# Geological Excursion to the Southwestern Sierra Nevada, California- Observations of the Surface Manifestations of Lithosphere Scale Processes: A Field Guide Prepared for the Meeting of the National Association of Geoscience Teachers, California State University, Fresno (October 8-10, 2010)

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## INTRODUCTION

The southern Sierra Nevada and adjacent regions preserve a rich history of lithosphere evolution that reaches well back into Paleozoic time, and which remains vigorous today. In viewing the numerous geologic maps that are available at various scales for the region, one may order the major features as records of distinct stages in lithosphere evolution. Clearly the massive array of granitoids that compose most of the southern Sierra bedrock record a major phase of crust and probably whole-scale lithosphere construction driven by subduction zone magmatism in the Mesozoic (cf. Saleeby et al., 2003). Careful examination of this mass of granitoids that we call the Sierra Nevada batholith (SNB) shows that it hosts numerous pendants of metamorphic rock. These metamorphic pendants record a rich history of Paleozoic ocean floor and continental margin tectonics, transform faulting and initiation of east-dipping subduction at the close of the Paleozoic; and then early Mesozoic sedimentation above the accreted Paleozoic rocks as well as the early phases of SNB arc activity (Saleeby, 2010). The geomorphology of the southern Sierra, the history of major river canyon incision, and sediments of the San Joaquin basin record the formation and west-tilting of the Sierra Nevada "microplate." This microplate constitutes a semi-rigid crustal block composed of the coupled Sierra Nevada-Great Valley geomorphic provinces, and which moves semi-independently of the Basin and Range and Mojave provinces as part of the greater San Andreas transform plate juncture system (Argus and Gordon, 1991). Perhaps one of the most profound late Cenozoic tectonic events resolved in the California region is the internal deformation of the southern half of the Sierra Nevada microplate as a result of the Pliocene-Quaternary foundering of the mantle lithosphere beneath the region (Saleeby et al., 2003, 2009; Zandt et al., 2004; Le Pourhiet et al., 2006; Nadin and Saleeby 2010).

This field trip takes an integrative approach in examining rock outcrops and geomorphic features along the western Sierra Nevada between latitudes ~37°N and ~35.5°N which reflect all major stages of lithospheric evolution (Fig. 1). On Day One we will start by examining outcrops of a deformed sub-oceanic Moho complex of the Early Ordovician Kings River ophiolite along the lower Kings River. Ophiolites are important because they represent on land fragments of oceanic crust and upper mantle that are emplaced along plate junctures. Following our early morning observations of the ophiolite we will drive into Kings Canyon National Park and observe stratigraphic and structural relations of the Neoproterozoic and lower Mesozoic Boyden Cave metamorphic pendant. In transit we will note the distinct transverse variations in SNB petrology that coincide with the now intruded out late Paleozoic lithospheric suture that joined abyssal lithosphere of Kings River ophiolite affinity to the ancient

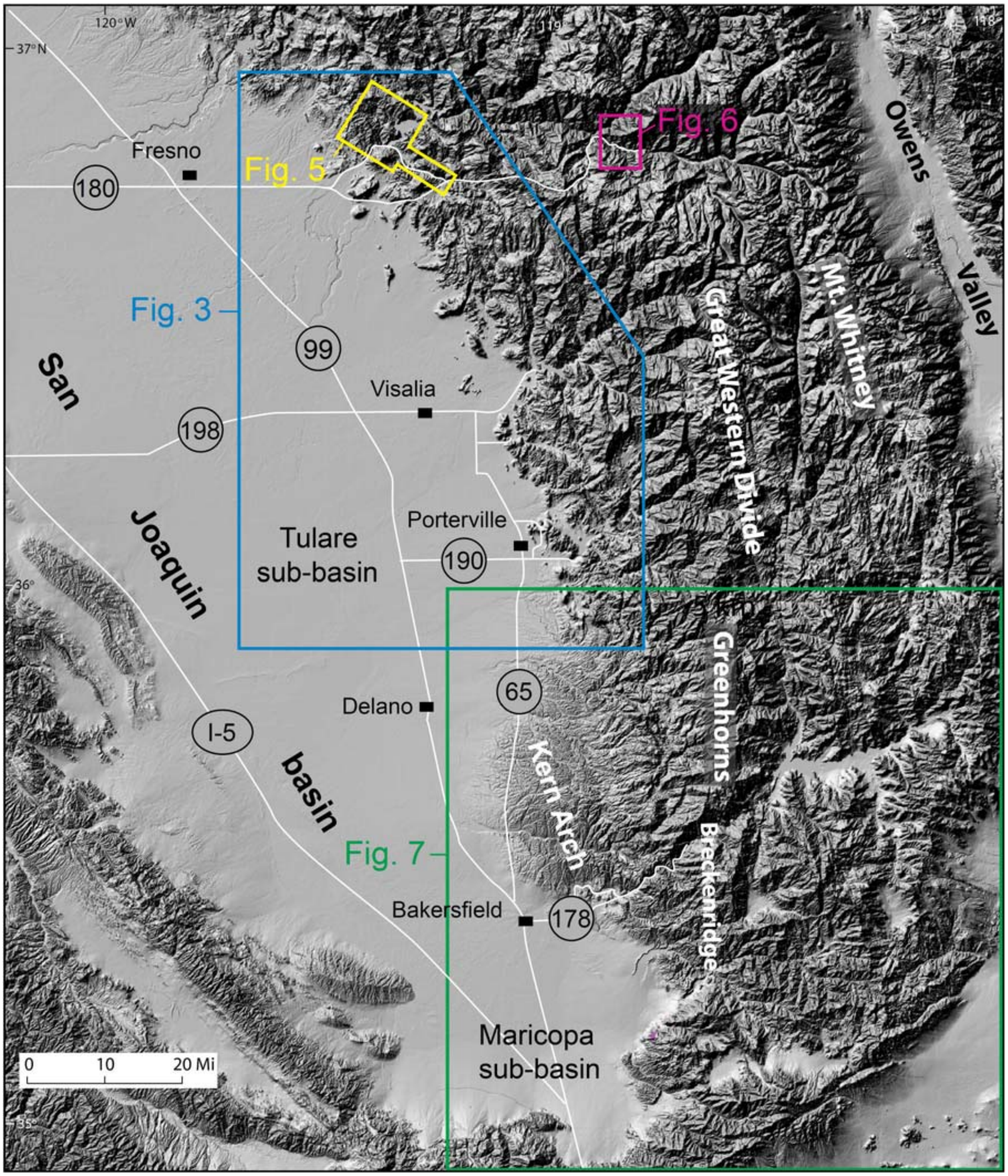
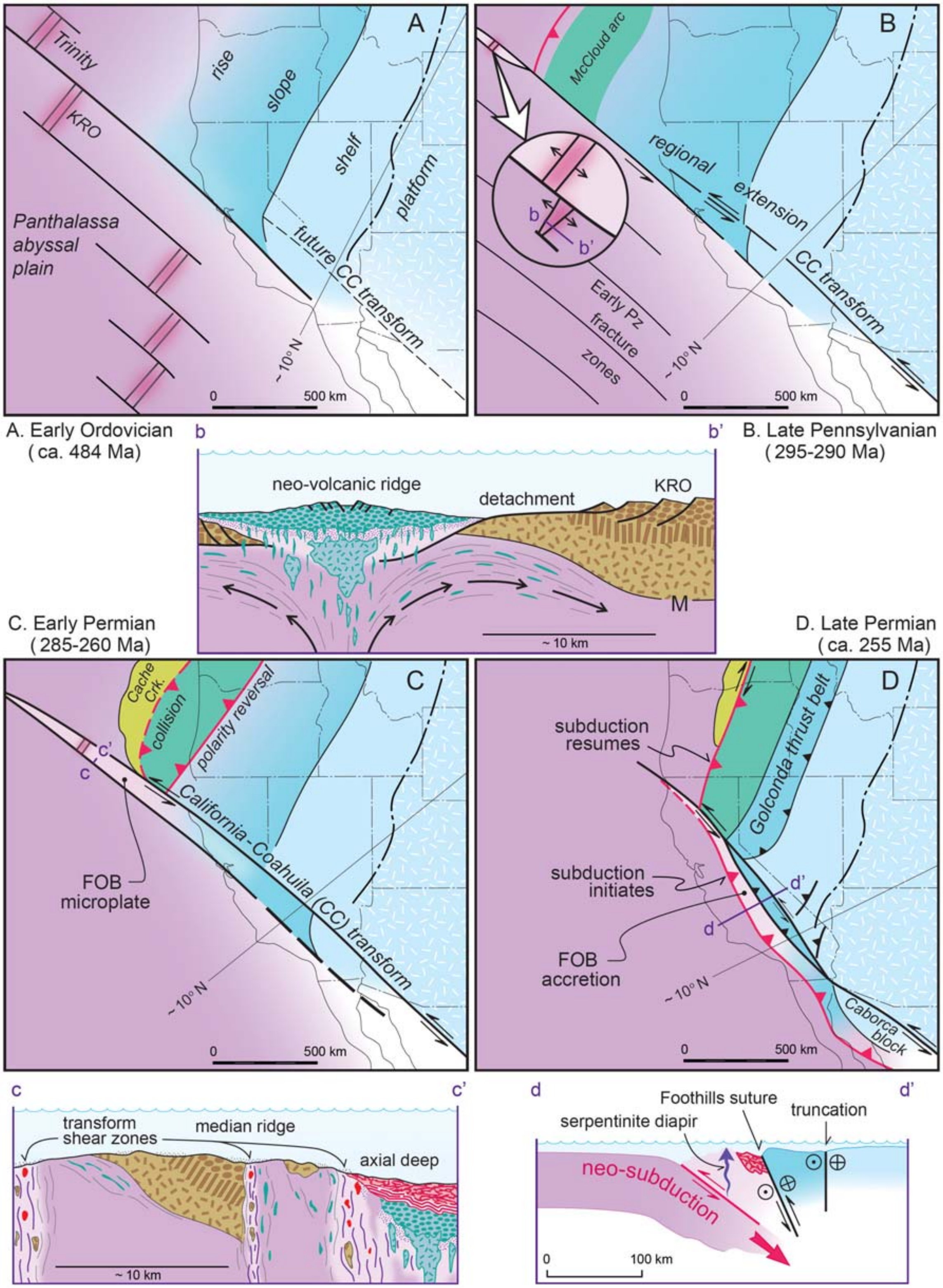



**Figure 1. Digital Elevation Model (DEM) of the southern Sierra Nevada region showing the general route of the field trip as well as select geographic and geomorphic features. Greater than 90 per cent of southern Sierra basement exposure is composed of "granites" of the Sierra Nevada batholith (SNB). The remainder is metamorphic pendant rock and sparse late Cenozoic sediments. Note locations of Figure 3, 5 and 7 map areas.**

passive margin of western North America, in part represented by the Neoproterozoic section in the Boyden Cave pendant. While in Kings Canyon we will observe the incision patterns of the Kings River that record a late Pliocene-Quaternary pulse of rock uplift and elevation increase that have resulted from the ongoing delamination of mantle lithosphere from beneath the region, with the complementary ascent and infill of asthenosphere (Wakabayashi and Sawyer, 2001; Stock et al., 2004; Clark et al., 2005). On Day two we will begin our activities in the lower Kaweah River area by observing the anomalous topography of the area that records Quaternary burial of mountainous topography of the Foothills of this region, which reflects subsidence related to mantle lithosphere foundering (Saleeby and Foster, 2004). We will then proceed southeastwards along the Sierra Foothills observing the distinct landscape of the Kaweah serpentinite melange belt, which represents the oceanic transform fault disruption of Kings River ophiolite affinity abyssal lithosphere. Slightly north of Porterville we will examine road cuts into the melange that reveal a number of its typical structural features. We will then proceed southwards towards Bakersfield slowly ascending up a Quaternary epeirogenic uplift called the Kern Arch (also commonly called the Bakersfield Arch). This uplift also has formed as a result of ongoing mantle lithosphere foundering (Saleeby and Saleeby, 2009; Saleeby et al., 2009). The early afternoon will be spent looking at evidence for Quaternary faulting of the Kern Arch and adjacent Sierra range front. The later afternoon will be spent making observations of the Neogene stratigraphy that is being incised across the Kern Arch, and which records early to middle Miocene deep marine conditions immediately adjacent to the southwestern Sierra, and late Miocene to early Quaternary building out of regionally extensive shallow marine and terrestrial sand sheets derived from the ascending Sierra Nevada.

