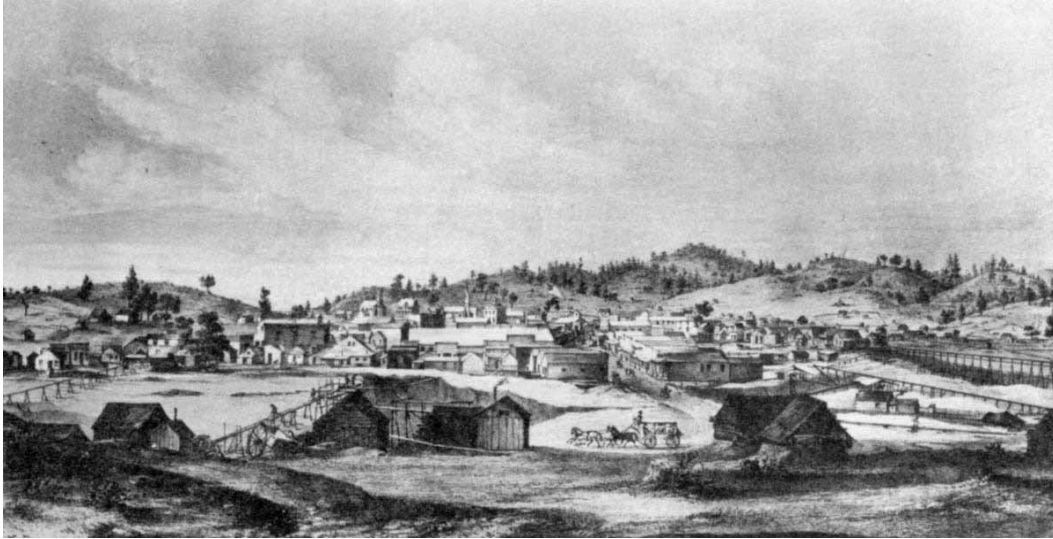
Figure 50 – Mining camps of Columbia CA, the "Queen of the Southern Mines".

Columbia, one of the last mining towns to be founded, was also one of the richest. Gold was discovered by accident on 26 March 1850 when **Thaddeus Hildreth** and four companions camped on a rainy night. While waiting for blankets to dry their efforts at panning showed gold. A human stampede to Hildreth's Diggings followed as news spread and the town quickly exponentiated in population and size from 6,000 in April 1850 to 15,000 a short time later when the name Columbia was adopted. The town was planned in 1852 and incorporated in 1854 but placer mining was hard work and water, badly needed to move gravel, was in short supply and seasonal at that. Typical of the era, the town was almost totally destroyed by fire in 1854 and brick and mortar construction was used to rebuild, a good thing for historians and fans of old buildings. According to Wells Fargo, $50M in gold was shipped from their office along the main street in Columbia.

Sonora, the Tuolumne County seat, was the richest of the southern mines and also the most urbanized yet old structures and mine workings are evident in the town and vicinity. The St. James Episcopal Church, built in 1857, still stands in majesty as the oldest Episcopal church in California. During the summer of 1848 a group of miners from Mexico made a huge discovery of placer gold and as they were joined by their countrymen from the State of Sonora in Mexico, the location became known as Sonoran Camp. Within a year as news spread the population jumped to between 15,000-20,000 people. By 1849, with the dilution of Mexicans by new people, a town government was established and the name Sonora was adopted. Scurvy spread in the early days of the town because of their unbalanced diet thus claiming the lives of many workers and filling the new hospitals, built to accommodate the epidemic. The first of these institutions was built in 1849. Fires swept the town in 1849, 1850, and 1853 causing virtual obliteration of all structures. In 1850, a law was passed to tax foreign miners $20 per month that touched off some violence. A war was averted between Mexican and American miners by retreat of the Mexicans as battle drew near but bloody reprisals followed as they moved to adjacent areas.

About 1848 Colonel George James, a lawyer from San Francisco, founded **Jamestown** or "Jimtown" as it was locally known. The region was popularized by Bret Harte stories were centered amid rich placer and hard-rock mines. By 1855 Jamestown held a population of 6,000 and tried, unsuccessfully, to get the county seat from Sonora.

To the south the towns of **Coulterville** and **Mariposa** loom large in gold history. Coulterville was named after storekeeper George W. Coulter. Gold was found in Maxwell Creek and Coulter abandoned his store along the Merced River to set up camp in what became Coulterville. The rich placer diggings were eclipsed by the discovery of the mother lode gold vein beneath the town. After placer mines had been worked out, intensive hard rock mining undermined the region.
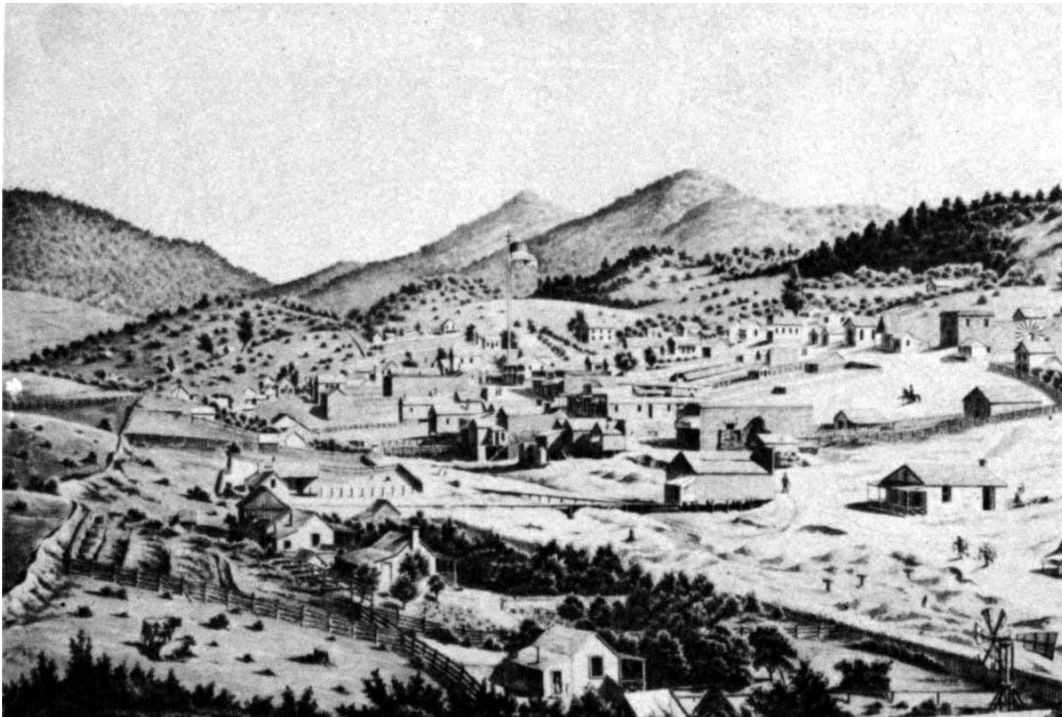
Figure 51 – View of Mariposa in the 1850s.

Mariposa (Figure 51) is located at the south end of Route 49. The town boasts connection with John C. Fremont and his famous Mariposa Grant, the first mining of gold+quartz veins in the state, events linked to the Mariposa-Indian War in 1850-51 and formation of the Mariposa Battalion which opened the path to the discovery of Yosemite Valley by white men. During the Spring of 1849, gold prospectors organized a camp bordering Mariposa Creek, roughly 0.5 miles south of the present town. The original town (Logtown) was replaced by Mariposa in 1852. Type locality for **mariposite**, a green chromian mica, both placer and hard rock gold vein mining were conducted in this area. We will look for mariposite along Route 140 west if time permits.

Mining Methods

Beautiful crystallized gold specimens, as shown below in Figure 52, were only rarely found in hard rock mines. Many of the crystalline gold specimens were saved or purchased and ultimately wound up in the collection of the California Division of Mines and Geology. Situated in the Ferry Building in east San Francisco in the 1980s, CM thinks the collection has been moved to Sacramento but is not sure. For now I will consider this potential optional stop depending if I can find out "Where's the Gold Collection From Them Thar Hills?"

Figure 52 – Rare wire gold specimen from the California gold belt. (Photo by C. Merguerian, 1980.)

Mining methods varied from traditional hard rock mining (Figure 53), to small-scale panning (Figure 54), large scale sifting and riffling operations (Figures 55, 56, 57), to dredging of streams by boat, and diversion of entire mountain streams to dig out their beds (Figures 58, 59). Sluice boxes, cradles, shakers and all forms of invention were created to simplify the process of looking for gold. The Chinese were used as slaves to do the laborious work of sifting through pebbles and sand in search of gold and when given the chance to work on their own. They were legendary in finding gold where the Americans had already given up, in search for richer diggings.

Placer deposits always involved lots of work because great quantities of water were needed to wash the gravels in the search for gold. Ingenious methods of diverting natural waters to create water-powered equipment and running water for washing and separating gold-laden sediment were devised. The hydraulic method of mining utilized water power in the form of high-pressure cannons that were used to wash out river gravels. Increased pressure resulted from gravity piping water from higher elevations in pipes of decreasing diameter to create a pressure head.

Figure 53 - Running mined out ore through a hand made tunnel.

Figure 54 – The traditional panning method for gold was tedious work but paid off for some. This is a drawing labeled Sonorans washing for gold.
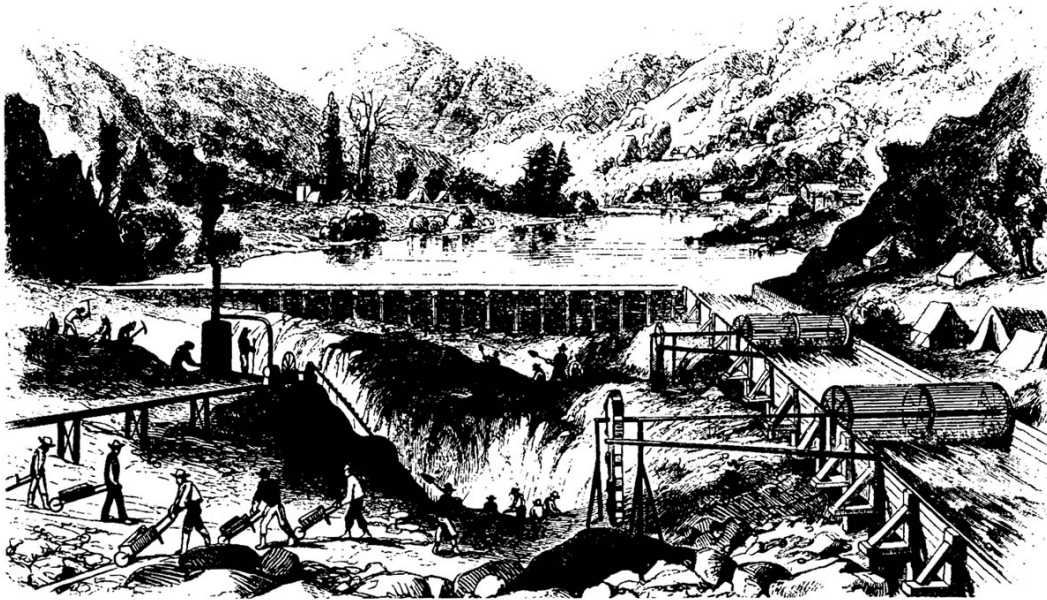
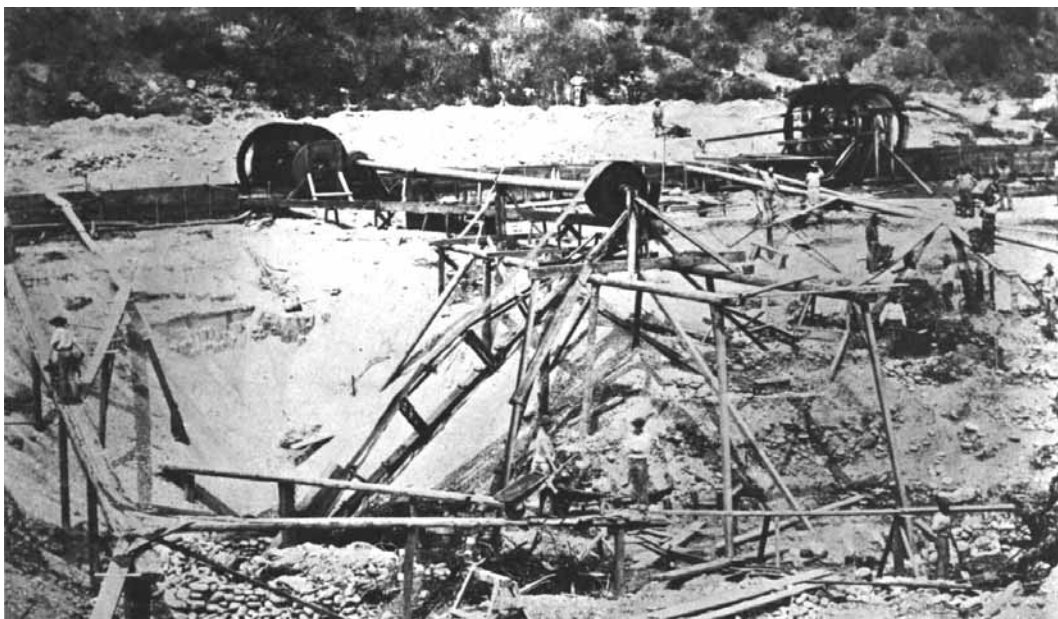**Figure 55** - Chinese in Mariposa, 1867.
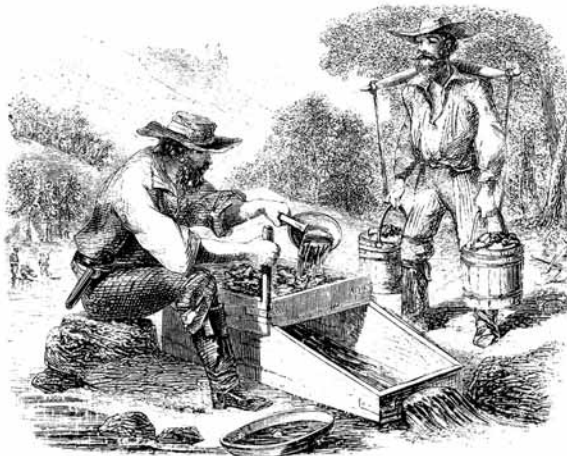
Figure 56 – Drawing showing the use of a cradle or rocker to separate gold from lighter density materials.

Figure 57 – Winnowing Gold at Chinese Camp.

Figure 58 – Diversion of a stream and search for gold in the ancient gravels at Murderer's Bar.

Figure 59 – Use of water power was an important energy source during the gold rush.

When most of the easily found gold was mined out the miners turned to ingenious methods of gold exploration. Recognizing that young lava flows (such as Table Mountain in Jamestown – Figure 60) that drape across the Foothills Belt over rode river gravels rich in gold, tunneling to extract the gold trapped beneath the lava became in vogue (Figure 61) and hard rock mining continued as well, boosted with the efficient use of stamping mills (Figure 62).

