28th Annual Fall Field *Frolic*

Department of Geological Sciences
California State University Northridge
August 19-21, 2010

Ductile shear zones of the southern Sierra Nevada:

Photos above from 2008 GEOL 310 field trip to map structures in the Kern Canyon shear zone

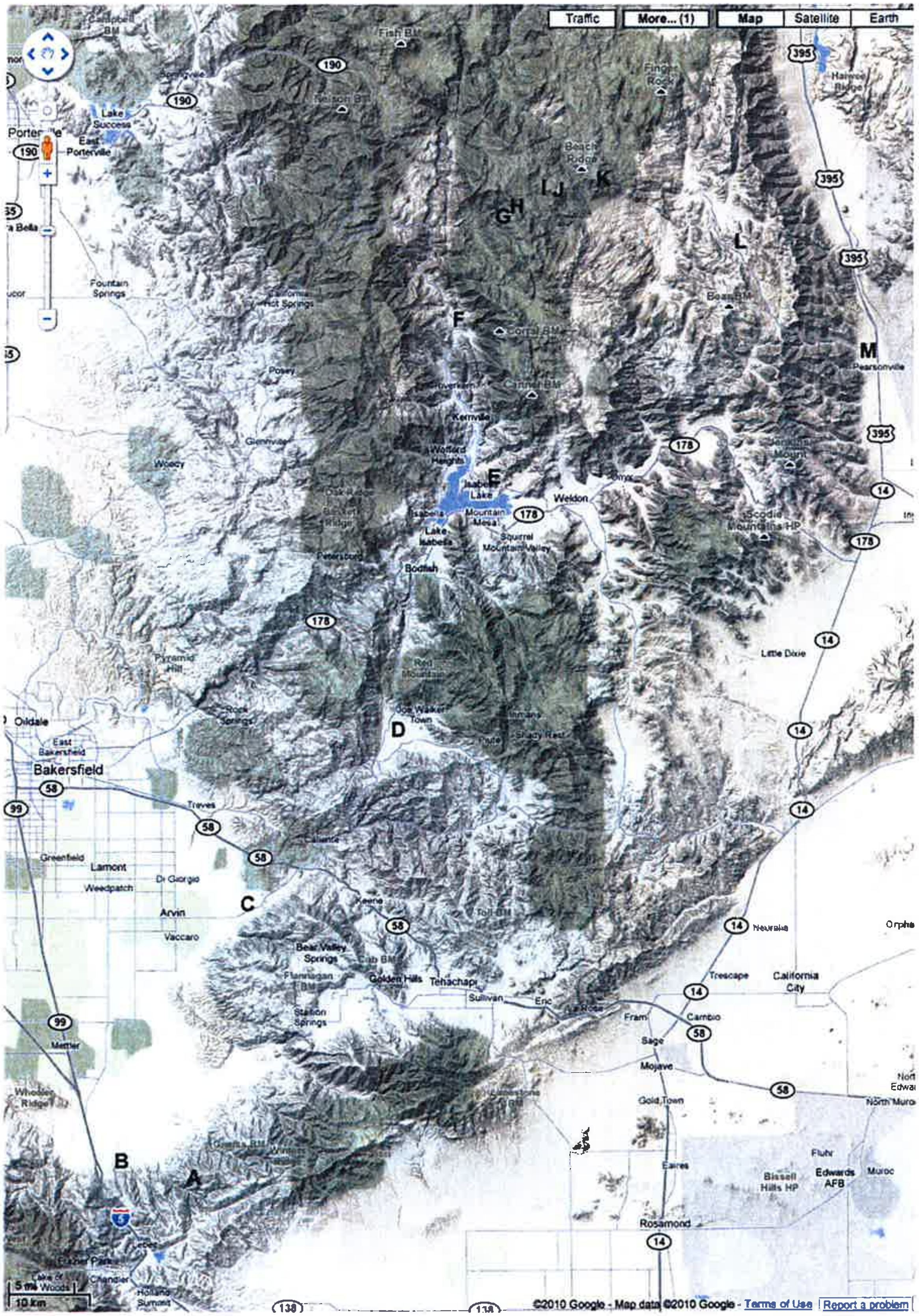
Itinerary highlights (letters keyed to road map on next page):

Thursday Aug. 19 – Lower crustal rocks of Tehachapi Mtns (A), Pleito thrust (B), White Wolf fault (C), Kern Canyon fault (D), roof pendant of L. Isabella (E), afternoon raft float trip on the upper Kern River. Camp along the Kern River (X).

Friday Aug. 20 – Rocks of proto-Kern Canyon fault zone (F), unusual conglomerate (G) and Alaskite of Sherman Pass (H), stratiform barite quarry (I), and gneisses of Dark Canyon shear zone (J). Camp at Troy Meadows Campground (Y).

Saturday Aug. 21 – More Kern plateau geology including stops at the Bald Mtn pendant (K), Kennedy pendant (L), and east base of Sierra Nevada (M).

Trip Leaders: D. Yule, D. Liggett, W. Behr, G. Dunne (in absentia)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Kernville
Wofford Heights
Isabella Lake
Lake Isabella
Mountain Mesa
Squirrel Mountain Valley
Bodfish
Onyx
Weldon
Pearsonville
Jenkins Mount
Scodie Mountains HP
Little Dixie
Peterson
Red Mountain
Pyramid Hill
Rock Springs
Oildale
East Bakersfield
Bakersfield
Treves
Greenfield
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Weedpatch
Di Giorgio
Arvin
Vaccaro
Caliente
Keene
Walker Town
Havilah
Shady Rest
Piute
Tollt BM
Bear Valley Springs
Cub BM
Flannagan BM
Golden Hills
Tehachapi
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Eric
La Rosa
Stallion Springs
Neuralia
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California City
Cambio
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Mojave
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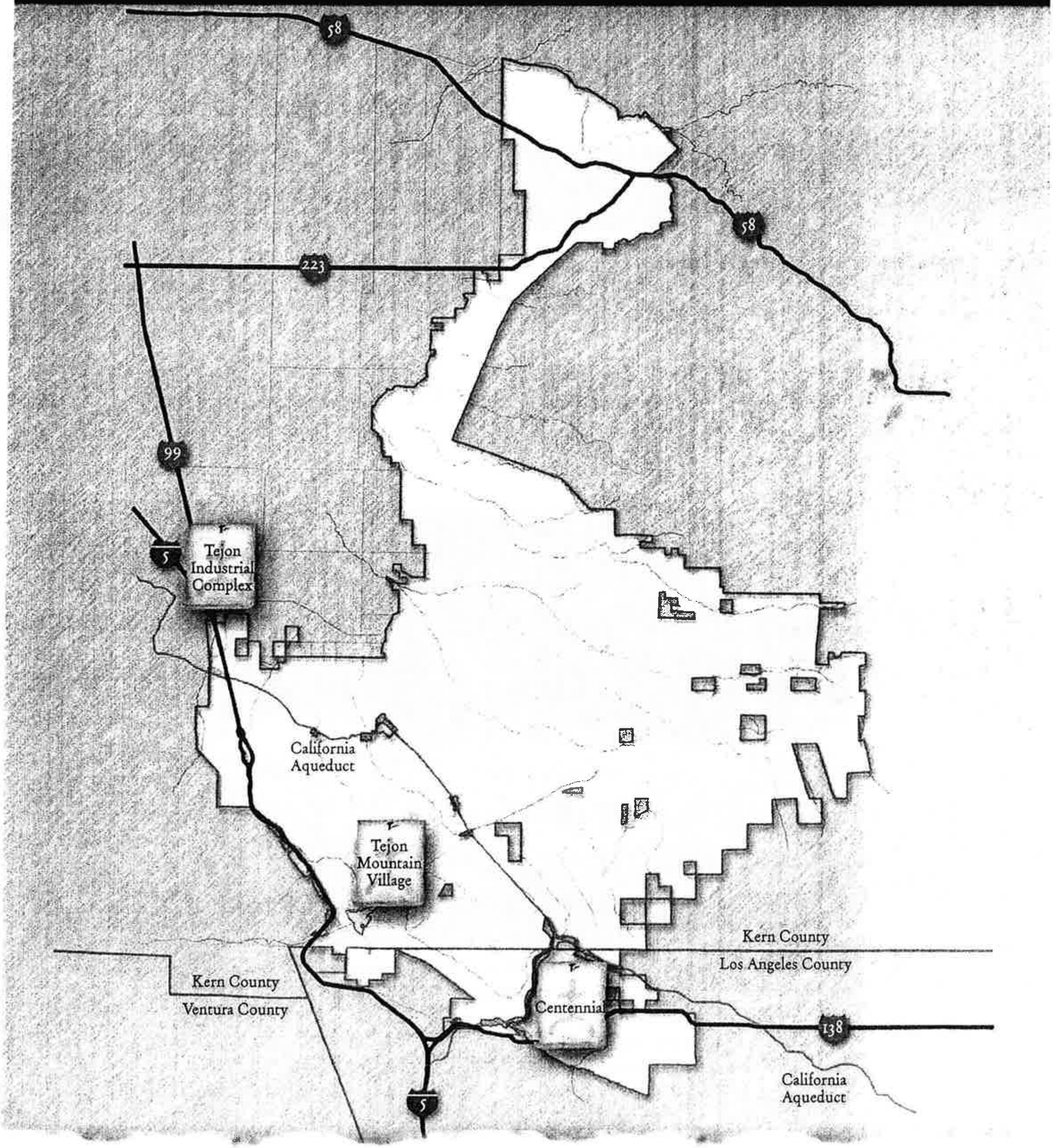

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Edmonston Pumping Plant

Name: EDMONSTON PUMPING PLANT
Category: WATER
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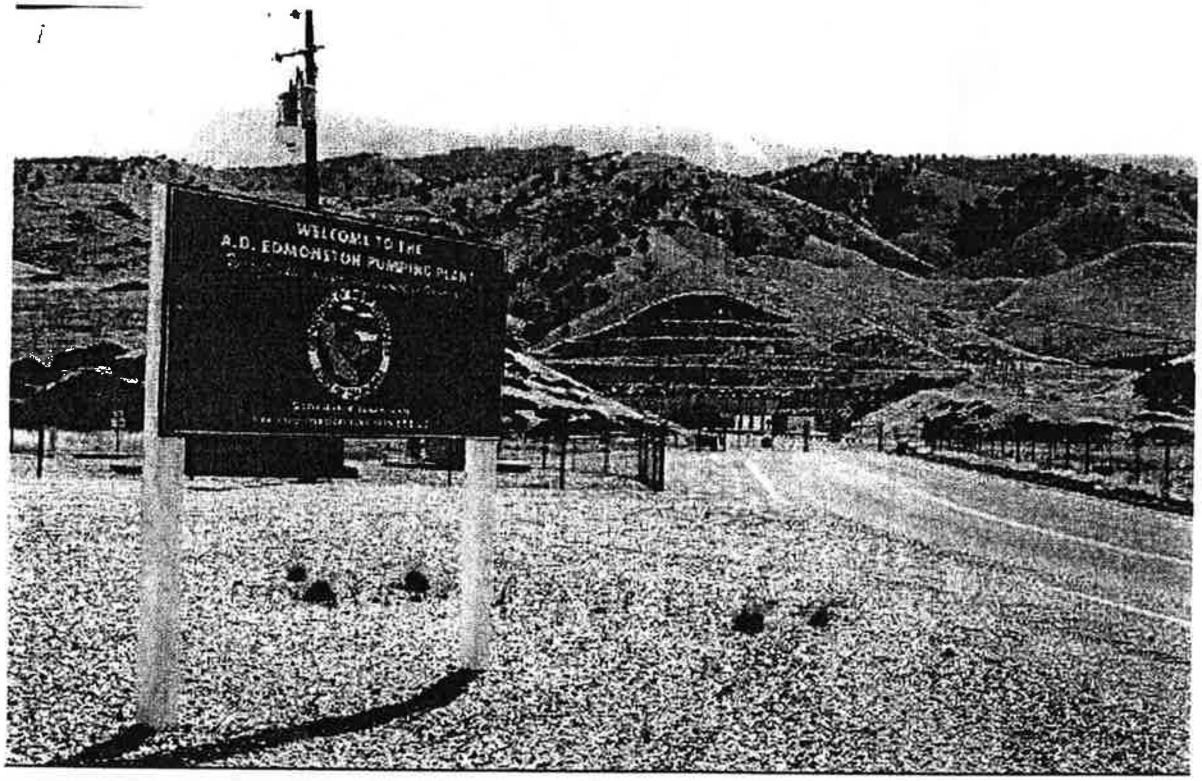

Description: The largest pumping station in the State Water Project, the plant raises the California Aqueduct's water 2,000 feet over the Tehachapi Mountains, after which it is all downhill to Los Angeles. The plant claims to lift water higher than anywhere else in the world. The California State Water Project is a network of dams, reservoirs, pumping stations, and 550 miles of canals and major conduits, that distribute water from Northern California to the agricultural industries of the San Joaquin Valley, and to the metropoli of Southern California.

Geological Society of America
Special Paper 419
2007

Thermal evolution and exhumation of deep-level batholithic exposures, southernmost Sierra Nevada, California

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United States Geological Survey, Menlo Park, California 94025, USA

ABSTRACT

The Tehachapi complex lies at the southern end of the Sierra Nevada batholith adjacent to the Neogene-Quaternary Garlock fault. The complex is composed principally of high-pressure (8–10 kbar) Cretaceous batholithic rocks, and it represents the deepest exposed levels of a continuous oblique crustal section through the southern Sierra Nevada batholith. Over the southern ~100 km of this section, structural/petrologic continuity and geochronological data indicate that ≥35 km of felsic to intermediate-composition crust was generated by copious arc magmatism primarily between 105 and 99 Ma. In the Tehachapi complex, these batholithic rocks intrude and are bounded to the west by similar-composition gneissic-textured high-pressure batholithic rocks emplaced at ca. 115–110 Ma. This lower crustal complex is bounded below by a regional thrust system, which in Late Cretaceous time tectonically eroded the underlying mantle lithosphere, and in series displaced and underplated the Rand Schist subduction assemblage by low-angle slip from the outboard Franciscan trench. Geophysical and mantle xenolith studies indicate that the remnants of this shallow subduction thrust descend northward through the crust and into the mantle, leaving the mantle lithosphere intact beneath the greater Sierra Nevada batholith. This north-dipping regional structure records an inflection in the Farallon plate, which was segmented into a shallow subduction trajectory to the south and a normal steeper trajectory to the north.

We combine new and published data from a broad spectrum of thermochronometers that together form a coherent data array constraining the thermal evolution of the complex. Integration of these data with published thermobarometric and petrogenetic data also constrains the tectonically driven decompression and exhumation history of the complex. The timing of arc magmatic construction of the complex, as denoted above, is resolved by a large body of U/Pb zircon ages. High-confidence thermochronometric data track a single retrogressing path commencing from widely established solidus conditions at ca. 100 Ma, and traversing through time-temperature space as follows: (1) Sm/Nd garnet ~770–680 °C at ca. 102–95 Ma, (2) U/Pb titanite

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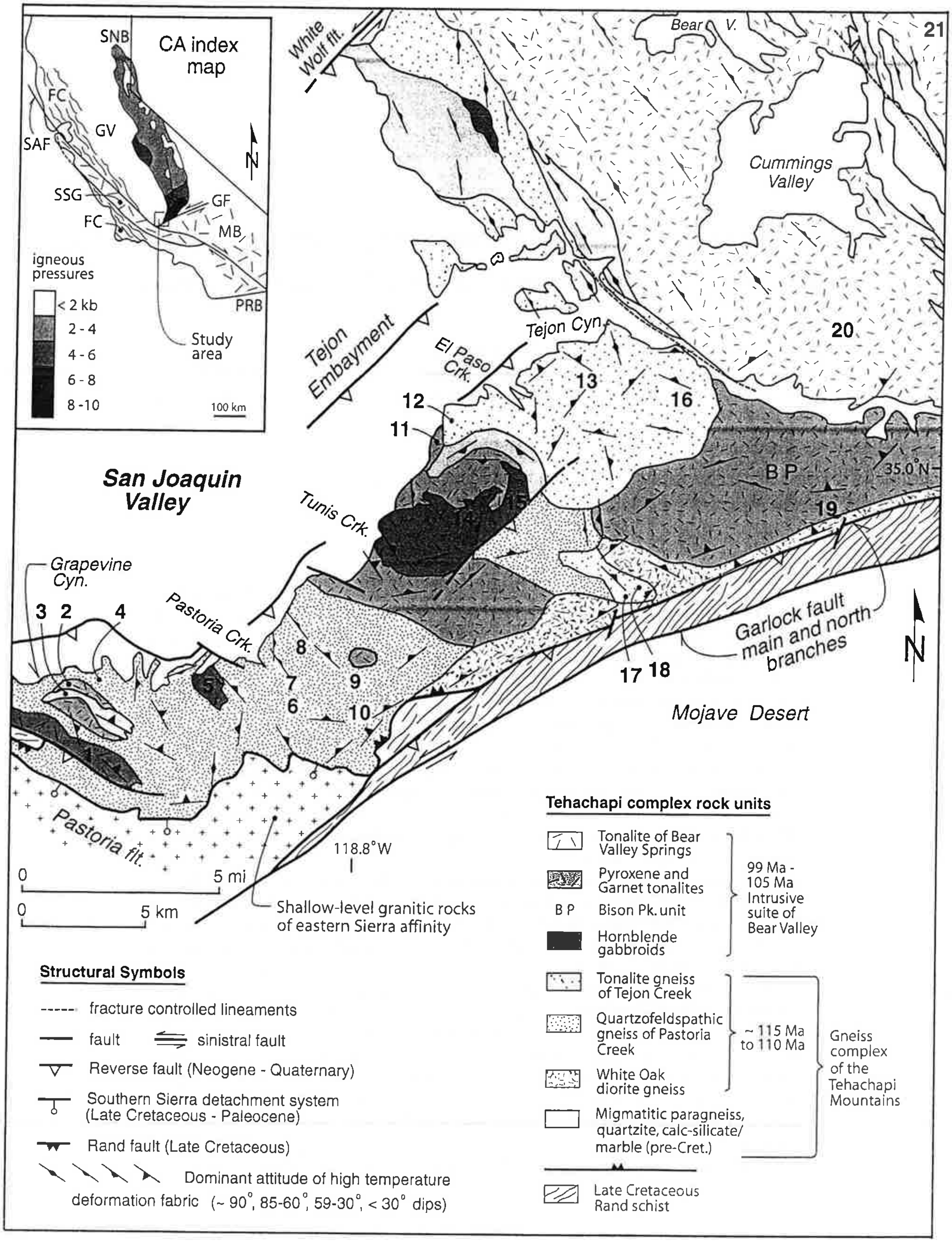
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Cummings Valley
Tejon Embayment
El Paso Crk.
Tejon Cyn
20
12
11
13
16
San Joaquin Valley
Tunis Crk.
15
B P
35.0°N
19
Grapevine Cyn.
3
2
4
Pastoria Crk.
5
8
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Garlock fault main and north branches
17
18
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Pastoria flt.
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Shallow-level granitic rocks of eastern Sierra affinity
Structural Symbols
fracture controlled lineaments
fault
sinistral fault
Reverse fault (Neogene - Quaternary)
Southern Sierra detachment system (Late Cretaceous - Paleocene)
Rand fault (Late Cretaceous)
Dominant attitude of high temperature deformation fabric (~ 90°, 85-60°, 59-30°, < 30° dips)
Tehachapi complex rock units
Tonalite of Bear Valley Springs
Pyroxene and Garnet tonalites
B P
Bison Pk. unit
Hornblende gabbroids
99 Ma - 105 Ma Intrusive suite of Bear Valley
Tonalite gneiss of Tejon Creek
Quartzofeldspathic gneiss of Pastoria Creek
White Oak diorite gneiss
~ 115 Ma to 110 Ma
Gneiss complex of the Tehachapi Mountains
Migmatitic paragneiss, quartzite, calc-silicate/marble (pre-Cret.)
Late Cretaceous Rand schist

Western Domain

Figure 2A is a time-temperature (*t-T*) plot for the western domain data. All data points for this domain are shown on the plot. The garnet and titanite points labeled 4, 6b, and 7 are shown with their analytical uncertainties and temperature range bars and are treated separately from the main data array. The main data points are shown with shaded areas that define high-confidence fields based on closure temperature ranges (Table 1) and the error-weighted means of the respective age determinations. Also shown on Figure 2 are apatite fission track and (U-Th)/He ages from the lower Grapevine Canyon area (Naeser et al., 1990; Niemi et al., 2004). The high-temperature end of the main array is constrained by the Sm/Nd garnet ages for the Bear Valley intrusives, which nearly converge with the Bear Valley suite U/Pb zircon ages. The temperatures used for the garnet data points are the thermobarometrically determined values. The U/Pb zircon ages for western domain pegmatite dikes lie within the Bear Valley suite garnet cluster. One of the pegmatite samples (5b) is intergradational with nonpegmatitic leucosome material of the sample 5 migmatitic diorite. Its U/Pb zircon age is nearly indistinguishable from the corresponding Sm/Nd garnet age. The main data array generally lies along a linear trend shown by the dashed line corresponding to a cooling rate of ~40 °C/m.y. This regression is constrained to commence with the youngest Bear Valley suite U/Pb zircon age determined in the western domain. This is not our preferred cooling trajectory for the western domain. The preferred trajectory is discussed below in the context of other factors, and includes the low-temperature apatite data.