## OVERVIEW OF GEOLOGIC HISTORY

The geologic history of western North America is accented by the development of a Neoproterozic passive margin that persisted through mid-Paleozoic time (Stewart, 1970; Davis et al., 1978). Spectacular exposures of such passive margin strata occur east of the Sierra Nevada and Owens Valley in the White-Inyo Mountains and Death Valley regions. Dismembered, variably displaced and metamorphosed remnants of such strata occur as metamorphic pendants in the southern axial to eastern SNB, including the Boyden Cave pendant. Facies trends along the southern extent of the passive margin sequence run southwestwards through central Nevada and extend to the eastern Sierra Nevada-Owens Valley region (Fig. 2) where they are truncated and overprinted by northwest trending Mesozoic structural trends and the northwest trending SNB (Davis et al., 1978; Stevens et al., 2005). Paleozoic strata in pendants of the SNB, as well as the Shoo Fly complex of the western to axial northern Sierra consist of various facies packages of the passive margin sequence that have been shuffled by superposed episodes of both sinistral and dextral strike-slip displacement along northwest trends, originating in the Permo-Carboniferous and punctuating Mesozoic time. The most fundamental of these was the Permo-Carboniferous transform truncation of the passive margin entailing ~1000 km of sinistral displacement of a large sliver of the passive margin into the interior of Mexico by the California-Coahuila transform, and its replacement by Paleozoic abyssal lithosphere (Fig. 2)(Saleeby, 1982, 2010; Stevens et al., 2005; Dickinson and Lawton, 2001). Part of the Paleozoic abyssal lithosphere was deformed into an oceanic metamorphic core complex, and then parts were further disrupted into serpentinite matrix melange along a major oceanic transform system that extended into the transform zone that truncated and displaced fragments of the passive margin (Fig. 2b and 2c). At the end of Permian time the transform plate juncture underwent a relative plate motion change leading to sinistral sense transpression, and then the initiation of subduction beneath the SW Cordillera. The buoyant serpentinite melange and its ≤20 km scale tectonic inclusions of abyssal lithosphere were



A
Trinity
KRO
rise
slope
shelf
platform
Panthalassa
abyssal
plain
future CC transform
~10° N
0
500 km
A. Early Ordovician
(ca. 484 Ma)
B
McCloud arc
regional
extension
CC transform
b
b'
Early Pz
fracture
zones
B. Late Pennsylvanian
(295-290 Ma)
neo-volcanic ridge
detachment
KRO
M
~ 10 km
C. Early Permian
(285-260 Ma)
C
Cache
Crk.
collision
polarity reversal
c'
c
California-Coahuila (CC) transform
FOB
microplate
D. Late Permian
(ca. 255 Ma)
D
subduction
resumes
Golconda thrust belt
subduction
initiates
d'
d
FOB
accretion
Caborca
block
transform
shear zones
median ridge
axial deep
Foothills suture
serpentinite diapir
truncation
neo-subduction
100 km


Figure 2

**Figure 2. Generalized plate tectonic model for the generation of the Kings River ophiolite along a fast spreading ridge in the Early Ordovician Panthalassa (proto-Pacific) ocean basin (A); followed by the generation of the Kaweah serpentinite melange in a Permo-Carboniferous leaky transform-slow spreading ridge system like that of the Cayman Trough (B & C); and the emplacement of the Kings-Kaweah ophiolite belt along the Foothills suture during subduction initiation (D). Insets show diagrammatic cross-sectional relationships at key time intervals. FOB=Foothills ophiolite belt. Color-coding for details of the ophiolite belt are the same as Figures 3 and 5. Color code for North American Paleozoic continental margin rocks is shown in A. The McCloud arc (B-D) is an off shore volcanic arc that extended along the outer edge of the passive margin through much of Paleozoic time. The Cache Creek (terrane) of C and D is an ocean island chain, like the modern Hawaiian chain, that rode in on Panthalassa oceanic crust and collided with the McCloud arc causing it to reverse its subduction polarity and to encroach upon and collide with the outer edge of the passive margin.**

accreted to the hanging wall of the neo-subduction zone forming a proto-forearc along the western Sierra Foothills region. The Kings River ophiolite and Kaweah serpentinite melange as well as other Paleozoic ophiolitic exposures of the western Sierra to the north, such as the Tuolumne, Bear Mountains, and Feather River complexes, were all accreted en masse at this time (Saleeby, 1982; 2010). A long history of Mesozoic forearc deformation, volcanism and sedimentation, and arc plutonism culminating with the SNB then overprinted the accreted abyssal lithosphere of the western Sierra Foothills.

The lithospheric boundary between the disrupted and truncated margin of the passive margin and accreted abyssal lithosphere of the western Foothills belt constitutes the Foothills suture (Saleeby 1992). Large volume arc magmatism of the SNB strongly overprinted this suture, particularly at deep crustal levels, and accordingly the petrology and geochemistry of the SNB reflects transverse positions relative to the suture. Along and to the west of the suture the SNB is dominated by magmatic products that were generated in the depleted mantle source of the accreted Foothills ophiolite belt, whereas to the east the SNB magmas were generated in continental lithosphere of the passive margin. Accordingly western zone SNB rocks are dominated by gabbro, diorite and tonalite, reflecting their depleted mantle source, whereas the axial to eastern SNB is dominated by large volume tonalite-granodiorite and subordinate granite, reflecting its continental source (Fig. 3 Inset). In parallel radiogenic isotopes of Sr, Pb and Nd reflect this transverse variation pattern (Saleeby et al., 2003). Another critical feature of the southern SNB is that owing to the existence of a substantial ancient continental crustal column within the axial to eastern SNB magma source regime abundant eclogitic (garnet-clinopyroxenite) residues and cumulates accumulated along the SNB crust-mantle boundary, apparently a layer up to ~50 km thick (Ducea and Saleeby, 1998; Saleeby et al., 2003). The accumulation of a thick section of such high-density rocks had profound consequences for lithosphere evolution in the Cenozoic. At the close of the Cretaceous the high-density eclogitic root of the SNB and underlying subduction mantle wedge peridotites were cooled to a conductive geotherm by the flattening of the Farallon plate as it subducted, a process that ultimately led to the Laramide orogeny of the western U.S. interior (Saleeby et al., 2003; Saleeby, 2003).

At the close of the Cretaceous and through early Tertiary time the crustal block that constitutes the Sierra Nevada microplate was situated along the western margin of an orogenic plateau that has been termed the "Nevadaplano" (Saleeby et al., 2009). The Sierra Nevada region remained amagmatic until Neogene time, and its plateau like surface began a period of slow erosional