Upper: View southwestward along Table Mountain, west of Jamestown in the Sierra Nevada foothills, California. *Lower:* Drawing emphasizing the important geological features and, in the background, restoring the scene to the conditions that probably existed just after the lava flowed down the channel.
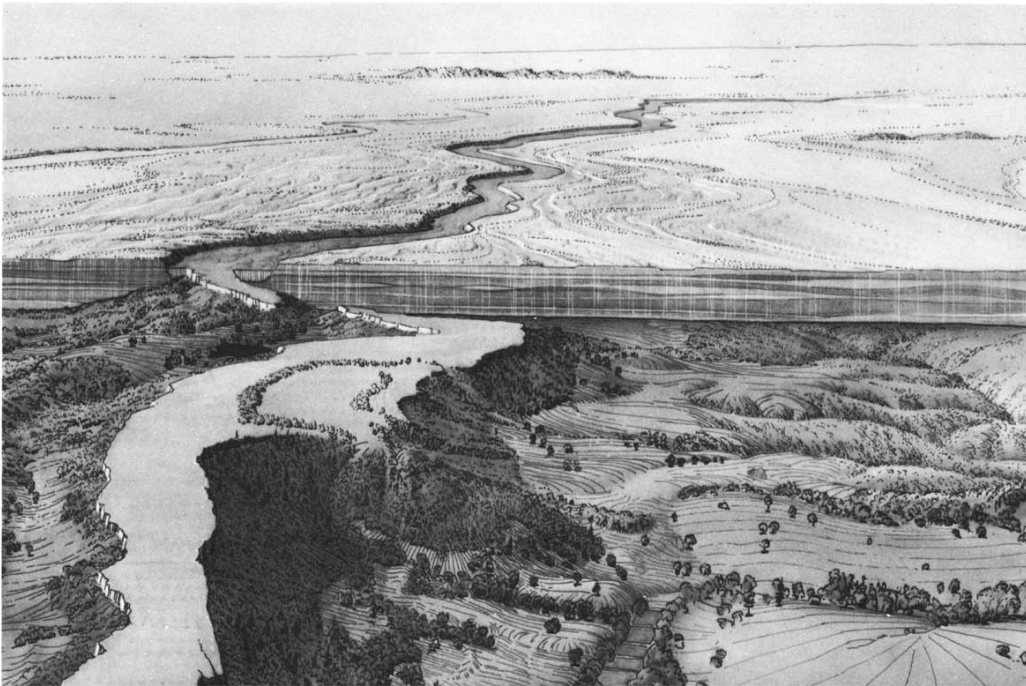
Figure 60 – Aerial view toward the SW showing Table Mountain lava flow in the vicinity of Jamestown, CA. The bottom drawing shows the present erosion state of the former lava flow in the foreground and a pre-erosional interpretation of the conditions that existed during the flow. (From Shelton, 1966.)

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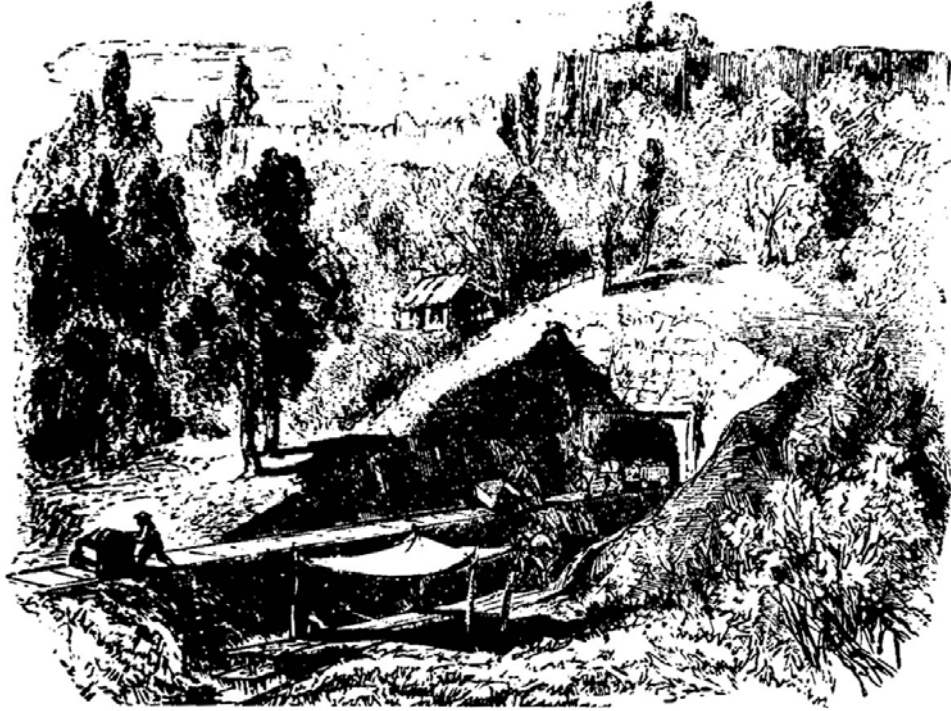
Figure 61 – In some cases it was advantageous to tunnel beneath eroded former lava flows that trapped auriferous gravels beneath them. This drawing titled "Tunneling at Table Mountain" shows such an operation.
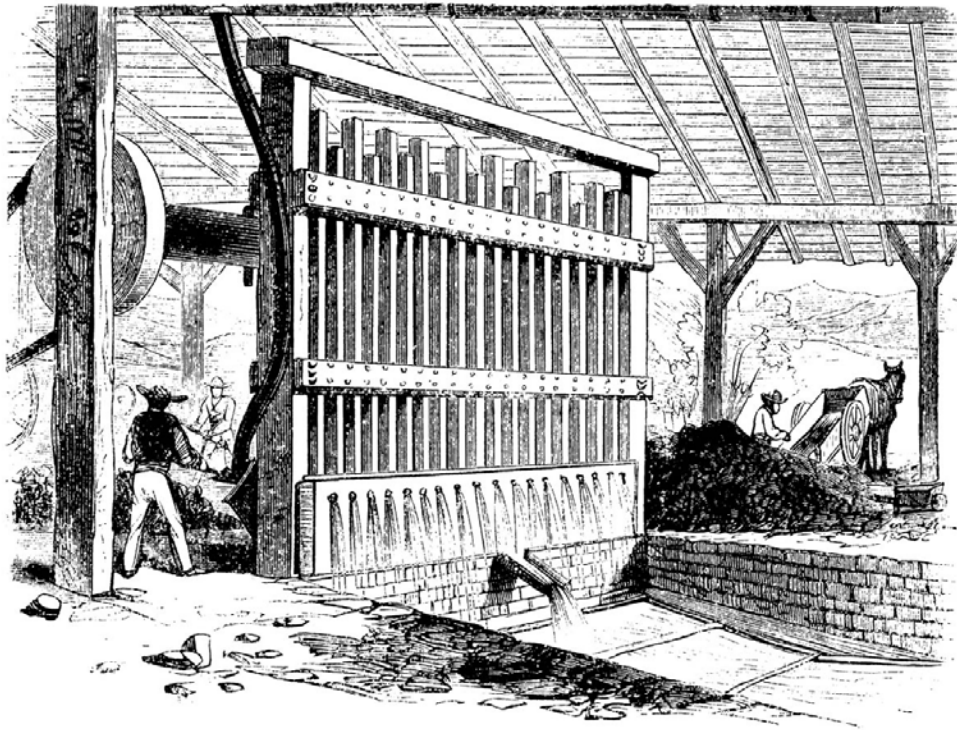
Figure 62 - The processing of hard rock gold-quartz vein was facilitated by stamping mills eventually but most of the early gold-quartz veins were broken up by man and animal power.

Geology of the Mother Lode Belt

The area of the southern mines (Figure 63) is an area of focus after we've investigated the broad scale geology of the foothills metamorphic belt. Refer back to Figures 12-14 for a generalized overview of the regional geology and then Figure 64 for a detailed map in the vicinity of Sonora, California home of the famous, Standard pluton. I will forgo the usual puns.
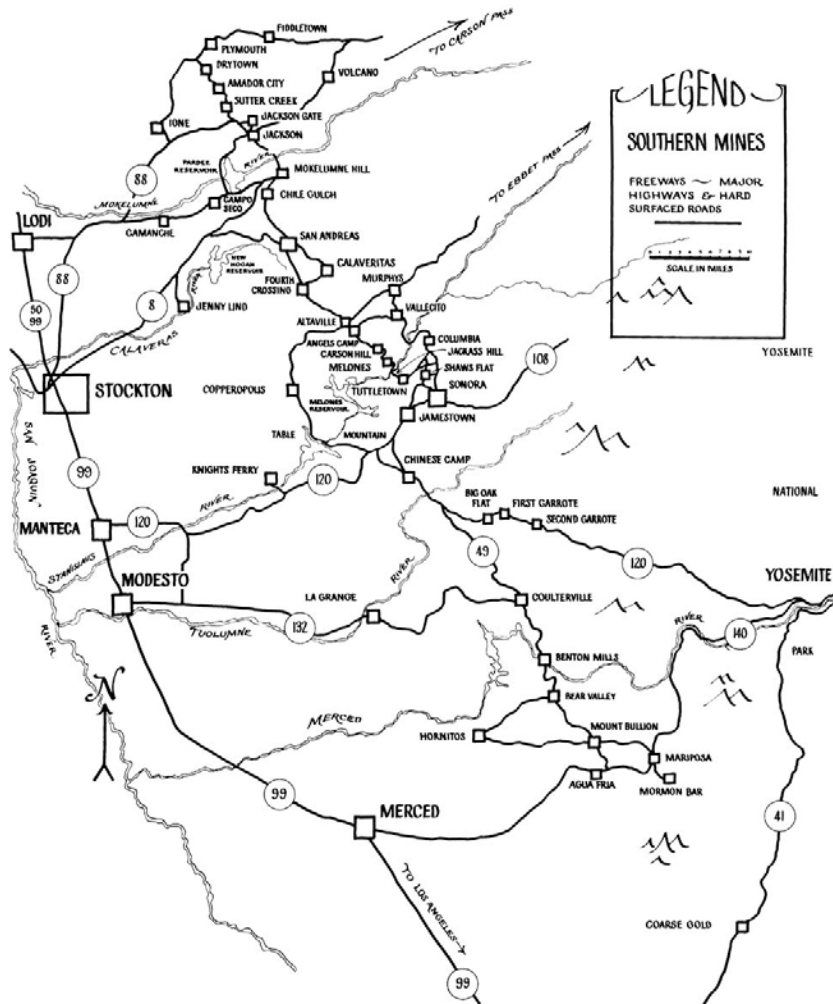
Figure 63 – Index map of the southern mines district.

The western metamorphic belt of the Sierra Nevada, the focus of gold-seeking prospectors since the mid-1800's, is deeply incised by a system of southwestward-flowing rivers that coalesce ultimately near San Francisco Bay. Draining the seasonal snowfields that form in the higher elevations of the range, from north to south these are the Feather, Yuba, American, Cosumnes, Mokelumne, Stanislaus, Tuolumne, and Merced Rivers. (See Figure 6.) The principal erosion of the southern half of the metamorphic belt began in the Oligocene (Huber, 1981) and has continued into the Quaternary at a somewhat accelerated rate. Southwestward

tilting of the Sierra Nevada block, which overlaps in time with the development of the Basin and Range province to the east, created a consequent stream system that, by the Eocene, produced an extensive planation surface.

During subsequent Quaternary rejuvenation, the main branches of the Stanislaus River and to a lesser extent its tributaries were deeply-incised through the Eocene planation surface leaving narrow hilltop residuals above 930 m elevation in the study area. A profound southwest sloping summit accordance is obvious on topographic maps and in the field. The steep v-shaped canyons have differential relief of 370-615 m, and offer the best exposures of the Shoo Fly Complex because the intervening ridges are choked with brush and mantled by Tertiary volcanic rocks or by a thick, lateritic, clayey paleosol that formed during Cenozoic tropical climates. The trellised drainage pattern of the Stanislaus River system (Figure 64) is indicative of emphatic control of north-northeast- and eastwest-trending brittle structural fabrics, joints, and faults in bedrock as well as the regional tilt.
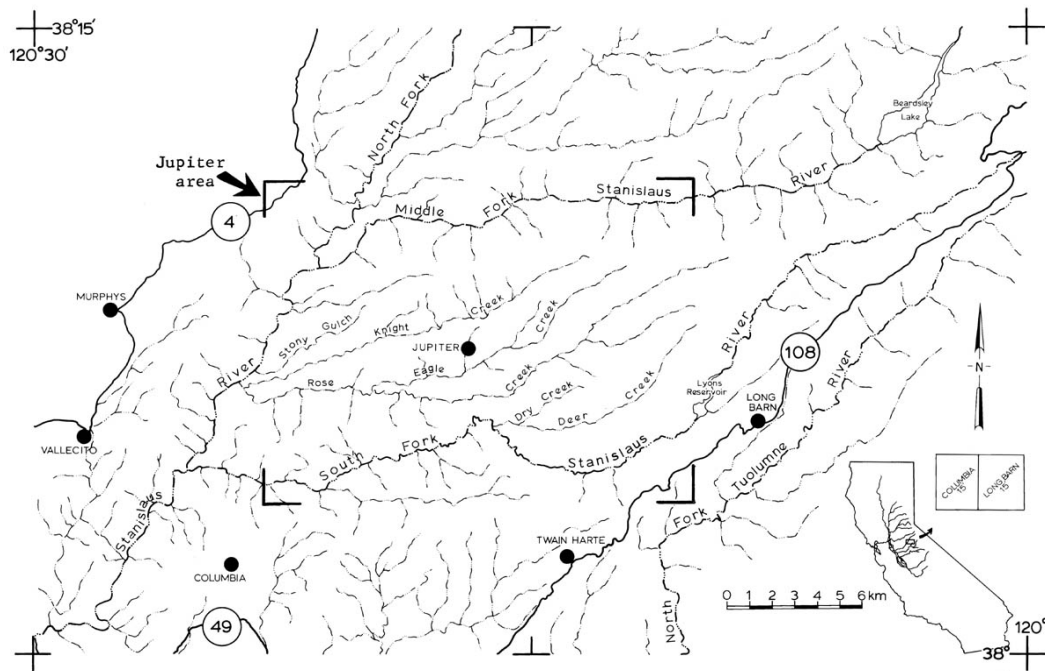
Figure 64 – Map of the Stanislaus River drainage system in Tuolumne County. The Jupiter area is outlined. The river system describes a trellised drainage pattern that is following young, brittle structural features trending NNE and ENE. (From Merguerian 1985a, Figure 4.)

Until the late 1970s, all metamorphic rocks south of lat. 39°N and east of the Melones fault (See Figures 12-14) were grouped with the Calaveras Formation by Clark (1964). The terrane has been subdivided into an eastern belt (Shoo Fly Complex) and a western belt (Calaveras Complex). The central belt (the Calaveras Complex) consists of a chaotic assemblage of upper Paleozoic to lower Mesozoic (?) argillite and siltstone, massive and rhythmically-bedded-chert, marble, talc-schist, and rare basalt. The age of the Calaveras remains uncertain, but Permo-Carboniferous fossils from limestone olistoliths (Turner, 1893; Schweickert and

others, 1977) indicate a maximum Carboniferous age for the complex. The Calaveras is bounded on the west by the Sonora fault (Schweickert and Bogen, 1983) and low grade metamorphic rocks of the Jurassic belt and is in ductile fault contact (Calaveras-Shoo Fly thrust) with the Shoo Fly Complex to the east (Figure 65).

The Shoo Fly Complex (Unit 1 in Figure 14) consists of a polyphase deformed, epidote-amphibolite grade assemblage of quartzite, quartzofeldspathic gneiss, granitoid orthogneiss, schist, and phyllite with subordinate marble and calc-silicate rocks (Merguerian, 1985a,b). The Calaveras Complex (Unit 2) is a deformed oceanic assemblage of chaotic argillite, chert-argillite, massive and rhythmically-bedded chert, and marble (Schweickert and others, 1977). The western belt (Unit 3) consists of folded slate, graywacke, phyllite, and augitic greenstone and pyroclastic rocks (Clark, 1964, 1970; Schweickert and Bogen, 1983). Thus, from east to west across the foothills metamorphic belt the rocks become progressively younger exhibiting less deformation and metamorphism.