We turn now to the sample 4, 6b, and 7 data points. Exposures in the western domain are dominated by the quartzofeldspathic gneiss of Pastoria Creek (Fig. 1). Both east and west of the Pastoria Creek area, gabbroic to tonalitic intrusives of the Bear Valley suite are abundant. In the Grapevine Canyon area, gabbroic to tonalitic intrusives of the younger suite and migmatitic paragneisses dominate the exposures. Regardless of the

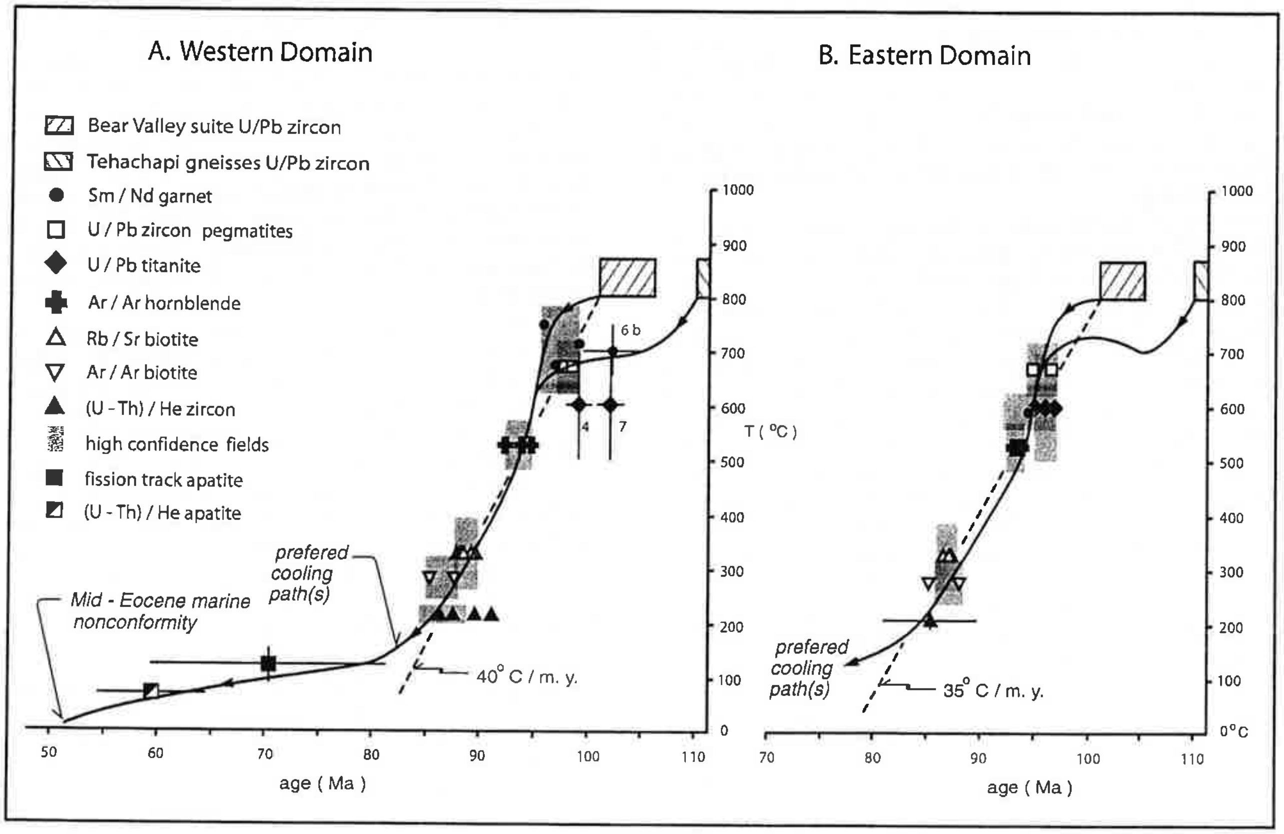

Figure 2. Time-temperature (*t-T*) plots for thermochronometric data from western domain (A) and eastern domain (B) of Tehachapi complex. Shaded areas represent high-confidence fields based on closure temperature ranges from Table 1, and from error-weighted means of multiple analyses of a given isotopic system (data tabulated in GSA Data Repository), or for individual analyses 2σ uncertainty used. U/Pb zircon ages from Saleeby et al. (1987), Pickett and Saleeby (1994), and GSA Data Repository. Samples not labeled in A: garnet Sm/Nd (1, 2, 5), hornblende Ar/Ar (6, 6b, 7), biotite Rb/Sr (3, 4, 6, 7, 9) and Ar/Ar (3, 7), He-zircon (4, 8, 9, 10). Apatite fission track and He data after Naeser et al. (1990) and Niemi et al. (2004), respectively. Samples in B: garnet Sm/Nd (15), titanite U/Pb (12, 13, 16), hornblende Ar/Ar (12, 17b), biotite Rb/Sr (11, 13, 17a) and Ar/Ar (11, 12, 17a), and He-zircon (14). Cooling paths discussed in text.

CDMG Bulletin 171

PREFACE

The major Arvin-Tehachapi earthquake of July 21, 1952, and the series of related earthquakes and aftershocks that followed, are but the latest of a succession of earthquakes demonstrating the position of California in the seismically active belt of geologically young, developing mountain ranges and valleys that rims the Pacific Ocean. The Kern County earthquakes of 1952 accounted for the loss of 14 lives and damage of over $60,000,000 in Kern and Los Angeles Counties.

Californians are becoming more earthquake-conscious, and rightly so, as California and Nevada have had over 90 percent of the earthquakes recorded in the United States and there is no evidence of any early decline in earthquake frequency in this area.

It behooves us, then, to be informed on earthquakes: their origin and geologic causes, their characteristics and behavior, where they are most likely to occur, their probable effects in disrupting the land surface and on engineering structures of all types, their effects on surface and subsurface water supply, the bearing of earthquakes and their causative faults on location of dams, canals, highways, and similar structures, and—through better understanding—how future losses in life and property can be reduced. The principal objective of Bulletin 171 is the presentation of information on all these things.

Probably no earthquake in history has received as intensive field study by as many scientifically trained people as the Arvin-Tehachapi earthquake and the related aftershocks. Epicenter of the earthquake was in the southern San Joaquin Valley, a great petroleum-producing area, where many geologists are based. Within a few hours hundreds of geologists from the oil companies, the United States Geological Survey, California Division of Mines, Division of Highways, Division of Water Resources, and the universities, were making observations of surface ground effects along the White Wolf fault, which was responsible for the earthquake. Just as quickly, field parties from the Seismological Laboratory of California Institute of Technology, Pasadena, were in the area setting up a group of portable seismographs, augmenting the records obtained at their permanent stations and obtaining unprecedented coverage of the aftershocks of a major earthquake. Engineering coverage was also complete, with hundred of engineers and builders assessing damage to buildings, highways, railroads, and other engineering structures, and directing repair and reconstruction.

In effect, the Division of Mines acted as a coordinating agency for compilation, editing, and publication of this series of papers dealing with the principal results of observations and data, from many sources, in three main categories: *Geology* (Part I), *Seismology* (Part II), and *Structural Damage* (Part III). Field work of the Division of Mines consisted in reconnaissance of the geology of the earthquake area and observations along the White Wolf fault zone. Through arrangement with the division, T. W. Dibblee, Jr., mapped the basic geology of over 1,000 square miles of the area as the basis for his paper on *Geology of the Southeastern Margin of the San Joaquin Valley* (Part I, Contribution 2). Drs. J. P. Buwalda and Pierre St. Amand did several weeks of intensive detailed field mapping along the White Wolf fault zone gathering data for their map and paper on *Geological Effects of the Arvin-Tehachapi Earthquake*. Other papers in Part I comprise discussions of the geologic setting of the earthquakes (Part I, Contribution 1), fault patterns and characteristics (Part I, Contributions 3, 4, 6, 8), geologic effects along the railroad (Part I, Contribution 7), effects on water levels and flow (Part I, Contributions 9, 10), and the uses of seismic methods in petroleum exploration (Part I, Contributions 11, 12). Part II presents the results of the extensive seismological observations, computations and conclusions of the Seismological Laboratory, headed by Dr. Beno Gutenberg, and includes papers by H. Benioff, B. Gutenberg, and C. F. Richter. Other papers in Part II include a general introduction to the science of seismology (Part II, Contribution 1), earthquake history (Part II, Contributions 2, 3) and the results of strong-motion records obtained by the United States Coast and Geodetic Survey. K. V. Steinbrugge and Donald F. Moran, both structural engineers with the Pacific Fire Rating Bureau, contributed the results of their extensive study of building damage to Part III. That part opens with a paper calling attention to the relation of structural damage to geology and closes with a technical paper dealing with the design of structures to resist earthquakes; other papers in Part III summarize damage to specific types of structure and installation.

In enlisting contributions from the 16 different agencies, selecting the 36 authors, suggesting the subject matter for the 34 papers, field checking, compiling, and editing manuscripts to produce this bulletin, we have kept in mind the place of the Division of Mines as a public information bureau on matters directly related to the mineral resources and basic geology of the State. The earthquake is a geological phenomenon and the extensive, disruptive, and complex events that occurred during and following the Arvin-Tehachapi earthquake are effects of a geological cause—an abrupt displacement along the White Wolf fault at a depth of a few miles below the ground surface near Wheeler Ridge at 4:52 PDT on the morning of July 21, 1952. Mining and petroleum geologists know faults for their importance in localizing mineral deposits, for displacing such deposits after their formation, and recognize their extreme importance to mineral exploration. Hence, the series of papers in Part I (*Geology*) deals with faults, fault patterns, and fault history. Many of the major oil fields in the earthquake-affected area of Kern County are in structural traps with one or more faults playing a major role in forming the oil pool. Recognition of a fault system or pattern, then, may be of great importance in judging the location and characteristics of faults on the alluvium-covered valley floor and therefore the possible location of an oil field. Similarly, the principles of the science of seismology and results of study of the seismograph records discussed in Part II (*Seismology*) has great economic importance, particularly as applied to petroleum exploration (Part I, Contributions 11, 12) on the floor of the valley, and have been responsible for the discovery of major

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3. KERN CANYON LINEAMENT

By Robert W. Webb *

Introduction. The recent earthquakes in the Tehachapi area of the southern Sierra Nevada have refocused attention of geologists on this critical area of California structure. The recent summary of the Arvin-Techachapi earthquake (California Division of Mines, 1952), calls attention to what may be a structural pattern in a series of faults (Jenkins, 1938; Nugent, 1942) whose geological relationships have never been established. The faults in question are known as the White Wolf, Breckenridge Mountain, Havilah Valley, Hot Springs, and Kern Canyon faults. The regional topographic pattern of these faults and the inter-segments between them will be referred to as the "Kern Canyon lineament." It seems pertinent to examine what is known currently about the structural pattern and to suggest a possible interpretation for the apparent pattern.

Geography of the Faults in the Lineament. The disconnected fault zones and inter-segments that appear to compose a structural lineament extend from the Tejon Hills in the southern San Joaquin Valley, northeastward and northward for more than 100 miles, beyond the headwaters of the Kern River. The faults have been studied, and evidence (Hoots, 1930, pp. 301-319; Lawson, 1906; 1904, pp. 291-376; Webb, 1936) for them presented. Between these are apparently unfaulted segments, none of which has been mapped in sufficient detail to prove positive connection, at least in the present-day structural pattern; other inter-segments are unmapped.

Historical Background. The first recognition of an important fault in the Kern River Canyon was by Lawson (1904), in the first of a series of three papers, discussing faulting in the upper Kern Basin. In a second paper (1906) he presents his observations made in the middle Kern Basin, the Havilah Valley, and Walker Basin, which suggested to him the apparent importance of faulting. A connection between the northern (Kern Canyon) faults and those in the Havilah and Walker regions was tentatively postulated. In his third paper on the Tehachapi Range (Lawson, 1906a) he recognized the important Tehachapi (White Wolf) fault, and raised the possibility of a connection between the earlier described faults and the White Wolf, although no connection between any of these faults was seriously implied, since he did not undertake geologic mapping. In 1922, the publication of a structural map of California (Seismological Society of America, 1922) showed the White Wolf fault, and that part of the Kern Canyon fault from the mouth of Golden Trout Creek nearly to Fairview, as "dead fault, well located;" the Breckenridge fault is symbolized as "probable fault, character and location uncertain." Additional geologic studies were not published until 1928, when faulting was mentioned incidental to other geologic problems (Hake, 1928; Miller, 1931). The White Wolf fault was mapped in 1930 (Hoots, 1930), and the Kern Canyon fault studied in 1936 (Webb, 1936). Interest in damsites along the Kern River was revived, and several reports appeared [1] (Marliave, 1938; Treasher, 1949, 1949a). Significant information on faulting in Hot Springs Valley, at the site of the new Isabella Dam near the junction of Kern, and South Fork of Kern River will appear with the full publication of these studies. A geologic map of the Kernville quadrangle was published in 1940 (Miller and

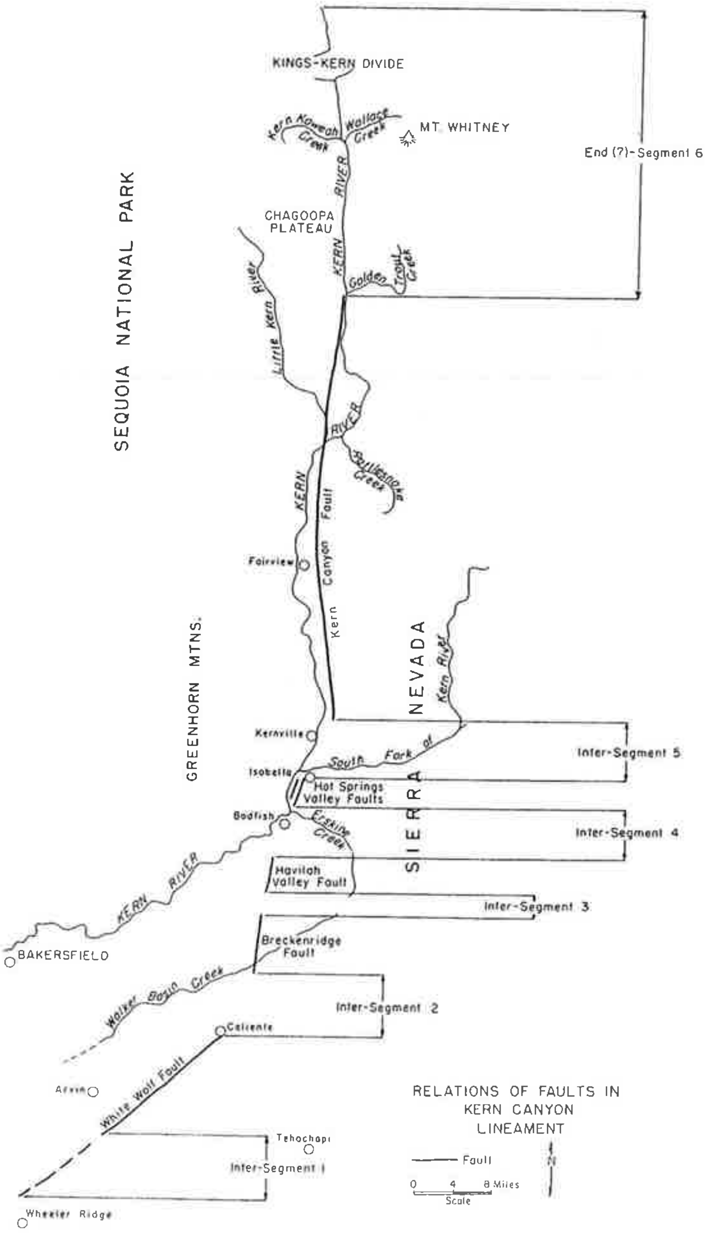

Figure 1.

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* Professor of Geology, University of California, Santa Barbara. Manuscript received for publication December, 1952.

[1] Holdredge, Clair, Personal communications, July 19, 1949, and Oct. 7, 1949.

7. ARVIN-TEHACHAPI EARTHQUAKE DAMAGE ALONG THE SOUTHERN PACIFIC RAILROAD NEAR BEALVILLE, CALIFORNIA†

By Donald H. Kupfer,* Siegfried Muessig,* George I. Smith,* and George N. White *

ABSTRACT

The Arvin-Tehachapi earthquake occurred in south-central California on July 21, 1952, on the White Wolf fault. Where the fault zone crosses the Southern Pacific Railroad, four tunnels were destroyed, rails were twisted and buckled, and in one area about 10 feet of crustal shortening was measured. The types of damage associated with the earthquake, and their distribution relative to each other, seem to have been caused by movement in a reverse- or thrust-fault zone that dips south. The damage resulted from compression and from subsequent relaxation along normal faults.

INTRODUCTION

Surface displacement during the Arvin-Tehachapi earthquake of July 21, 1952 took place principally along the White Wolf fault, the trace of which lies along the base of a pronounced escarpment that forms the northwest slope of Bear Mountain, Kern County, California (California Division of Mines, 1952; Benioff, et al., 1952; Buwalda, 1952). Severe damage occurred where a fault zone, presumably an extension of the White Wolf fault, crosses the Southern Pacific Railroad tracks 1,500 feet southeast of Bealville Railroad Station. Before the earthquake the tracks here made an S-shaped curve and passed through four tunnels; all three limbs of the curve and three of the four tunnels were intersected by the fault zone.

The authors visited the area on the day of the earthquake. On that day and the two days following, they examined the fault trace at several points between Bealville and the bend in the road east of Arvin.

As bulldozers were about to destroy much of the evidence of earth movement along the railroad, the plane-table map was made by the authors on July 22, 1952. On August 14 and 15 Kupfer and Smith revisited the area and examined the damage in tunnel 5, which had been impassable during the previous visit. The purpose of this report is to present the authors' observations—most of which can not be made again—and their conclusions.

Acknowledgments. The authors wish to thank Mr. D. J. Russell, president of the Southern Pacific Railroad Co., for the courtesy and cooperation that he and his men extended during the investigation; Messrs. E. E. Earl, G. F. Mehrwein, D. P. Boykin, F. M. Misch, W. Jaekle, W. E. Bussey, and S. T. Moore, all officials of the company, were particularly helpful. The Kern County Land Co. loaned the plane-table equipment.

Terminology. The tunnels on the Southern Pacific Railroad are numbered consecutively from Bakersfield to Mojave. In local railroad parlance, the directions on the track are referred to as "west" toward Bakersfield and "east" toward Mojave, without regard to actual compass direction. This terminology is used in this report only when referring to location of tunnel portals. Distances are given from the west portals of tunnels, and "left" and "right" refer to the left and right side of a train heading toward Mojave or Los Angeles. Figure 1 shows the general relations of the area affected; figure 2 represents in more detail two of the tunnels and the part of the tracks that were disturbed; and the photograph in figure 4 shows their relation to local topography.

GENERAL GEOLOGY

In the area of the railroad tracks and tunnels, the bedrock is predominantly granular intrusive rock, cut by small pegmatite dikes. No microscopic examination of the rock was made, but it seems to range in composition from a quartz diorite to a gabbro. It has been altered and decomposed to an undetermined depth, and bulldozers were therefore able to make sloping cuts 100 feet or more into the bedrock without the use of explosives.

During the reconstruction of tunnel 3, an exposure of nonintrusive bedrock, which is now partly concealed by the finished tunnel, was found. It is a wedge of arkosic material that was exposed from the arch of the tunnel to a point 50 feet along the left (east) embankment. Most of this rock is unbedded, compact, and fine-grained, but it contains a few rounded cobbles up to a foot in diameter. The top of this mass is in horizontal contact with intrusive rock; in some places the contact is indistinct, in others it is sharply defined by a zone of gouge 1 inch to 2 inches thick. The lower contact was not exposed. No further information was collected about this rock and it is now concealed. For this reason its structural relations are doubtful.

DISPLACEMENT ALONG THE WHITE WOLF FAULT DURING THE EARTHQUAKE

The general trend of the trace of the White Wolf fault is N. 55° E., subparallel to the Garlock fault, which lies 18 miles southeast. The trace of the recent offset was generally represented by several minor but conspicuous fractures that cut the surface in en echelon, parallel, or braided patterns along a zone up to 1,000 feet in width. The relative displacement of the surface along most of these fractures was less than a foot, but locally was up to 4 feet. Fractures of the normal, reverse, thrust, and strike-slip types were observed.

Along the base of the Bear Mountain scarp due east of Arvin the movements apparently took place on a thrust fault; the southeast block was thrust relatively over the northwest block. Two tear faults were observed.

In the vicinity of U. S. Highway 466 and the railroad the surface fractures appeared to be on normal faults with downthrow on the southeast. The average displacement was 6 to 8 inches and included a strike-slip component.

DAMAGE ALONG THE SOUTHERN PACIFIC RAILROAD TRACKS

The railroad tracks between Bakersfield and Mojave were damaged by the earthquake in many places. Boulders and large rock masses slumped onto the tracks and most of the larger fills settled slightly, so that much of the track had to be cleared, leveled, and straightened. In the S-curve area near Bealville, the track and tunnels

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† Publication authorized by the Director, U. S. Geological Survey.

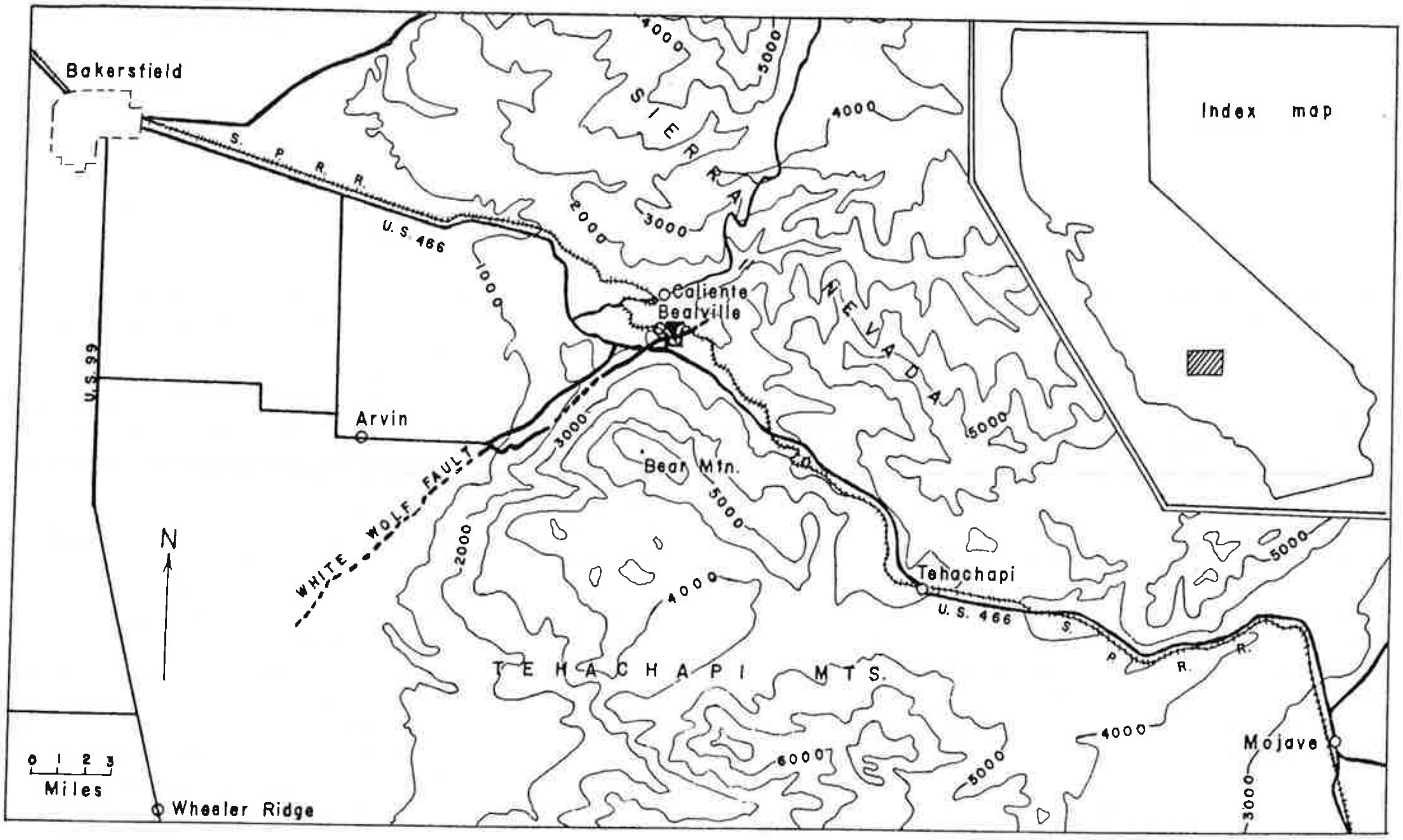

FIGURE 1. Trace of White Wolf fault, partially from data from T. W. Dibblee Jr. (this bulletin). Location of *Map of railroad route east of Bealville* (fig. 2) is shown by solid rectangle. Topography from U. S. Geological Survey Caliente quadrangle. Contour interval 1000 feet. Datum mean sea level.

were so severely damaged that all traffic on the line was suspended for 25 days.