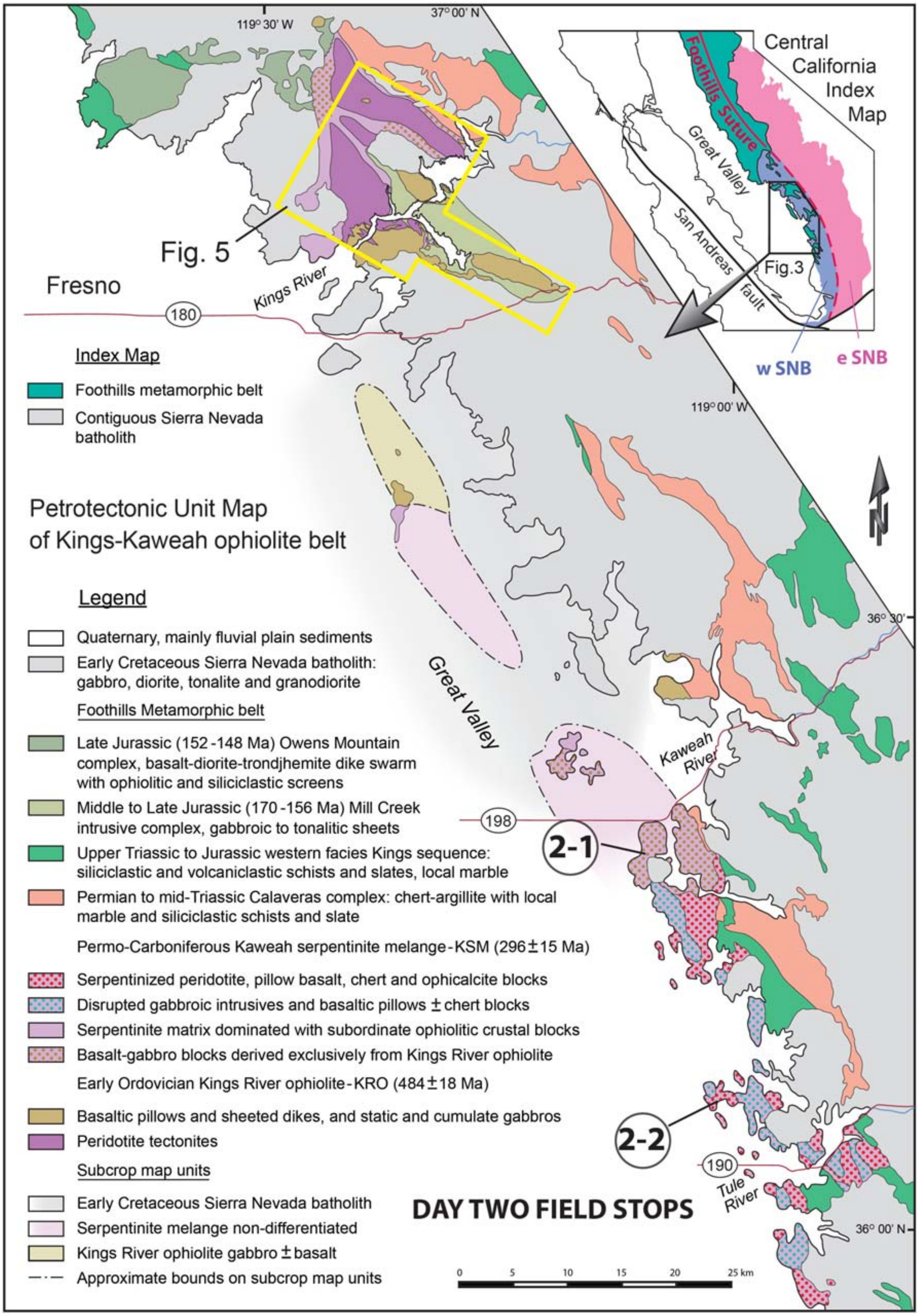

119° 30' W
37° 00' N
Central
California
Index
Map
Foothills Suture
Great Valley
San Andreas
fault
Fig.3
w SNB
e SNB
Fig. 5
Fresno
Kings River
180
119° 00' W
Index Map
Foothills metamorphic belt
Contiguous Sierra Nevada batholith
Petrotectonic Unit Map of Kings-Kaweah ophiolite belt
Legend
Quaternary, mainly fluvial plain sediments
Early Cretaceous Sierra Nevada batholith: gabbro, diorite, tonalite and granodiorite
Foothills Metamorphic belt
Late Jurassic (152-148 Ma) Owens Mountain complex, basalt-diorite-trondjhemite dike swarm with ophiolitic and siliciclastic screens
Middle to Late Jurassic (170-156 Ma) Mill Creek intrusive complex, gabbroic to tonalitic sheets
Upper Triassic to Jurassic western facies Kings sequence: siliciclastic and volcaniclastic schists and slates, local marble
Permian to mid-Triassic Calaveras complex: chert-argillite with local marble and siliciclastic schists and slate
Permo-Carboniferous Kaweah serpentinite melange-KSM (296±15 Ma)
Serpentinized peridotite, pillow basalt, chert and ophicalcite blocks
Disrupted gabbroic intrusives and basaltic pillows ± chert blocks
Serpentinite matrix dominated with subordinate ophiolitic crustal blocks
Basalt-gabbro blocks derived exclusively from Kings River ophiolite
Early Ordovician Kings River ophiolite-KRO (484±18 Ma)
Basaltic pillows and sheeted dikes, and static and cumulate gabbros
Peridotite tectonites
Subcrop map units
Early Cretaceous Sierra Nevada batholith
Serpentinite melange non-differentiated
Kings River ophiolite gabbro ± basalt
Approximate bounds on subcrop map units
Great Valley
Kaweah River
198
2-1
36° 30'
2-2
190
Tule River
DAY TWO FIELD STOPS
36° 00' N
0
5
10
15
20
25 km

Figure 3

**Figure 3. Generalized map of the western Sierra Nevada between latitudes 36°N and 37°N showing Kings River ophiolite, Kaweah serpentinite melange and metasedimentary rock pendants along the eastern margin of the ophiolite belt as well as the area of the cross cutting Sierra Nevada batholith (SNB). Note location of Figure 5 and day two field stops. The inset map at upper right shows the generalized Foothills metamorphic belt of the central Sierra Nevada breaking into metamorphic pendants of the southern Sierra as well as the boundary between the mafic western SNB and the felsic eastern SNB. This boundary corresponds to the "fossil" trace of the Foothills suture, the boundary between accreted ophiolite belt and the truncated edge of the North American passive margin.**

denudation at an average rate of ~50 m/m.y. (Clark et al., 2005). At ca. 20 Ma a slab window began to migrate beneath the southern Sierra as a consequence of the impingement of the Mendocino Triple Junction into the California active margin (Atwater and Stock, 1998). Up to this point in the Cenozoic the high-density eclogitic root of the southern SNB appears to have been supported in a gravitationally metastable state by the subducting Farallon plate. Beginning at ca. 20 Ma warm buoyant asthenosphere of the slab window came in contact with the base of the Sierran mantle lithosphere and an intense upper mantle instability resulted. Mendocino Triple Junction migration and the early stages of San Andreas transform system entailed a nontrivial component of normal extensional strain transmitted across the southern Sierra region. A combination of this extensional strain and the negative buoyancy of the eclogitic root drove high magnitude extension directly east of the Sierra Nevada, starting at ca. 15 Ma in the Death Valley region, and then propagating to the Owens Valley-eastern Sierra escarpment system by ca. 10 (Le Pourhiet et al., 2006; Saleeby et al., 2009). The instability entailed the east to west and south to north delamination (foundering) of the eclogitic root from the southern SNB in Pliocene-Quaternary time (Fig. 4). Replacement of these high-density rocks by asthenosphere inflow has resulted in ~1 km of rock uplift along the southeastern Sierra Nevada, and to the southwest across the Great Western Divide, Greenhorn-Breckenridge Mountains and Kern Arch. Viscous drag against mantle lithosphere still attached to the base of crust as well as crustal flexure resulted in ~500 m of anomalous subsidence in the Tulare sub-basin of the San Joaquin Valley (Saleeby and Foster, 2004). The distinct pattern that one observes in maps of the Sierra Nevada-Great Valley whereby the continuous trend to the western Foothills becomes embayed by Quaternary sediments between 36°N and 37°N reflects this anomalous subsidence pattern arising from delamination dynamics (Figs. 1 and 4).

## FIELDTRIP ROUTE AND STOP DISCRIPTIONS

### Day One

Day One focuses on the extreme contrasts in Paleozoic paleogeography across the Foothills suture as exhibited in metamorphic pendant rocks exposed along the Kings River. We start by looking at exposures of the Early Ordovician (ca. 485 Ma) Kings River ophiolite in the western Foothills and then progress to the Neoproterozoic passive margin strata and their lower Mesozoic marine overlap sequence in the Boyden Cave pendant. The Foothills suture is intruded out in this region by the SNB, but as we progress eastwards by automobile you will notice the SNB rocks getting progressively lighter and more granitoid in composition, reflecting the magma source regime change across the intruded suture. The trip starts by departing Fresno eastbound on (State Highway) SH-180 towards Kings Canyon (Fig. 1). After ~ 15 mi we enter the town of Centerville where we turn left onto Trimmer Springs Road. After ~9.5 mi we park in a turnout in a sharp gulley that enters the Kings River Valley on the north, ~0.2 mi downstream

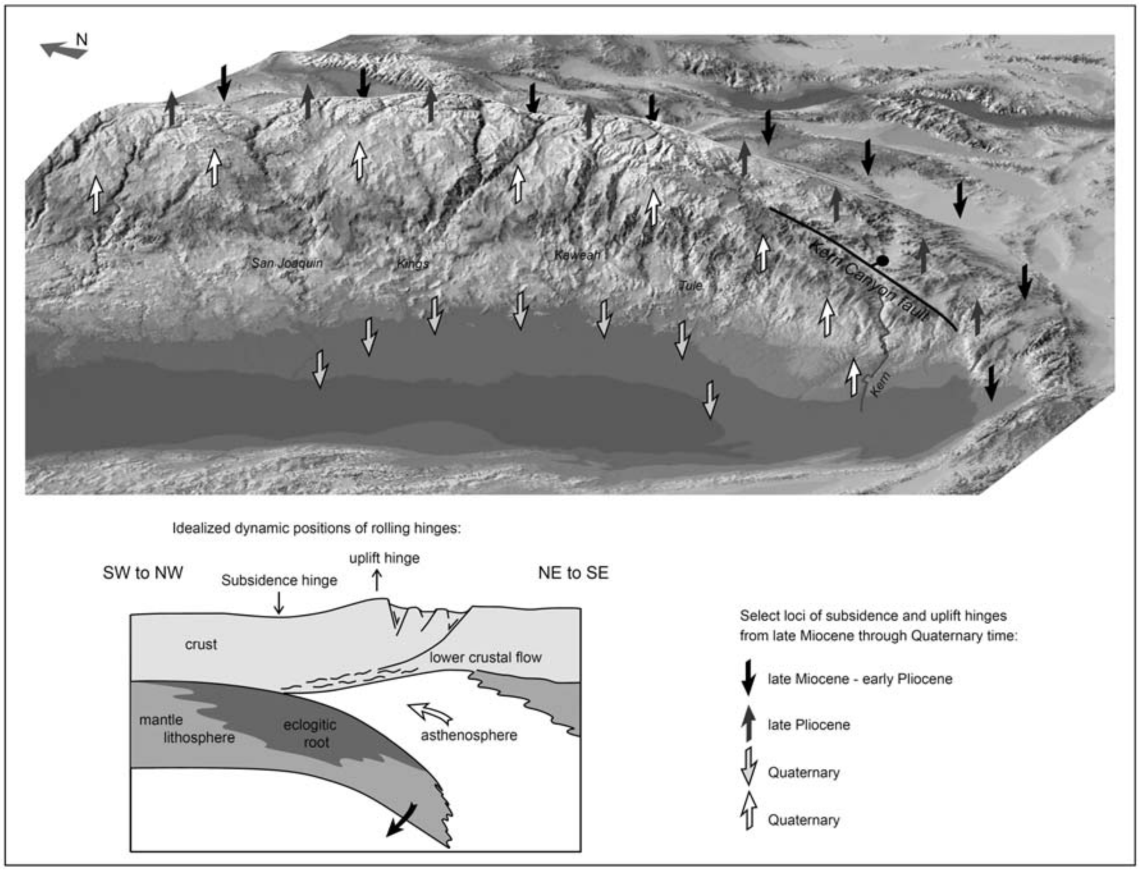



**Figure 4. Oblique digital elevation model of southern Sierra Nevada region showing generalized positions of subsidence and uplift rolling hinges for select times that migrated through the region in response to mantle lithosphere foundering based on thermo-mechanical modeling of Le Pourhiet et al. (2006), and constraints on Sierran landscape evolution and eastern San Joaquin subsidence and uplift patterns. Inset shows idealized positions of subsidence and uplift hinges in cross section view in relation to progressive peeling away of mantle lithosphere and inflow of asthenosphere. The peeling force bows the crust down leading to subsidence while the release of the lithosphere and the inflow of buoyant asthenosphere forces the crust up leading to uplift.**

from the bridge that crosses the Kings River. Here we will examine road cuts in the upper mantle peridotites of the Kings River ophiolite.