Regionally important tectonic boundaries separate the tectonostratigraphic units. Both the Calaveras-Shoo Fly thrust and the Sonora fault are east-dipping syn-metamorphic ductile shear zones that truncate and transpose structural and metamorphic fabrics in older units to the east. The Calaveras-Shoo Fly thrust truncates lithologic units of the Shoo Fly (Figure 66). The thrust is marked by a 1-2 km wide zone of syn-metamorphic ductile deformation characterized by intense localized isoclinal and rootless folds, sheared and imbricated rock units, and blastomylonite and other ductile fault rocks (Merguerian, 1983, 1985a).

The **Sonora fault** (See Figures 13, 14, 65) is a ductile shear zone that separates actinolite-stilpnomelane-bearing phyllite and greenschist from the Calaveras Complex (Schweickert and Bogen, 1983). Locally, dikes of the **Sonora mafic dike swarm** are deformed and truncated against the Sonora fault zone (Figure 67). They occupy a 1550 km^2 area over 55 km long and 25 km wide centered near lat. 38°N and long. 120°15'W. Over 1000 dikes have been mapped in the Shoo Fly and Calaveras Complexes by Merguerian and Schweickert (unpub. data), respectively.

Volcanic and volcaniclastic rocks of the Oligo-Miocene Valley Springs and Mio-Pliocene Relief Peak Formations (Slemmons, 1966) occur above 1000 m elevations in the eastern part of the Jupiter area. (See Figure 65.) White, fine-grained individual rhyolitic ash flow units up to 20 m thick of the Valley Springs Formation are found near Mount Knight (Crandall Peak quadrangle) and Grant Ridge (Twain Harte quadrangle).

The Relief Peak Formation is a tan- to gray-brown poorly-sorted, mudflow breccia (lahar) with rounded cobbles and boulders up to 0.5 m in diameter. The clasts are matrix supported and range in composition from predominantly volcanic rocks such as andesite, rhyolite, obsidian, and pumice, to sedimentary rocks such as chert and limestone, and rare silicified tree limbs. The matrix is composed of clay and fine-grained volcanic rock fragments and is strongly cemented creating remnant erosional surfaces with protruding, immovable boulders. Channelized lahars are found on the south rim of the Middle Fork Stanislaus River canyon. These Mio-Pliocene volcanic materials are shown on Figure 65 in shades of yellow and tan.
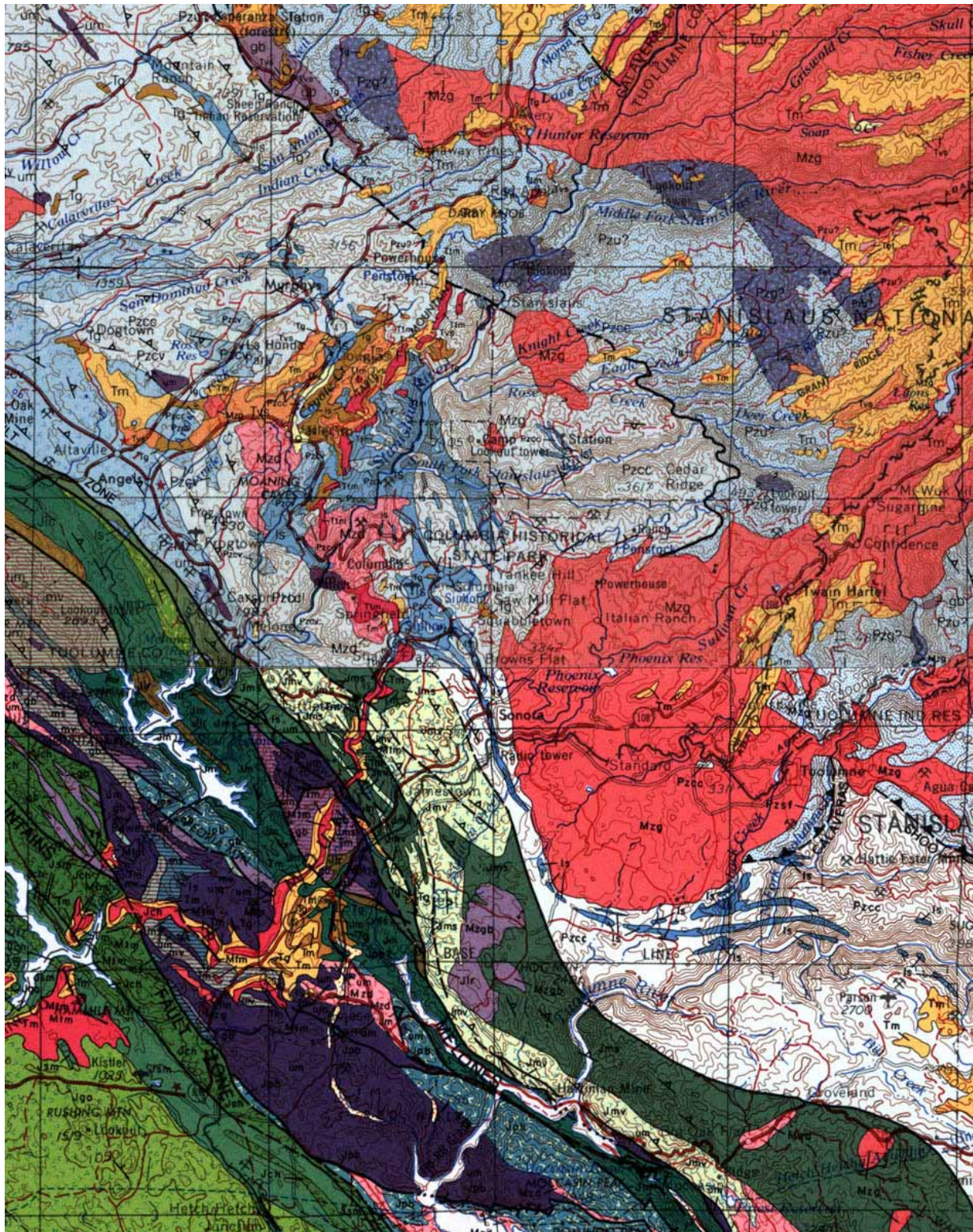
Figure 65 – Geological map of the southern mines area showing Units 1, 2, and 3 and the west intrusive margin of the Sierra Nevada batholith. Sacramento and San Francisco-San Jose sheets. (Adapted from Wagner and others, 1981, 1990.)
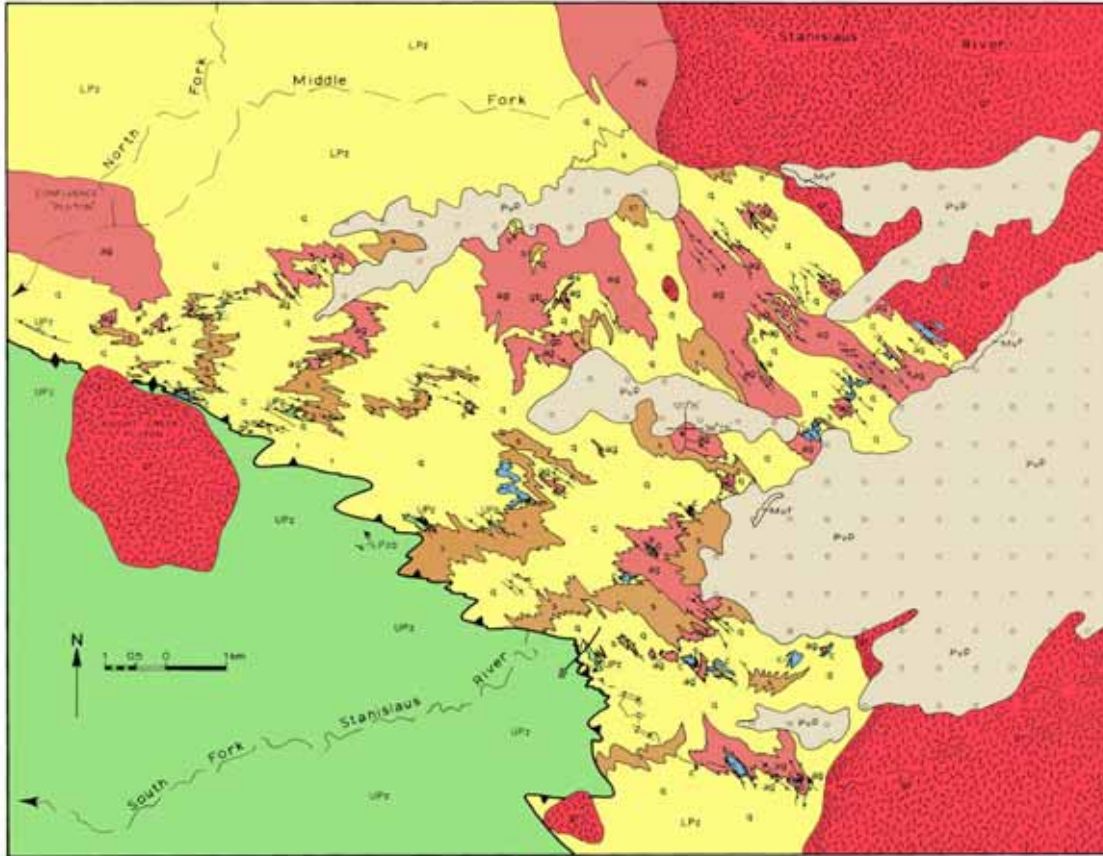
Figure 66 – Bedrock geologic map of the Calaveras and Shoo Fly Complexes in the Jupiter area, Tuolumne County, California. (Colorized from Merguerian, 1985a,b.)
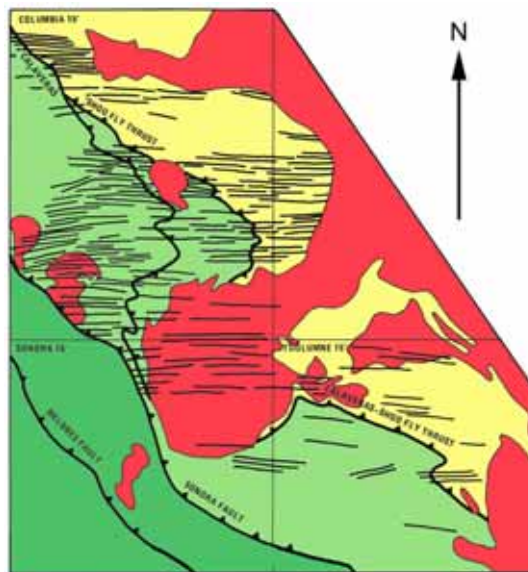
Figure 67 – Cartoon showing the geology in the vicinity of the Standard pluton (Shoo Fly is yellow). Note the truncation along the Sonora fault of east-west trending mafic dikes of the Sonora Dike Swarm. Same coloring as Figures 12-14, and 66. (Colorized from Schweickert and Bogen, 1983, Figure 2.)

Geology of the Shoo Fly Complex

Mylonitic rocks of the Shoo Fly Complex form a region of epidote-amphibolite grade quartzose and granitoid gneiss, schist, subordinate calcareous rocks, and rare amphibolite in the west-central foothills of the Sierra Nevada range in California. The Shoo Fly is engulfed to the east by the Sierra Nevada batholith and to the west is in thrust contact with east-dipping argillite, chert, and marble of the Calaveras Complex. The thrust juxtaposes rocks of constrasting lithology, age, structure, and metamorphism. The Shoo Fly probably originated as a thick sequence of slope and rise sediments deposited near the Cordilleran lower Paleozoic shelf edge.

The Shoo Fly has endured a complicated Phanerozoic structural history involving seven superposed deformations occurring at variable crustal depths. The first four of these events (D_1-D_4) involved tight to isoclinal folding and local shearing under varied medium grade metamorphic conditions (Figures 68-70). The last three (D_5-D_7) are marked by open folding and retrograde metamorphism of the older fabrics. Early in this evolution, between D_1 and D_2, metasedimentary rocks of the Shoo Fly Complex were discordantly intruded by sills and plutons of gabbro, granite, and syenite which subsequently formed orthogneiss bodies, an important lithologic component of the Shoo Fly in Tuolumne County (Merguerian and Schweickert, 1987).

The Calaveras-Shoo Fly thrust formed during D_3 and is a folded syn-metamorphic ductile shear zone that varies in width from 1-2 km and has been traced for over 90 km from lat. 38°05'N to 37°30'N. A remarkable along-strike D_3 textural consistency in the Calaveras-Shoo Fly thrust zone includes the formation of 1) megascopic isoclinal, intrafolial, and rootless F_3 folds with a penetrative axial-planar S_3 mica foliation, spaced dutile shears and widespread transposition, 2) ellipsoidal slivers of foliated Shoo Fly flattened parallel to S_3 and highly elongated parallel to L_3 stretching lineations in sheathing mylonitic envelopes, 3) zones and seams of mylonite layering with highly strained and polygonized quartz ribbons with abrupt grain-size variations between layers, 4) macro- to microscopic strained quartz augen with internal sutures and core and mantle structure, rounded feldspar augen exhibiting marginal granulation, bent twins, corrosion, and cracking with local replacement by muscovite, 5) highly laminated phyllonitic textures in schistose rocks with frayed mica augen surrounded by anastomosing S_3 folia of smaller recrystallized micas and quartzose ribbons, and 6) late-stage D_3 injections of protocataclasite, pseudotachylyte, foliated granitoid sills, and minor folding.

The recognition of D_3 mylonitization of D_1+D_2 fabrics along the Calaveras-Shoo Fly thrust (Figure 69) indicates that upper plate Shoo Fly rocks record a more complex, earlier structural history than the lower plate Calaveras rocks. During the formation of the thrust the Calaveras Complex experienced its first regional deformation which was characterized by long-limbed isoclinal folds and the development of a penetrative flattening foliation. In the thrust zone, syn-metamorphic flattening, imbrication and intense silicification of the Calaveras occurs. The thrust and related structural features were folded by east-west-trending F_4 folds which are in turn crosscut by mid-Jurassic plutons and mafic dikes of the Sonora dike swarm. The preceeding structures and igneous bodies are cut by N32°W and N30°E steep to vertical cleavages which are traceable into open, possibly conjugate, F_5 and F_6 folds that formed during the Nevadan orogeny of Late Jurassic time. The youngest N60°W to E-W vertical cleavage (S_7) is probably of Late Cretaceous age. Stereonets (Figure 71) and a cartoon (Figure 72) act as a summary.
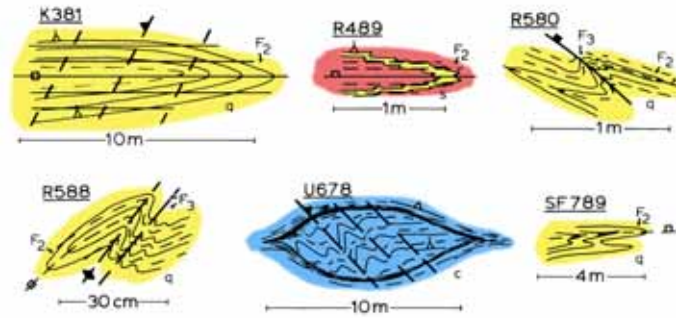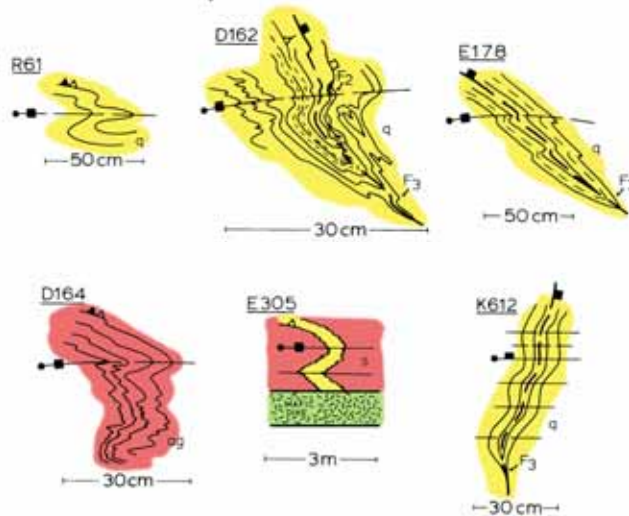
Figure 68 – Sketches of typical D_2 structures in the Shoo Fly Complex. (From Merguerian, 1985a.)
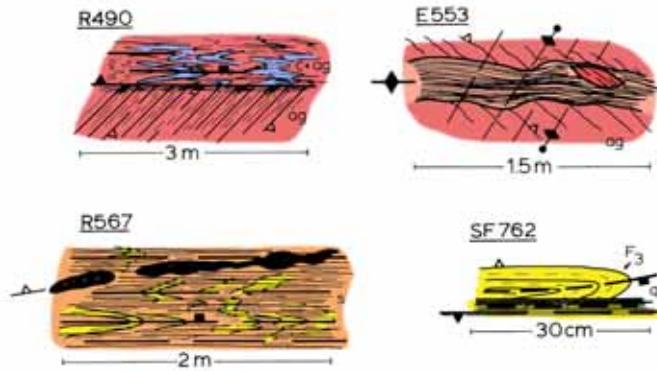
Figure 69 – Sketches of typical D_3 shear structures in the Shoo Fly Complex. (From Merguerian, 1985a.)