The tunnels in this area are lined with steel-reinforced concrete walls from 12 to 24 inches thick. Large slabs of concrete that broke away from all other adjacent support were held in place by the reinforcing steel for several days, but continued aftershocks finally broke them loose.

Tunnel 3. Tunnel 3, originally 700 feet long, actually runs a little west of south from the "west" portal. It was undamaged from this portal to a point 548 feet south, where a displacement approximately at right angles to the centerline of the tunnel fractured both walls from floor to arch. When examined on the morning of July 22, both concrete walls of the tunnel were displaced about 2 feet horizontally, the south side to the east. By the time the plane-table map was made that afternoon, the left (east) wall had collapsed inward. From this fracture to the "east" portal, a distance of 152 feet, the walls of the tunnel were broken and large slabs of concrete were loosened but kept from falling by the steel reinforcement. In the last 70 to 90 feet of the tunnel, the concrete was thoroughly shattered; the arch was broken, and the tunnel was caved in.

In repairing this tunnel, 206 feet of the damaged end was converted into an open cut, or "daylighted." After daylighting, the west wall of the new cut was examined and two zones of broken and crushed rock were observed, one 605 feet and the other 620 feet from the west portal. At a point 570 feet from the west portal (76 feet south of the new east portal) a fracture was observed on which movement had occurred after the daylighting, and by August 15 this movement had amounted to about an inch. On November 1, when Smith visited the area, the displacement had increased to several inches. This fracture strikes N. 15° E. and dips 35° SE. at waist height but flattens out upward. At the top of the new tunnel portal the fracture is nearly flat. The arkosic material described in the section on "General Geology" occurs under this fault.

Between Tunnels 3 and 4. Between tunnels 3 and 4 the track was laid mostly on fill. The rails between the north side of this fill and the south end of tunnel 3 had been contorted into bends with radii of 20 feet or more, as if the ground under the track had been shortened.

No fractures were observed under the tracks, but a small normal fault was observed in the bedrock about 300 feet east of the fill between tunnels 3 and 4. The vertical displacement on the fault appeared to be about 2 feet. On July 22, its strike was N. 80° W. and its dip 50° SW—into the hill. On August 14 it had a similar strike, but the dip had flattened to 37° SW, probably by slumping.

Tunnel 4. Tunnel 4, originally 334.4 feet long, runs about east southeast. Its walls were cracked or broken from the west portal to a point about 85 feet from the east portal. Midway between the portals, in a zone about 50 feet wide, large breaks had occurred and the walls

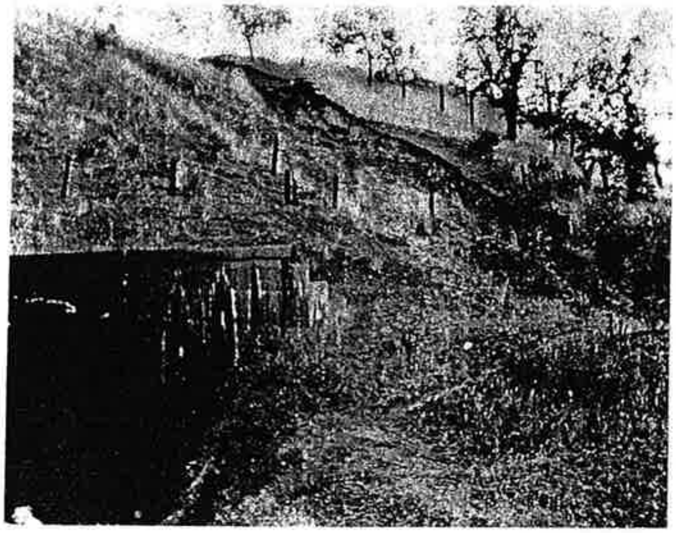

FIGURE 8. Surface expression of the normal fault shown in figure 7. The fault was traced several hundred feet to the right of the area shown in the photograph. View north.

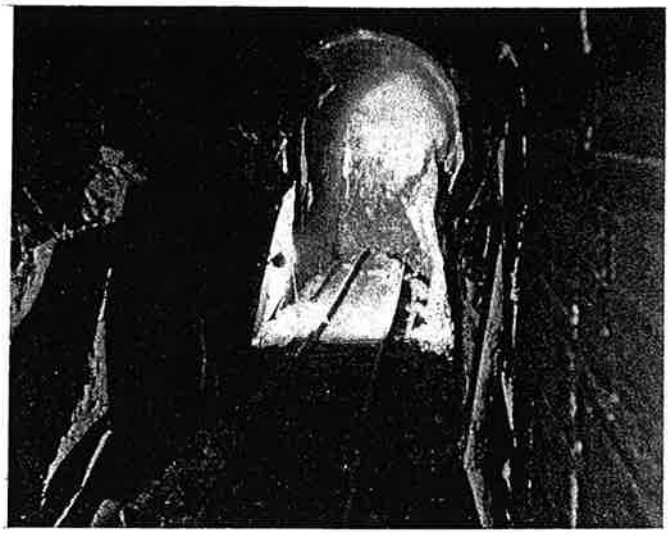

FIGURE 9. Cracked and buckled walls in tunnel 5. Camera is on the cave-in at 833 feet from the west portal; looking toward the cave-in at 632 feet. The tracks are bowed up about 1½ feet.

Tunnel 6. Tunnel 6 was not on the main fault zone. Its walls were shattered and broken, mainly by longitudinal cracks in the arch, and the tunnel was displaced to the left with respect to the tracks. In the hillside above the tunnel there were fractures roughly parallel to the tunnel, suggesting that the ground through which the tunnel passed slumped downhill a few feet as a result of the earthquake, while the track moved somewhat less. Tunnel 6 has been daylighted.

Beyond Tunnel 6. Beyond tunnel 6, in the east arm of the S-curve, the track was warped by settling of fills and covered in places by landslides; otherwise it was not seriously damaged. Where the fault zone crosses the track, the rails were slightly buckled and the fills had slumped 2 feet. Thirteen inches of rail were removed from the tracks during realignment. There are fractures trending N. 53° E. on both sides of the track in this area.

As tunnel 7 lies southeast of the general area described above and is not on the main fault zone, it was not visited. The concrete walls of the tunnel are said to have been cracked by the initial shock, but not broken. Later shocks, however, worked some of the concrete loose and necessitated repairs.

EVIDENCE OF SHORTENING AND VERTICAL DISPLACEMENT IN THE FAULT ZONE

The major fault damage in the vicinity of the Southern Pacific tracks near Bealville was confined to an east-west zone about 500 feet wide. The fault zone was well delimited where it cut tunnels 3 and 4, and also where it cut tunnel 5, though at the surface its boundaries were obscure.

Tunnels 3 and 4. The most spectacular evidence of crustal shortening was that afforded by twisted and contorted rails found near the east portal of tunnel 3, where measurements made by the Southern Pacific engineers the day after the earthquake indicate that the earth's crust was shortened by 10.9 feet.

Measured shortening near tunnels 3 and 4.

	S.P.R.R. (tape)	U.S.G.S. (stadia)
Tunnel 3	2.3 feet	2.0 feet
Between tunnels 3 and 4	8.6 feet	9.6 feet
Tunnel 4	0	—1.7 feet
Total shortening	10.9 feet	9.9 feet

All this shortening occurred between the northernmost break in tunnel 3 and the west portal of tunnel 4; outside of this zone neither the rails nor the ties had

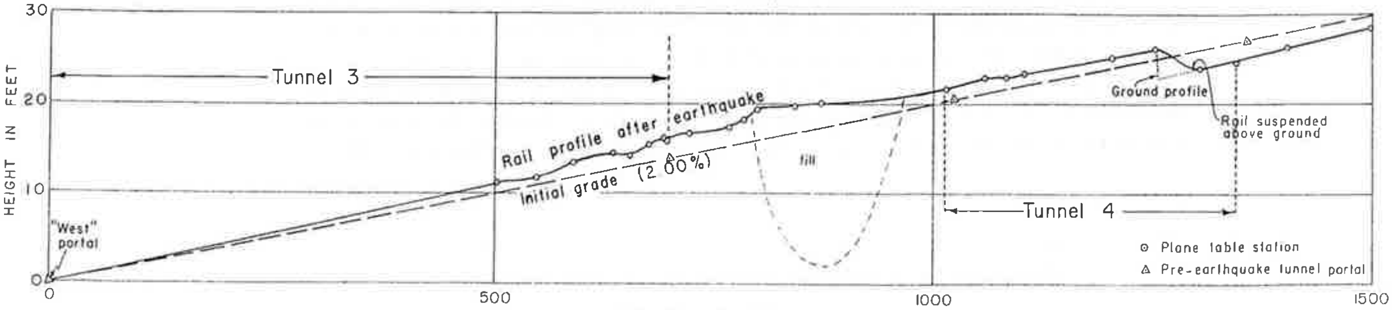

FIGURE 10. Profile along the tracks showing grade before and after earthquake. Datum is west portal of tunnel 3. Tunnel positions indicated are those immediately following earthquake. Vertical exaggeration x10.

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Disruption of regional primary structure of the Sierra Nevada batholith by the Kern Canyon fault system, California

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ABSTRACT

Regional spatial variation patterns in igneous emplacement pressures, initial $^{87}Sr/^{86}Sr$ (Sr_i) values, zircon U/Pb ages, and pluton bulk compositions of the Sierra Nevada batholith are disrupted by the ~130-km-long proto–Kern Canyon fault, a Late Cretaceous ductile shear zone in the southern Sierra Nevada batholith. Vertical displacement and horizontal shortening across the proto–Kern Canyon fault in its early history are roughly constrained by the disruption of a regional primary batholithic structure that is recorded in petrologic and geochemical spatial variation patterns. The disruption of these patterns suggests that the proto–Kern Canyon fault underwent (1) subvertical west-directed reverse faulting that was instrumental in the exhumation and deep exposure of the southern part of the Sierra Nevada batholith, and (2) southward-increasing reverse/thrust displacement. The disruption of otherwise smoothly varying geobarometric gradients across the central part of the proto–Kern Canyon fault suggests up to ~10 ± 5 km of east-side-up reverse displacement across the shear zone. Southward from this area, the proto–Kern Canyon fault truncates, at an oblique angle, the petrologically distinct axial zone of the Sierra Nevada batholith, which suggests that up to ~25 km of normal shortening occurred across the southern part of the proto–Kern Canyon fault. Normal shortening is further supported by the coincidence of the $Sr_i = 0.706$ isopleth with the proto–Kern Canyon fault from the point of initial truncation southward. Zircon U/Pb ages from plutons emplaced along the shear zone during its activity indicate that this shortening and vertical displacement had commenced by 95 Ma and was abruptly overprinted by dominantly dextral displacement with small east-side-up reverse components by 90 Ma. Conventional structural and shear fabric analyses, in conjunction with geochronological data, indicate that at least ~15 km of dextral shear slip occurred along the zone between 90 and 86 Ma, and another 12 ± 1 km of dextral slip occurred along the northern segment of the zone between 86 and 80 Ma. This later 12 ± 1 km of dextral slip branched southwestward as the ductile-brittle Kern Canyon fault, abandoning the main trace of the shear zone near its central section. Dextral shearing in the ductile regime was replaced by brittle overprinting by 80 Ma.

The timing of initiation and the duration of reverse-sense displacement along the proto–Kern Canyon fault correspond closely with the shallow flat subduction of the Franciscan-affinity Rand schist along the Rand fault beneath the southernmost

Nadin, E.S., and Saleeby, J.B., 2008, Disruption of regional primary structure of the Sierra Nevada batholith by the Kern Canyon fault system, California, *in* Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs, and Batholiths: Geological Society of America Special Paper 438, p. XXX–XXX, doi: 10.1130/2008.2438(15). For permission to copy, contact editing@geosociety.org.

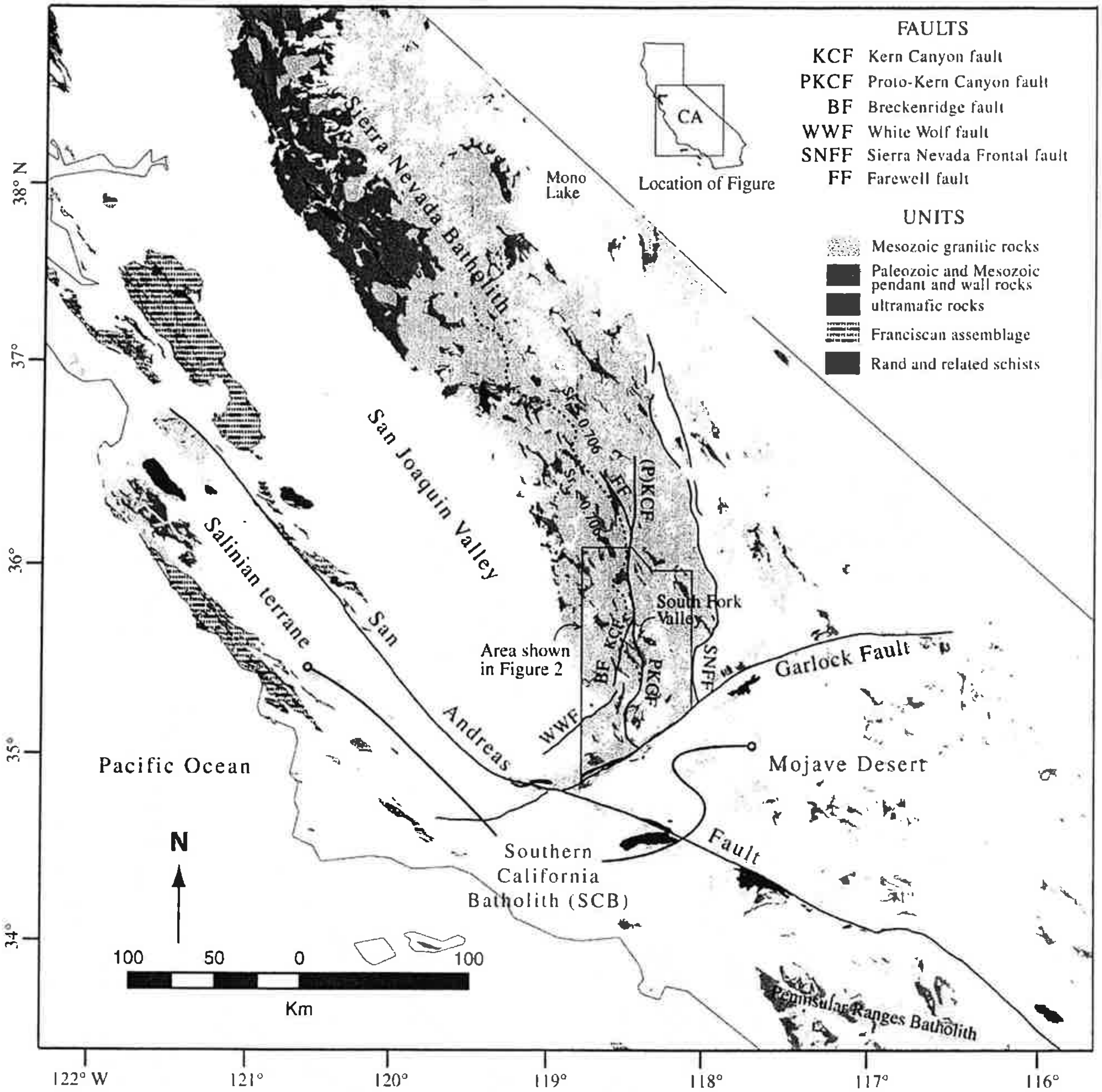
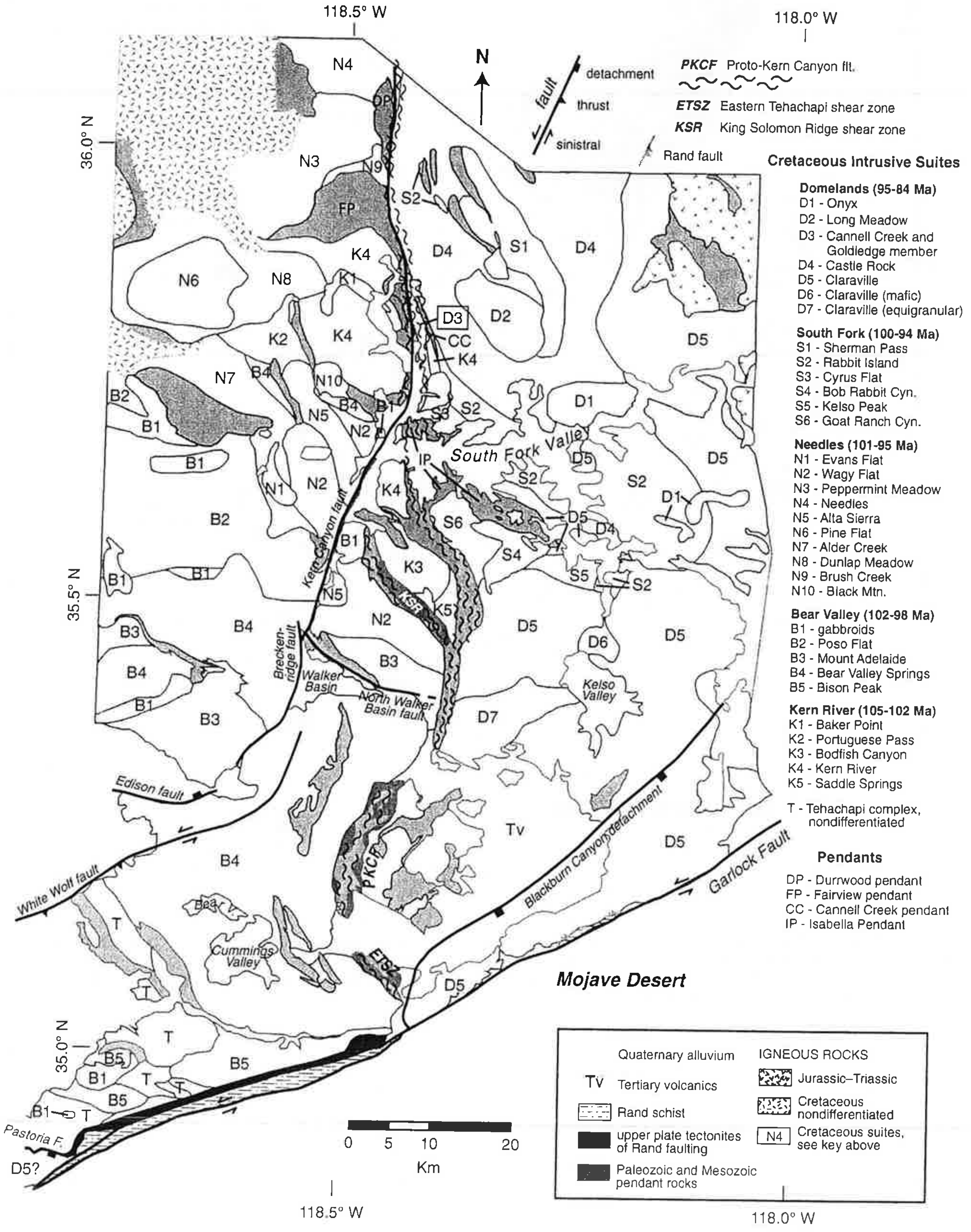


Figure 1. Map of southern California, showing geologic features discussed in the text. The Mesozoic granitic rocks of the Sierra Nevada and associated Peninsular Ranges batholith, Salinia, and Mojave Desert (including the southern California batholith [SCB]), and pendant rocks are of particular interest. Remnants of the Rand schist and associated schists, and the greater Franciscan complex, are also highlighted. The proto–Kern Canyon fault and Kern Canyon fault are shown transecting the southern part of the Sierra Nevada batholith and truncating the $Sr_i = 0.706$ isopleth. The Farewell fault branches out of the northern part of the Kern Canyon fault.

Figure 2. Map outlines of individual plutons forming the intrusive suites of the southern Sierra Nevada batholith referred to in the text. In general, the older Kern River (K), Bear Valley (B), and Needles (N) suites lie to the west of the proto–Kern Canyon and Kern Canyon faults, while the younger South Fork (S) and Domelands (D) suites lie to the east. Critical rock fabrics that constrain early and later motion along the fault system are in the granite of Cannell Creek (D3) and its associated Goldledge member. Also labeled are the Durrwood, Fairview, Cannell Creek, and Isabella pendants, which lie along and are disrupted by the proto–Kern Canyon fault. At its southernmost extent, the proto–Kern Canyon fault merges with the Eastern Tehachapi shear zone, and this system is truncated to the south by the Garlock fault. The Rand schist and upper-plate tectonites are shown in windows adjacent to the Garlock fault, and the locations of the King Solomon Ridge shear zone and the North Walker Basin fault are also shown.