*Stop 1-1:* The lower Kings River has incised along a severely deformed Oceanic Moho section in this area. To the north-northwest of us across Red Mountain lies a vast section into the oceanic upper mantle, and to the south across Tivy Mountain lies a section into gabbros of the lower oceanic crust (Fig. 5). Road cuts that we examine here consist of mylonitic and ultramylonitic harzburgite (olivine e> orthopyroxene rock) and dunite (olivine rock) with transposed intrusive bodies of mylonitic hornblende-clinopyroxenite and amphibolized gabbros. The reddish-brown to greenish peridotites are laced with transposed hydrothermal veins that formed by infiltration of seawater during ocean floor deformation and

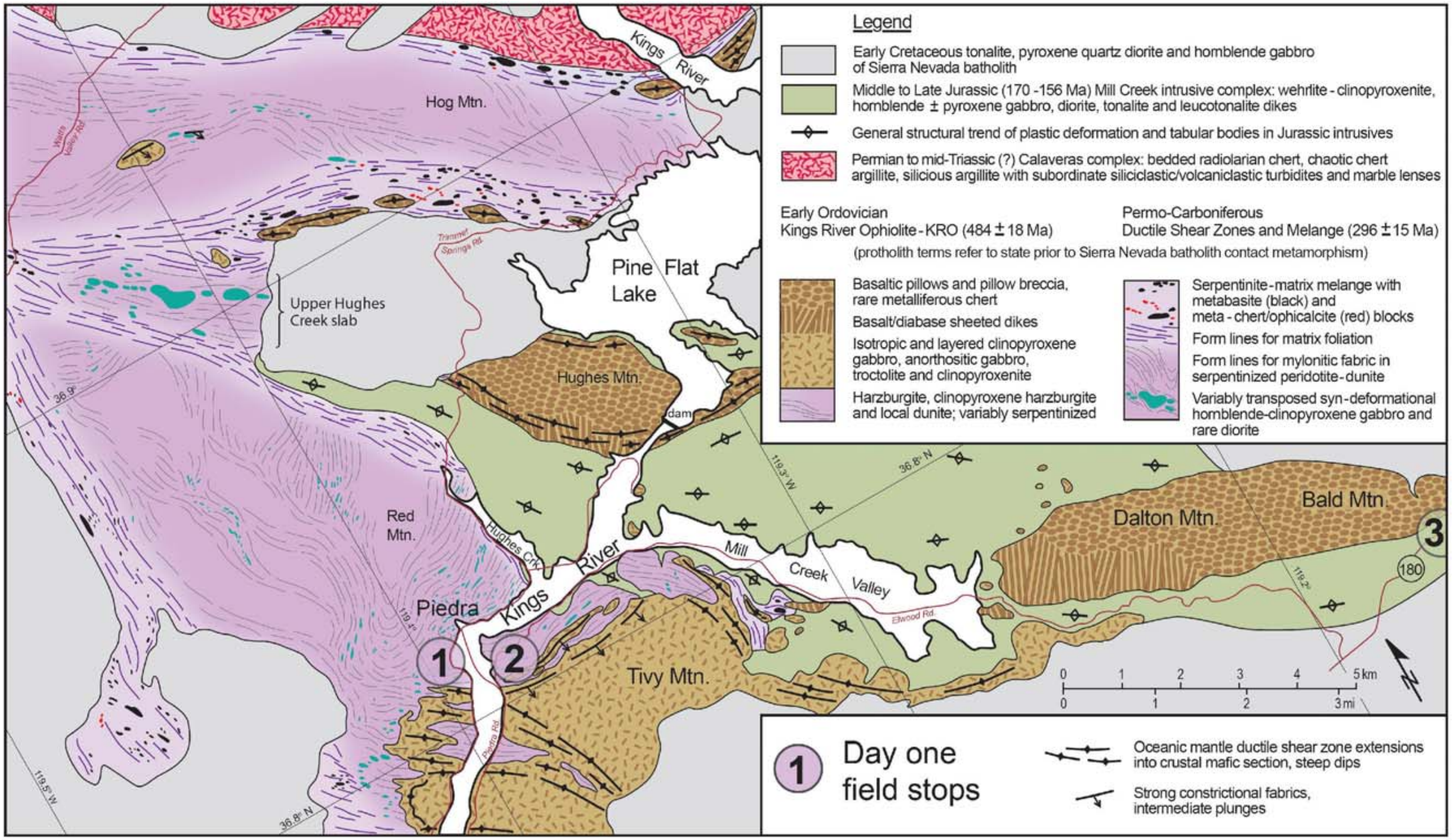



Figure 5. Geologic map of the Kings River ophiolite showing locations of Day One field stops (geology after Saleeby, 1978, 2010). The ophiolite section is broken into 5 to 10 km long tectonic slabs that are bounded by serpentinite melange zones or cross cutting intrusions of the Sierra Nevada batholith (SNB). The Permo-Triassic Calaveras complex is a chert-rich metasedimentary assemblage that represents pelagic deposits that formed on top of the ophiolite belt before and as it was accreted to North America.

retrograde metamorphism. The veins consist of various mixtures of antigorite, talc, high-Mg chlorite and local fuchsite (green mica) clusters where chromite lenses were deformed and altered. High strain sheath folds are commonly observed, but at this location superposed open folds of possible Mesozoic age are well developed along the road cuts. Deformation and retrograde ocean floor metamorphism developed at this level of the Kings River ophiolite along an oceanic metamorphic core complex, probably at the intersection of a spreading ridge and major transform fracture zone (Fig. 2b) (Saleeby, 1978, 2010). Thus the structural features that we examine formed up to thousands of kilometers away in the Paleozoic Panthalassa ocean basin. Core complex deformation is concentrated here along the Moho section where high shear strain resulted from large magnitude extension that was not fully compensated for by mid-ocean ridge basalt magma genesis and mafic crustal accretion. Note on Figures 3 and 5 that the Red Mountain-Tivy Mountain deep ocean floor section is cut along its margins by serpentinite melange. Melange is a commonly chaotic mixture of coherent blocks of rock suspended in a penetratively deformed matrix.

From Stop 1-1 we proceed eastwards ~0.2 mi and then turn right across the Kings River bridge and proceed ~0.7 mi and turn left onto Elwood Road. At ~0.2 mi we will park at a graded driveway that runs northwards on the left, and then hike ~50 m directly north up to some distinct outcrops.

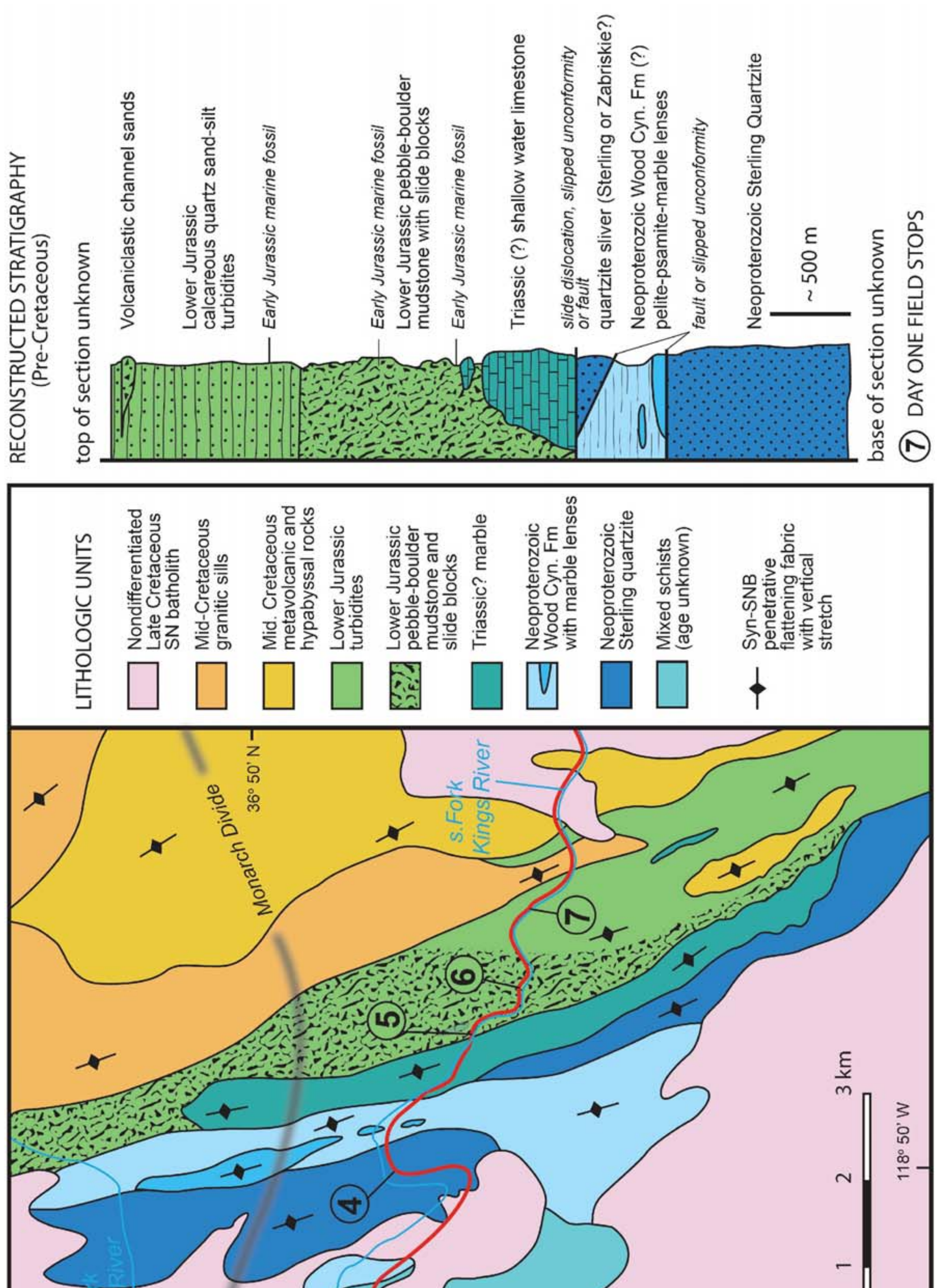
*Stop 1-2:* This outcrop represents the deepest levels of the Tivy Mountain cumulate gabbro section where it is intensely deformed adjacent to underlying mylonitic peridotites of the sub-oceanic upper mantle section (Fig. 5). The protoliths at this location consist of layered clinopyroxene gabbro and plagioclase clinopyroxenite that are intensely deformed into L-tectonites. Strain measurements on the remnants of distorted clinopyroxene grains from coarser gabbro layers indicate a minimum stretch of ~1000 per cent during mylonitization. Only remnant porphyroclasts of diopsidic-augite and calcic plagioclase remain from the protolith. The main phases present in the rock are a green hornblende and sodic to intermediate plagioclase. Locally Mg-chlorite is concentrated in thin layers along with green hornblende, possibly reflecting a wehrlitic (olivine>clinopyroxene) protolith. Also there are remnants of sodic-scapolite lying along hot (amphibolite grade) tensile fractures, and also partially transposed into shear bands. These represent high-temperature influx of seawater into the Moho-level deformation and retrograding zone.