Figure 70 – Sketches of typical D_4 structures in the Shoo Fly Complex. (From Merguerian, 1985a.)
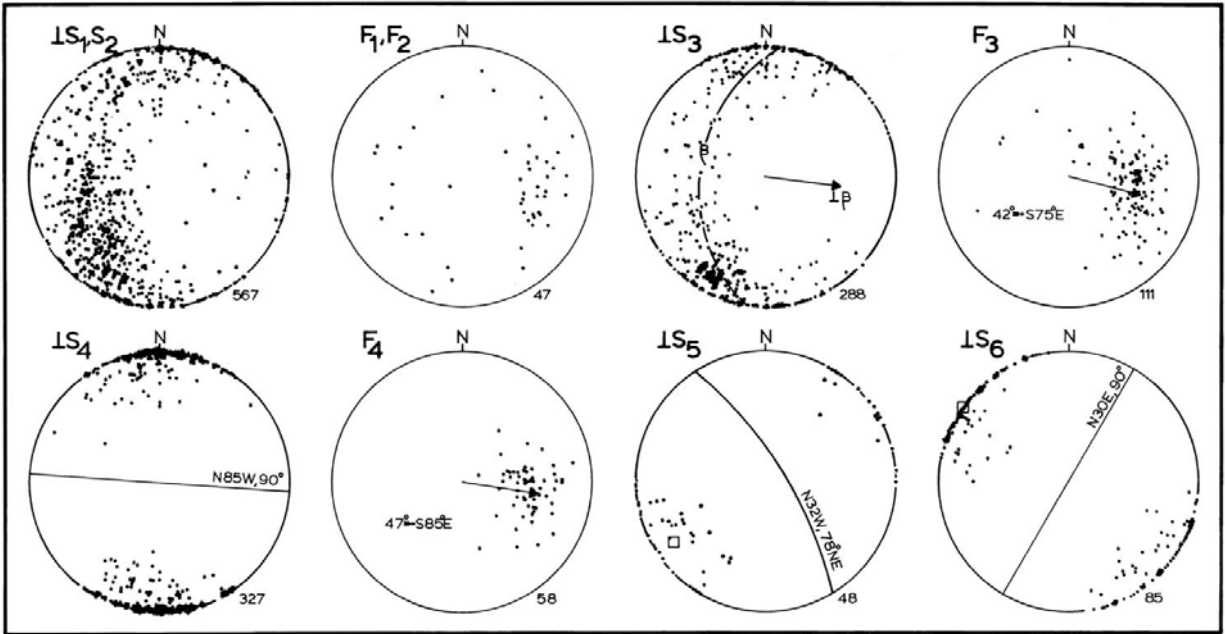
Figure 71 – Stereonet plots of the structural features recorded in the Shoo Fly Complex. (From Merguerian, 1985a.)
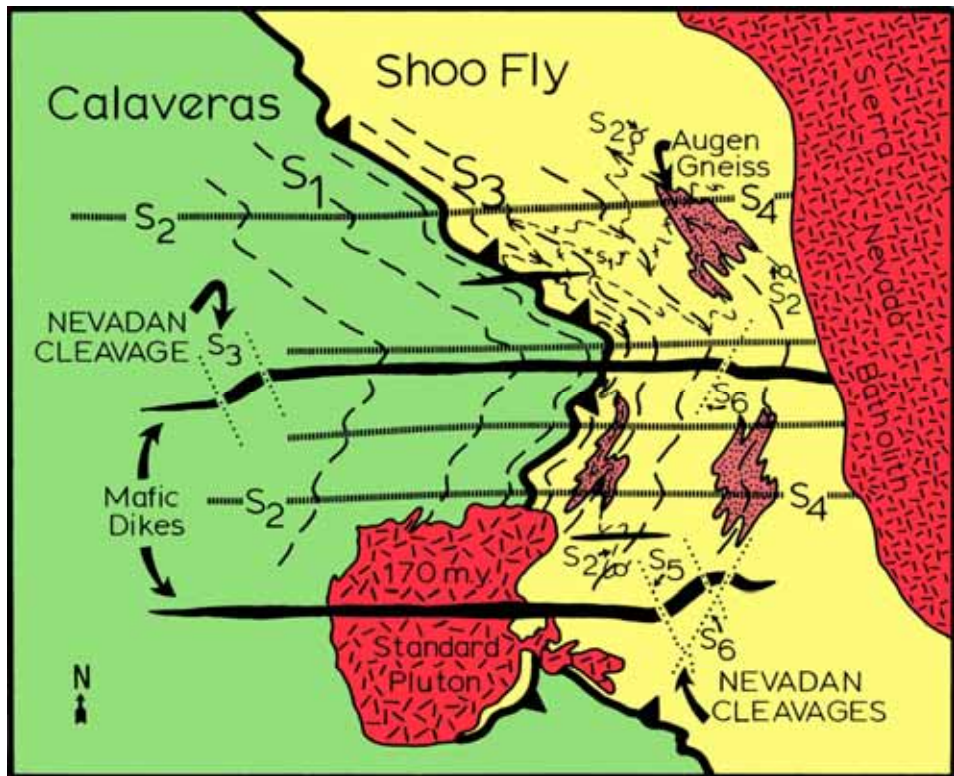

Figure 72 – Cartoon showing the different structural relationships found across the Calaveras-Shoo Fly thrust. Note that the thrust is cut by the 170 Ma Standard pluton which is itself cut by mafic dikes of the Sonora Dike Swarm. (From Merguerian, 1985.)

Mafic dikes of the Sonora dike swarm

The Shoo Fly and Calaveras Complexes are multiply-intruded by a swarm of mafic dikes near lat. 38°N. Over 1000 lamprophyre dikes have been mapped in the Shoo Fly and Calaveras by Merguerian and R.A. Schweickert (our unpub. data). In the Shoo Fly, the dikes are sub-parallel to E-W-trending axial surface traces of folds that deform the Calaveras-Shoo Fly thrust (See Figures 67, 72.) The dikes occur as solitary sheets and dikelets 3-5 cm thick and as dense 25 m-wide zones of profuse multiple injections with anastomosing chilled margins. Individual dikes within these zones have an average thickness of 1 m and offshoots are common. Three textural types have been recognized:

1. light-gray to dark-gray spessartite and vogesite lamprophyres with non-oriented subhedral to euhedral phenocrysts of pargasitic amphibole, light-green amphibole, augite, and plagioclase up to 4 mm long. The dikes are generally less than 0.4 m thick.

2. gray-green to gray-black, dense, dominantly aphyric lamprophyre dikes which locally possess augite and brown amphibole micro- phenocrysts and have medium- to coarse-grained cores when thicknesses exceed 2 m.

3. dark-gray mottled medium- to coarse-grained, labradorite-phyric pyroxene-free lamprophyre dikes. The phenocrysts are euhedral to subhedral (up to 4 mm) and the dikes are typically thicker than (1) or (2).
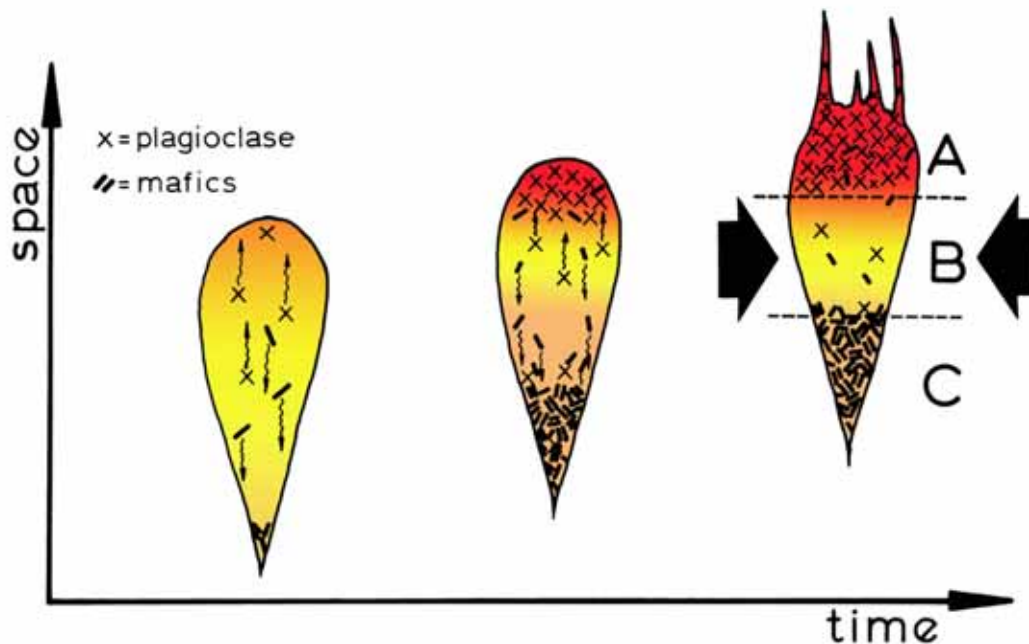
Figure 73 – Differentiation model to explain the separation of minerals that resulted in the intrusion of Group A (plagioclase-phyric), Group B (aphyric), and Group C (clinopyroxene- and hornblende-phyric) basalt and andesite dikes of the Sonora Dike Swarm. (From Merguerian, 1985a.)

Cross-cutting relationships and chilled margin observations indicate that the dominantly aphyric dikes (2), which comprise over 35% of the mafic dike swarm, are of median relative age and thickness. They always cross-cut the thicker plagioclase-rich dikes (3) and are in turn cut by thinner lamprophyre dikes (1). Sequential intrusion may have been the result of differentiation and gravity separation and tectonic squeezing of the source magma chamber as shown in Figure 73. A 157-159 Ma K-Ar hornblende age for the dikes has been reported by Sharp (1980).

Petrographic and limited geochemical studies indicate that the Sonora mafic dike swarm is composed of calc-alkalic andesite and subordinate basalt and slightly younger calc-alkalic lamprophyres. The dikes are mineralogically interesting in that they are strongly enriched in primary amphibole and plagioclase phenocrysts and groundmass phases. According to Jakes and White (1972) hornblende andesites are found in both island arc and continental margin arc settings. Typically, the marginal arc rocks contain more than 25% hornblende, less than 25% clinopyroxene (typically calcic), some biotite, and rare hypersthene phenocrysts. These are traits shared by the Sonora dikes.
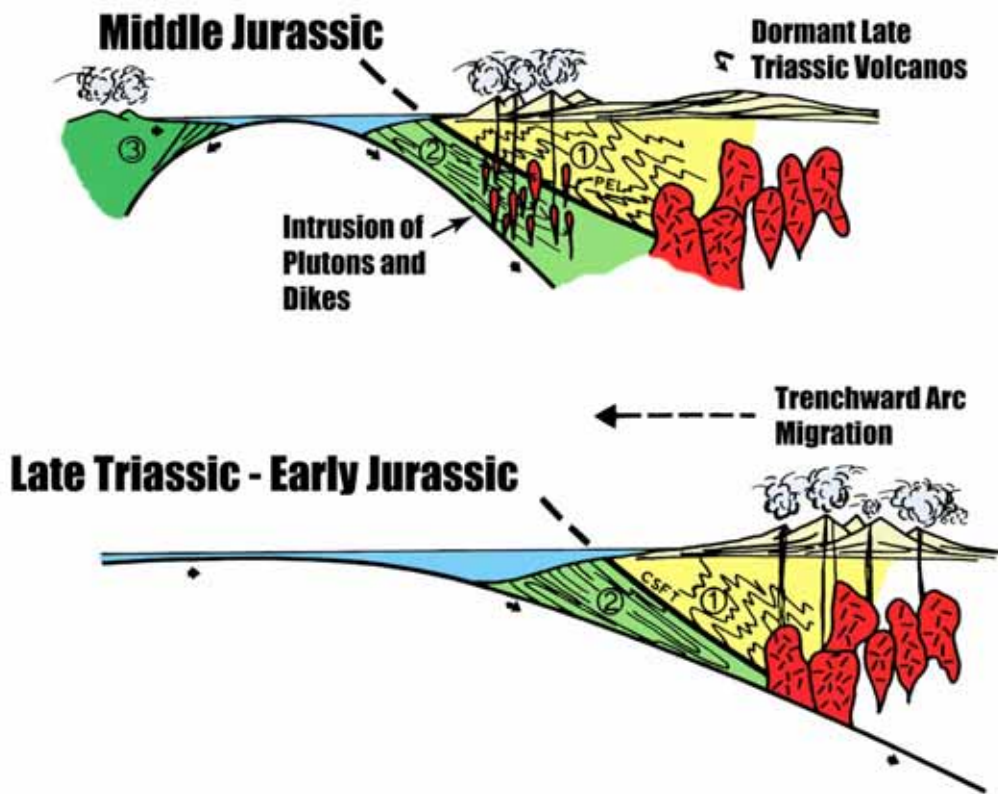
Figure 74 – Cartoon showing the pre-Nevadan development of the Cordilleran margin between late Triassic and middle Jurassic time. The Sonora dike swarm probably formed in a near-trench subduction regime with opening of east-west S_2/S_4 metamorphic surfaces (maximum extension perpendicular to page) due to subduction stress transmitted into the overriding plate. PEL=present erosion level, S=Standard pluton, CSFT=Calaveras-Shoo Fly thrust. The cross-section is at 38°N lat. Units 1, 2, and 3 are circled (Refer to Figure 14). From Merguerian, 1985a.