118.5° W
118.0° W
36.0° N
35.5° N
35.0° N
N
fault
detachment
thrust
sinistral
Rand fault
PKCF Proto-Kern Canyon flt.
ETSZ Eastern Tehachapi shear zone
KSR King Solomon Ridge shear zone
Cretaceous Intrusive Suites
Domelands (95-84 Ma)
D1 - Onyx
D2 - Long Meadow
D3 - Cannell Creek and Goldledge member
D4 - Castle Rock
D5 - Claraville
D6 - Claraville (mafic)
D7 - Claraville (equigranular)
South Fork (100-94 Ma)
S1 - Sherman Pass
S2 - Rabbit Island
S3 - Cyrus Flat
S4 - Bob Rabbit Cyn.
S5 - Kelso Peak
S6 - Goat Ranch Cyn.
Needles (101-95 Ma)
N1 - Evans Flat
N2 - Wagy Flat
N3 - Peppermint Meadow
N4 - Needles
N5 - Alta Sierra
N6 - Pine Flat
N7 - Alder Creek
N8 - Dunlap Meadow
N9 - Brush Creek
N10 - Black Mtn.
Bear Valley (102-98 Ma)
B1 - gabbroids
B2 - Poso Flat
B3 - Mount Adelaide
B4 - Bear Valley Springs
B5 - Bison Peak
Kern River (105-102 Ma)
K1 - Baker Point
K2 - Portuguese Pass
K3 - Bodfish Canyon
K4 - Kern River
K5 - Saddle Springs
T - Tehachapi complex, nondifferentiated
Pendants
DP - Durrwood pendant
FP - Fairview pendant
CC - Cannell Creek pendant
IP - Isabella Pendant
South Fork Valley
Kern Canyon fault
Breckenridge fault
Walker Basin
North Walker Basin fault
Kelso Valley
Edison fault
White Wolf fault
Blackburn Canyon detachment
Garlock Fault
Cummings Valley
Bear
Pastoria F.
Mojave Desert
Tv
D5?
0 5 10 20
Km
Quaternary alluvium
Tv Tertiary volcanics
Rand schist
upper plate tectonites of Rand faulting
Paleozoic and Mesozoic pendant rocks
IGNEOUS ROCKS
Jurassic–Triassic
Cretaceous nondifferentiated
N4 Cretaceous suites, see key above

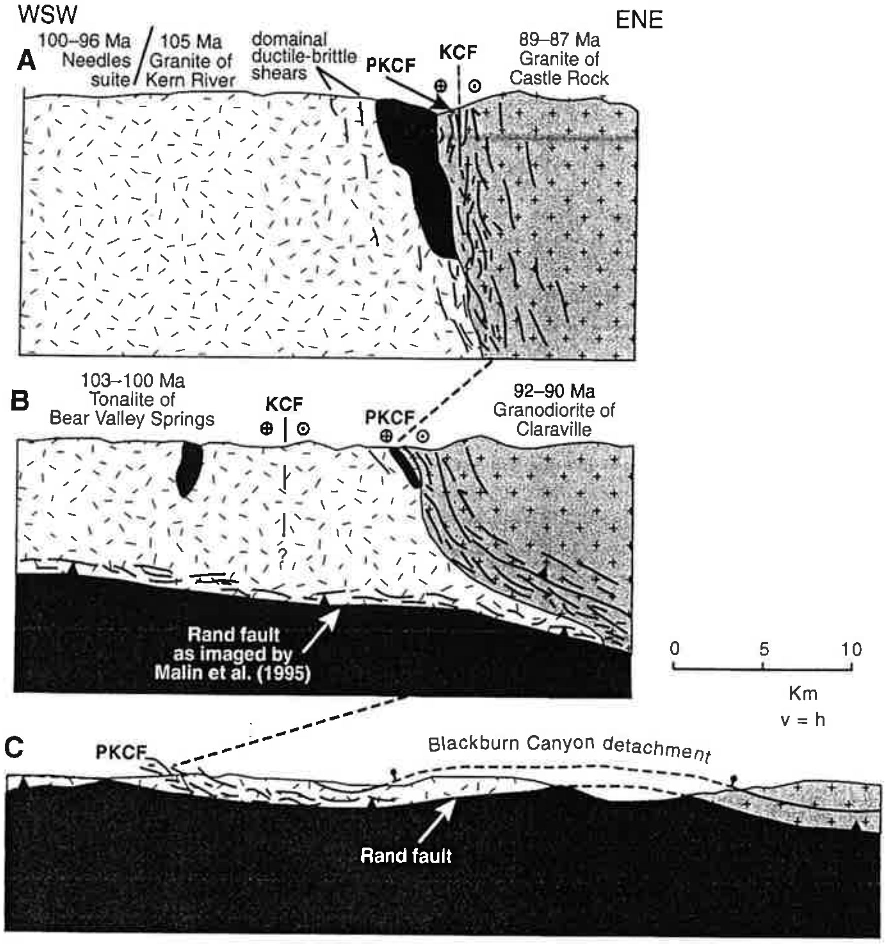


Figure 3. Cross sections across the proto–Kern Canyon fault, from north to south, showing its shallowing dip southward and eventual transition into the Rand fault. (A) Near latitude 35.8°N, the proto–Kern Canyon fault is steep and localized along the western edge of the Domelands intrusive suite. Pendant rocks, shown in dark gray, are also highly sheared. (B) Near latitude 35.4°N, the dip of the proto–Kern Canyon fault shallows eastward, and the Kern Canyon fault branches from it to the west. The shear zone is again localized along the western edge of the Domelands intrusive suite. (C) Near latitude 35°N, the dip of the proto–Kern Canyon fault shallows further and roots into upper-plate tectonites of the Rand fault. The Blackburn Canyon detachment is shown placing younger, shallower-level Late Cretaceous upper-plate intrusive rocks against lower-plate intrusive rocks, which are in turn in fault contact with the Rand schist.

extensional modification of the Rand fault system (Wood and Saleeby, 1998; Saleeby, 2003) obscure the kinematic relations along the southernmost proto–Kern Canyon fault. Structural and age relations reviewed here indicate that the ductile deformation history of the northern segment of the proto–Kern Canyon fault outlived that of the southern segment, and that dextral motion along the southern Kern Canyon fault replaced that of the southern proto–Kern Canyon fault as the Kern Canyon fault merged into the proto–Kern Canyon fault from the south.

Dextral Displacement

The dextral displacement history of the proto–Kern Canyon fault entails a complex pattern in the partitioning of motion between the principal trace of the shear zone and both the Kern Canyon fault and the Farewell fault zone. In order to resolve the vertical offset history of the proto–Kern Canyon fault, the subsequent dextral motion must first be backed out. We present here an overview of the constraints on the dextral displacement along the system (after Moore and du Bray, 1978; Ross, 1986; Saleeby and Busby-Spera, 1986; Busby-Spera and Saleeby, 1990; Saleeby and Busby, 1993; Nadin, 2007). Palinspastic restoration of the dextral displacements is subsequently used as a means to better utilize disrupted spatial variation patterns of the greater Sierra Nevada batholith as markers of vertical displacement and normal shortening across the system. Figure 4 shows a summary of: (1) offset geologic markers along the system; (2) results of local dextral shear-strain profiles along well-exposed transects of the shear zone (after Ramsay and Graham, 1970); and (3) a summary of principal dextral/reverse slip-line orientations determined for ductile fabrics. The shear strain–derived dextral displacement values are local minimum values for the following reasons. Firstly, many of the S-C mylonites contain composite C surfaces as well as superposed high-strain shear bands. Secondly, sets of late- to postshearing crenulations locally disrupt the principal ductile fabrics of the system. Finally, these analyses omit displacements that took place in the brittle regime as well as along fault surfaces.

We focus first on Kern Canyon fault dextral displacement. Based on the mapping of Ross (1986), and refinement of some

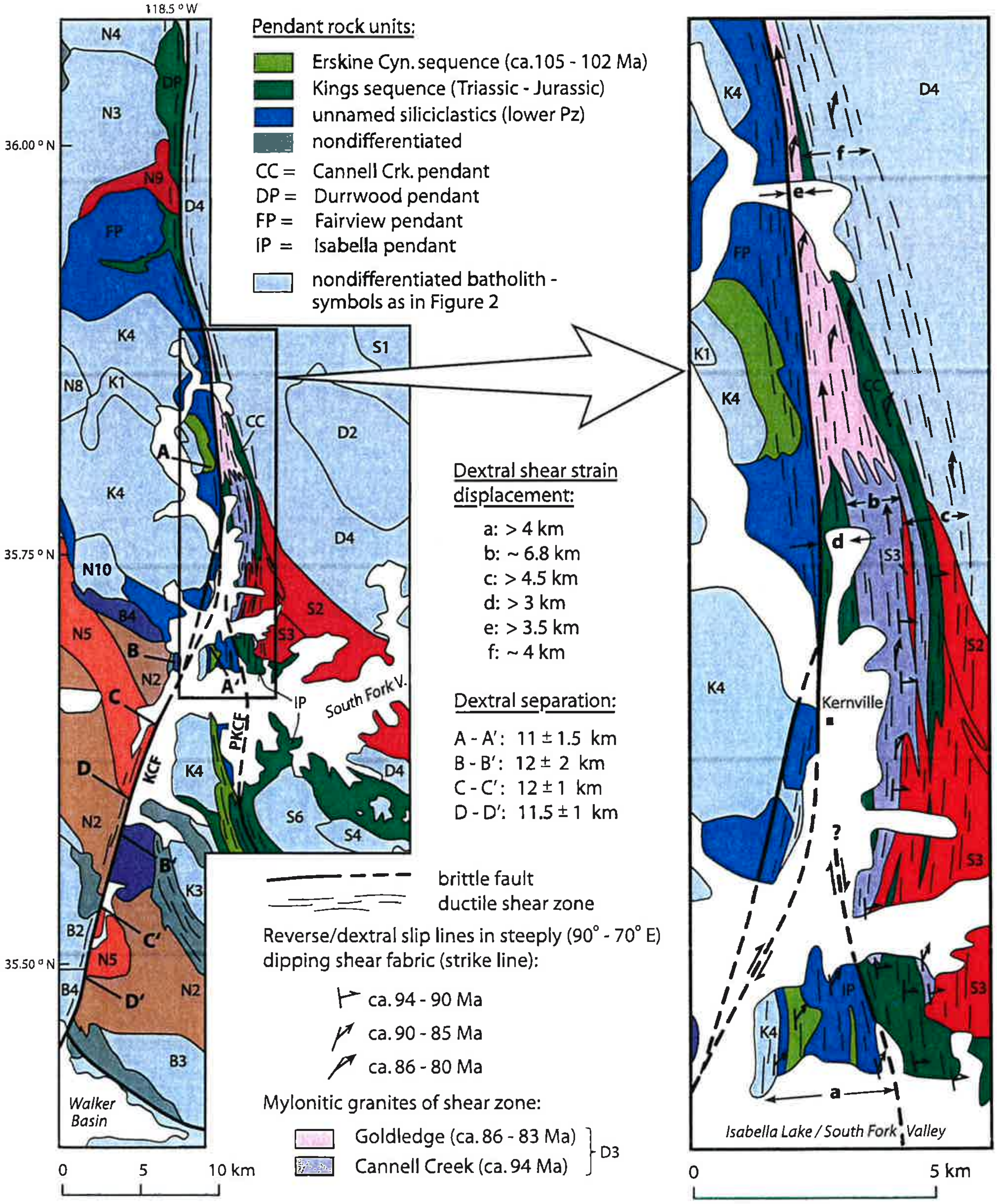


Figure 4. Detailed map of central region of Figure 2, showing dextral separations on Kern Canyon fault (KCF) (modified after Ross, 1986) and inset map showing locations of traverses along which shear strain was analyzed (after Ramsay and Graham, 1970). Also shown are dextral displacement components as well as principal slip lines determined in this study for transition zone between southern and northern segments of proto–Kern Canyon fault. Selected plutons are colored to elucidate their displacement patterns along the system. Pluton unit symbols are as on Figure 2.

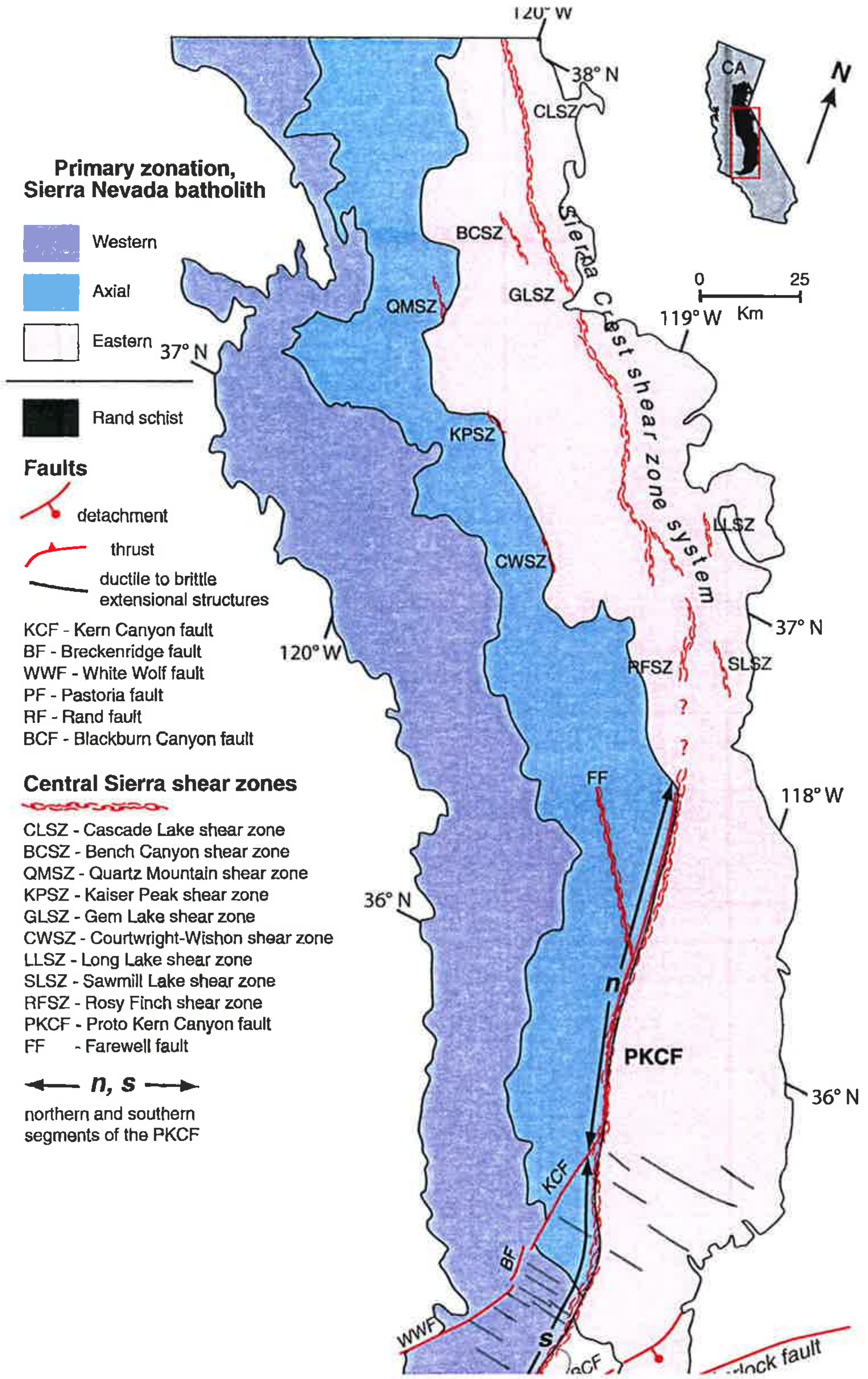


Figure 10. Primary zonation of the Sierra Nevada batholith, and Late Cretaceous shear zones related to the proto–Kern Canyon fault. Northern and southern segments of the proto–Kern Canyon fault, and the NW-striking Farewell fault are delineated. The Blackburn Canyon and Pastoria faults are proposed to be detachment faults that brought upper-crustal batholithic rocks to their present positions above deeper-level rocks (Wood and Saleeby, 1998).

18.5

Quaternary reactivation of the Kern Canyon fault system, southern Sierra Nevada, California

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ABSTRACT

The Kern Canyon fault, the longest fault in the southern Sierra Nevada, is an active structure and has been reactivated at discrete times over the past ~100 m.y. in response to changing lithospheric stresses. After initiation as a Cretaceous transpressional structure, the Kern Canyon fault transitioned into a dextral strike-slip shear zone that remained active as it was exhumed into the brittle regime during regional Late Cretaceous uplift of the Sierra Nevada batholith. The Kern Canyon fault was reactivated during Miocene regional extension as part of a transfer zone between two differentially extending domains in the southern Sierra Nevada. Subsequent normal displacement along the fault began in Pliocene time. New evidence for fault activity, which continued into late Quaternary time, includes its current geomorphic expression as a series of meters-high, west-side-up scarps that crop out discontinuously along the fault's 130-km length. Relocated focal mechanisms of modern earthquakes confirm ongoing normal faulting, and geodetic measurements suggest that the Sierra Nevada is uplifting relative to the adjacent valleys. This evidence for recent activity overturns a long-held view that the Kern Canyon fault has been inactive for more than 3.5 m.y. Its reactivation indicates that deformation repeatedly localized along a preexisting crustal weakness, a Cretaceous shear zone. We propose that a system of interrelated normal faults, including the Kern Canyon fault, is responding to mantle lithosphere removal beneath the southern Sierra Nevada region. The location of the active Kern Canyon fault within the Sierra Nevada–Great Valley microplate indicates that deformation is occurring within the microplate.

INTRODUCTION

The Sierra Nevada batholith of California is one of the world's largest batholiths, and was assembled by multiple intrusive events largely during Cretaceous time. The mountain range and westward-adjacent Great Valley, filled largely with sediments eroded from the batholith, together constitute a semi-rigid crustal block termed the Sierra Nevada microplate, whose velocity and rotation vectors differ from those of the rest of North America (Argus and Gordon, 1991; Dixon et al., 2000; Sella et al., 2002). This "microplate" is bounded to the west by the San Andreas transpressive plate junction. To the east are the Eastern California Shear Zone and its northward continuation, the Walker Lane (Fig. 1), which together form the western boundary of the Basin and Range extensional province (e.g., Jones et al., 2004). Geodetic data show that the Eastern California Shear Zone–Walker Lane belt is undergoing dextral shear that accounts for ~20% of total relative motion between the North American and Pacific plates (Dokka and Travis, 1990; Thatcher et al., 1999; Dixon et al., 2000; Gans et al., 2000; Bennett et al., 2003; Oldow et al., 2008; Hammond and Thatcher, 2007).

Many studies have shown that there is active faulting in the eastern Sierra Nevada range front (recent selected references: Le et al., 2007; Surpless, 2008; Taylor et al., 2008). There have also been predictions of extensional deformation within the southern part of the Sierra Nevada batholith (Jones et al., 2004) and, more recently, evidence for uplift of the southern Sierra Nevada relative to the Owens Valley to the east (Fay et al., 2008; see Fig. 1 for location). This study presents the first documentation of active extensional structures *within* the range that are consistent with the predicted uplift.

We define the Kern Canyon fault system as an ~130-km-long zone of faulted basement, with several parallel, near-vertical fault strands that strike generally northward from the southern edge of the Sierra Nevada along the batholith's long axis (Fig. 1). Latitude 35.7°N, at the Isabella basin (Fig. 2), is a geographically significant location for defining Kern Canyon fault geometry. South of the Isabella basin, the Kern Canyon fault has been interpreted to connect with the Breckenridge scarp and the White Wolf fault (Fig. 1; e.g., Ross, 1986). Across this northeast-striking segment of the fault zone, brittle deformation is localized along discrete fractures across an ~150-m-wide zone at the currently exposed surface. This segment developed ca. 86 Ma as a plastic-to-brittle structure during exhumation of the southernmost part of the batholith (Nadin and Saleeby, 2008; Saleeby et al., 2009). North of the Isabella basin, brittle structures of the Kern Canyon fault overprint the proto–Kern Canyon fault (labeled PKCF in Fig. 1), a 2-km-wide zone of pervasively ductilely sheared igneous and metamorphic rocks. The proto–Kern Canyon fault was a transpressive structure that accommodated arc-normal shortening and dextral offset from 100 to 80 Ma (Nadin and Saleeby, 2008).

Part of the Kern Canyon fault system near the latitude of the Isabella basin was remobilized as an early to middle Miocene oblique-slip transfer zone between two extensional domains, one at the southernmost end of the San Joaquin basin and the other just east of the Isabella basin (see Fig. 2 for landmarks; see fig. 8 of Mahéo et al., 2009, for extensional domains). The Breckenridge scarp and White Wolf fault segments of the Kern Canyon fault system lie between these extensional domains and are undergoing Quaternary offset, with the notable 1952 M = 7.3 Kern County earthquake attributed to the White Wolf fault. However, focal mechanisms along the Breckenridge scarp, the White Wolf fault, and the Kern Canyon fault segment north of the Isabella basin indicate substantially different styles of modern deformation, which we describe in this paper.

The Kern Canyon fault has long been considered inactive because a 3.5 Ma lava flow (Dalrymple, 1963) was reported to cap its northern end (Webb, 1936). Our recent field investigations reveal that the basalt is pervasively fractured and measurably displaced along the trace

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GSA Bulletin; September/October 2010; v. 122; no. 9/10; p. 1671–1685; doi: 10.1130/B30009.1; 9 figures; 2 tables.