Study of Figures 3 and 5 reveals that the Kings River ophiolite consists of several tectonic slabs that are up to ~20 km in major dimension, and that these are bounded by either serpentinite-matrix melange zones, or cross-cutting plutons of the SNB. Due to ever increasing accessibility limitations we cannot readily observe much of the ophiolite. From Stop 1-2 we will continue eastwards and then southwards on Elwood Road. We will wind through the contact zone between the 170-156 Ma Mill Creek arc intrusive complex (early SNB) and the ophiolite (Fig. 5). At first poorly exposed serpentinite melange and Tivy Mountain type gabbro will be on our right, and then further on a large slab of basaltic-sheeted dikes and pillow basalt will be on our left. After ~13 mi Elwood Road ends at SH 180 where we turn left (east) and continue ~2.6 mi where we park at a large turnout on the south side of the road. At this location we are in a quartz diorite phase of the Mill Creek intrusive complex (Fig. 5), the earliest SNB intrusive present in the western Sierra Foothills south of ~37.5°N. Our attention, however, will here be on boulders derived from Bald Mountain to the north of the highway area, a large mass of pillow basalt that formed the upper crustal levels of the Kings River ophiolite (Fig. 5).

*Stop 1-3:* At this location we will very carefully cross to the north side of the highway, and once we have crossed attempt to stay at curbside, and not wander into the high speed traffic that is typical of this area. We first see road cut and creek bed exposures of the Mill Creek intrusives. Immediately to the west of the creek the road cut penetrates the remnants of a debris flow derived from Bald Mountain. We will see fragments of broken pillows and well-developed basaltic hyaloclastite. We then walk carefully ~75 m to the west to another small creek bed along the roadside. Here a number of boulders of well-developed pillow basalt may be easily observed. The pillows are best preserved as textural variations in fracture faces of the boulders. The rocks are currently completely recrystallized to hornblende hornfels as a result of SNB contact metamorphism, and thus the pillow structures are ghosts that show well developed quenched rinds and inter-pillow hyaloclastite and calcareous ooze, now recrystallized to calc-silicate mineral assemblages. The Kings River ophiolite pillow lavas and sheeted dikes are mid-ocean ridge basalts, based on major and trace element data, and on radiogenic isotopic data. Their geochemical composition is complementary to the Tivy Mountain gabbroic cumulates with the cumulates representing the settling of early formed crystals as the basaltic magmas rose to their eruptive levels (Saleeby, 2010).

After observing the blocks of pillow basalt we will drive eastwards on SH 180 through mainly SNB rocks for ~20 mi to the entrance of Sequoia-Kings Canyon National Park. After entering the Park we continue ~21 mi to Stop 1-4. After ~10 mi we begin to drop into the Kings Canyon area. Note the large open valley of the Kings River, and as we descend into the canyon how it is accented by a steep inner slot. Incision of the inner slot reflects headward erosion from a new base level established at ~3.5 Ma in conjunction with delamination-related rock uplift. Our first stop in the Boyden Cave pendant of Kings Canyon (Fig. 6) is at a spectacular road cut located above Horseshoe Bend on the Kings River.

*Stop 1-4:* The Horseshoe Bend area offers three dimensional exposures through a massive quartzite unit that is interpreted to be correlative to the Neoproterozoic Sterling Quartzite of the Death Valley region passive margin sequence (Saleeby and Busby, 1993). Detrital zircon U/Pb geochronological studies are in progress in order to test this lithologic correlation, in that fossils have yet to be recovered. Compositionally the rock is a uniform feldspathic quartz arenite. Bedding in the Boyden Cave pendant is transposed into a vertical orientation with thicker bedding remnants arranged as intercalated lenticals. Metamorphism and deformation have masked primary structures and textures in the quartzite. Spaced biotite lamina are pervasive, and are commonly debated on the outcrop to be of primary cross-bedding versus a metamorphic solution and/or slip cleavage origin. The steep shape fabric that pervades the quartzite also pervades the entire pendant and represents vertical stretch of the pendant under peak metamorphic conditions, developed as the neighboring plutons of the SNB were emplaced. Such syn-batholithic ductile deformation is common in pendants of the axial SNB, and is thought to have arisen by downward directed return flow of the pendants that was dynamically linked to the rapid ascent of large volume felsic magmas (Saleeby, 1990; Saleeby et al., 2003). The “Sterling Quartzite” of the Boyden Cave pendant has a structural thickness of ~1000 m. This slightly exceeds the maximum stratigraphic thickness of the Sterling Quartzite in the Death Valley (Stewart, 1970). This implies some component of structural thickening, or repetition before syn-batholithic vertical transposition and attenuation by vertical stretch, for such stretch would appreciably thin the section in the pendant during deformation. In the Death Valley region the Sterling Quartzite is depositionally overlain by interbedded quartzite, shale, siltstone and subordinate limestone of the Wood Canyon Formation.



RECONSTRUCTED STRATIGRAPHY
(Pre-Cretaceous)
top of section unknown
Volcaniclastic channel sands
Lower Jurassic calcareous quartz sand-silt turbidites
Early Jurassic marine fossil
Early Jurassic marine fossil
Lower Jurassic pebble-boulder mudstone with slide blocks
Early Jurassic marine fossil
Triassic (?) shallow water limestone
slide dislocation, slipped unconformity or fault
quartzite sliver (Sterling or Zabriskie?)
Neoproterozoic Wood Cyn. Fm (?) pelite-psamite-marble lenses
fault or slipped unconformity
Neoproterozoic Sterling Quartzite
~ 500 m
base of section unknown
7 DAY ONE FIELD STOPS
LITHOLOGIC UNITS
Nondifferentiated Late Cretaceous SN batholith
Mid-Cretaceous granitic sills
Mid. Cretaceous metavolcanic and hypabyssal rocks
Lower Jurassic turbidites
Lower Jurassic pebble-boulder mudstone and slide blocks
Triassic? marble
Neoproterozoic Wood Cyn. Fm with marble lenses
Neoproterozoic Sterling quartzite
Mixed schists (age unknown)
Syn-SNB penetrative flattening fabric with vertical stretch
m.Fork Kings River
s.Fork Kings River
Monarch Divide
36° 50' N
118° 50' W
180
4
5
6
7
0
1
2
3 km


Figure 6

**Figure 6. Generalized geologic map of the Boyden Cave metamorphic pendant that shows day one field trip stop locations. To the right of the map a diagrammatic columnar section is shown for Paleozoic and lower Mesozoic parts of the pendant. The yellow tone units represent a mid-Cretaceous volcanic accumulation and intrusive sill sequence that was constructed across the lower Mesozoic part of the section. Subsequent SNB plutonism tilted and deformed the entire pendant section that was displaced and strained downwards during the ascent of high-volume granitic magma pulses shown now as nondifferentiated SNB.**

Driving eastwards from Horseshoe Bend the Sterling Quartzite is in a deformed mixed gradational contact with an ~500 m thick banded pelite, psammite and subordinate marble unit that is interpreted to be metamorphosed Wood Canyon Formation (Fig. 6). After ~1.4 mi we reach a thick marble within which Boyden Cave is developed. We park at the cave touring parking lot. Time will not permit us to tour the caves, but it is a highly desirable experience if one has time to return to the area. In addition to the great natural beauty that the cave has to offer, its tremendous vertical extent in Kings Canyon has offered an important opportunity to use cosmogenic dating techniques on various levels of cave deposits as a means of quantifying incision rates of the Kings River (Stock et al., 2004). These workers resolved an acceleration of river incision to as high as 0.2 mm/yr starting at ca. 2.7 Ma, which corresponds to the cutting of the steep inner slot of Kings Canyon. These erosion rates slowed to ~0.03 mm/yr at ca. 1.5 Ma. Tomorrow we will discuss parallel synchronous accelerated subsidence in the Tulare sub-basin immediately to the west, with both the uplift and subsidence reflecting epeirogenic deformation related to ongoing mantle lithosphere delamination.

*Stop 1-5:* This stop entails an ~200 m walk originating in the Boyden Cave parking lot, crossing the Kings River bridge and then proceeding eastwards along SH 180. We start in the marble unit that lies in discordant contact above the Wood Canyon Formation. The favored interpretation for this contact is that it is a profound angular unconformity with remnants of the Neoproterozoic Death Valley section below, and Triassic (?) limestone, now metamorphosed to marble, above (Saleeby and Busby, 1993). This interpretation has not been confirmed by faunal data, the only fossils yet recovered from the marble are poorly preserved sponge-like bodies that are not age diagnostic. Nevertheless, angular unconformable relations between Triassic carbonates and deformed lower Paleozoic passive margin are widespread in metamorphic rocks of the Sierra Nevada, and in regions to the east (Saleeby and Busby, 1993). The actual contact in the Boyden Cave pendant is difficult to observe, and where exposed it has been deformed by the vertical stretch fabric obscuring its finer details. As displayed in the Boyden Cave parking lot the marble possesses a steep banding between light grey and more graphite rich darker grey layers, and local lamina of calc-silicate mineral clusters. As we pass over the bridge we will cross the poorly exposed contact with Lower Jurassic argillite and metamorphosed pebble-boulder mudstone. We will first observe an ~10 m diameter carbonaceous limestone (marble) boulder within a dark argillite matrix. As we progress along the road cuts we will cast our views southwards across the river and see an array of quartzite cobbles and boulders that range up to 2 m in diameter within the argillite matrix. Continuing along the road we will observe an outcrop along the north side of the highway that is characterized by numerous deformed cobbles and bedding fragments of quartzite and metavolcanic rock within the argillite. The cobbles exhibit the same steep stretch fabric that pervades the pendant. Matrix materials only faintly exhibit the deformation fabric, with finely annealed fabrics dominating and reflecting the final stages of contact metamorphism through the hot sub-solidus regime of the adjacent plutons. We have extracted an Early Jurassic ammonite from the argillite matrix materials along the south side of the river, in this area (Saleeby and Busby, 1993), and additional Early Jurassic ammonites and bivalves were extracted from argillite matrix material from ~150 m up section from the end of our road traverse, and in turbidite interbeds near our next stop (Moore and Dodge, 1962; Jones and Moore, 1973). The preservation of virtually non-deformed fossils in the matrix materials, the form of clast clusters and bedded remnants within argillite matrix materials, and a lack of definitive tectonic deformational fabrics that predate the development of the high temperature vertical stretch fabric lead us to interpret the pebble boulder argillite unit as one or more olistostromes, or large-scale submarine debris flows. Olistostromes represent one class of melange, having formed under soft sediment gravity sliding conditions. We will further discuss melanges when we return to the western Foothills on day two.

After returning to the vehicles we continue ~0.5 mi eastwards on SH 180 where we will carefully park on the opposite side of the highway, where the only pullouts are for some distance along the highway in this area. We will then walk back to the west ~100 m where we will observe spectacular structures in a cliff face along the north side of the highway.