Oscillatory zoning in plagioclase, compositional zoning and multiple twinning in amphibole, exsolution in clinopyroxene, embayed and rimmed phenocrysts, and marked porphyritic textures suggest a two-stage cooling history for the parent magma. Glomeroporphyritic textures suggest that early-formed crystals clumped together either within the magma chamber or during upward rise of the partly-crystallized magma. Sequential intrusion of the dikes of Groups A, B, and C could mark periodic rise of phenocryst-enriched magmas tapped from such a chamber or chambers. Older dikes (Group A) are thicker, on average, than younger dikes, suggesting either that the amount of magma decreased with time or that extension waned with time. Mineralogic and chemical similarities (Merguerian, 1985a) between the Group A, B, and C dikes suggest they had a similar ancestry.

Despite the fact that mafic dike swarms in continental regions are commonly interpreted to represent injection of new ocean-floor basalt during regional extension, the calc-alkaline dikes of the Sonora swarm were probably related to subduction and marked a stage in the development of a continental margin arc. Significantly, the dikes are spatially associated with a belt of middle-Jurassic calc-alkaline continental arc plutons intruded across the Paleozoic and Mesozoic basement rocks of the foothills metamorphic belt (Figure 74). As such, the dikes provide an important structural marker in the Shoo Fly and Calaveras Complexes. The intrusion of the Sonora dike swarm and plutons of equivalent middle Jurassic age (Sonora, Parrotts Ferry, Vallecitos, etc.) may have all formed during oversteepened subduction related to the Nevadan orogeny as modeled in Figure 74.

That's plenty of detail for the purposes of our field trip. Let's move on to the discussion of the third segment of our journey – the high Sierra of Yosemite Valley and Tioga Pass.

Segment 3
Yosemite and the Sierra Nevada Batholith

Segment 3 involves driving up the west slope of the Sierra Nevada range from 2,000' elevations in the Calaveras and Shoo Fly to elevations >10,000' in the vicinity of Tioga Pass (Figure 75). The "discovery" of Yosemite Valley in 1864 created quite a stir and brought attention to the preservation of natural areas for the public. Indian legend had long told of a magic valley nestled high up in the mountains. It took the adventurous spirit of James Mason Hutchings (Figure 76) to discover and popularize the region in his Hutchings Magazine.
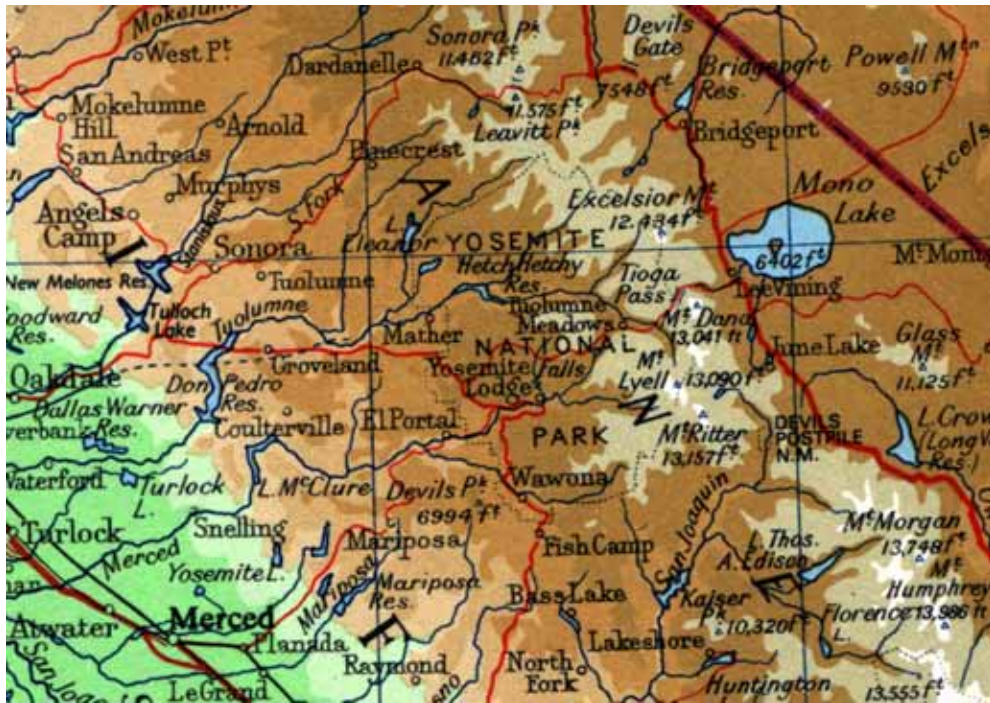

Figure 75 – Index map of Segments 3 and 4.

## Discovery of Yosemite Valley

Yosemite Valley, a former mysterious Indian stronghold, was popularized in the October 1859 edition of Hutchins' California Magazine. After bloody Indian uprisings in 1851 and 1852, word spread through Mariposa or fabulous waterfalls and immense, steep cliffs along long valleys. James M. Hutchings, an Englishman, became intrigued with the stories. Enough so that he engaged an artist, Thomas A. Ayers to assist in preparing illustrations for his new magazine about California. With Indian guides, in June 1855 Hutchings, Ayers, and two companions set foot on the trail to find and document Yosemite Valley. They spent five days in the valley, with Ayers recording the beauty with hand drawings (Figures 77, 78). Three other parties were organized to the same end and by the end of the year (1855) forty-two visitors had seen Yosemite. Fifty years later 10,000 visitors came and after a century the number of visitors had topped a million.

Figure 76 – James Mason Hutchings, miner and publisher of "The California Magazine" circa 1900.
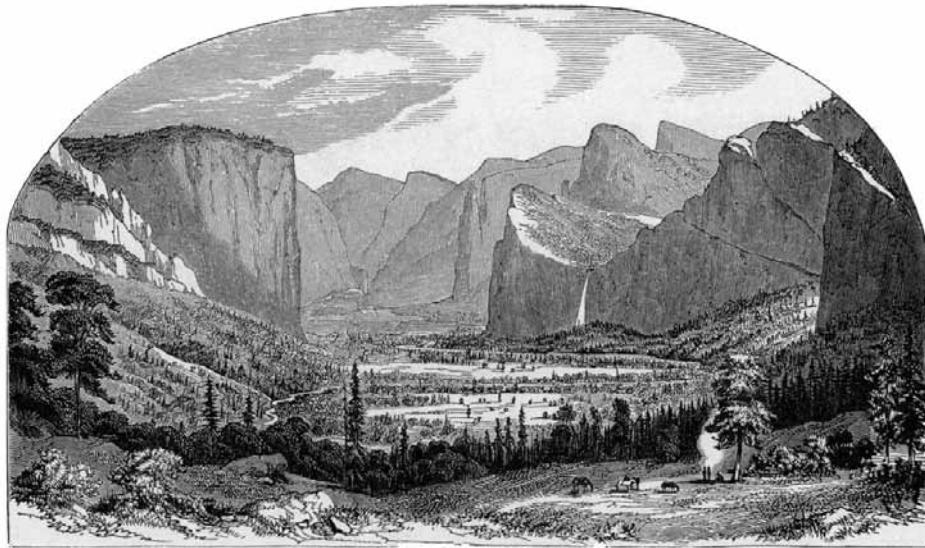
Figure 77 – View of the Yo-Semite Valley from Open-eta-noo-ah (Inspiration Point) on the Mariposa trail. Hutchings California Magazine, October 1859.

Near View of the YO-SEMITE FALLS,
2,500 FEET IN HEIGHT.
[From a Photograph by C. L. Weed.]

Figure 78 – View of the Yo-Semite Falls. Hutchings California Magazine, October 1859.

Geology of the Yosemite Valley

Details on the igneous geology of the Sierra Nevada have been extensively discussed above. (See Figures 17, 18; Table 1.) The geomorphic development of the landforms are covered in this section. A relief map of the region shows as a long gash in a dissected mountainous region with a flat floor (Figure 79).

Figure 79 – Shaded relief map of the Yosemite Valley.

The valley was formed by the combined effects of rapid downcutting of the Merced river and modification of that channel by a valley glacier. Figure 80, which I have digitally rearranged and enhanced, shows six stages in the development of the valley from Matthes (1950). The **Broad Valley Stage** (A) ended the Miocene the result of uplift to the east and stream erosion. The ancient Merced river occupies the base of a valley less than 1,000' deep. The **Mountain-valley Stage** (B) ended the Pliocene and witnessed rapid uplift and subsequent downcutting of the Merced to produce a steep walled valley 1,800' deep that featured hanging valleys.

The **Canyon Stage** (C) was in the early Pleistocene when a third and largest ratchet upward of the Sierran block took place along the eastern border faults. The Merced cut a 3,000' canyon in a raging torrent of Sierran meltwater and many hanging valleys were formed. The Ice age was starting and cirque glaciers may have formed. The **El Portal Glacial Stage** (D) saw a thick valley glacier flow through Yosemite and create a broad U-shaped valley (Figure 81). All of the northern uplands with the exception of El Capitan and Eagle Peak were ice covered. Half Dome extended 700' above the ice flow (Figure 82).

During the **Wisconsinan Glacial Stage** (E) valley glaciers returned to Yosemite but were not as thick as the previous stage and did not overtake the valley. The glacier descended to about the position of Brideveil Falls, based on the position of the moraine. This event modified the valley to its present dimension. The Modern Stage (F) witnessed the formation of ancient lake Yosemite, fed by glacial meltwater. Over time, coarse sediment from the Merced river built out a delta and eventually filled the lake to produce its present flat valley floor.

An index map to the features of Yosemite Valley (Figure 83) will be useful as we examine the rock structures, sentinels of time and geological change.
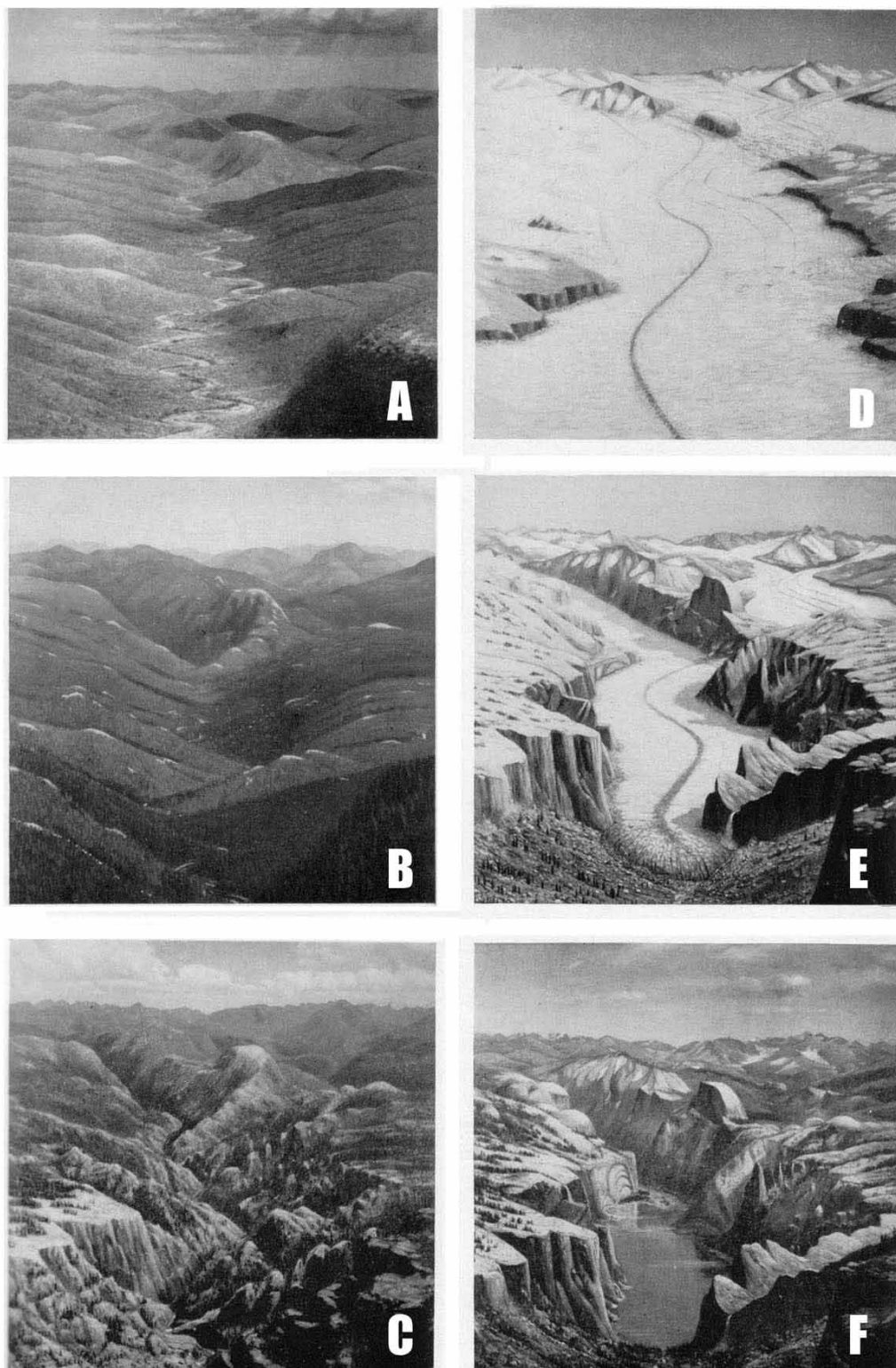
Figure 80 – Composite diagram showing the six stages in the formation of Yosemite Valley. (From Matthes, 1950, Plates 2-7.)

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Figure 81 – View of Yosemite Valley showing the broad U-Shaped valley form created by glacial ice. Note the hanging valley to the right, the result of truncation of a former drainage by the ice. (From Harris and Tuttle, 2002.)