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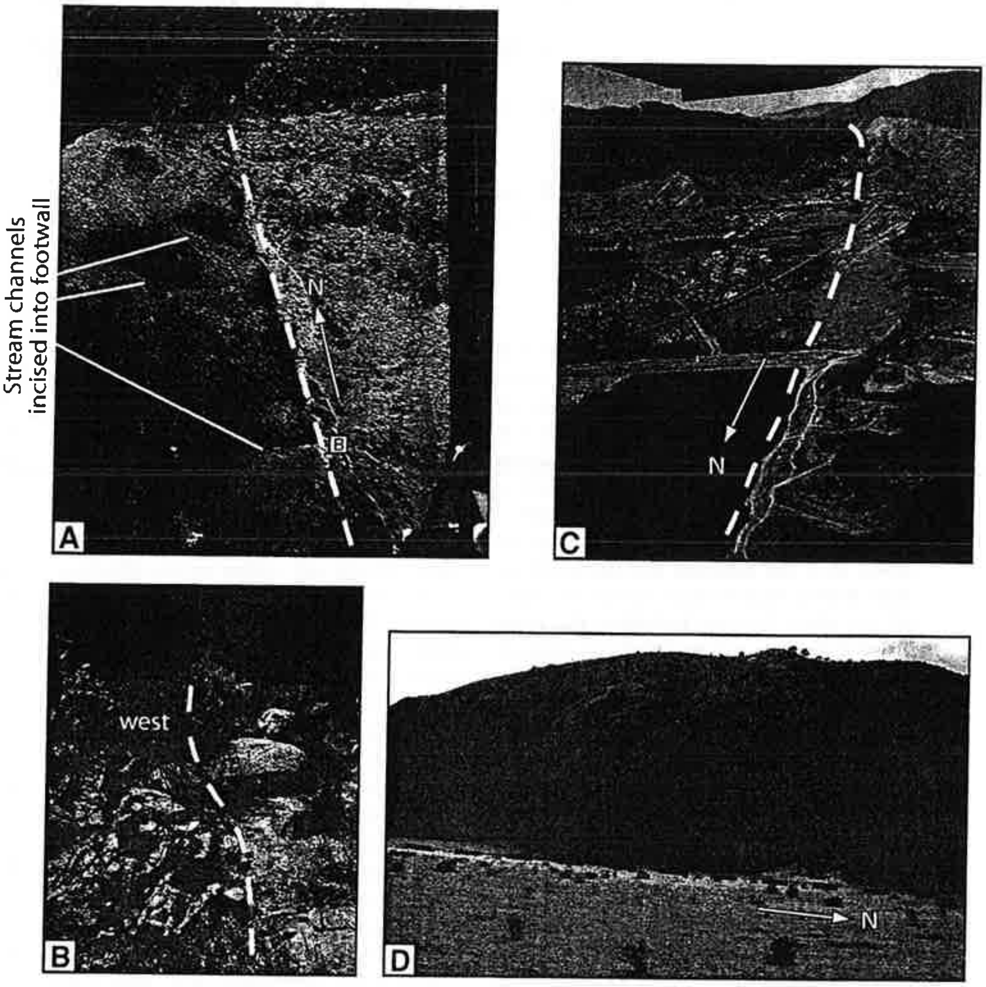

Figure 6. Photographs of some key scarps discussed in the text, with the Kern Canyon fault sketched in as a dashed line for reference. (A) Oblique aerial photograph of an eroded scarp at Rincon Spring (location 6 on Fig. 2) is ~4 m high. Stream channels are deeply incised into the uplifted footwall but do not cross the ponded Quaternary alluvium of the hanging wall. Letter B indicates the location of (B) Cretaceous granitic basement in fault contact with Quaternary glacial debris. The fractures in the granitic basement strike northward, parallel to the strike of the Kern Canyon fault, shown as a white line. (C) Oblique aerial photograph of Engineer Point (location 3 on Fig. 2), a focus of U.S. Army Corps of Engineers (USACE) investigations because it is the site of a dam that crosses the Kern Canyon fault. It is also the fault contact between Cretaceous basement and Quaternary alluvium at the western edge of the Isabella basin, and this fault contact is continuous for 9 km southwards through the town of Lake Isabella and into Havilah Valley. (D) A short scarp (10 m high) forms a basement-alluvium fault contact at the west edge of Havilah Valley (location 2 on Fig. 2). USACE trenching through the hanging wall alluvium in Havilah Valley reveals sediment deformed by liquefaction, and another trench just south of Havilah Valley yielded a 3.3 ka charcoal age in ruptured alluvium (USACE Lake Isabella Dam Situation Report, January 9, 2009; Hunter et al., 2009).

geological literature. The Kern Canyon widens at Little Kern Lake, which formed in 1868 on the west bank of the Kern River when ~0.2 km^3 of rock dammed the river during earthquake-triggered failure (Townley and Allen, 1939; Ross, 1986) of the canyon's eastern slope. South of the lake, more elongate, flat, alluvium-filled meadows line the Kern Canyon fault in the midst of rugged topography.

At latitude ~36.2°N, the Kern Canyon fault leaves the Kern River channel and cuts through a steep, ~450-m-high cliff capped by a 3.5 Ma basalt (Fig. 5A; Webb, 1936, 1946; Dalrymple, 1963; Moore and du Bray, 1978) that is on average ~100 m thick but locally thickens in paleochannels to ~300 m (Dalrymple, 1963). The basalt cap is the most commonly cited evidence for lengthy quiescence of the Kern Canyon fault. Probably because it is only accessible via lengthy, rugged trails or by helicopter, field observations come only from the original reports by Webb (1936, 1946). In these reports, Webb simply stated that a series of lava flows covered the trace of the fault, and that there was no evidence with which to ascertain the nature of movement on the Kern Canyon fault. [Moore and du Bray (1978) subsequently verified Hill's (1955) mapping of the Kern Canyon fault as dextral and estimated offset at 7–13 km, increasing from north to south.] Despite numerous earthquake epicenters in the vicinity of the fault (described in detail in the next section), Moore and du Bray (1978) concluded that there was no measurable offset of the basalt since its deposition. However, they were looking for dextral offset consistent with their observations of offset pluton contacts. Post–3.5 Ma activity along the Kern Canyon fault was thus dismissed (e.g., Jones and Dollar, 1986; Busby-Spera and Saleeby, 1990), despite the seismic activity in the area.

We report here evidence gathered from field investigations facilitated by the U.S. Army Corps of Engineers that the Kern Canyon fault displaces the basalt cap. As seen from the air, the lava surface is broken by a sharp topographic notch of ~20 m height on the west side of the Kern Canyon fault trace (Fig. 5A). On the ground in this location, generally coherent outcrops west of the fault end abruptly in a gully where deeply weathered basalt is pervasively sheared and fractured parallel to the trace of the Kern Canyon fault, resulting in an apparent west-side-up scarp of ~2 m height (Fig. 5B). Because the topographic break along the trace of the fault is deeply weathered, the fault here is expressed as a zone of pervasive fracture ~50 m

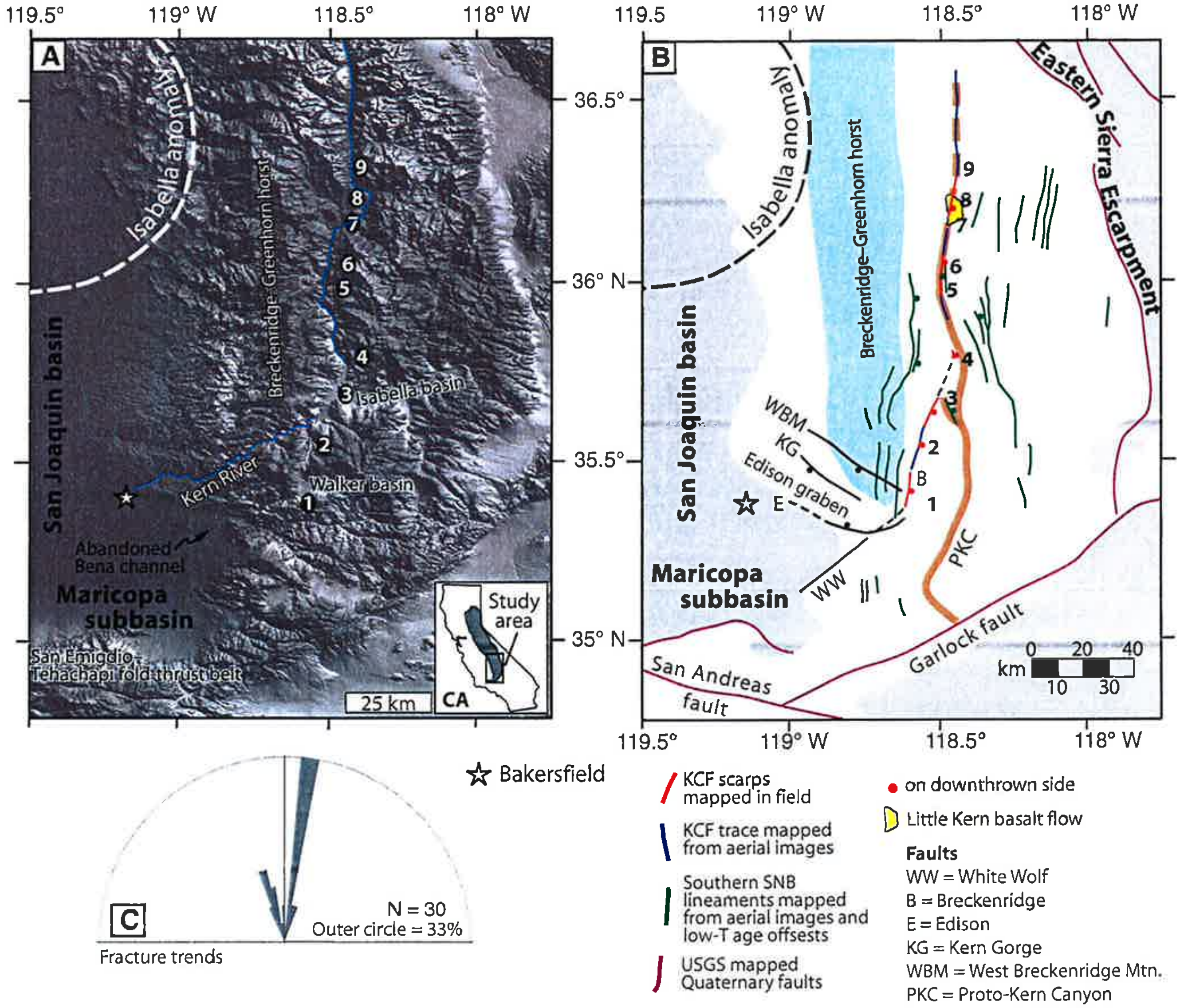

Figure 2. Digital elevation model (DEM, A), fault and lineament map (B), and rose diagram of faults and lineaments (C) of the southern Sierra Nevada. Both the DEM and the fault map show numbered locations of scarps mapped in the field and described in Table 1, as well as the outline of the surface projection of the "Isabella anomaly," discussed in detail in the text. (A) The DEM is labeled with sparse geographic information so that the reader can examine its topography. (B) The 30 faults and lineaments shown here were mapped in the field and from aerial and advanced spaceborne thermal emission and reflection radiometer images, and are represented in the rose diagram of (C). USGS—U.S. Geological Survey.

sheared, and altered over a width of ~150 m. For 60 km north of the Isabella basin (Fig. 2, at latitude 35.7°N), it is a north-south–striking brittle structure that overprints a mylonite zone termed the proto–Kern Canyon fault (Figs. 1 and 2B; Busby-Spera and Saleeby, 1990).

The proto–Kern Canyon fault is a Late Cretaceous structure that, along with several other ductile shear zones in the central to southern Sierra Nevada, arose in response to changes in subduction trajectory of the Farallon plate beneath the California region (Busby-Spera and Saleeby, 1990; Tikoff and Greene, 1994; Greene and Schweickert, 1995; Tobisch et al., 1995; Tikoff and Saint Blanquat, 1997). The proto–Kern Canyon fault is a dextral reverse-slip fault exposed along an oblique crustal section that traverses ~25 km of batholithic emplacement depths from its northern to its southern end (Pickett and Saleeby, 1993; Nadin and Saleeby, 2008). It is ~150 km long and up to 2 km wide. Foliation within the shear zone dips steeply to the west and to the east. North of the Isabella basin to latitude ~36.1°N, ductile fabrics strike northward. South of the basin, they follow a slightly sinuous southeastward trajectory (Fig. 2B) and eventually root into lower-crust tectonites of the Rand thrust system, exposed immediately north of the Garlock fault (Nadin and Saleeby, 2008).

FIELDTRIP GUIDE TO THE METAMORPHIC FRAMEWORK ROCKS OF THE LAKE ISABELLA AREA, SOUTHERN SIERRA NEVADA, CALIFORNIA

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INTRODUCTION

Metamorphic framework rocks of the southern Sierra Nevada occur primarily as N to NW striking, steeply dipping septa, within or separating granitoid plutons. The Lake Isabella area offers an excellent opportunity to study some of the interesting structural and stratigraphic problems posed by the southern Sierra framework rocks. Figure 1 is a generalized geologic map of the Lake Isabella region which focuses mainly on the metamorphic framework rocks. The map is derived primarily from our detailed mapping which was based on several earlier field studies. The general distribution of the major igneous and metamorphic units of the region was originally mapped by Miller and Webb (1940) with contributions by Jenkins (1961) and Alvarez (1962). Miller and Webb (1940) termed the distinctive quartz-rich metasedimentary rocks and marble of the region the Kernville series. Detailed mapping immediately adjacent to Lake Isabella by L.E. Weiss (unpublished data) revealed some of the complex deformation patterns in rocks of the Kernville Series, and also led to the discovery of the only fossil locality of the region. In later regional studies Saleeby and others (1978) noted that the Kernville Series and newly discovered silicic metavolcanic rocks of the area were similar to the Kings sequence of the central Sierra as defined by Bateman and Clark (1974). Metamorphic framework rocks referred to as the Kings sequence by these workers consist of quartz-rich metasedimentary strata, marble, local pelite and scattered intervals of silicic metavolcanic rocks forming numerous steeply dipping septa in the central part of the range. Recognizing that regional workers are more familiar with Kings sequence rocks of the central Sierra, Saleeby and others (1978) suggested that Kernville Series rocks be termed Kings sequence, and that such rocks also extend southward from the Lake Isabella area to the southern terminus of the range. Thus the Kings sequence extends for ~300 km along the axis of the Sierra Nevada, and constitutes one of the major framework elements of the range.

The purpose of this fieldtrip is to present an overview of the structure and "stratigraphy" of the Kings sequence in the Lake Isabella area, and to focus attention on four topics of regional interest:

1. All fossil ages reported thus far from the Kings sequence are early Mesozoic in age, mainly Late Triassic to Early Jurassic (Christensen, 1963; Jones and Moore, 1973; Saleeby and others, 1978; Busby-Spera, 1983). Bateman and Clark (1974) and Saleeby and others (1978) suggested that such ages may represent the general age span of all Kings sequence rocks. Based on regional considerations, however, one would expect to find Paleozoic shelfal strata along the axial Sierra Nevada region. Thus far Paleozoic ages are only known from the western metamorphic belt and from roof pendants of the east-central Sierra (Bateman and Clark, 1974; Saleeby, 1979; Sharp and others, 1982). During the fieldtrip we will discuss whether or not any elements of the Kings sequence from the Lake Isabella region may be Paleozoic in age. The early Mesozoic fossil locality is from a very representative part of the "section," and thus significant Paleozoic elements seem unlikely.

2. Silicic to intermediate metavolcanic rocks of the axial and eastern Sierra are generally interpreted as the products of an early Mesozoic Andean arc. Deformation of these rocks is commonly attributed to Late Jurassic orogenesis that distinctly pre-dated the emplacement of the Sierra Nevada batholith. Our field and geochronological studies in the Lake Isabella region show that the metavolcanic rocks of this region were erupted unconformably above largely nonvolcanic Kings sequence strata during the mid-Cretaceous and then deformed in mid- to Late Cretaceous time.

3. The development of pervasive metamorphic tectonite fabrics and isoclinal folds in Sierran metamorphic framework rocks are generally interpreted as regional orogenic deformations that distinctly pre-dated the emplacement of the Sierra Nevada batholith. In this context batholith-related metamorphism has been regarded as a static overprint imparted on the earlier regional fabrics. Our work in the Lake Isabella region shows, however, that metamorphic tectonites developed during batholith emplacement, when steeply-plunging stretching and steeply-dipping flattening fabrics tightened pre-existing folds into isoclinal geometry. One explanation for such deformation patterns is the downward return flow of framework septa dynamically linked to silicic magma ascent (Saleeby and others, 1986).

4. Deformational and metamorphic fabrics related to mid-Cretaceous batholith emplacement and earlier orogenic deformation were transposed into greenschist facies phyllonites and mylonites in Late Cretaceous time along a north-south trending belt inferred to represent the proto-Kern Canyon fault. North of Kernville the phyllonite belt

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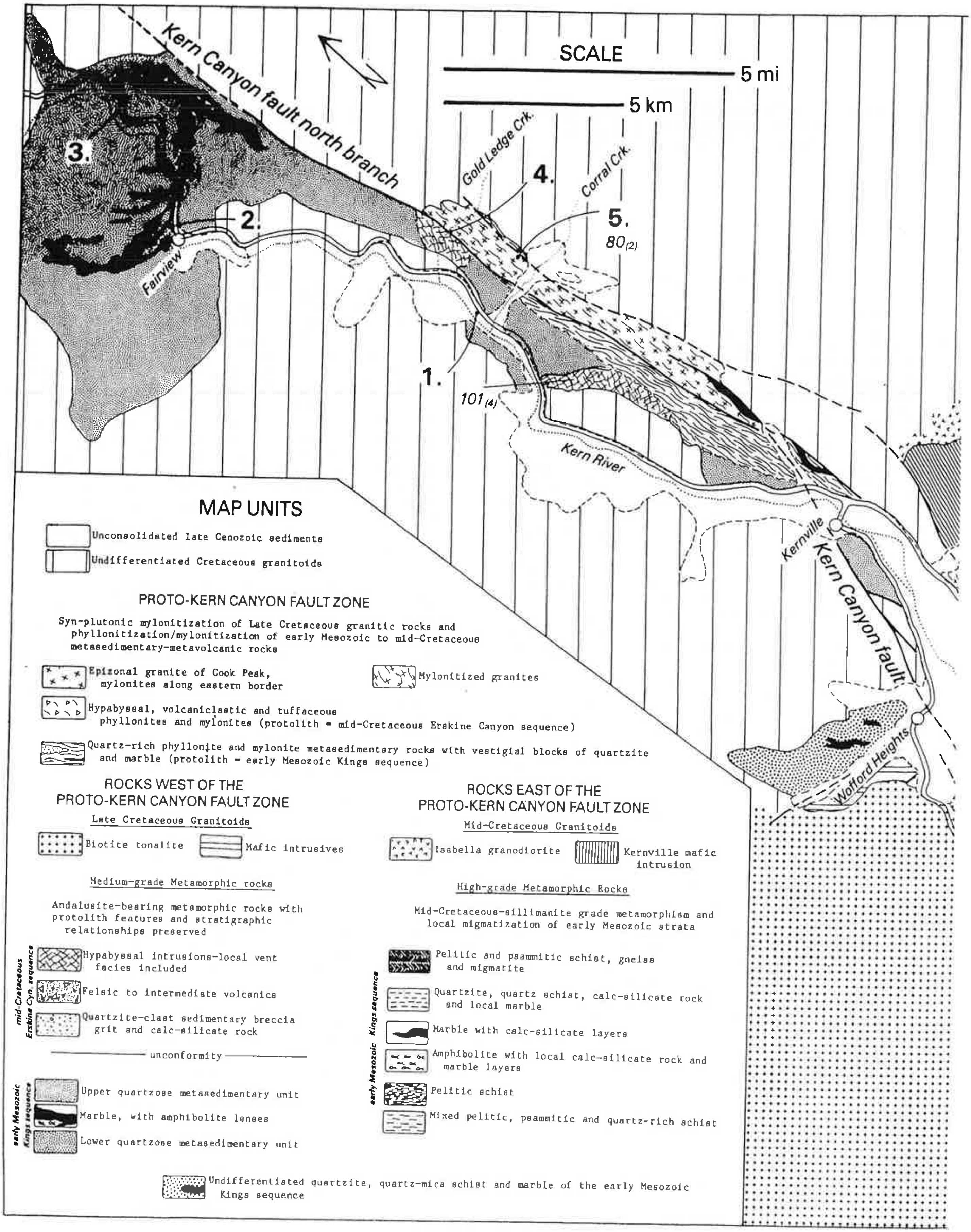
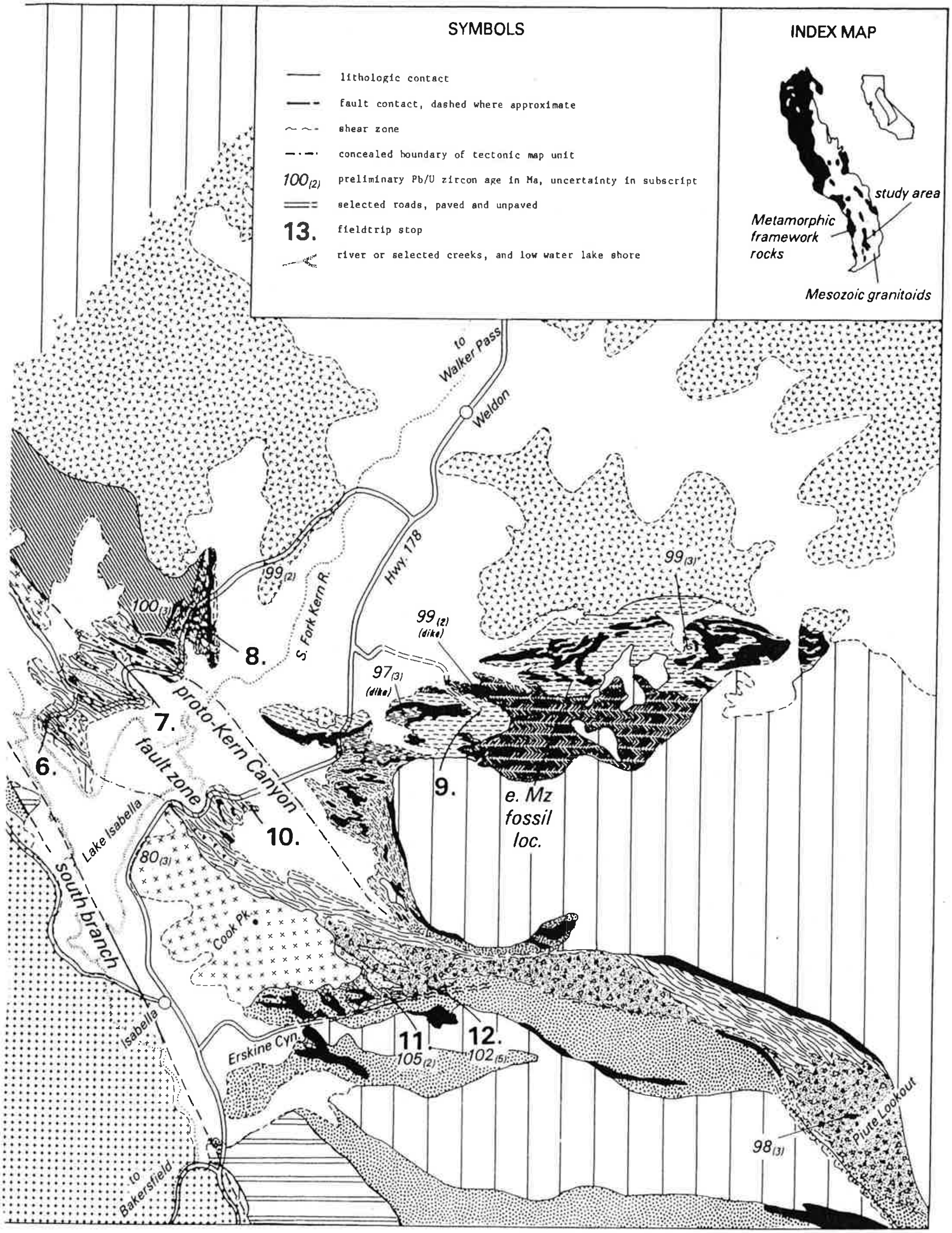

SCALE
5 mi
5 km
Kern Canyon fault north branch
Gold Ledge Crk.
Corral Crk.
3.
2.
4.
5.
80(2)
1.
101(4)
Fairview
Kern River
Kernville
Kern Canyon fault
Wofford Heights
MAP UNITS
Unconsolidated late Cenozoic sediments
Undifferentiated Cretaceous granitoids
PROTO-KERN CANYON FAULT ZONE
Syn-plutonic mylonitization of Late Cretaceous granitic rocks and phyllonitization/mylonitization of early Mesozoic to mid-Cretaceous metasedimentary-metavolcanic rocks
Epizonal granite of Cook Peak, mylonites along eastern border
Mylonitized granites
Hypabyssal, volcaniclastic and tuffaceous phyllonites and mylonites (protolith = mid-Cretaceous Erskine Canyon sequence)
Quartz-rich phyllonite and mylonite metasedimentary rocks with vestigial blocks of quartzite and marble (protolith = early Mesozoic Kings sequence)
ROCKS WEST OF THE PROTO-KERN CANYON FAULT ZONE
Late Cretaceous Granitoids
Biotite tonalite
Mafic intrusives
Medium-grade Metamorphic rocks
Andalusite-bearing metamorphic rocks with protolith features and stratigraphic relationships preserved
mid-Cretaceous Erskine Cyn. sequence
Hypabyssal intrusions-local vent facies included
Felsic to intermediate volcanics
Quartzite-clast sedimentary breccia grit and calc-silicate rock
unconformity
early Mesozoic Kings sequence
Upper quartzose metasedimentary unit
Marble, with amphibolite lenses
Lower quartzose metasedimentary unit
ROCKS EAST OF THE PROTO-KERN CANYON FAULT ZONE
Mid-Cretaceous Granitoids
Isabella granodiorite
Kernville mafic intrusion
High-grade Metamorphic Rocks
Mid-Cretaceous-sillimanite grade metamorphism and local migmatization of early Mesozoic strata
early Mesozoic Kings sequence
Pelitic and psammitic schist, gneiss and migmatite
Quartzite, quartz schist, calc-silicate rock and local marble
Marble with calc-silicate layers
Amphibolite with local calc-silicate rock and marble layers
Pelitic schist
Mixed pelitic, psammitic and quartz-rich schist
Undifferentiated quartzite, quartz-mica schist and marble of the early Mesozoic Kings sequence


SYMBOLS
lithologic contact
fault contact, dashed where approximate
shear zone
concealed boundary of tectonic map unit
100(2) preliminary Pb/U zircon age in Ma, uncertainty in subscript
selected roads, paved and unpaved
13. fieldtrip stop
river or selected creeks, and low water lake shore
INDEX MAP
study area
Metamorphic framework rocks
Mesozoic granitoids
to Walker Pass
Weldon
Hwy. 178
S. Fork Kern R.
99(2)
100(3)
8.
7.
6.
proto-Kern Canyon fault zone
99(2) (dike)
97(3) (dike)
99(3)
9.
e. Mz fossil loc.
10.
Lake Isabella
south branch
80(3)
Cook Pk.
Isabella
11
12.
105(2)
102(5)
Erskine Cyn.
98(3)
Piute Lookout
to Bakersfield

(mainly Cretaceous) plutonic rocks of the upper Kern Canyon that suggest a southward increase in right-lateral slip, with up to 13 km of displacement just north of the Figure 1 map area. Reliable slip indicators in or south of the map area have not been recognized.