*Stop 1-6:* This stop entails observations of the cliff face and outcrops along the road in rocks that we interpret as a large (~50 m-scale) intact slide block of metamorphosed well-bedded calcareous quartz sandstone. The interior of the block is deformed by a series of upright Chevron folds whose axial planes coincide with the vertical stretch fabric that pervades the pendant. The bedding structure that is cut by the Chevron folds was partially disrupted prior to folding with possible earlier recumbent fold remnants present. Disruption occurred in the ductile regime, but with no hint remaining of a solid state deformation fabric. The quartzite beds along the margin of the block become progressively disrupted as they pass into the hosting laminated quartzite-argillite matrix of the bedded block. The interior of the folded block is cut by a recrystallized vertical dike that has a mineralogical and chemical composition suggesting that it was derived from a silty argillite protolith. If this is correct then this intrusion represents an early stage clastic dike derived from the hosting argillite matrix. We interpret the large folded block as a semi-intact slide block that was deformed and transported en masse within the Lower Jurassic olistostrome sequence. Bedding in the interior of the block was disrupted and possibly involved in recumbent folding during transport in a semi- to non-lithified state. The margins of the block were highly disrupted and transposed into the soft sediment flow fabric of the argillite matrix. The block was cut by one or more clastic dikes that were derived from the matrix during or shortly after transport. The block was rotated into an orientation such that upon the imposing of the superposed vertical stretch fabric the beds were end loaded leading to the Chevron fold set. The disrupted margins of the block and its transposition zone into the matrix continued to flow along the existing transposition fabric while the block bedding was folded, both in a common strain field during the imposing of the high temperature vertical stretch fabric.

As we return to the vehicles we can review the structural relations along the east margin of the folded block where the argillite matrix is pervaded by a myriad of thin quartzite lamina. Proceeding eastwards in our vehicles one may note that the quartzite layering in the argillite becomes more orderly eastwards until we pass into a well-bedded coherent section (Fig. 6). This is a section of quartz rich turbidites that was either laid down depositionally above the olistostrome sequence, or conceivably rode atop the olistostromes as a huge slide block. If such were the case the slide block would be of ≥5 km scale. Evaluation of this possibility is inhibited by truncation of the

Boyden Cave section by the hosting SNB (Fig. 6). Exposure limitations of the pendant and finite strain related to the vertical stretch inhibit a full evaluation of these two possibilities. Our final stop for the day is in the turbidite section ~0.7 mi east of Stop 1-6. We again park along the north side of the highway and traverse back to the outcrops along the north side of the highway.

*Stop 1-7:* At this stop we observe some primary features in the turbidite section. Jurassic turbidite sections are common as unconformable remnants and tight infolds above various Paleozoic pendant rocks, including the Foothills ophiolite belt, throughout the Sierra Nevada (cf. Saleeby and Busby, 1993; Saleeby, 2010). Careful examination of the Boyden Cave pendant turbidites along the north side of the highway reveals remnants of grading, convolute bedding and flame structures, all of which yield east-facing directions. Grading is quite common, although obscure. It is preserved primarily as modal variations in mafic minerals versus quartz in that primary textures are completely overprinted by contact metamorphism, and protolith bulk compositions at millimeter-scale are controlled by the detrital grain sorting mechanism. After ~150 m of traversing westwards we will encounter what appears to be a low amplitude internal angular unconformity within the turbidites. If this is indeed a primary structure, and not a highly planar thin fault, a similar facing direction may be derived for the turbidites as determined earlier. After examining this structure we return to the vehicles and drive back to Fresno along SH 180.

**Day Two**

Day Two blends a more eclectic mixture of geologic features in our observations. We depart the Fresno area by driving south on SH 99 ~40 mi, and then turning off eastwards onto SH 198 towards the south entrance of Sequoia National Park (Fig. 1). After ~10 mi the Sierran Foothills will come into view. The first part of Day Two activities will entail mainly landscape viewing. As we approach the Foothills you will see that there is not a well-defined range front, but instead a series of mainly steep sided hills sticking out of the fluvial plain built by the Kaweah River. These hills represent inselbergs, or the tops of mountains protruding out of the surface of a buried mountainous topography. This is the only region of the entire western Sierra Nevada Foothills where such a distinct landscape occurs. Excess subsidence along the eastern edge of the Great Valley has resulted in this anomalous landscape, due to viscous downward drag imposed by the delamination of the underlying mantle lithosphere (Fig. 4)(Saleeby and Foster, 2004). This anomalous subsidence began in the late Pliocene and has characterized much of the Quaternary, although over the past ~0.6 Ma it has slowed markedly. Thus the anomalous subsidence of this area corresponds in time to the rapid uplift pulse that Stock et al., (2004) have resolved for the southern Sierra Nevada. Following Stop 2-1 we will drive for ~30 mi southwards along this distinct segment of the Foothills before the geomorphology changes appreciably. After ~16 mi eastwards on SH 198 we turn southwards onto SH 65 and at ~2 mi enter the town of Exeter, and turn east onto Rocky Hill Drive. We proceed ~2.5 mi eastwards, and then park adjacent to a locked gate in a sharp northward turn in the road. Unfortunately we can no longer access the outcrops that are slightly uphill from the locked gate, but we can make some useful observations from our parking spot.

*Stop 2-1:* Visibility permitting, this is a good location to view part of the region of Inselberg landscape, as it extends off to the northwest. Inselbergs show up clearly in the DEM of Figure 1, north and east of Visalia. We can also observe the distinct grassy slopes and scattered outcrops of the Kaweah serpentinite melange. Finally, we can observe a distinct contact between the melange and the 120 Ma Rocky Hill granodiorite stock to the south (Fig. 3). This stock is ~2 km in diameter and composed of a fairly mafic hornblende-biotite granodiorite. In spite of its "grantitic" composition, isotopically it is primitive, being derived from a depleted mantle source like most other western SNB rocks. In terms of major element composition it appears to have fractionated off of a fundamentally gabbroic to dioritic parental magma system, like many of the 125-115 Ma intrusives of this region of the Foothills (Saleeby and Sharp, 1980; Clemens-Knott and Saleeby, 1999).

After these brief observations we will return to SH 65 and proceed southwards towards the town of Porterville. As we drive we can observe miles of distinct melange landscape to the east characterized by grassy slopes and various sharp outcrops. The slopes are underlain by serpentinite matrix materials and the sharp outcrops are melange blocks composed of serpentinized peridotite, gabbro, basalt, chert and ophicalcite (carbonate cemented serpentine breccias) (Saleeby, 1999). The distinct landscape pattern that the melange makes is accented by small granodioritic to tonalitic stocks that are the same age and of similar composition as the Rocky Hill Stock. We drive ~13.5 mi south out of Exeter on SH 65 to Strathmore where we turn east on County Road J28. After ~3.4 mi we turn southwards onto Road 256 and climb ~3 mi up to a saddle area in the Foothills, and stop along a road cut through the melange (Figs. 1 and 3).

*Stop 2-2:* We will make most of our observations along the south side road cut. Here we see a typical cut through the vertically foliated serpentinite matrix of the melange. We will observe several different varieties of metachert blocks, one of which is characterized by Fe-Mn lamina, and another that has been deformed into a blastomylonitic banded metaquartzite. Focus at this stop is on a 10-20 m thick massive metabasalt block that crops out along the south side of the road. Close attention to the margins of the block show that it is partially armored by a basalt-serpentine-mafic arenite. Attention will also focus on nearby matrix materials that possess textures and fabrics suggestive of a detrital origin, now highly obscured by deformation and metamorphism. Detailed mapping of the melange (Saleeby, 1978, 1979, 2010) reveals three distinct melange mixing mechanisms: 1. High shear strain under an overburden with the influx of sea water such that mylonitic peridotites, akin to those observed at Stop 1-1, texturally grade into serpentinite schists, typically antigorite±talc, that entrain blocks of ocean floor crustal rocks that are typically highly tectonitic; 2. diapiric emplacement of serpentinite dikes and stock-like bodies into mafic crustal rocks and their progressive disruption into melange; and 3. diapiric surfacing of serpentinite on the sea floor, and then massive down slope movement and olistotromal formation of melange. All three of these mechanisms are recognized as important tectonic processes along major oceanic fracture zones and spreading ridge-transform intersections (Bonatti and Honnorez, 1971; Bonatti et al., 1971; 1973; 1974; Fox et al., 1976). Detailed mapping and structural analysis of the marginal relations of the Kings River ophiolite slabs, and the Kaweah serpentinite melange indicates that the detrital-olistostromal mechanism was non-trivial in the case of the Kaweah melange.

From Stop 2-2 we continue southwards ~3 mi to SH 190 in Porterville. We turn west and proceed ~1.8 mi to SH 65 and then go south. Within ~5 mi we will see the landscape changing by a subduing and then loss of inselbergs followed by a gradual southward rise in elevation as we climb up onto the highly dissected landscape of the Kern Arch (Figs. 1 and 7). Exposures are poor, even in road cuts, but regional mapping and subsurface data indicate that first we pass through the Quaternary Tulare Formation and then deeper into the marine upper Pliocene San Joaquin Formation (Klausing and Lohman, 1964; Saleeby and Saleeby, 2009). The Kern Arch is extensively faulted, and the drainage pattern resembles that of a trellis. Much of the surface consists of thick colluvium, which

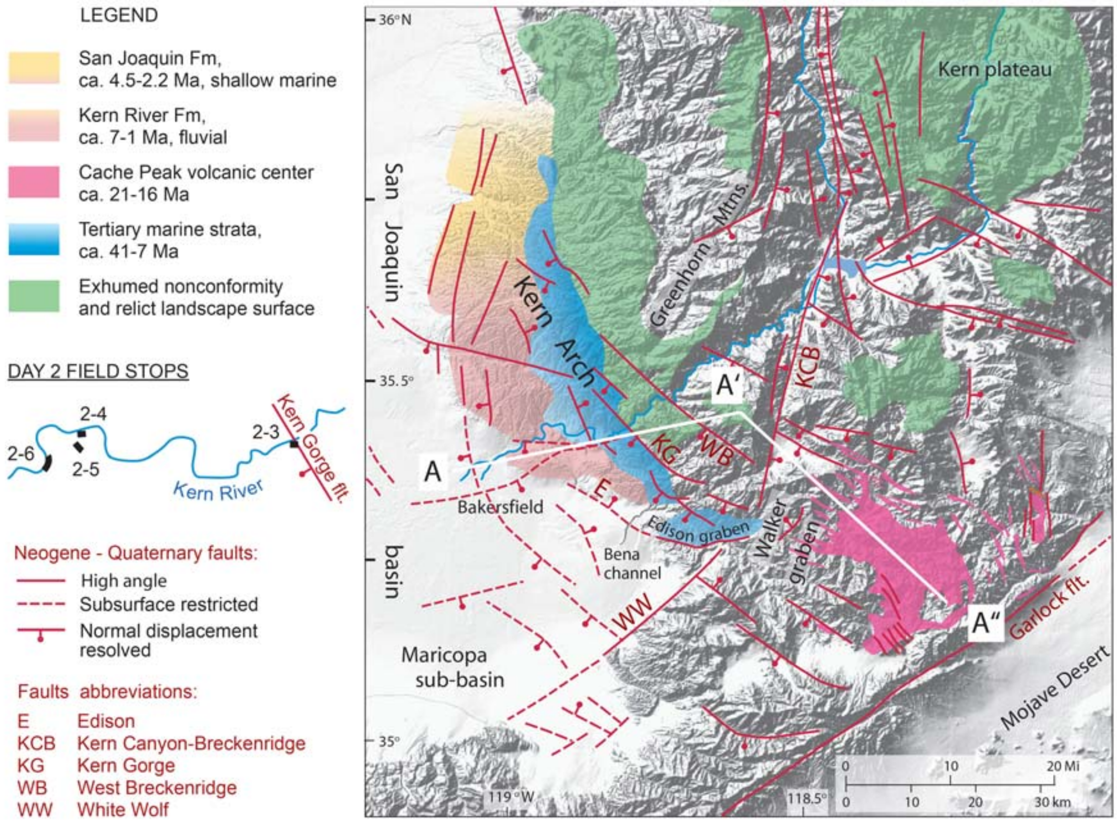



**Figure 7. Digital elevation model of the southern Sierra Nevada showing late Cenozoic faults and Tertiary strata undergoing incision across the Kern Arch, an actively growing topographic promontory extending from the western Sierra Nevada into the San Joaquin basin. Also shown is the Cache Peak volcanic center and the resolved extent of the low relief relict landscape surface that has formed a low relief surface across interfluves, that was inherited from a Late Cretaceous plateau surface that formed across the proto-Sierra Nevada region. Note the trace of the Figure 8 cross-section (A-A'-A"). Inset to the left center of the map shows the last four locations of Day Two field stops.**