Figure 82 – Aerial view toward the WNW of Half Dome and the surrounding peaks of the Sierra with the Tuolumne River drainage visible in the distance. Half Dome extended 700' above the top of the El Portal glacier. (From Harris and Tuttle, 2002.)
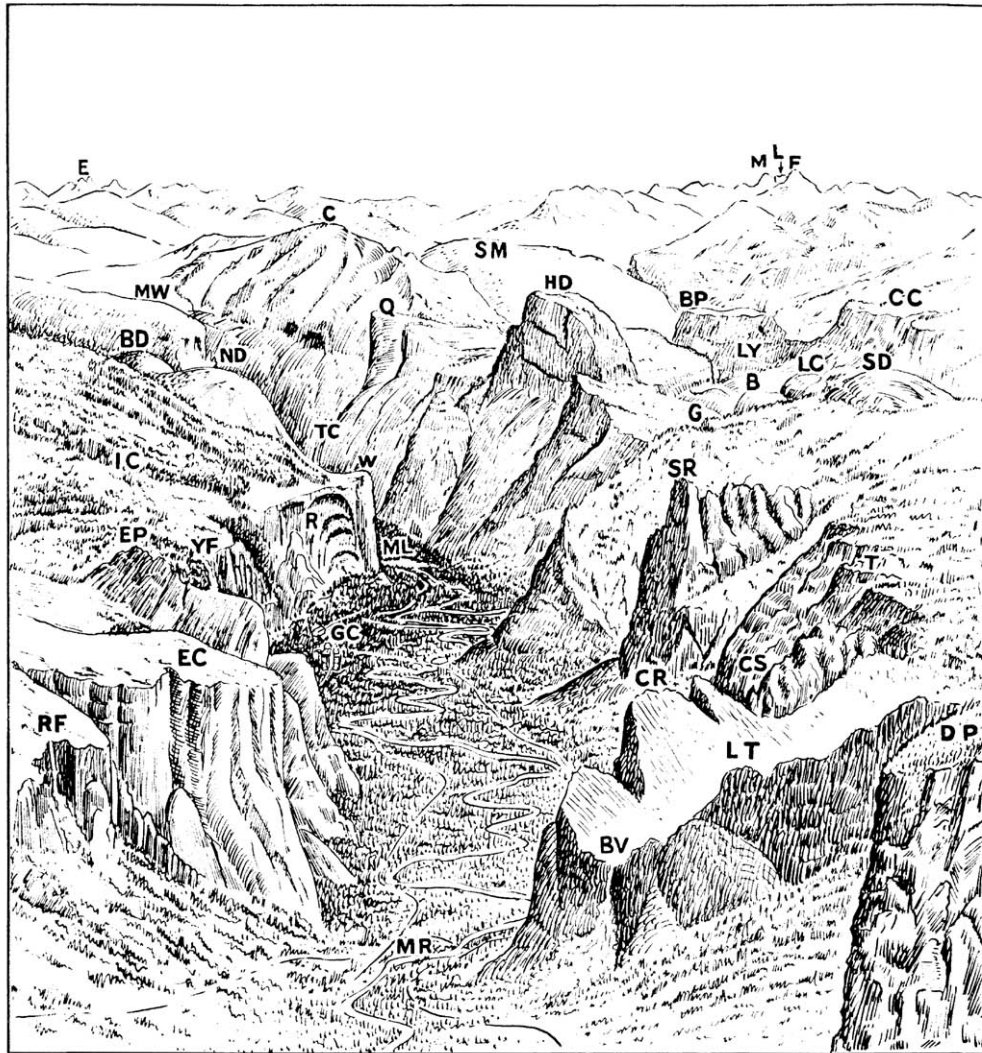
RF	Ribbon Fall	MW	Mount Watkins	LC	Liberty Cap
EC	El Capitan	E	Echo Peaks	B	Mount Broderick
EP	Eagle Peak	C	Clouds Rest	SD	Sentinel Dome
YF	Top of Yosemite Falls	SM	Sunrise Mountain	G	Glacier Point
GC	Government Center	Q	Quarter Domes	SR	Sentinel Rock
IC	Indian Creek	HD	Half Dome	T	Taft Point
R	Royal Arches	M	Mount Maclure	CS	Cathedral Spires
W	Washington Column	L	Mount Lyell	CR	Cathedral Rocks
TC	Tenaya Canyon	F	Mount Florence	BV	Bridalveil Fall
ML	Mirror Lake	BP	Bunnell Point	LT	Leaning Tower
ND	North Dome	CC	Cascade Cliffs	DP	Dewey Point
BD	Basket Dome	LY	Little Yosemite	MR	Merced River

Figure 83 – Index map of the various geological and other features of Yosemite Valley. View to the west. (From Matthes, 1930, 1950.)

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Segment 4
Mono-Inyo Craters and the Long Valley Caldera

The **Mono Craters** are a 17-km-long chain of rhyolite domes and flows that were erupted from 35,000 to about 600 years ago (Figure 84). All but four of the 24 exposed domes and flows of the Mono Craters are less than 10,000 years old (Figure 85). The most recent eruptive episode occurred between A.D. 1325 and 1365, during which time there were several explosive eruptions and five separate lava flows that oozed onto the surface, including Panum Dome and North Coulee flow (Figures 86, 87). Unless indicated otherwise, the bulk of the material in this segment is derived from *quake.wr.usgs.gov/VOLCANOES/LongValley/,* including images and figure captions. See this website for individual photographer credit.

Figure 84 – View to the southwest of Mono Lake showing the Panum Crater (R) and other features. (From Shelton, 1966.)

Extending from eastern California and Nevada, the basin and range province extends into Arizona and bordering Mexico. In a nutshell, the province is dominated by normal fault blocks of upper crust produced by oblique slip and tensional fragmentation (Hamilton and Myers, 1966). The crust has been thinned by tension but thickened by Cenozoic surface volcanism and by intrusion at depth. Renowned for the stark character of the resultant landscape, Basin and Range topography is rooted in Cenozoic crustal extension related to the development of the San Andreas fault system, inland development of horst and graben structure, and coseismic erosion of the ranges and infilling of the basins. In southern California and Arizona the trend of the ranges are NW-SE, essentially parallel to the San Andreas trend.

The plan here is to follow the field trip route suggested by Tierney (1995) and for CM to wing as he has never set foot in the region before. We will use index (See Figure 19) and geological maps (See Figure 20).

Figure 85 - Aerial view of a lava dome nestled within Panum Crater, which was built by the explosive ejection of tephra. The explosive eruptions also generated three pyroclastic flows and a surge, and built the ring of tephra that surrounds the Crater. The dome was the last lava flow erupted during Mono eruptive episode between A.D. 1325-1365. From http:/quake.wr.usgs.gov/VOLCANOES/LongValley.

Figure 86 – Aerial view towards the north from above the South Coulee (dark, irregular surface at bottom of photo). The light, smooth dome in the center of the photo is mantled with thick layers of tephra. Between the South Coulee and the smooth dome are 4 small explosion craters. Mono Lake is at the top of photo. The hills beyond Mono Lake are the Adobe Hills, a tertiary volcanic complex. From http:/quake.wr.usgs.gov/VOLCANOES/LongValley.

Figure 87 - View from the crest of the Mono Craters is looking toward the north. Mono Lake is visible on the right side of the photograph; the Sierra Nevada are the snow-covered peaks on the left. The original blocky surface of the red-colored lava dome sticks up through tephra erupted from one of the North Coulee vents; a remnant of a crater rim cuts through the photograph. The blocky lava outcrops are also active fumaroles releasing water vapor (steam) and carbon dioxide gas. From http:/quake.wr.usgs.gov/VOLCANOES/LongValley.

Long Valley Caldera (From *quake.wr.usgs.gov/VOLCANOES/LongValley/*)

The Caldera. Long Valley Caldera is a 15- by 30-km oval-shaped depression located 20 km south of Mono Lake along the east side of the Sierra Nevada in east-central California. (See Figures 19 and 20.) This area of eastern California has produced numerous volcanic eruptions over the past 3 million years, including the massive caldera-forming eruption 760,000 years ago. The most recent eruption occurred just 250 years ago in Mono Lake at the north end of Mono-Inyo Craters volcanic chain.

Volcanic Unrest. In May of 1980, a strong earthquake swarm that included four magnitude 6 earthquakes struck the southern margin of Long Valley Caldera associated with a 25-cm, dome-shaped uplift of the caldera floor. These events marked the onset of the latest period of caldera unrest that continues to this day. This ongoing unrest includes recurring earthquake swarms and continued dome-shaped uplift of the central section of the caldera (the resurgent dome) accompanied by changes in thermal springs and gas emissions.

USGS Monitoring. In 1982, the U.S. Geological Survey under the Volcano Hazards Program began an intensive effort to monitor and study geologic unrest in Long Valley caldera. The goal of this effort is to provide residents and civil authorities in the area reliable information on the nature of the potential hazards posed by this unrest and timely warning of an impending volcanic

eruption, should it develop. Most, perhaps all, volcanic eruptions are preceded and accompanied by geophysical and geochemical changes in the volcanic system. Common precursory indicators of volcanic activity include increased seismicity, ground deformation, and variations in the nature and rate of gas emissions.

Appendix 1 - Geologic Structure - a Primer

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Luckily, our Geology classes and field trips are an exception. We will not try to bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will read- and hear about today. But, if you are to understand what we are talking about, you need to know some important definitions. In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, structures in sedimentary- vs. metamorphic rocks, and tectonostratigraphic units.

We begin with some concepts and definitions based on the engineering discipline known as **strength of materials**. Given today's sophisticated laboratory apparatus, it is possible to subject rocks to temperatures- and pressures comparable to those found deep inside the Earth.

Imagine taking a cylinder of rock out of the Earth and torturing it in a tri-axial compression machine to see what happens. Some geologists get a big charge out of this and tell us (the field geologists) that they really understand how rocks behave under stress. [CM thinks they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on field observation and inference than from rock-squeezing data to gain a feel for the complex nature of how rocks are deformed in nature.]

Despite the limitations of the experimental work, measurements in the laboratory on specimens being deformed provide some fundamental definitions. One key definition is the **elastic limit**, which is the point at which a test specimen no longer returns to its initial shape after the load has been released. Below the elastic limit, the change of shape and/or volume (which is known as **strain**) is proportional to the stress inside the specimen. Above the elastic limit, the specimen acquires some permanent strain. In other words, the specimen has "failed" internally. Irrecoverable strain manifests itself in the distortion of crystal lattices, grain-boundary adjustments between minerals composing the rock, and minute motions along cleavage- or twin planes.

When differential force is applied slowly (or, according to CM, over long periods of time), rocks fail by *flowing*. This condition is defined as behaving in a **ductile fashion** (toothpaste being squeezed out of a tube is an example of ductile behavior). Folds are the result of such behavior. If the force is applied under low confining pressure or is applied rapidly (high strain rates), rocks do not flow, but *fracture*. This kind of failure is referred to as rocks behaving in a **brittle fashion** (as in peanut brittle). The result is faults or joints. Once a brittle failure (fracture) has begun, it will propagate and may produce offset thus forming a fault surface. Joint surfaces commonly exhibit distinctive "feathers" which show the direction of joint propagation.

In some cases, during deformation, rocks not only undergo simple strain, but also recrystallize. New metamorphic minerals form and newly formed metamorphic minerals acquire a parallel arrangement. More on metamorphic textures later. From the laboratory studies of rock deformation, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary **planar- and linear features** within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on four letters of the alphabet: D, F, S, and M. Episodes of deformation are abbreviated by (D_n), of folding by (F_n), of the origin of surfaces (such as bedding or foliation) by (S_n), and of metamorphism by (M_n), where n is a whole number starting with 1 (or in some cases, with zero). Bedding is commonly designated as S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural history of an area, for example, one might write: "During the second deformation (D_2), F_2 folds formed; under progressive M_1 metamorphic conditions, an axial-planar S_2 foliation developed."

In dealing with the geologic structures in sedimentary rocks, the first surface one tries to identify positively is **bedding** or **stratification**. The boundaries of strata mark original sub-horizontal surfaces imparted to sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping, stratal disharmony, and clastic dikes are possible). Rather, resolved tangential force that creates differential stress must be applied to provide the driving force to bring about folds and faults.

It's now time to turn to some geometric aspects of the features formed as a result of deformation of rocks in the Earth. We start with folds.
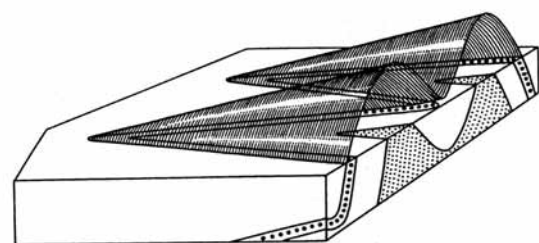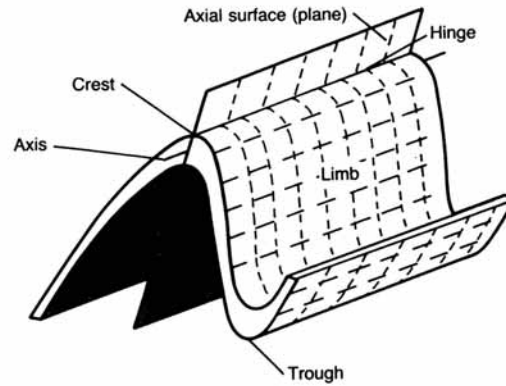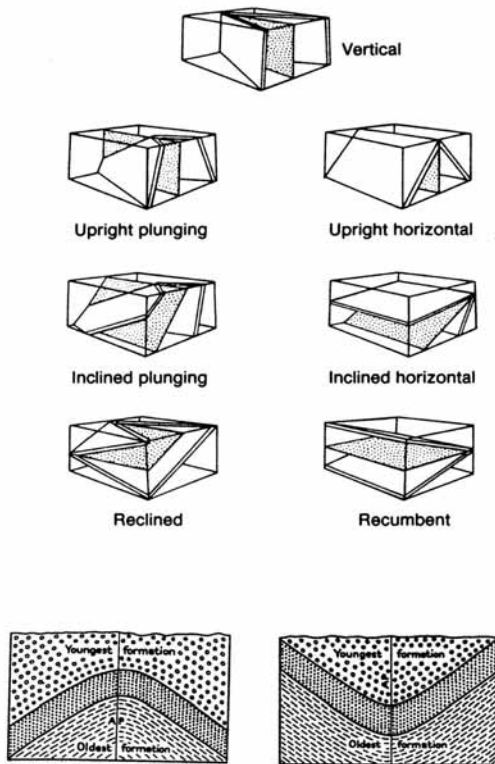
Folds

If layers are folded into convex-upward forms we call them **anticlines**. Convex-downward fold forms are called **synclines**. In Figure A1-1, note the geometric relationship of anticlines and synclines. **Axial planes** (or **axial surfaces**) physically divide folds in half. Note that in Figure A1-1, the fold is deformed about a vertical axial surface and is cylindrical about a linear **fold axis** which lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the **hinge line** (which is parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

In eroded anticlines, strata forming the limbs of the fold *dip away from* the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs *dip toward the hinge area*. Given these arrangements, we expect that in the arches of eroded anticlines, older stratigraphic layers will peek through whereas in the eroded troughs of synclines, younger strata will be preserved.
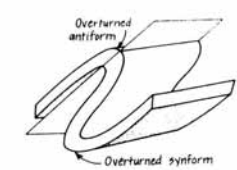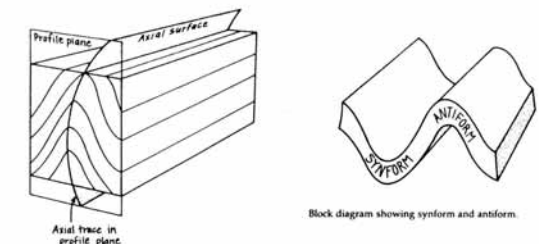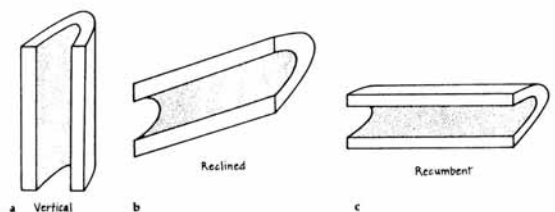
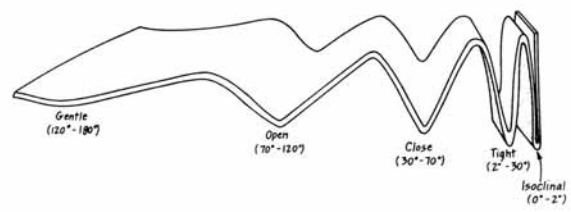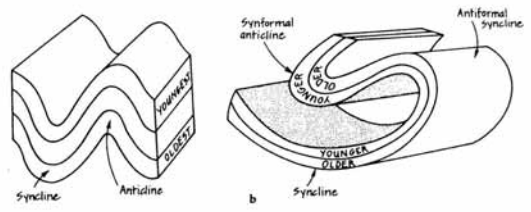**Figure A1-1** - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

In metamorphic terranes, field geologists are not always sure of the correct age relationships of the metamorphosed strata. Therefore, it is helpful to make use of the general terms **antiform** and **synform** which describe the folds by whether they are convex upward (antiform) or concave upward (synform) but do not imply anything about the relative ages of the strata within them.