The Kern Canyon fault has been broken into two branches in the study. The north branch separates Cretaceous granitic rocks from the Kernville-Fairview framework septum. The south branch truncates small remnants of septa, but runs mainly through batholithic rocks. These batholithic rocks, like those studied to the north of the map area by Moore and duBray (1978), show a narrow zone of brittle deformation along the trace of the fault. We present evidence here for Late Cretaceous ductile deformation of granitoids along the north branch of the Kern Canyon fault and its southern extension along the phyllonite belt of the proto-Kern Canyon fault zone. From the north shore of Lake Isabella northward to Gold Ledge Creek (and possibly beyond) we have mapped thin, discontinuous mylonitic granite bodies. These show recrystallization of microcline, suggesting deformation at a relatively high temperature, probably as the granites cooled and solidified. One of the granitic mylonites, named here the Gold Ledge granite (Fig. 1), has yielded a zircon age of 80 Ma.

Kings sequence rocks exposed along the Kern Canyon fault between Kernville and Corral Creek (Fig. 1) contain superimposed phyllonitic cleavage and shear surfaces. The phyllonitic belt is roughly coextensive with the mylonitic granitoids, with both diverging eastward from the modern Kern Canyon fault south of Kernville. The belt of phyllonitic rocks south of Kernville is believed to be the southern branch of the proto-Kern Canyon fault. This belt of rocks in the area of the lake consists primarily of siliceous phyllonites derived from quartz-rich clastic rocks. Lenses of mylonitic quartz sandstone and porphyritic metavolcanic or meta-hypabyssal rock are encased within the siliceous phyllonites along with lenses of phyllonitic metavolcanic - meta-hypabyssal rock and marble. The phyllonitic cleavage is superimposed over high-grade metamorphic fabrics of D2 and, as mentioned above, the cleavage is also observed to overprint D1 structures north of Kernville. The phyllonitic belt runs southward through the Erskine Canyon area where it becomes the main deformation fabric in the Erskine Canyon sequence. This deformation belt continues to the southern end of the Figure 1 map area where it is the main fabric in the Puite Lookout ashflow unit. Additional mylonitic granitoids and deformed Kings sequence rocks continue southward from the Puite Lookout area.

The phyllonite belt and zones of mylonitic granitoids are believed to represent the proto-Kern Canyon fault zone. This zone coincides with the north branch of the fault, but diverges from the south branch. The relative importance of the proto-fault zone versus the modern branches of the system in terms of net slip are unknown. It is clear that the proto-fault zone resulted in a tremendous amount of structural relief between the mid-Cretaceous volcanic and hypabyssal rocks to the west (Erskine Canyon sequence) and coeval plutonic rocks and related high-grade metamorphic derivatives of the Kings sequence to the east.

ROADLOG

The twelve stops planned for the field trip are labeled on Figure 1. Additional helpful maps include the Bakersfield Sheet (1:250,000) of the Geologic Map of California (Smith, 1964), and the Kern County roadmap published by the Automobile Club of Southern California. The road log begins at the eastern edge of the town of Kernville at the "T" intersection of Sierra Way and Kernville Road. Driving north on Sierra Way from the intersection, numerous roadcut exposures of moderate- to low-dipping Kings sequence are passed. These beds represent the upper map unit of the western Kings sequence assemblage. The first stop is at 7.9 mi prior to a relatively sharp right-hand bend in the road. Narrow parking areas are available off the shoulder of the road on both sides.

Stop 1

This stop is intended to provide a sampling of turbidites from the upper quartz-rich map unit of the Kings sequence western assemblage. An upward-thinning and upward-fining sequence of turbidite beds (7 m thick) is well-exposed along the shore of the Kern River here. The thick beds can be classified as Mutti and Ricci-Lucchi turbidite facies A and B, and the thin beds show Bouma divisions a and b. Siliceous argillites cap each bed; these are deformed into flame structures and rip-up clasts by overlying beds (Fig. 2D). This upward-thinning sequence may represent the fill of a deep marine channel. Metasedimentary rocks stratigraphically below these turbidites, between the highway and the Kern Canyon fault, are calcareous quartzites and marbles, with locally preserved medium-scale cross-lamination. These probably represent a shallow marine facies.

The coarse- to medium-grained sandstones at this locality are dominantly composed of monocrystalline and polycrystalline quartz, but subordinate plagioclase and potassium feldspar are present. The fine-grained sandstones are recrystallized to felsite with opaque minerals, sericite and biotite. Dark greenish beds contain concentrations of calc-silicate minerals suggesting an original calcareous cement. In thin section, the monocrystalline quartz grains commonly show marginal recrystallization, with some grains nearly completely recrystallized. Fine-grained quartz also replaces feldspars along cleavage and margins of grains, and there is sericitization of the potassium feldspar. Much of the quartz is strained, and some is ribboned. The recrystallization of the quartz makes it difficult to determine whether or not any grains were originally polycrystalline and of a sedimentary or felsic volcanic source. The presence of plagioclase and potassium feldspar, as well as relict monocrystalline quartz, suggests that the provenance of these sandstones is at least in part igneous.

A moderately well-developed cleavage lies subparallel to bedding at this locality (N40W, 25 SW). In thin section this structure is seen to be primarily a solution cleavage. The cleavage is crenulated by a vertical, N20W cleavage (barely visible here) that becomes progressively stronger toward the Kern Canyon Fault to the east.

Return to vehicles and continue north. At 15 mi (from original intersection) Fairview Forest Service Campground is reached. Pull off in overflow parking area on northwest side of road.

Stop 2

This stop is intended to serve as an overview and discussion of the Fairview area Kings sequence and to prepare observers for the drive through the steep canyon walls leading to Stop 3. Looking northwestward across the Kern River excellent exposures of generally EW trending marble and quartzite can be observed. The orientation of these beds is controlled by D1 structures. Looking northeastward some complex contact patterns can be seen in thick marble beds. Many of the complex patterns are too small-scale to show on Figure 1. The patterns result from the interference of D1 and D2(?) structures. As noted above the D1 structures of this region are transposed by NNW trending structures believed to be D2, but the transposition structures could possibly be related to D3. The actual transposition zone is out of view from Stop 2.

Continuing northward another 2.7 mi (total = 17.7 mi) a sharp right hand bend in the road and river is encountered and then a left hand bend. Stop 3 is planned for the area between the two bends; however, parking may be difficult off the right side of the road. It is suggested that you drive another 0.6 mi to Limestone Forest Service Camp and turn around. Driving southward abundant parking is available just prior to the first bend or at the second bend.

Stop 3

This stop is intended to provide a sampling of the lower quartz-rich unit of the western assemblage. Excellent exposures are present along the shore of the river and in the adjacent road cut. Looking across the river one can assess the bedded nature of this unit with the distinct NW-trending ridges forming the sharp bends in the river due to resistant thick recrystallized quartzite beds. The thick beds are virtually 100 percent quartz. Darker and thinner quartz-rich and more argillaceous beds constitute much of the section here. The compositions of the sands are overwhelmingly quartzose with a dominance of monocrystalline grains. Most grains are strained and many have recrystallized margins. Dark and maroon impurities in the sandstone beds and in finer-grained interbeds are dominated by biotite + muscovite ± minor calc silicate minerals. Detrital plagioclase occurs as a minor component. A 1 m thick plagioclase phyric felsic tuff bed in this section lies on the west side of the river. Excellent preservation of detrital textures can be observed along stream-polished exposures on the southeast side of the river.

Sedimentary facing indicators are present in the polished stream exposures on the northwest side of the river. These include graded and amalgamated beds with scoured bases and current ripples, all indicating a southward facing direction. Many of the thinner beds (<1 m) of this unit exhibit features suggestive of turbidite deposition much like strata of Stop 1. The thick, massive quartzite interbeds are somewhat of an enigma becuase they appear to be purer in quartz detritus. Perhaps they represent grain flow deposits shed into the turbidite sequence from a slightly different source area.

Cleavage surfaces are developed mainly in argillaceous interbeds. The orientation of most of these surfaces is that typical of D2. However, a clear overprint pattern has not been observed in the area of Stop 3, and the cleavages may be rotated D1 structures.

Return to vehicle and continue driving south for 5.5 mi. Turn left on dirt road ("Bryn Canyon"). The turn is about 100 yards north of Gold Ledge Forest Service Campground, if it is missed on the first pass. The unpaved road runs parallel to the highway; after a short distance it curves east. Continue 0.5 mi to where two roads (5A and 5B) branch off to the left and take the second one (5B). Continue to the end of the road (0.3 mi) and park. A small trail continues east from the right side of the flume about two hundred yards to the north-south creek along the Kern Canyon fault. Walk south along the creek.

Stop 4

This stop focuses on the Kern Canyon fault and evidence of a Late Cretaceous component of movement. Here, a hypabyssal intrusion (mapped as metamorphic rocks on the Bakersfield sheet) lies west of the Kern Canyon fault, and the Gold Ledge mylonitic granite lies to the east. The hypabyssal intrusion has a patchy porphyritic texture with plagioclase phenocrysts set in a dark green microcrystalline groundmass. Mafic dikes are common. Within several meters of the fault, the hypabyssal intrusion is cut by many interconnected fracture planes. A crush-breccia zone ~10 m wide marks the trace of the fault and includes three rock types: the hypabyssal intrusion, the Gold Ledge granite, and small pods of metasedimentary rock.

Along the east margin of the crush zone, we will examine ultramylonitic textures in the Gold Ledge granite. There has been severe grain size reduction, recrystallization of potassium feldspar as well as quartz, and mafic minerals are destroyed. As one traverses eastward away from the fault, the grain size gradually becomes coarser, the recrystallization and realignment of potassium feldspar decreases, and biotite is progressively better preserved. At other localities, to the south (Fig. 3A), folded, strongly foliated and partially recrystallized felsic dikes lie within 20 m of the fault. Ductile deformation of the Gold Ledge mylonitic granite provides evidence for movement of the proto-Kern Canyon fault as the pluton cooled and solidified. Zircon ages on the granite indicate intrusion and fault movement of ~80 Ma.

Note: The granite float with the K-spar megacrysts is from the pluton that cross-cuts, locally engulfs and, to the north, obliterates the mylonitized Gold Ledge granite (Fig. 1). This granite is cut by the narrow crush-breccia zone but is not mylonitized. Geochronological work is in progress on the cross-cutting granite.

Return to Sierra Way and turn south (left) and continue back towards Kernville. At 2.5 mi from the return point onto the paved road, leave the highway by turning left onto an unpaved road to the

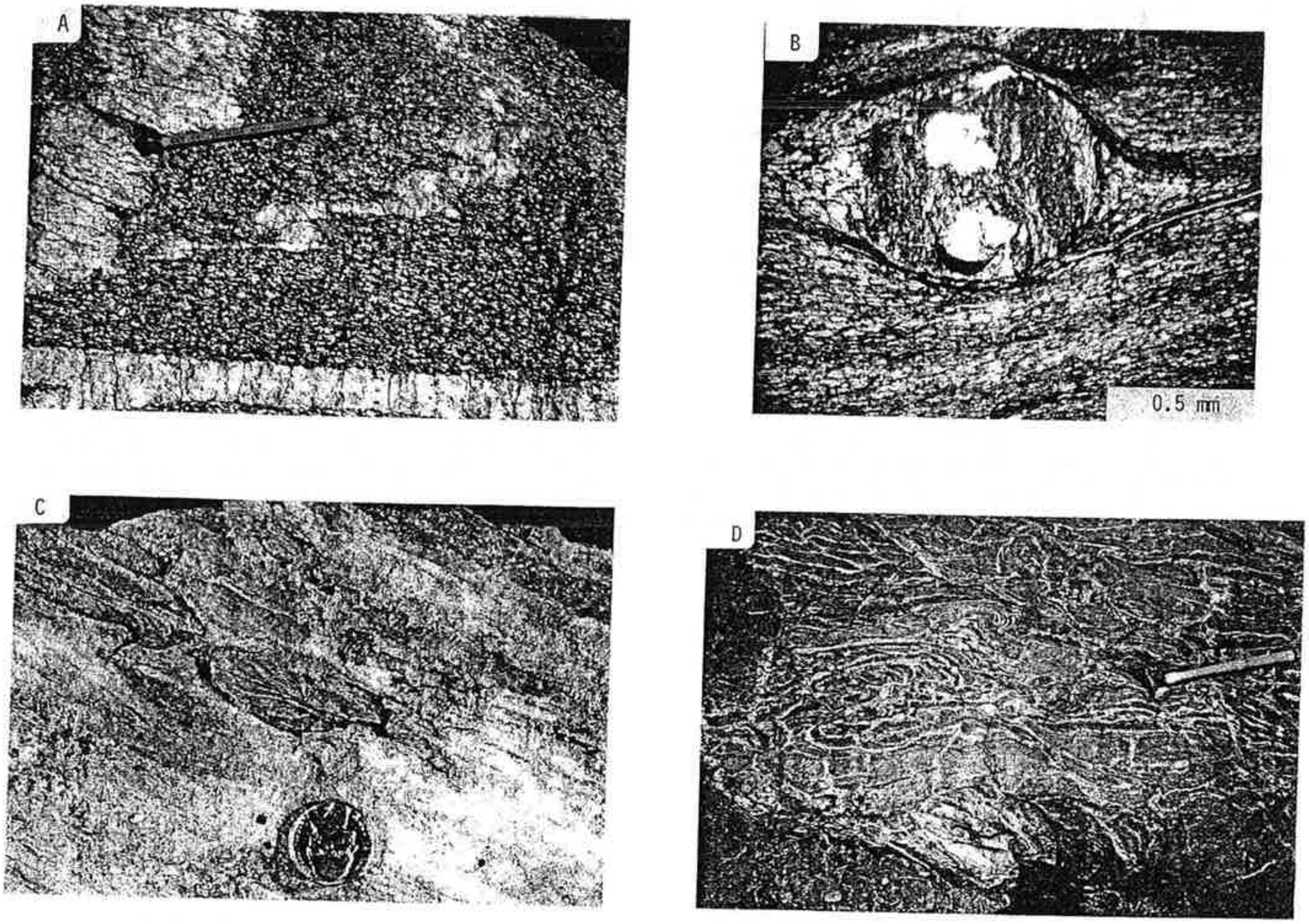


Figure 3. Assortment of field shots and photomicrograph. A: Folded and mylonitized felsic dikes within Gold Ledge mylonitic granite. B: Photomicrograph of relict and andalusite porphyroblasts set as partially retrograded porphyroclast within pelitic phyllonite, crossed nicols. C: Distorted bivalves from Kings sequence preserved on cleavage surface. D: Deformed migmatite from pelitic-psammitic unit of eastern assemblage of Kings sequence.

east that runs parallel to the highway for 0.4 mi. Continue east 0.8 mi more (past road cut in metasedimentary rocks) and take the left fork across Corral Creek (0.2 mi) to the right fork that continues up the north side of the creek. Go 0.3 mi and park; walk down to the creek and cross the small bridge.

Stop 5

This is a very accessible place to view the Gold Ledge granite at a distance of 0.5 km from the Kern Canyon fault. Although a foliation is defined by alignment of quartz, feldspars and biotite, there is no grain size reduction of feldspars, or alteration of mafic minerals, except along thin (cm-scale), spaced zones of mylonitic shear. Felsic dikes are generally sub-parallel to the foliation and none are folded. Schlieren are well-preserved and are also oriented parallel to foliation. The 80 Ma U-Pb zircon age sample was collected here. This relatively undeformed granite can be walked, with continuous exposure, through progressively greater degrees of mylonitization toward the Kern Canyon Fault at this and numerous other localities.

In this area, a long thin belt of metasedimentary rock lies in fault contact with the eastern boundary of the Gold Ledge granite; these in turn are intruded on the east by the granite that truncates the Gold Ledge granite north of Gold Ledge Creek (Fig. 1) The calc-silicates that make up this small pendant are thoroughly mylonitized.

Return to Sierra Way, turn left (south) and go back into the town of Kernville. At the "T" intersection of Sierra Way and Kernville Road begin logging the mileage as you continue south on Sierra Way. At 4.7 mi turn right on paved road that leads down to the lake. At about 0.6 mi park on either side of the road.

Stop 6

This stop focuses on vestigial blocks of quartz-rich sandstone and volcanic or hypabyssal rock within the phyllonite unit. The phyllonite matrix is only locally exposed in this area, but roadcuts between Stops 6 and 7 and outcrops at Stop 10 offer excellent exposures for examination. Time permitting, we will hike to the top of hill 3066, the high rounded hill to the south of the road.

Upon walking up the north slope, numerous outcrops of deformed quartz-rich rocks are encountered. Varieties include: 1) knobby outcrops with well-preserved detrital textures, some with distinct blue quartz grains; 2) felsic mylonite with flat-lying lineations; 3) bedded sandstone with steeply-plunging tight folds; and 4) blocks of bedded sandstone with EW bedding and cleavage (D1) attitudes crossed by NNW D3 cleavage surfaces. At the top of the hill, a well-exposed quartz sandstone block shows remnants of a D1 fabric cut by spaced D3 cleavage surfaces. Traversing down to the northeast towards the gully, fragments of mylonitic porphyritic felsite are encountered. Strong deformation in this area makes it impossible to resolve a volcanic versus hypabyssal origin for the felsites.

Return to vehicles and drive back to intersection with Sierra Way. Turn right (south) and continue driving through the phyllonite belt. The sharp point at about 1.4 mi is the terminus of a large vestigial slab of Kings sequence quartzites, similar to rocks at and in the vicinity of Stop 1. The slab forms the major resistant NNW-trending ridge north of the road. At 1.7 mi turn left (north) onto the unpaved road that heads up an alluviated drainage area. Go through gate and leave it as it was found. Drive 1.1 mi to sharp switchback and park.

Stop 7

At this stop we will traverse from the margin of a large amphibolite unit of the high-grade eastern assemblage westward into the phyllonite zone. The amphibolite constitutes the single largest mafic metamorphic body within the area of Figure 1. It is typically a dense, dark, moderately banded plagioclase + green hornblende ± diopside ± quartz ± calcite rock with local thin layers of marble and calc-silicate rock. Coarse crystalloblastic textures developed during the main foliation forming event (D2), along with steeply-plunging, tight, commonly intra-folial folds. Continuity of fabrics and structures with those of Stop 8, and similar spatial relations between amphibolite lenses of the south shore and features of Stop 9, indicate a D2 origin for the amphibolite fabric and related structures. The east margin of the large amphibolite unit is in contact with marble and with pelitic to quartz-rich schist. The overall massive character of the amphibolite, in conjunction with little evidence of reaction with neighboring metasedimentary rocks, suggests an igneous versus metasomatized sedimentary origin for the amphibolite. Local layers of marble and calc-silicate rock suggest a bedded protolith sequence with a volcanic origin for the mafic rocks. Local lenses of similar amphibolite but with relict hypabyssal textures occur in metasedimentary units to the east. They may represent shallow-level intrusives related to the metabasalt protolith of the larger amphibolite unit. The amphibolite unit in the Fairview area (western assemblage) contains both hypabyssal and volcanic protolith features as well.

Traversing westward from the interior of the amphibolite unit, a homoaxial ductile deformation fabric reduces the coarse crystalloblastic fabric to a protomylonitic to phyllonitic fabric with retrograde growth of biotite and chlorite. This superposed fabric is present primarily along the southwest margin of the amphibolite and is related to D3 fabric development in the adjacent phyllonite belt. The amphibolite is bounded on the southwest by pelitic to psammitic phyllonitic rocks. A conspicuous white metaquartzite lens runs along much of the contact. Quartz grains within the lens show extreme ductile deformation and marginal recrystallization. Traversing up the unpaved road from the quartzite a couple of marble lenses within the phyllonite can be seen. Throughout the phyllonite unit such marble lenses have fabrics showing ductile deformation and grain size reduction of previously coarsely recrystallized calcite (D3 overprinting D2). Farther up the road, relict andalusite porphyroblasts in phyllonitic pelitic rocks occur as retrograded porphyroclasts (Fig. 3B). This is again related to a D3 overprint on D2 metamorphic fabrics.