strongly undermines surface mapping. Much of what we know about the Kern Arch comes from oil field subsurface data, and much of what we can report at this stage derives from one of ours (Z.S.) extensive experience working as a petroleum geologist in major oil fields of the Arch, as well as our ongoing, as of yet published research. Our interpretation of the Kern Arch is that it is the southwest continuation of a zone of Quaternary excess rock uplift and elevation increase, relative to all other areas of the Sierra Nevada microplate. This zone consists of the Great Western Divide of the upper Kings, Kaweah and Tule drainages, the Greenhorn-Breckenridge Mountains and the Kern Arch (Figs. 1 and 7).

At ~ 47 mi on SH 65 turn left at James Road. After ~3.3 mi James Road turns southwards and becomes N. Chester Avenue. After ~1 mi turn east on the China Grade Loop. At ~2.6 mi China Grade Loop makes a 90° right bend, crosses the Kern River and in ~0.8 mi meets Alfred Harrell Highway in a 90° bend. Turn east on Alfred Harrell Highway. Our last three stops are along Alfred Harrell Highway, but first we will proceed directly to Stop 2-3. As we pass ~2.2 to 2.7 mi along the highway you will see on the south side of the road the splendid exposures of Stop 2-6. Continue past these, for now. At 4.3 mi we enter Hart Park. Stay to the right on the highway. At ~10 mi Alfred Harrell Highway abuts SH 178. Turn left (east). As we proceed up SH 178 you will see the abrupt Sierran range front expressed here as the Kern Gorge fault. You will also see the lower Kern River Gorge dissected sharply through the footwall of the fault. Geomorphic studies of the lower Kern River Gorge show that it is unique among all western Sierra river canyons, having formed in the Quaternary (Figueroa and Knott, 2010). At ~4.4 mi on SH 178 we park on the right immediately adjacent to the Kern Gorge fault scarp (Fig. 7).

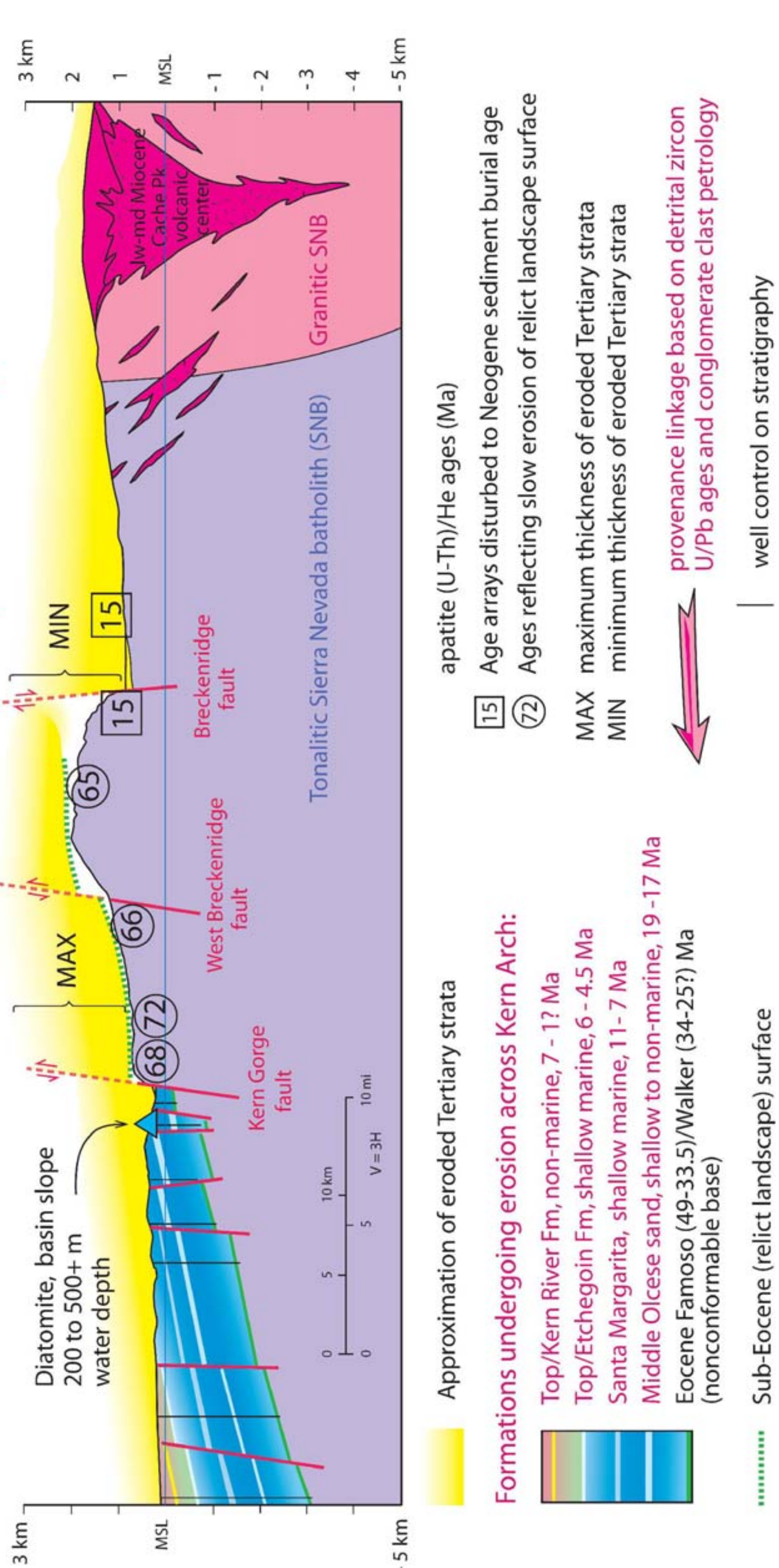
*Stop 2-3:* The Kern Gorge fault is a Quaternary normal fault with an approximate normal slip component of 600 m (Maheo et al., 2009). The fault exposes in its footwall ca. 105 Ma mafic tonalite that is deformed into a blastomylonite that formed in the Late Cretaceous at ca. 80 Ma. The fault follows the mylonitic fabric along much of its exposed length. The mylonite belt projects westwards into the subsurface in such a way as to suggest that it is continuous with the footwall of a major Late Cretaceous detachment system that underlies the Maricopa sub-basin (Figs. 1 and 7) of the southern San Joaquin basin (Saleeby et al., 2009). This is one of a number of southern Sierra region Late Cretaceous detachment faults that resulted in the rapid deep crustal exhumation of the southernmost SNB and Great Valley (Wood and Saleeby, 1998; Saleeby, 2003; Saleeby et al., 2007, 2009). Viewing the footwall along the north side of the Kern River Gorge one can see a penetrative fracture set paralleling both the fault and the mylonitic fabric. Many of these fractures have small normal displacements along them, which is typical of penetrative fracture sets that are proximal to many members of the southern Sierra Nevada fault system that is shown in Figure 7. The footwall of the Kern Gorge fault has a distinct flat-topped geomorphology with its interfluves deeply weathered and in many places covered by a thin mantle of tonalitic grus. Such is the character of the relict landscape surface that was eroded slowly above the SNB through Cenozoic time (Clark et al., 2005; Maheo et al., 2009). The relict landscape surface is further resolved regionally by ca. 70 apatite He ages as shown in Figure 7. Study of the DEMs in Figures 1 and 7 reveal broad meanders in the lower Kern Gorge, despite its steep entrenchment into basement. This meander form mimics the meanders of the lower coarse of the river where it is incising into the Tertiary section. We interpret this as a sign of the lower Kern Gorge representing an antecedent drainage.

The surface of the Kern Gorge fault footwall maps into continuity with the basal nonconformity of the eastern San Joaquin basin Tertiary section. This is readily visualized in Figure 7 where the nonconformity remains intact in relay ramps to the north of the Kern Gorge area between en echelon segments of the range front normal fault system. This relationship is profound in that middle Miocene diatomite that was deposited at bathyal water depths is exposed along SH 178 just 2 km from the Kern Gorge fault, and it occurs in the subsurface juxtaposed against the fault (Fig. 8). In that a considerable portion of the Neogene section consists of fine-grained marine strata, it follows that Neogene marine conditions extended eastwards for a nontrivial distance across the footwall of the Kern Gorge fault (Maheo et al., 2009; Saleeby and Saleeby, 2010). Considering that the apatite He ages determined on the footwall surface conform to those typical of the relict landscape surface (Clark et al, 2005; Maheo et al., 2009), and considering geothermal gradients that are typical of the region, such sediment overburden on the footwall could not have exceeded ~2 km (Maheo et al., 2009). In contrast, the region east of the Kern Canyon-Breckenridge fault has been dropped down by Quaternary normal faulting forming a graben (Walker graben) within which much of the 21-16 Ma Cache Peak volcanic center was ponded (Figs. 7 and 8). This resulted in the accumulation of a >2 km thick Neogene section, and accordingly the apatite He ages of the basement surface were reset to middle Miocene ages by thermal blanketing.

As we view the landscape to the west we see the dissection pattern of the Tertiary section of the Kern Arch. We can also see normal fault offsets in strath terraces of the hanging wall. One should visualize the Tertiary section as extending eastwards, over our heads, and thinning eastwards across the uplifted block between the Kern Gorge and Kern Canyon-Breckenridge faults. We define the uplifted block as the Breckenridge-Greenhorn horst (Figs. 7 and 8). The tilting and incision of upper Pliocene strata off the west and north flank of the Arch signal its rise in the Quaternary (Saleeby et al. 2009), consistent with the Quaternary age of the Kern Gorge fault, and active normal displacements along the Kern Canyon-Breckenridge fault (Nadin and Saleeby, 2010). Furthermore a permanent GPS station situated on top of the relict landscape surface of the footwall yields a staggering vertical uplift rate of 2.3 mm/yr (Nadin and Saleeby, 2010). Holocene offsets along the Kern Gorge fault have not been resolved, but such has been resolved along the same structural zone to the northeast along the lower slopes of the Kern Arch (Guacci et al., 1978). The Kern Arch has long been recognized as being extensively cut by late Cenozoic high-angle faults, and such faults form important petroleum trap structures in strata as young as Pliocene-early Quaternary (Nugent, 1929; Z. Saleeby, proprietary industrial data). We now backtrack to our final three stops moving through the Neogene stratigraphy of the Kern Arch. We go back ~4.4 mi and turn north on Alfred Harrell Highway, and then proceed ~5.2 mi and park along the north side of the road at Hart Park. We briefly examine road cut exposures along the south side of the road.