Realize that in the upright folds shown in Figure A1-1, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles) aligned parallel to the axial surfaces of folds. Such penetrative metamorphic fabrics are called **foliation**, if primary, and **schistosity**, if secondary. Minerals can also become aligned in a linear fashion producing a **metamorphic lineation**. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction. Because folds in metamorphic rocks are commonly **tight-** to **isoclinal** (high amplitude-to-wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally be parallel to the re-oriented remnants of stratification (except of course in the hinge areas of folds). Thus, in highly deformed terranes, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they tend to mark regional fold-hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that axial surfaces can be tilted, to form inclined or **overturned folds**. Or the axial surfaces may be sub-horizontal, in which case the term **recumbent folds** is used. In both overturned folds and recumbent folds, the fold axes may remain subhorizontal. (See Figure A1-1.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a **plunging fold**). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). **Vertical folds** (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In **reclined folds**, quite common in ductile shear zones, the fold axes plunge directly down the dip of the axial surface.

In complexly deformed mountain ranges, most terranes show the superposed effects of more than one set of folds and faults. As a result of multiple episodes of deformation, the ultimate configuration of folds can be quite complex (i. e., plunging folds with inclined axial surfaces and overturned limbs).

We need to mention one additional point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, the M's, and the Z's. Looking down plunge in the hinge area of a northward-plunging anticlinal fold, for example, dextral shearing generates asymmetric Z folds on the western limb and sinistral shearing forms S folds on the eastern limb. Usually only one variety of small, asymmetric folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), one should be on the lookout for a fold axis. The hinge area is dominated by M folds (no sense of asymmetry).

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the last forces that ultimately produced the fold. Therefore, the orientation of the folds give some hint as to the direction of application of the active forces (often a regional indicator of relative plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

Faults

A **fault** is defined as *a fracture along which the opposite sides have been displaced*. The surface of displacement is known as the fault plane (or fault surface). The enormous forces released during earthquakes produce elongate gouges within the fault surface (called **slickensides**) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides (Figure A1-2, inset). The block situated below the fault plane is called the **footwall block** and the block situated above the fault plane, the **hanging-wall block**. Extensional force causes the hanging-wall block to slide **down** the fault plane producing a **normal fault**. [See Figure A1-2 (a).] Compressive forces drive the hanging-wall block **up** the fault plane to make a **reverse fault**. A reverse fault with a low angle (<30°) is called a **thrust fault**. [See Figure A1-2 (b).] In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Experimental- and field evidence indicate that the asymmetry of slickensides is not always an ironcled indicator of relative fault motion. As such, displaced geological marker beds or veins are necessary to verify relative offset. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named **dip-slip motion**.

Rather than simply extending or compressing a rock, imagine that the block of rock is sheared along its sides (*i. e.*, that is, one attempts to rotate the block about a vertical axis but does not allow the block to rotate). This situation is referred to as a shearing couple and could generate a **strike-slip fault**. [See Figure A1-2 (c).] On a strike-slip-fault plane, slickensides are oriented subhorizontally and again may provide information as to which direction the blocks athwart the fault surface moved.

Two basic kinds of shearing couples and/or strike-slip motion are possible: **left lateral** and **right lateral**. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is **left lateral** [illustrated in Figure A1-2 (c)]. If the block across the fault appears to have moved to the right, the motion is **right lateral**. Convince yourself that no matter which block you can choose to observe the fault from, you will get the same result! Naturally, complex faults show movements that can show components of dip-slip- and strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.
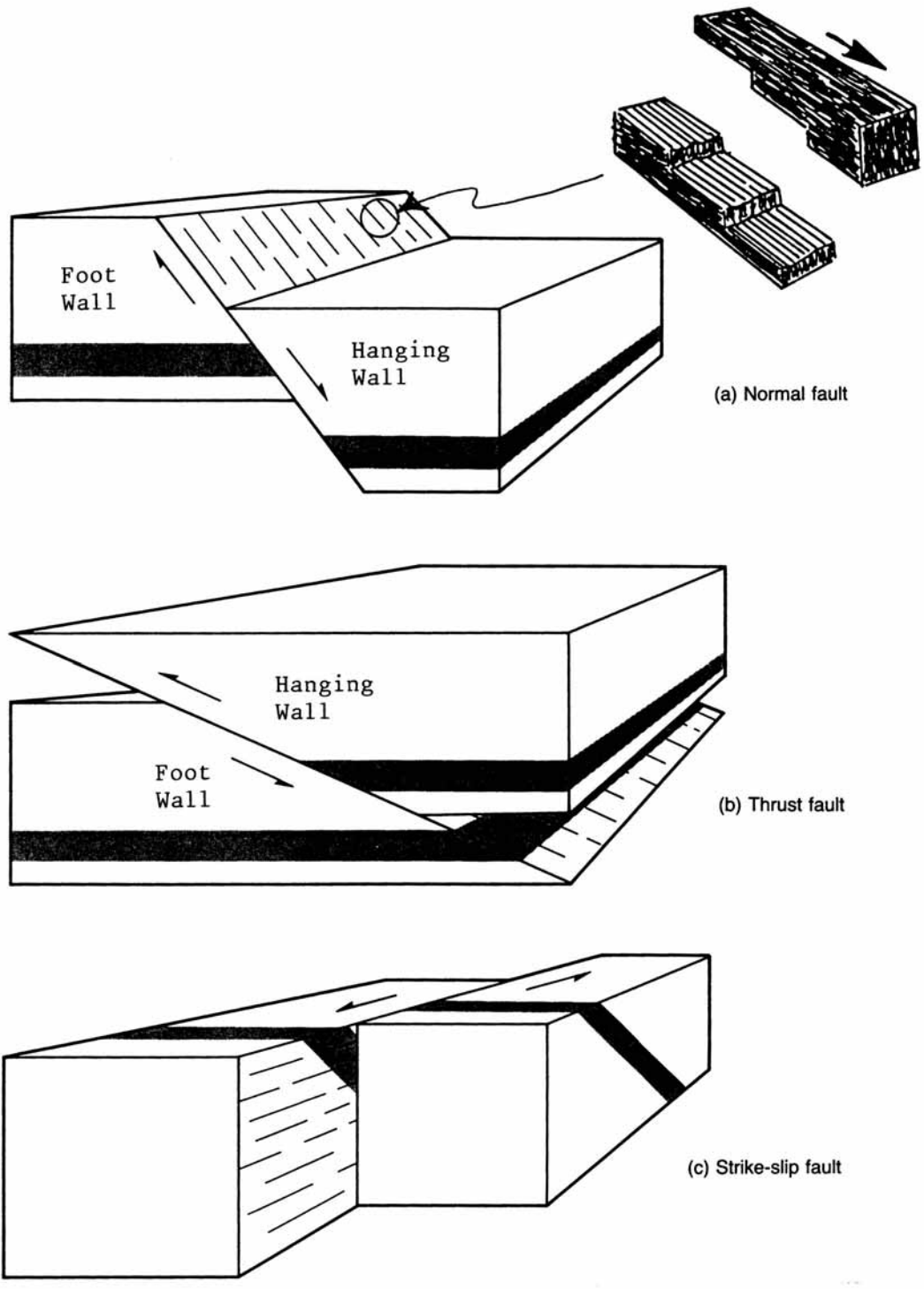
Figure A1-2 - The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (black) has been offset by horizontal movement (left-lateral offset shown here). Inset (d) shows segments of two blocks along a slickensided surface show how the jagged "risers" of the stairsteps (formed as pull-apart tension fractures) can be used to infer sense of relative motion. [(a), (b), (c), Composite diagram from introductory texts; (d), J. E. Sanders, 1981, fig. 16.11 (b), p. 397.]

Tensional- or compressional faulting resulting from brittle deformation, at crustal levels above 10 to 15 km, is accompanied by seismicicity and the development of highly crushed and granulated rocks called **fault breccias** and **cataclasites** (including fault gouge, fault breccia, and others). Figure A1-3 lists brittle- and ductile fault terminology as adapted from Sibson (1977) and Hull et al. (1986). Begining at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called **mylonites** (Figure A1-3).

The identification of such ductile fault rocks in complexly deformed terranes can be accomplished only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988), which can easily be "missed" in the field without careful microscopic analysis. Cameron's Line, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile fault zone (mylonite) having a complex geologic history.

Over the years, field geologists have noted special geologic features associated with thrust faults. Because they propagate at low angles with respect to bedding, thrusts commonly duplicate strata. In addition, thrust faults can displace strata for great distances and wind up transporting rock deposited in one environment above rocks deposited in markedly disparate environments. In such cases, we call the displaced strata of the upper plate above a thrust fault an **allochthon** or describe an entire displaced sequence of strata as an **allochthonous terrane** (see Tectonostratigraphic Units below). In other words, *allochthonous rocks were not originally deposited where they are now found*. By contrast, regions consisting of rock sequences that were originally deposited where they are now found constitute an **autochthon** or **autochthonous terrane**.

Interesting geometric patterns result from the erosion of overthrust sheets of strata that have been folded after they were overthrust. When the upper plate (allochthon) has a "hole" eroded through it, we can peer downward through the allochthon and see the autochthon exposed in a **window**, **inlier**, or **fenster** surrounded by the trace of the thrust fault that was responsible for the dislocation (Figure A1-4). By contrast, if most of the upper plate has been eroded, only a remnant **outlier** or **klippe** may remain. (See Figure A1-4.) Both klippen and windows produce similar map-scale outcrop patterns. The difference is that the thrust surface typically dips *toward* the center of a klippe (a remnant of the allochthon) and *away from* the center of window (which shows a part of the underlying autochthon).

Bedding-plane thrusts are more-localized features but are geometrically the same as thrust faults in that they involve layer-parallel shortening of strata and produce low-angle imbrication of strata. They can easily be "missed" in the field but result in overthickening of strata and can produce anomalous stratigraphic thickness in sedimentary units. The field geologist can identify them by careful bed-by-bed examination of known sequences based on duplication of key- or marker beds and by identification of highly veined dislocation surfaces.
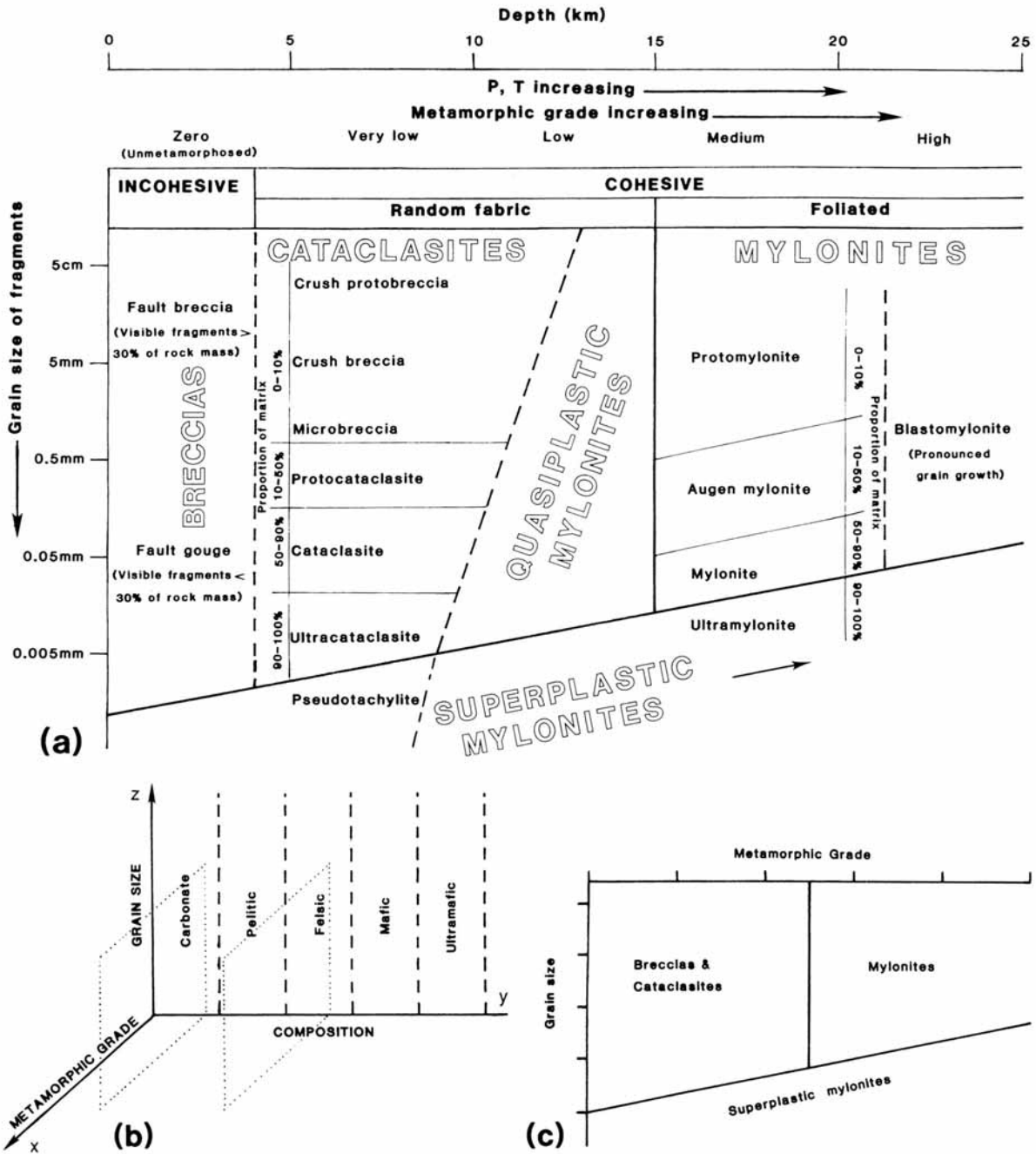
Figure A1-3 - Fault-rock terminology. (a) Classification of fault rocks that have been derived from quartzo-feldspathic lithologies (e. g. granite) (adapted from Sibson, 1977); (b) the grain size - metamorphic grade - lithologic composition grid used for classifying fault rocks (after Hull et al., 1986); (c) fault-rock diagram for marl showing expanded mylonite and superplastic mylonite fields as compared to those shown on the diagram for granite in (a) (from Marshak and Mitra [1988]).