Return to vehicles and drive back out to the paved road. Turn left (east) and continue for 1.8 mi and then park at broad turnout on right.

Stop 8

This stop presents some of the high grade metamorphic and plutonic features associated with the D2 event. From the parking area walk up the small hill just to the right of the road. Within about 100 yards you will encounter coarsely recrystallized banded pelitic granofels with deep red garnet porphyroblasts. The mineralogy of this rock is garnet + biotite + sillimanite + cordierite + plagioclase + K-feldspar + quartz. Granofelsic or migmatitic fabrics occur in the pelites within about 50 m of the contact with the mid-Cretaceous tonalite-gabbro Kernville pluton. Contact metamorphic textures are typically strongly schistose, however. Cordierite and K-feldspar are lost and andalusite coexists with sillimanite 1 km to the west just along the east side of the amphibolite unit.

Looking northward across the road one can easily spot the Kernville pluton (named by Miller and Webb, 1940). The core phase of the pluton consists of hornblende leucogabbro and pyroxene-hornblende gabbro. The outer phase grades between hypersthene quartz diorite and granodiorite with tonalite predominating. Zircon ages of 100 ± 3 Ma have been obtained on tonalitic and quartz dioritic phases. Across the road one can also see a tightly folded marble which occurs as an infold of the metasediments in the edge of the pluton. The contact between the pelite and a mixed pelitic, psammitic and quartz schist unit to the west also shows the geometry of the infold. Looking due west towards the point that terminates the south-trending hilly ridge against the lake, isoclinally folded marble layers are visible as light grey streaks. Relationships between metamorphic textures and fold structures of the marble show that much of the strain is linked to the metamorphic peak.

Next, carefully drop down into the roadcut watching closely for cars and trucks. Just above the roadcut you will have crossed a poorly exposed contact between the pelite and the Kernville pluton. Within the roadcuts, excellent exposures of xenolith-rich tonalite can be observed. The xenoliths were derived from pelitic and psammitic schist of the wallrocks. Contamination of the mafic to tonalitic magma with such wallrock exposures of the matrix material for the phyllonite belt yet discovered. Here the steeply-dipping D3 planar fabric of the phyllonite produces tombstone-like exposures. The phyllonite consists of fragmented and ductilely-deformed quartz grains showing marginal recrystallization of porphyroclasts and widespread recrystallization of fine matrix material. The dark color of the rock results from fine granulation of biotite and, locally, aluminosilicates that developed during the D2 metamorphic peak. White mica and, locally, chlorite are observed as retrograde phases growing along the D3 fabric. Steeply-plunging dextral sense kink folds are superimposed over the D3 phyllonitic fabric. Such kink folds are also mapped in marble layers which occur within the phyllonite. Most of the phyllonite appears to have been derived from the quartz-rich and pelitic rocks of the Kings sequence. However, lenses of porphyritic felsic to intermediate meta-igneous rock occur in the Stop 10 area as in the north shore (Stop 6).

Looking westward from Stop 10 the east margin of the ~80 Ma Cook Peak granitic pluton can be observed. This pluton represents an epizonal intrusion that was emplaced along the proto-Kern Canyon fault zone during its movement history. The pluton's eastern contact with the phyllonite belt is in some places a thin mylonite zone, and elsewhere a brittle shear zone. Brittle shear zones also overprint the D3 fabric in numerous locations throughout the phyllonite belt.

Return to vehicles and continue driving westward on Highway 178. After about 4 mi you will enter the town of Isabella. Drive southward on Lake Isabella Blvd., the main street through town. From the center of town, the Kernville Rd.-Lake Isabella Blvd. intersection, drive 0.8 mi south and then turn left (southeast) on Erskine Creek Rd. Drive 4.5 mi and then park in clearing on south side of road past ruins of an old building.

Stop 11

This stop focuses on quartzite clast sedimentary breccia and grit, calc-silicate rocks, and penecontemporaneous hypabyssal intrusives of the Erskine Canyon sequence. Walk northward across Erskine Creek and enter the mouth of the sharp canyon cut into the steep south-facing slope. As you cross the creek you may notice a large rhyolitic float block with remnants of peperite. This stop will consist of a traverse up the steep canyon as far as possible and then out of the canyon westward across a steep talus slope. Along the steep slopes the remnants of an unconformity between the basal breccias of the Erskine Canyon sequence and the underlying Kings sequence can be observed. In most places the unconformity is obliterated by hypabyssal intrusions of the Erskine Canyon sequence.

The quartzite-clast breccias of the Erskine Canyon Sequence have angular to subrounded clasts of quartzite (with folded cleavage) and vein quartz, up to 70 cm in size, supported in a meta-argillite (quartz, biotite and garnet) or meta-calcareous mudstone matrix. Stratification is generally lacking or very crudely developed; however, the occasional graded bed or sets of graded beds with scoured bases provide evidence that: 1) the section is upright (N40-50W, 45NE) and 2) deposition was subaqueous (lacustrine or marine). The coarseness and angularity of the debris, as well as the restricted clast types, suggests accumulation at the base of a fault scarp. Penecontemporaneous rhyolite volcanism provides evidence that this basin was a volcano-tectonic depression.

The quartzite-clast debris deposits, and interstratified argillites and calcareous mudstones, form the host sediment for well-developed peperites on the margins of rhyolite sills and dikes in Erskine Canyon. Peperite is defined as the product of interaction between magma and wet sediment. Wet, unlithified sediment and pressures of less than 200 bars (that is, a maximum of 1 km of sediment or 2 km of water column) are required to form peperites (Kokelaar, 1982). Thus, recognition of peperite is important for demonstrating contemporaneity of volcanism and sedimentation. Zircon ages on the peperitic rhyolite sills in Erskine Canyon are 105 ± 2 Ma, and the host quartzite-clast breccias must be of similar age. Furthermore, zircon ages of 102 ± 5 Ma have been determined on ash-flow tuff that lies stratigraphically above the quartzite clast breccia (Stop 12).

Textures of peperites can be used to infer the degree of lithification of the host sediment at the time of intrusion. Brooks and others (1982) proposed the following progression with increasing wetness of environment: (1) injection of rigid sedimentary clasts into the magma, (2) injection of fluidal sediment into shrinkage fractures and between jig-saw pieces formed by thermal contraction of the magma ("quiet fragmentation"), (3) dispersal of magma into sediment by steam explosions, (4) globulation (formation of very irregular, complex forms by deformation of plastic masses of magma) followed by granulation (through shrinkage cracking) and (5) formation of small pillow-like masses with infragmented margins. Numbers (3) through (5) dominate the peperites in Erskine Canyon, with (2) locally present. Number (3) results in unsorted volcanic fragments supported in the host sediment; sharply pointed fragile corners and smoothly curved (conchoidally fractured) surfaces are formed by shrinkage cracking during rapid cooling (Fig. 4A). The fluidal behavior of magma required for (4) and (5) (Fig. 4B) is possible in rhyolite magmas if steam enters the magma to reduce its viscosity.

Our traverse up the steep canyon will begin in the rhyolite hypabyssal intrusion in Erskine Canyon which locally contains irregular masses of andesite apparently mixed during intrusion by magma mixing. Traversing up the steep canyon and across the talus slope, peperites and sedimentary host rocks are encountered along with the white massive rhyolitic intrusives. Traversing westward and down off the talus slope the intruded unconformity is crossed where marble and quartz-rich schist of the Kings sequence are exposed.

Return to vehicle and continue driving southeast on Erskine Creek Rd. After an additional 1.2 mi park in clearing near switchback which starts up south facing slope east of steep canyon (Spring Gulch). Walk up jeep trail that follows south end of Spring Gulch.

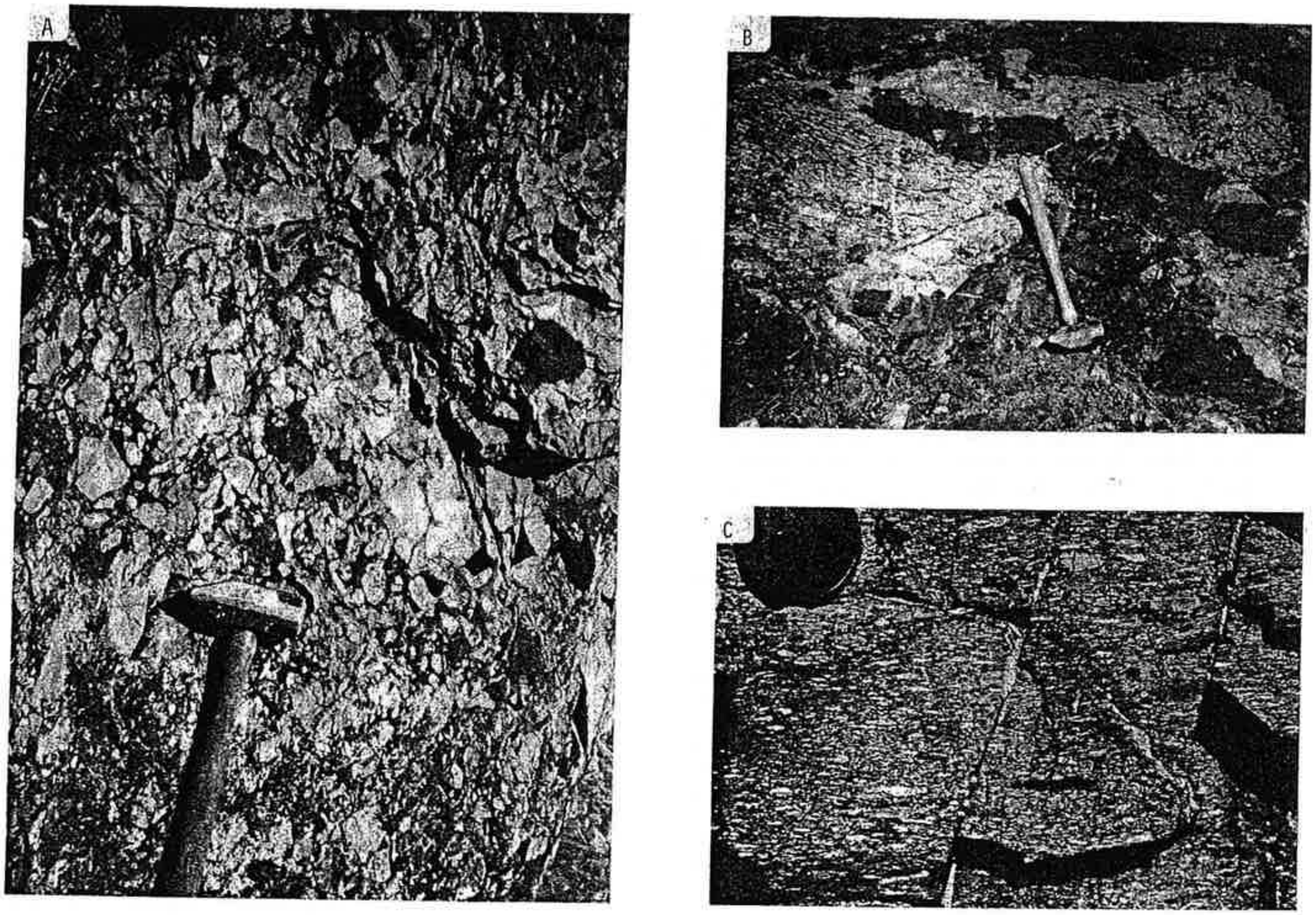


Figure 4. Field shots from the Erskine Canyon sequence. A: Peperite showing angular and conchoidally fractured rhyolite clasts within silty and calc-silicate matrix. B: Peperite showing injection of rhyolitic magma globs into soft sediment. C: Ash flow tuff of Stop 12 showing D3 flattening of pumice lapilli.

Stop 12

This stop offers a glimpse of the felsic volcanic section which appears to overlie the quartzite clast breccia. A mixed felsic to intermediate volcanic and sedimentary section lies above the breccia, and is in turn overlain by rhyolitic ash flow tuff. The base of the ash-flow tuff is encountered about 100 yards up the jeep trail. The ash flow shows the effects of D3 fabric development which northward and eastward disrupt the volcanic section and tectonically mix it with siliceous phyllonites of the Kings sequence basement. In the ashflow tuff deformed relict pumice lapilli and quartz and feldspar phenocrysts can be observed. A zircon date of 102 ± 5 Ma was obtained at this locality. The ashflows may continue for up to 15 km southward where in the Piute Lookout area a 98 ± 3 Ma zircon age was determined.

Return to vehicles and drive back out of Erskine Creek Road. A freeway onramp onto Highway 178 can be entered about 0.5 mi west along the Kernville Road from Lake Isabella Blvd. Southwest on the highway leads to the San Joaquin Valley, northeast leads to the southern Owens Valley.

ACKNOWLEDGEMENTS

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REFERENCES CITED

Allen, C.R., and Whitcomb, J.H., 1980, Southern California seismic arrays: U.S. Geological Survey Open-File Report 80-6, p. 416-419.

Alvarez, L., 1962, Geology of the Isabella area, Kern County, California, scale 1:62,500, University of Utah, unpubl. M.A. thesis.

Bateman, P.C., and Clark, L.D., 1974, Stratigraphic and structural setting of Sierra Nevada Batholith, California: Pacific Geology, v. 8, p. 79-89.

Brooks, E.R., Wood, M.M., and Barbutt, P.L., 1982, Origin and metamorphism of peperite and associated rocks in the Devonian Elwell Formation, northern Sierra Nevada, California: Geol. Soc. America Bull., v. 93, p. 1208-1231.

Busby-Spera, C.J., 1983, Paleogeographic reconstruction of a submarine volcanic center: Geochronology, volcanology and sedimentology of the Mineral King Roof Pendant, Sierra Nevada, California, Ph.D. dissertation, 290 pp., Princeton Univ., Princeton, N.J.

Christensen, M.L., 1963, Structures of metamorphic rocks at Mineral King, California: Calif. Univ. Pub. in Geological Sciences, v. 42, p. 159-198.

Elan, R., 1985, High grade contact metamorphism at the Lake Isabella north shore roof pendant, southern Sierra Nevada, California: Univ. of So. California., unpubl. M.S. thesis, 202 p., 1 plate.

Jenkins, S.F., 1961, A structural study of a portion of the Kernville Series, scale 1:23,820, University of California, Berkeley, unpubl. M.A. thesis.

Jones, D.L., and Moore, J.G., 1973, Lower Jurassic ammonite from the south-central Sierra Nevada, California: U.S. Geol. Survey Jour. Res., v. 1, no. 4, p. 453-458.

Kokelaar, B.P., 1982, Fluidization of wet sediments during the emplacement and cooling of various igneous bodies: J. Geol. Soc. London, v. 139, p. 21-33.

Miller, W.J., and Webb. R.W., 1940, Descriptive geology of the Kernville Quadrangle, California: California Jour. Mines and Geol., v. 36, p. 343-378.

Moore, J.G., and duBray, E., 1978, Mapped offset on the right-lateral Kern Canyon fault, southern Sierra Nevada, California: Geology, v. 6, p. 205-208.

Saleeby, J.B., 1979, Kaweah serpentinite melange, southwest Sierra Nevada Foothills: Geol. Soc. America Bull., v. 90, p. 29-46.

Saleeby, J.B., Goodin, S.E., Sharp, W.D., and Busby, C.J., 1978, Early Mesozoic paleotectonic-paleogeographic reconstruction of the southern Sierra Nevada region: in Mesozoic Paleogeography of the Western United States, D.G. Howell and K.A. McDougall (eds.), S.E.P.M. Pacific Coast Paleogeography Symposium 2.

Saleeby, J.B., Sams, D.S., and Tobisch, O.T., 1986, A down plunge view of the Sierra Nevada batholith: from resurgent caldera to ultrametamorphic levels: Geol. Soc. America Abst. with Prgms., v. 18, in press.

Sams, D.S., and Saleeby, J.B., 1986, U/Pb zircon and implications on the structural and petrologic development of the southernmost Sierra Nevada: Geol. Soc. America Abst. with Prgms., v. 18, in press.

Sharp, W.D., Saleeby, J.B., Schweickert, R., Merguerian, C., Kistler, R., Tobisch, O., and Wright, W.H., 1982, Age and tectonic significance of Paleozoic orthogneisses of the Sierra Nevada Foothills metamorphic belt, California: Geol. Soc. Am. Abst. with Prgms., v. 14, no. 4, p. 233.

Smith, A.R., 1964, Geologic map of California, Bakersfield Sheet (1:250,000), Calif. Div. of Mines and Geology.

Webb, R.W., 1946, Geomorphology of the middle Kern River basin, southern Sierra Nevada, California: Geol. Soc. America Bull., v. 57, p. 355-382.

August 2010 Fall Field Frolic Stops, Kern Plateau (Sherman Pass to East Base of Sierra)

Prepared by Dr. George Dunne, Professor Emeritus

Welcome to the Kern Plateau! This segment of the 2010 Fall Field Frolic will consist of eight geologic stops, as depicted in Figure '0'.

Grande Geo-Overview and Significance of Kern Plateau Geology

Starting first at the scale of the entire southwestern US Cordillera, three parallel, southwest-trending continental margin facies belts of Paleozoic age can be traced across Nevada and adjacent eastern California. As arrayed from southeast to northwest, these belts are the cratonic (as seen in Grand Canyon), continental shelf (as seen in Death Valley), and continental slope and rise, as seen within the Roberts Mountains allochthon (=thrust plate), which is widely exposed in central and west-central Nevada. In eastern California, these belts intersect obliquely and are largely obliterated by the northwest-trending Sierra Nevada batholith of Mesozoic age. Figure 1 depicts exposures of deep water Paleozoic strata in western Nevada and eastern California. These have been preserved in a large thrust plate that was pushed up onto the continental shelf in mid-Paleozoic time.

Two important observations were made about these facies belts in the 1960's:
1) The belts do not reappear among Paleozoic rocks along the western side of the Sierra Nevada batholith. That is, for some reason, the belts "ended" within the region that was to be later occupied by the Sierra Nevada batholith.
2) A large exposure of Paleozoic slope and rise strata, looking amazingly like those in west-central Nevada, as exposed in the El Paso Mountains in the northwest Mojave Desert as well as on the south side of the Garlock fault in the Goldstone and Pilot Knob areas. We'll refer to all three of these areas as "the El Paso terrain". In the late 1980's, George Dunne and his CSUN students expanded the outcrop area of the El Paso terrain by recognizing that three large pendants of the Kern Plateau in the southeast Sierra also contain strata belonging to the El Paso terrain (see again Figure 1).

The map arrangement and locations of the three continental margin facies belts relative to the El Paso terrain immediately raised the question of how exposures of the slope and rise strata ended up being located so far south, seemingly on-trend with where continental shelf facies strata should be located (see again Figure 1). Two hypotheses were advanced to explain this apparent locational discrepancy:

a) the Cordilleran continental margin, as it entered the location of the future Sierra Nevada batholith, was configured from the day it was born—perhaps as a transform fault offset of a rifted continental margin— to have an abrupt change in trend from southwest to southeast. In such a case, the three facies belts would have turned to the southeast as well and perhaps become much narrower than they were in Nevada, with the slope and rise facies belt passing through the western Mojave Desert.

or, alternatively

b) the Cordilleran continental margin, as it entered the location of the future Sierra Nevada batholith, was truncated in late Paleozoic time by a left-lateral strike slip fault that displaced fragments of the three facies belts southeastward, with one such fragment getting "stuck" to become the El Paso terrain, while other portions of the margin continued to move southeastward, ending up in northwest Mexico. In the later region, the displaced belts comprise what is commonly called the Caborca terrain.

Testing of both of these hypothesis has to date convinced most geologists that hypothesis 'b' best fits available data. It is sometimes called the continental truncation hypothesis. The El Paso terrain is estimated to have traveled at least 200 km to the southeast, whereas the Caborca terrain is estimated to have traveled ~800 km to the southeast. Indirect evidence suggests that the left-lateral truncation faulting occurred in Pennsylvanian and/or Permian time, perhaps developing episodically and extending over a significant interval of time.

The truncation fault is more likely a fault zone with multiple sub parallel strands. None of the truncation zone fault strands have been identified in outcrop with certainty. That is, the fault zone is essentially "cryptic". It may be that it has been completely buried by post-faulting rocks and/or intruded out by post-faulting intrusions. Alternatively, some strands of the zone may be exposed but not recognized as part of the truncation zone. The latter could be so if the truncation zone strands were reactivated as a different type of fault in later times, as a result of changing stress regimes. Such fault reactivation, although challenging to decipher, has been recognized in numerous faults around the world.

So, to summarize, what does the Kern Plateau have to do with this "Big Story"?

There are three large pendants of pre-batholithic strata exposed on the Kern Plateau. (review Figs. 1, 2) These are, from south to north, the Indian Wells , Kennedy Meadows, and Bald Mountain pendants. George Dunne and his students have studied these three larger pendants and their surroundings and have arrived at three important conclusions:

1) These pendants are composed mostly of deep-water continental slope and rise strata of Paleozoic age that are correlative with similar strata found in the El Paso terrain and in west-central Nevada.
2) These pendants are bounded on both sides by northwest-trending ductile shear zones that were active at multiple times and moving in different slip senses.

3) The strata forming these pendants were caught up within the left-lateral continental truncation zone and displaced southward to their present locations, and the ductile fault zones bounding the pendants may well be strands of the truncation fault zone.

To conclude, the traverse across the Kern Plateau that you are about to make will give you the opportunity to observe the following:

- Cretaceous, Jurassic, and Triassic components of the Sierran batholith
- ductilly deformed granitoids and metasedimentary strata caught up in both strands of the inferred truncation fault zone that are exposed on the Plateau
- typical and atypical deep water Paleozoic strata of the El Paso terrain
- some nice scenery, already!

Enjoy!

Stop 1: Unusual conglomerate

Nearing Sherman Pass from the west, watch for turnoff (to right) to Round Meadow. About 0.2 mi past, look for a minor dirt road to left, which enters area of large trees that is flanked by a low, sharp ridge to its left (west). Pull into this dirt road, park, and walk up onto sharp ridge to examine rocks that support it.

Unusual conglomerate of uncertain affinity and age. Speculatively, these rocks, which float within a sea of granitoid intrusives, may be part of Mesozoic Kings Sequence. The rock is unlike deep-water Paleozoic preserved in pendants farther east along road. An alternative hypothesis is that these rocks form a cover sequence of the Snow Lake block???

At this point, one might note that back near Round Meadow, we passed across the Durrwood Meadows fault zone. Last significantly activity was in1983-1984, with few 4.0 to 4.9 quakes plus numerous smaller aftershocks which defined a north-striking normal fault, with most foci located at about 5 km depth. This fault zone is interpreted to represent a transitional feature between the extending Basin & Range province to the east, and the more stable Sierra Nevada crustal block.