*Stop 2-4:* This road cut displays the diatomite facies of the middle Miocene Round Mountain Silt, an extensive marine unit along the southeast San Joaquin basin. Formation of diatomite is restricted to suboxic and anoxic conditions below a well-developed oxygen minimum layer, at upper bathyal water depths of ≥200 m (Ingle, 1975), and shielded from heavy terrigenous influx (Calvert, 1974). The diatoms of this facies indicate an open ocean environment and are estimated to be 16-15 Ma in age (Olson, 1988). Sediments of this facies were deposited on the basin slope, and seismic lines reveal the presence of an E-W trending shelf edge to the north of this exposure (Bloch, 1991). The trend of this shelf and the abundance of deep water diatom and foraminiferal species (Bandy and Arnal, 1969) indicates that the geometry of middle Miocene basin differed considerably from that of the present day southeast San Joaquin basin. This shelf trends at high angles to the current western Sierra range front further indicating that Neogene marine conditions extended for a non-trivial distance across, what is now, the western Sierra basement uplift.

The Round Mountain silt is overlain by the locally unconformable Santa Margarita Formation, an extensive upper Miocene shallow water plutoniclastic sand sheet. This sand sheet extends obliquely across the prior E-W shelf break along a NW-SE shoreline trend. We interpret this sand sheet, and its NW-SE trend as reflecting regional west tilting, basement rock uplift and river incision resulting from the ca. 10 Ma initiation of the Sierra Nevada microplate. Facies trends in the San Joaquin basin changed again in the mid-Pliocene with a marine embayment extending across the position of the future Tulare sub-basin and extending southwards across the Kern Arch and Maricopa sub-basin. Deposition of the generally fine-grained upper Pliocene San Joaquin Formation followed. We interpret these changes as reflecting the onset of epeirogenic transients related to underlying mantle lithosphere delamination



A
A′
A″
Kern Arch
Breckenridge - Greenhorn horst
Walker graben
provenance linkage
Diatomite, basin slope 200 to 500+ m water depth
MAX
MIN
68
72
66
65
15
15
Kern Gorge fault
West Breckenridge fault
Breckenridge fault
lw-md Miocene Cache Pk volcanic center
Tonalitic Sierra Nevada batholith (SNB)
Granitic SNB
3 km
MSL
- 5 km
2
1
- 1
- 2
- 3
- 4
0 5 10 km
0 5 10 mi
V = 3H
Approximation of eroded Tertiary strata
Formations undergoing erosion across Kern Arch:
Top/Kern River Fm, non-marine, 7 - 1? Ma
Top/Etchegoin Fm, shallow marine, 6 - 4.5 Ma
Santa Margarita, shallow marine, 11- 7 Ma
Middle Olcese sand, shallow to non-marine, 19 -17 Ma
Eocene Famoso (49-33.5)/Walker (34-25?) Ma (nonconformable base)
Sub-Eocene (relict landscape) surface
apatite (U-Th)/He ages (Ma)
Age arrays disturbed to Neogene sediment burial age
Ages reflecting slow erosion of relict landscape surface
MAX maximum thickness of eroded Tertiary strata
MIN minimum thickness of eroded Tertiary strata
provenance linkage based on detrital zircon U/Pb ages and conglomerate clast petrology
well control on stratigraphy


**Figure 8**

**Figure 8. Cross-section across the Kern Arch and adjacent Sierra Nevada based on oil well data and Figure 7 structures. Yellow tone depicts approximate thickness of Tertiary strata eroded off of arch, as well as maximum and minimum thicknesses eroded off adjacent Sierran basement based on apatite He age relations. The large red and pink arrow depicts the provenance linkage between the eastern Sierra Nevada granitic basement and Cache Peak volcanic center for Neogene strata deposited in eastern San Joaquin basin. Detritus derived from tonalitic western SNB is absent from such strata consistent with the western SNB having been covered with a sediment blanket in the Neogene. The deep marine diatomite section that is situated immediately adjacent to the Sierra range front of this region underscores the fact that marine conditions extended across the western Sierra of this region in the Neogene.**

(Saleeby and Foster, 2003; Saleeby et al., 2009). During the latest Miocene to early Pliocene paleogeographic transition, and extending into the early Quaternary, an extensive deltaic-fluvial plain system prograded northwestwards from the area of the Bena channel and Edison graben (Fig. 7) building the extensive sand sheet of the Kern River Formation, the subject of our last two stops. We continue driving west on Alfred Harrell Highway ~0.2 mi and then turn left on a small unpaved road just prior to the Kern County Sherriff's Department Shooting Range. We proceed ~0.1 mi and then park at the confluence of two small side gullies.

*Stop 2-5:* Exposures along the spur lying between the two side gullies consist of fluvial sandstone of the Kern River Formation that is similar to channel sandstones of our last stop. Our focus here is on exposures of overlying conglomeratic layers exposed a short distance up the eastern side canyon. Clasts of the Kern River Formation conglomerates are dominated by eastern SNB and northern Mojave Desert granitoids and Neogene andesitic and dacitic volcanic rocks of the Cache Peak volcanic center (Figs. 7 and 8). Notably absent are western SNB-type tonalites, such as those that form bedrock for the lower Kern River Gorge. Some Neogene volcanic clasts range up to meter-scale boulders. These are unlikely to have been transported by fluvial mechanisms alone from the Cache Peak center. However, in upper Miocene to lower Pliocene strata exposed to the east of the Bena Channel within the Edison graben (Fig. 7) we have discovered thick mudflow deposits that carry such boulders. The only such mudflows yet discovered are exposed in the dissected strata of the Edison graben. We therefore tentatively interpret the delivery of the boulders into the southeast San Joaquin basin by mudflows originating at the Cache Peak volcanic center that was ponded within the Walker graben. It appears that the Edison graben formed a structural trough through the west wall of the larger Walker graben (Maheo et al., 2009), and that the mudflows were channeled through this trough. The great lateral extent that the boulders are dispersed over suggests an extensive run out apron for the mudflows. Subsequent fluvial processes have winnowed most of the mudflows leaving the boulders suspended in fluvial sands. The copious eastern SNB cobbles and Cache Peak volcanic cobbles and boulders of the Kern River Formation, as well as the lack of western SNB detritus underscores the fact that much of the western Sierra in this region lay beneath a blanket of eastern San Joaquin basin strata, and that the lower Kern River Gorge formed in the Quaternary. A final note at this location: Near the transition between the fluvial sandstone layers and the conglomeratic layers there lies an ~1-2 m thick volcanic ash. Laser ablation ICP-MS U/Pb ages on zircon microphenocrysts are in progress for this and other ash layers of the region, in hopes of better resolving stratigraphic and temporal relations.

Returning to Alfred Harrell Highway we continue west ~2 mi, leaving Hart Park, and park along the north side of the Highway. Here we examine the excellent road cuts along the south side of the highway. Care must be taken in crossing the Highway, and in not wondering off the curbside, for vehicles move rapidly along this stretch of the highway.

*Stop 2-6:* These exposures constitute the informal type area for the Kern River Formation. Lithofacies of the Formation include crudely bedded coarse conglomerate and sands (Stop 2-5), large to medium scale trough cross-bedded sandstone with scoured bases, and finely laminated to massive siltstone and mudstone. The lower age of this formation has been poorly constrained based on the presence of Hemphillian fauna (Savage et al., 1954), which is considered to be late Miocene to early Pliocene. The age of 8.2 Ma was assigned to the base of Kern River Formation by Bartow and Pittman (1983), based on the similarity with Merthen fauna located ~ 200 miles to the north. These workers do not give a detailed justification for this age assignment. A cored ash layer from ~ 300 m above the base of the Formation in a well ~ 2 km north of Stop 2-6 has yielded a 6.15 ±0.05 Ma Ar/Ar age on sanidine phenocrysts (Baron et al., 2007). Projection of this low-dipping ash layer westwards and southwards, which is poorly constrained due to extensive faulting across the Kern Arch, suggests the ash sits in the lower portion of the Formation. An age of ca. 8.2 Ma for the base of the Formation is possible in that our detrital zircon U/Pb data and conglomerate clast studies link the Kern River Formation lithosome to sands and gravels of the upper part of the middle to upper Miocene Bena Formation that appears to have been localized within the Edison graben. An age of 8.2 Ma for the main lithosome seems unlikely in that the Kern River Formation lies above the shallow marine Santa Margarita Formation, which at least locally is as young as ca. 7 Ma (Goodman and Malin, 1992). We have adopted a ca. 7 Ma upper age limit for the main Kern River lithosome, but recognize that some lobes of the lithosome probably range back well into the late Miocene. The upper age limit of the Kern River Formation is poorly constrained. Our detrital zircon U/Pb and conglomerate clast studies show that the Pleistocene wall of the Bena channel (Fig. 7) constitutes the youngest recognized part of the lithosome. The Quaternary uplift of the Kern Arch, leading to dissection of the Kern River Formation, and the Quaternary incision of the lower Kern Gorge indicate a Pleistocene cessation to the delivery of the Kern River Formation lithosome.

Interpretations for the origin of the Kern River Formation are highly divergent. Earlier studies have generally interpreted Kern River Formation as a braided alluvial system with sediments delivered to the San Joaquin basin primarily through the lower Kern River Gorge (Nicholson, 1980; Miller, 1986; Kodl et al., 1990). This is at odds with a Quaternary origin for the Gorge. Our detrital zircon and clast provenance studies (Saleeby and Saleeby, 2010) clearly show a Walker graben-SE Sierra-northern Mojave provenance for channel sands and conglomerates of both the Kern River and upper Bena Formations, as well as the wall of the Bena channel. Based on these studies and field observations we consider Kern River Formation to have formed as a braided to meandering fluvial system, with dominant paleocurrent direction from the southeast, primarily through the Edison graben. Pliestocene sediments of the Bena channel wall represent the last voluminous detritus channeled through the Edison graben (Fig. 7). The late Miocene initiation of this massive sand+gravel/boulder sheet is interpreted as a result of accelerated west tilting and eastern margin uplift of the newly established Sierra Nevada microplate.

This concludes our field trip. We proceed back down Alfred Harrell Highway, retracing our earlier route, except it is suggested that as N. Chester turns west into James Road you continue west past the James Road northwest segment whereupon in ~3 mi you will pass SH 65, and then in another ~1 mi you will take SH 99 north ~100 mi back to Fresno.

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