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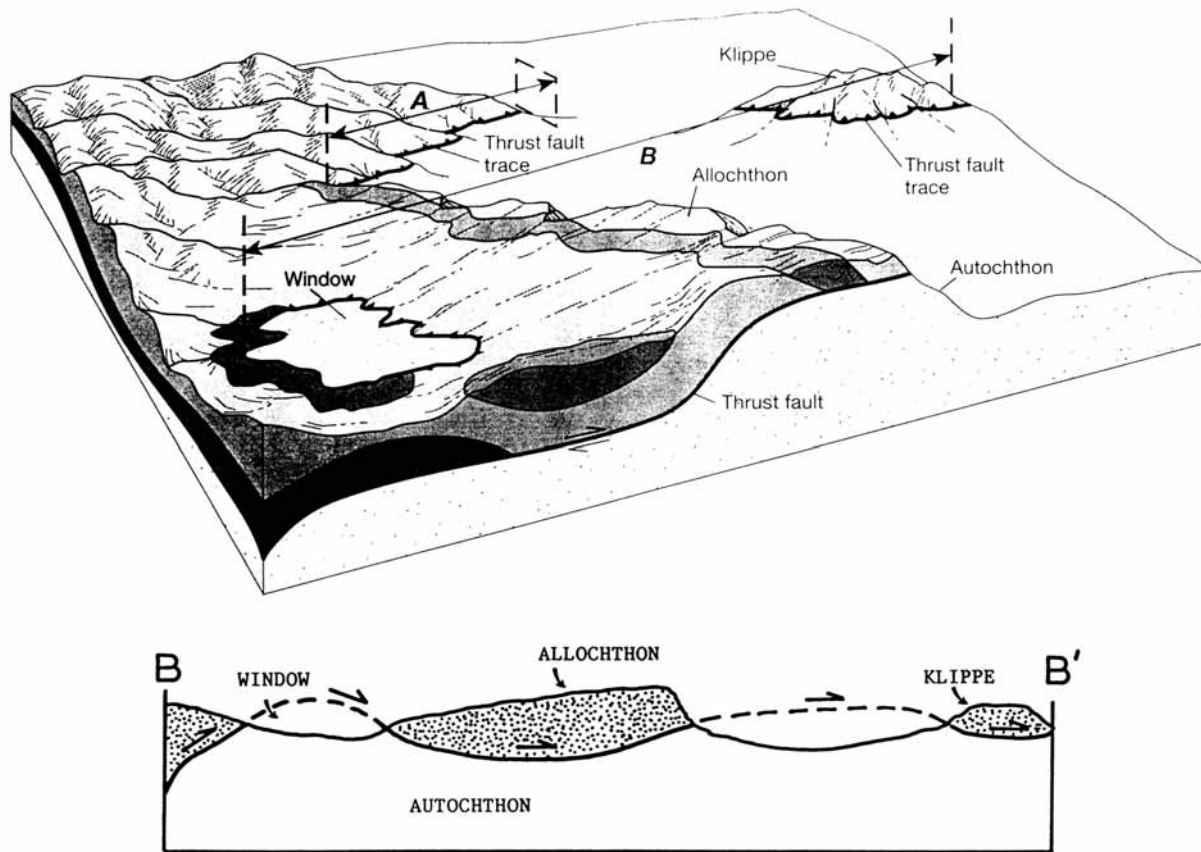
Figure A1-4 - Block diagram illustrating the relationships between allochthons, autochthons, klippen, and windows. (Twiss and Moores, 1992, p. 99) with section B-B' drawn by CM.

During episodes of mountain building associated with continuous subduction and/or collisions near continental margins, thrusting is typically directed from the ocean toward the continent. Accordingly, one of the large-scale effects of such periods of great overthrusting is to impose an anomalous load on the lithosphere that causes it to subside and form a **foreland basin**. These basins receive tremendous quantities of sediment that fill the basin with debris derived from erosion of uplifted areas within the active collision zone. In the late stages of convergence, forces transmitted from the collision zone into the developing foreland basin create a diachronous secondary stage of folding and continent-directed overthrusting of the strata filling the foreland basin. Thus, a thrust may override debris eroded from it.

Surfaces of Unconformity

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure A1-5), such surfaces represent mysterious intervals of geologic time where the local

evidence contains no clues as to what went on! By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.
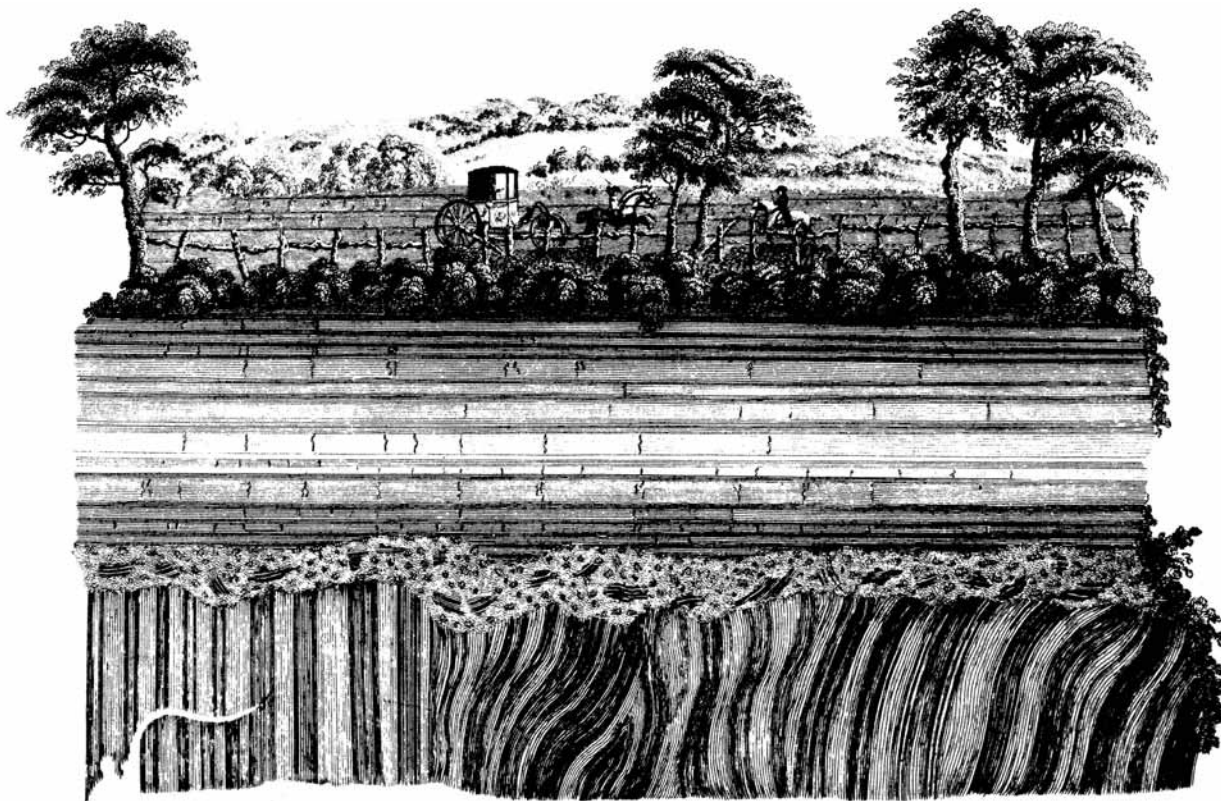
Figure A1-5 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Unconformities occur in three basic erosional varieties - angular unconformities, nonconformities, and disconformities (Figure A1-6). Angular unconformities (such as the River Jed) truncate dipping strata below the surface of unconformity and thus exhibit angular discordance at the erosion surface. Nonconformities separate sedimentary strata above the erosion surface from eroded igneous- or metamorphic rocks below. Disconformities are the most-subtle variety, separating subparallel sedimentary strata. They are commonly identified by paleontologic means, by the presence of channels cut into the underlying strata, or by clasts of the underlying strata in their basal part. The strata above a surface of unconformity may or may not include clasts of the underlying strata in the form of a coarse-grained, often bouldery basal facies.

Following the proposal made in 1963 by L. L. Sloss, surfaces of unconformity of regional extent within a craton are used as boundaries to define stratigraphic *Sequences*.
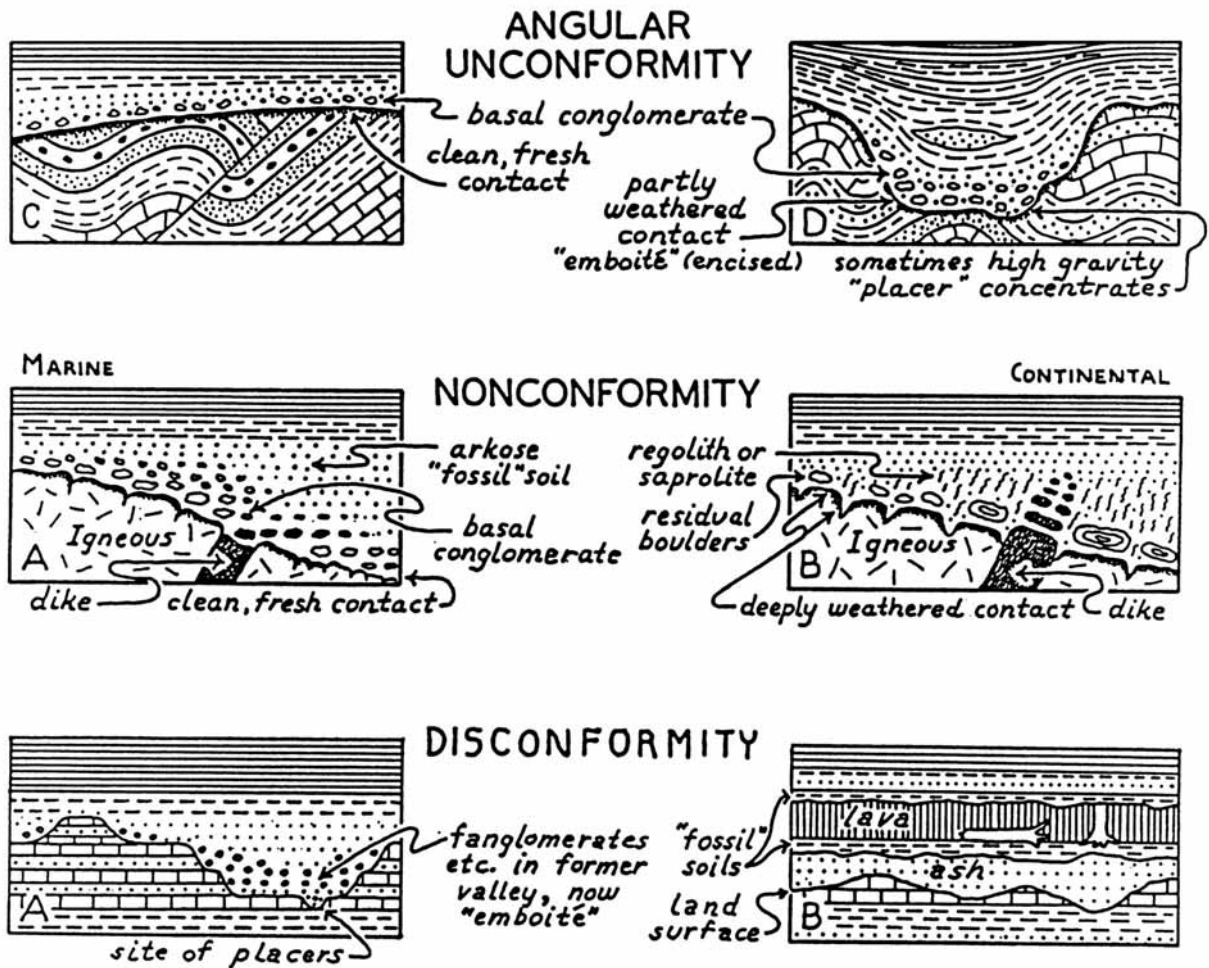
ANGULAR UNCONFORMITY

basal conglomerate
clean, fresh contact
partly weathered contact
"emboité" (encised)
sometimes high gravity "placer" concentrates

NONCONFORMITY

MARINE
CONTINENTAL

arkose "fossil" soil
basal conglomerate
Igneous
dike — clean, fresh contact
regolith or saprolite
residual boulders
Igneous
deeply weathered contact — dike

DISCONFORMITY

fanglomerates etc. in former valley, now "emboité"
"fossil" soils
lava
ash
land surface
site of placers

Figure A1-6 - Various types of unconformities, or gaps in the geologic record. Drawings by Rhodes W. Fairbridge.

Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above-, below-, and within strata. During normal deposition, or settling from a fluid in a rainfall of particles, massive, essentially poorly stratified successions may result. The presence of **strata** implies a change in deposition and as a result most geologists appreciate the significance of layering in sedimentary rocks as marking **CHANGE** in big letters, be it a change in parent area of the sediment, particle size, or style of deposition. Thus, **bedding** can best be viewed as marking the presence of mini-surfaces of unconformity (diastems). During high-energy transport of particles, features such as **cross beds, hummocky strata, asymmetric current ripple marks,** or **graded beds** result. Cross- and hummocky bedding, and asymmetric current ripple marks are deposited by moving currents and help us unravel the paleocurrent directions during their formation. Graded beds result from a kind of a "lump-sum distribution" of a wide range of particles all at once (usually in a gravity-induced turbidity flow).

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Thus, graded beds show larger particle sizes at the base of a particular layer "grading" upward into finer particles.

Secondary sedimentary features are developed on already deposited strata and include **mud (or desiccation) cracks, rain- drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts**. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure A1-7.

Together, these primary- and secondary sedimentary structures help the soft-rock structural geologist unravel the oft-asked field questions - namely.... **Which way is up?** and **Which way to the package store?** The direction of younging of the strata seems obvious in horizontal- or gently tilted strata using Steno's principle of superposition. But steeply tilted-, vertical-, or overturned beds can be confidently unravelled and interpreted structurally only after the true topping (stratigraphic younging) direction has been determined. As we may be able to demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

Structures in Sedimentary- vs. Metamorphic Rocks

For hard-rock geologists working in metamorphic terranes, simple sedimentary observations will not allow the card-carrying geologist to know "Which way is up" **at all**. Rather, because of intense transposition and flow during ductile deformation, stratification, fossils for age dating, tops and current-direction indicators are largely useless except to identify their hosts as sedimentary protoliths. Thus, according to CM, "*at the outcrop scale, metamorphism can best be viewed as the great homogenizer*." Commonly during metamorphism, the increase in temperature and -pressure and presence of chemically active fluids severely alter the mineral compositions and textures of pre-existing rocks. As a result, in many instances, typical soft-rock stratigraphic- and sedimentologic analysis of metamorphic rocks is not possible.

Tectonostratigraphic Units

In metamorphic terranes, **tectonostratigraphic units** can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile-fault zones (mylonites), surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic (ancient crustal), continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). The collective adjectives *miogeosynclinal* (for the shallow-water shelf deposits) and *eugeosynclinal* (for the

deep-water oceanic deposits) have been applied to the products of these contrasting depositional realms.
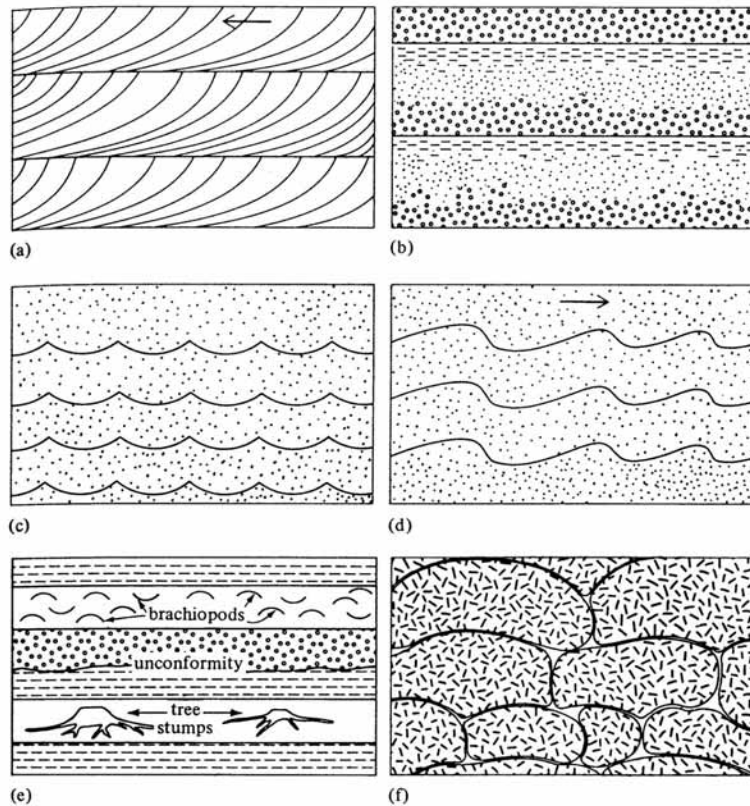
Figure A1-7 - Diagrammatic sketches of primary sedimentary structures (a through e) and cross sections of pillows (f) used in determining topping (younging) directions in rocks.

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