Return to Sherman Pass Road and continue uphill (East)

Stop 2: Sherman Pass Viewpoint (geographic and geologic overview)

At pass, pull right into large paved viewing area, complete with Porta-Potty.
If weather cooperates, from here one can look east across part of Kern Plateau to Olancha Peak and the Whitney Crest. From a viewpoint to the left (consult Dave Liggett for best spot) one can see Bald Mountain pendant and lookout, which we will visit later. This pendant is the northernmost of three composed of deepwater Paleozoic strata.

Granitoid at the pass is the Alaskite of Sherman Pass, which has yielded a U-Pb date on zircon of 99.3 Ma. It is an older member of the South Fork Intrusive Suite of Saleeby and others (2010), which was emplaced between 100 and 93 Ma.

Continue east on Sherman Pass Road;

For next several miles, the road passes through more Alaskite of Sherman Pass, which locally encloses small elongate masses of diorite, migmatite, and thoroughly metamorphosed host rock of uncertain affinity. We also begin seeing more and more elongate intrusive bands of a fine-grained biotite granite (the biotite looks a bit like pepper flakes, hence the informal name of "salt-and-pepper" granite). This unit has not been dated. It may be a texturally distinct phase of Sherman Pass or part of the younger Domelands Intrusive Suite that is centered farther east.

Look for signed turnoff to left leading to Bonita Meadows. Turn left onto this road.

Optional Stop: Mildly deformed granite

If making optional stop here, immediately pull to side of Bonita Meadows Road and park. Cross southward over Sherman Pass Road and up gentle slope beyond. Here one finds mostly float masses of 'salt-and-pepper' and Alaskite of Sherman Pass. The granite in a few of these blocks contains slightly to moderately flattened quartz crystal, which in thin section appear to have been ductilly deformed. Rare insitu exposures reveal a faint, very local near, vertical foliation defined by the quartz. One hypothesis for this foliation: growth of the pluton via incremental emplacement of magma batches, with deformation of early-emplaced batches, after they had mostly solidified, by later batches shouldering their way into place. Can you think of other possible hypotheses?

Following the Optional Stop (if made), continue ahead (north) on Bonita Meadows Road. In 0.4 mile turn right onto USFS 22S24 and follow it for 0.8 mile to where a fallen tree blocks further travel. Park as convenient and make short hike to the top of the hill to the left of the fallen tree via either of two routes: (a) follow the dirt road beyond the fallen tree, swinging first left and uphill, then through a switchback or two until you reach top of hill, or, alternatively, (b) straight up the slope to your left. Either route brings you to a large quarry on the hill top.

Stop 3: Stratiform barite quarry in Bald Mountain pendant

From this quarry, stratiform barite (barium sulphate) was mined. Approximately 80% of mined barite is added to drilling muds to make them of sufficient density to keep pressurized oil and gas from rushing up the drill hole and spraying into the air or water. It can do this because its density (4.48 g/cc) is very high. To appreciate this property, consider the typical density of "heavy" rocks such as basalt. Do you recall it?

Stratiform barite is a somewhat unusual rock within the Cordilleran orogen of the western US. The term stratiform means that the barite occurs as depositional layers within an enclosing sedimentary sequence. Stratiform layers of barite are being deposited in the modern ocean in numerous locations, but everywhere within or on deepwater sediments underlain at depth by basaltic oceanic crust. Ancient stratiform barite deposits of the western US have been known for decades to be present in Paleozoic deep-water strata exposed in Nevada and that are interpreted to have been deposited on the continental slope and rise. In Nevada, over 90% of these deposits are of either Devonian or Ordovician age.

Stratiform barite deposits occur here in the Bald Mountain pendant and in the Kennedy Meadows pendant to the south. Modest volumes of barite were episodically mined from these two exposures into the early 1980's. Leaning on analogy with Nevada stratiform barite deposits, the presence of stratiform barite in these two pendants leads to the following two inferences: (1) these two pendants are likely to be composed in part of Ordovician and/or Devonian strata; (2) pendant strata, at least those enclosing the stratiform barite, were deposited in deep marine water on a continental slope or rise that was underlain by oceanic crust. Additional support for the latter inference is the observation that rare layers of basalt and basaltic debris in all three pendants have trace element signatures typical of oceanic basalts. Keep these inferences in mind when we reach stops 5 and 6. In the meantime, return to the vehicles and backtrack out to Sherman Pass Road. Turn left (eastward) onto this road and proceed 1.8 miles to a wide turnout on the left side of the road. Pull out here (watch for oncoming traffic!) and park.

Stop 4: Gneissic granitoids of the Dark Canyon Shear Zone

Now that we are located within ductilly deformed granitoids belonging to the southwestern deformation zone crossing the Kern Plateau, it is time to present a summary of what we know about such rocks before we closely examine the exposures before us.

Grande Geo-Overview of Ductile Deformation Zones

Each of the three largest Kern Plateau pendants is bounded on its southwest side by discontinuous remnants of what may have been a through-going ductile deformation zone that trends northwest and dips northeast. One pendant—Kennedy Meadows— also features remnants of a ductile deformation zone along its northeast flank (see Fig. 2). We will look at the one exposure of this latter zone at Stop 7. These two flanking deformation zones may have once been of regional extent, but they have been largely obliterated by Middle Jurassic and younger granitoid plutons of the Sierran batholith. We know a few important characteristics about the kinematics and age history of these deformation zones, but many questions remain to be answered.

Southwest zone:

Pendant strata adjacent to the southwest deformation zone are more strongly deformed than pendant strata farther removed (to the northeast) from the zone. Similarly, some older plutons such as that at Walker Pass, which intrudes the southwest margin of the Indian Wells pendant, when traversed northeastward toward the pendants, become progressively more foliated and lineated. Caught up in the heart of these zones are lenses of mylonitic and locally migmatitic granitoids, some of which cannot readily be correlated to other "in-place" plutons in the region.

Age Relations:

Dating of some of the intrusive units that interact with the southwest deformation zone provide constraints on the timing of deformation. Some important dates, all utilizing the U-Pb method except where noted, are as follows:

- Kennedy pendant: fine-grained mylonitic granitoid yields age of between 225 and 230 Ma ; intruded by a less deformed gneissic granitoid yielding age in the same range.; both are intruded by undeformed Long Valley pluton at 147 Ma.
- Bald Mountain pendant: Dark Canyon gneiss has yielded age of between 210 and 220 Ma.; is intruded by nondeformed granite at 80 to 85 Ma; migmatitic mylonite lens just to west also yields age of between 210 and 220 Ma
- Indian Wells pendant: The deformed Walker Pass pluton that intrudes the southwest side of the Indian Wells pendant has yielded a U-Pb age of 246 Ma. This Early Triassic pluton is the oldest recognized in the southeast Sierra and it is coeval with plutons intruding the west side of the El Paso Mountains; a felsic dike, dated at 182 Ma, cuts across pre-existing foliation in the deformed Walker Pass.. Following its intrusion, the dike was tightly folded during ongoing or later renewed ductile deformation. Undeformed granitoids cutting across these deformed intrusions yield a date of 90 Ma.

Overall deformational Timing, Southwest zone:
One protracted or two or more episodic deformational events were active after 246 Ma but before 182 Ma, with additional deformation following 182 Ma, with most if not all deformation in the southwest zone being completed by 148 Ma.

Northeast zone (Kennedy pendant only):
This zone is defined by a diffuse northwest-trending belt of variably foliated and lineated Sacatar Quartz Diorite, which in this area has yielded a U-Pb date of 171 Ma and a multiple whole rock Rb/Sr isochron of 177 Ma. Caught within this zone are two small, isolated bodies of deformed granitoid intrusives; an older, more strongly deformed mylonite (180 to 185 Ma), which is intruded by a less deformed granite (155-158 Ma). All three of the above are intruded by an undeformed mafic suite yielding a date of ~155 Ma.

Overall deformational Timing, Northeast zone:
An earliest documented episode of ductile deformation occurred between 185 Ma and 171 Ma, with more deformation occurring as late as ~158 Ma. Deformation had ended by ~155 Ma

Slip sense in these deformation zones:

At Indian Wells, more than a dozen good slip indicators (S/C fabrics, asymmetric augen tails, etc) point to a consistent "down-to-the-northeast' normal sense of slip.

Along the southwest side of the Kennedy pendant, in pendant strata immediately adjacent to the deformed granitoid, numerous locations contain swarms of counterclockwise asymmetric folds, the axes of which plunge steeply northeast in the deformational foliation plane. This geometry suggests a left-slip component of motion in this area.

In the Dark Canyon gneiss at Bald Mountain, as noted previously, we have observed a modest number of slip indicators that express right-lateral slip in some areas and left-lateral slip in others.

What to make of these observations? Well, the classic response is "More work needs to be done"! Which it does. Given the extended timing window and slip sense information that is available, it seems likely that these deformation zones experienced two or more episodes of deformation, during which different senses of slip prevailed in response to changing regional stresses. Such changing stresses could have been responses to changing plate convergent velocities along the west coast, and also to the mechanics of magma emplacement in the batholith. It is tempting to think that both the southwest and northeast deformation zones were initiated during the late Paleozoic continental truncation event and experienced significant amounts of left slip that help account for the seemingly "too far south" location of the strata in these pendants and of the El Paso Mountains/Goldstone/Pilot Knob "out of place" Paleozoic strata as well. Additional left slip could have occurred on these zones during the Jurassic when relative plate convergence directions are inferred to have been oblique with a strong left-lateral component. Right lateral slip indicators may have formed during the Cretaceous, when right-slip ductile fault zones are inferred (Snow Lake fault) and known (Sierra Crest shear zone system) to have formed within the growing Sierran batholith.

Examine the Dark Canyon gneiss in outcrop:

Guided by Doug Yule and Whitney Behr, examine the exposures of the Dark Canyon gneiss next to the parking area, and/or across the Sherman Pass Road. Note the strong foliation and very weak down-dip lineation. If you look at exposures with your line of sight both parallel to this lineation and at right angles to it (but still along the foliation plane), you may be able to see rare mineral fabrics (S-C fabrics, asymmetric tails on porphyroclasts, shear bands, etc.) suggestive of a certain sense of dip slip or strike slip motion during or following their creation. Discrete planar shear zones that cut across the main foliation at a small angle have offset granitic dikelets and quartz veins that postdate the main foliation in both right-lateral and left-lateral senses have been observed. What do you see?

Pull back out on Sherman Pass Road and continue east. At 0.9 miles, pull right into to wide spot on right road side and park.

Stop 5: Calcareous quartzite of the Bald Mountain pendant

Here we see an example of a relatively little altered distinctive lithosome composed of variable proportions of calcite and quart grains. Diffuse parallel bedding defined by lighter and darker gray color bands are apparent. The quart grains are texturally mature. Depending on the proportions of the two component minerals, this rock can be called calcareous (or limy) quartzite or arenaceous (or sandy) limestone. Locally it contains sparse rip-up clasts of darker colored siliciclastic rocks that form its host strata, as well as climbing ripple cross bedding. Considered together, its features support the interpretation that this lithosome, beds of which are common in the Bald Mountain and Indian Wells pendant, was emplaced by gravity flows of material that originated in shallower water of the continental shelf environment. This same distinctive lithosome is present in the El Paso terrain, pendant strata farther north in the Sierra (Mt. Morrison block) and in western Nevada. In all these areas, the unit contains Middle Devonian fossils, and we suggest a similar age for the beds before you.

As you return to the vehicles, observe the fine grained, generally dark, thin and parallel bedded siliciclastic strata that are the most common rocks in the pendants. Before metamorphism, they were shale, mudstone, quartz siltstones, and fine quartz sandstones. Feldspar constitutes just 1 or 2% of these rocks. The dark gray color reflects a relative abundance of organic carbonaceous material, which is now mostly graphite. The well preserved bedding, lack of fossils or of signs of bioturbation, and abundant graphite together suggest that the despositional environment lacked any bottom critters, most likely because of paucity of oxygen. Most of these strata were probably deposited as turbidites, but some may have originated as "contourites" or as hemipelagic 'rain'.

Continue driving eastward on Sherman Pass Road. You will be driving across strike through the Bald Mountain pendant, then into the granitoids intruding its east margin. At 2.0 miles, there will be a wide dirt turnout to the right, and a dirt side road with a sign indicating the route up to the Bald Mountain Lookout. Because parking is somewhat limited at the top of this side road, it is wise to consolidate passengers into as few vehicles as possible before proceeding up the lookout road. Proceed uphill on the lookout road and park at the gate at the top. It is a short walk up to the top of Bald Mountain. Take your camera and binoculars.

Stop 6: Top of Bald Mountain

Kern Plateau Geomorphology As viewed from Bald Mountain lookout.

Based on review by Jayko, A.S., 2009 Deformation of the late Miocene to Pliocene Inyo Surface, eastern Sierra region, California, in Oldow, J.S. and Cashman, P.H., eds., Late Cenozoic Structure and Evolution of the Great Basin-Sierra Nevada Transition: GSA Special Paper, 447, p. 313-350.

The Kern Plateau is the incised remnant of a widespread composite erosion surface that once covered much of the southern Sierra. Remnants can be recognized along the Sierran crestal region from south of Walker Pass to as far north as the Bishop region. Looking to the southern horizon from Bald Mountain reveals one nicely preserved remnant of this surface. Although some unresolved conflicts exist, most geologic and geochronological data envision that the Sierra had attained moderate elevations, generally between 2500 feet and 6600 feet, and significant drainage canyons, by Late Cretaceous and/or early Cenozoic time. From early Cenozoic to late Miocene (~10 Ma) time, the Sierran block was relatively stable and eroding slowly, creating the widespread Kern Plateau.

Around 10 Ma, there occurred widespread basaltic to intermediate volcanism across much of the Kern Plateau. Some remnants of these flows can be seen to the south and southeast of Bald Mountain. Also beginning about 10 Ma, the Sierran block began rotating in down-to-the-west sense about a subhorizontal axis located near the Great Valley/Sierran Foothills contact. This rotation resulted in uplift of the High Sierra by as much as 8000 feet, with most of the uplift occurring from 4 Ma to the present. The Sierran frontal fault system, which separates the Sierran block from the Basin and Range to the east, also became active about 10 Ma, with accelerated normal and right-normal slip beginning about 5 Ma.

This accelerated uplift has been attributed by some (ref: Saleeby, J., et al., 2003, Production and loss of a high-density batholithic root, southern Sierra Nevada, California; Tectonics, v. 22, no. 6) to late Miocene into Pliocene delamination of the dense, eclogitic root that had formed by differential crystallization and differentiation of the Sierran lithosphere as the batholith formed through Mesozoic time. This dense mass peeled away and downward from the less dense upper portion of the batholith, and presently forms a downward-projecting "drip" centered under a portion of the southwest Sierra and adjacent southern San Joaquin Valley, as identified by gravity, magnetic, and seismic velocity signatures in that area. It is speculated that initiation of the delamination was in some way linked to the development, beginning about 10 Ma, of highly extended terrain in the southern Basin and Range just to the east of the Sierra.

After enjoying the grand view of the southern Sierra from atop the tower, take a brief look at the pendant strata underlying the mountaintop. The several bands of pale gray, massive appearing strata passing across the ridge are thoroughly baked calcareous quartzite. Most of the darker strata are fine grained siliciclastics like those described at the last stop. Look closely at such strata cropping out just north of the tower base. These are interpreted to be repetitious sequences of fine grained turbidites. What features can you make out in these rocks that support or refute this interpretation? Can you find any depositional top indicators?

Return down to Sherman Pass Road, collect parked vehicles, and proceed eastward.

Only reconnaissance mapping has been conducted of the large and complex intrusive terrain forming the northeast side of the Bald Mountain and Kennedy Meadows pendants extending all the way to the east base of the Sierra. The vast majority of intrusives in this region have been lumped into a unit of batholithic size called the Sacatar Quartz Diorite, first described by the pioneering geologic mappers in this region, William Miller and Robert Webb (Descriptive Geology of the Kernville Quadrangle, California (1940): Calif. Jour. Mines and Geology, vol. 36, p. 343-378). Subsequent Wilderness Studies by the USGS have continued to utilize this name. With two interesting exceptions noted elsewhere in this field guide, a handful of reconnaissance U-Pb dates plus one multiple-whole-rock Rb-Sr date from the Sacatar have yielded ages in the span 166 Ma – 177 Ma. Rocks attributed to the Sacatar are diverse in their textures and compositions, but with most rocks being granodiorite and quartz diorite. Some ambitious geologist needs to conduct a focused study the Sacatar terrain in order to properly characterize it.

As we leave the Bald Mountain turnoff, we are driving through a large pluton that bounds the east side of the Bald Mountain Pendant that I have informally named the granite of Beach Ridge. It has not appeared on any previously published geologic maps, and whether or not it should be folded into the Sacatar unit is uncertain. It is a granite that contains prominent purple-pink K-spar phenocrysts. At a few locations along the road, you might catch sight of steeply inclined, thin bands of greenish gray float in roadcuts. These are remnants of near vertical, northwest striking mafic dikes that are typically 0.5 to 1 m thick. Granite plutons bearing purple-pink K-spar phenocrysts commonly yield Middle Jurassic radiometric dates in eastern California. The mafic dikes intruding the granite of Beach Ridge may be part of the widespread Independence dike swarm (148 Ma), which would be consistent with a Middle Jurassic age for the otherwise undated Beach Ridge pluton.

As we approach the Black Rock Ranger Station junction (approximately 5.5 miles from Bald Mtn turnoff), the granite of Beach Ridge gives way to a one or more intrusions with diverse compositions; this intrusive hodge podge continues eastward beyond Black Rock Station for about 3.6 miles, to about the vicinity of the Mahogany Road turnoff to the right. Eastward from this point to the vicinity of the Kennedy Meadows store, a new pluton is present. Its distinctive, uniform, medium gray outcrops are seen on both sides of the road as we head southeast across various meadows and flats for the next two miles beyond Mahogany road. This pluton is predominantly a medium grained biotite hornblende quartz diorite and diorite, and previous mappers have included it within the Sacatar. Samples collected from roadside exposures of this unit at about the mid-point of this 2-mile span have yielded K-Ar (hb) and U-Pb radiometric ages of 148±2 Ma, the same age as the Long Valley pluton which intrudes the southwest side of the Kennedy pendant., and which is of similar texture and composition, and which has also been lumped into the Sacatar. It is tempting to think, then, that these two intrusions, both composing the southwest-most portions of the large, composite Sacatar quartz diorite intrusion in their respective map areas, are correlative and represent an identifiable Late Jurassic component of the Sacatar, which elsewhere has yielded Middle Jurassic radiometric ages.

Stop 7: Ductile deformation zone, Northeast side of Kennedy Pendant (presented by Whitney Behr, Department of Earth Sciences, USC)

Return to Vehicles and continue southeast on the Kennedy Meadows Road

We head down-down-down the spectacular road in Nine Mile Canyon. In the roadcuts, note the wide variety of granitoids, their cross cutting relationships, and their structures. All of this rock is provisionally included in the Sacatar Quartz Diorite. Much sorting out remains to be done with this unit.

As we reach the gentler slope of the top of the alluvial fan, a black, large-diameter pipe running across the mouth of the canyon comes into view. This is a portion of the original Los Angeles Aqueduct that was completed in 1913, and which is still in operation. These large pressurized pipes were used wherever the aqueduct crossed a canyon. Elsewhere the aqueduct utilized contour-following channels or tunnels (a total of 52 miles worth of the latter). The aqueduct system remains an amazing feat of engineering considering its age. It is entirely gravity-powered and reaches northward 226 miles to capture water. It required 5 years to construct but was completed under its estimated budget of $25 million.

Farther down the alluvial fan we see a large-diameter white pipe crossing our route. This is part of a second Los Angeles Aqueduct, running approximately parallel to the first one, that was finished in 1970 in order to provide increased water carrying capacity. These two aqueducts provide ~70% of LA's drinking water.

Stop 8: East base of Sierra: Coso Range geology and cryptic strike-slip fault

Just as we reach Highway 395, pull to the side briefly and gaze across the highway to the Coso Range and its lava flows and volcanoes. The Coso volcanic field is of late Cenozoic age and rests unconformably on Sierran granitoid basement rocks of Jurassic age. The first phase of eruptive activity in the volcanic extended from ~ 3.6 Ma to 3.0 Ma. A second phase began about 1 Ma and continued episodically through at least 40 Ka, and possibly until the Holocene. This second phase has consisted of a bimodal mix of rhyolite and basalt eruptions, with few rocks of intermediate composition. The rhyolite takes the form of 39 domes and short flows clustered on an uplifted block of basement, all located over (to the north of) the skyline marked by basalt volcanic cones. Rhyolite was erupted between 1 Ma and 300 Ka. The basaltic cones on the skyline ridge are the youngest dated volcanics in the field, yielding ages of about 40 Ka.

The cluster of rhyolite domes sit above a low velocity zone located at a depth of about 5 km, which may mark a zone of magma or, at least, very hot rock. Several hot springs and fumaroles are clustered among the domes. A geothermal power plant was completed in this area in 1987. It's deepest production zone is at 3.6 km where the temperature is ~ 350° C.

One last point of geologic interest should be noted here. Looking northward along the east base of the Sierra, you can see the point where the Coso Range (to the right) has its closest approach to the Sierra (to the left), This is called the Little Lake Gap by some. It is speculated that through this gap there passes a right lateral strike slip fault with ~65 km of slip that extended well northward along the Owens Valley and presumably southward beneath alluvium in front of us. Limited exposures of bedrock features related to this fault have been found at Little Lake gap, but elsewhere the fault is cryptic. This slip amount and sense has been determined by the separation, in this amount and sense, of the following features in the Owens Valley area:

- The Golden Bear dike and its distinctive granitic host pluton; the dike, dated at 83 Ma, and its host pluton intersect the west side of the inferred fault just south of Independence, and reappear of the east side of the fault in the northern Coso Range (ref.: Kylander-Clark, A.R.C., et al., Evidence for 65 km of dextral slip across Owens Valley, California: GSA Bulletin, July/August issue, 2005, p. 962-968)
- The Independence dike swarm: a major strand of the swarm intersects the west side of the inferred fault just east of the Alabama Hills and reappears in the Coso Range near Little Lake Gap (ref.: Bartley, J. M., et al., Large Laramide dextral shear across Owens Valley, eastern California, and extensional unroofing of the southern Sierra Nevada: GSA Abstracts with Programs, 2003, v. 35, no. 6, p. 305)
- Devonian submarine channel and fan system: the channel intersects the west side of the fault near Crowley Lake, and reappears on the east side south of Big Pine (ref.: Stevens, Calvin, and Pelley, Tina, 2006, Development and dismemberment of a Middle Devonian continental-margin submarine fan system in east-central California: GSA Bulletin, January/February issue, v. 118, no. 1/2, p. 159-170)

Tha, Tha, Tha, That's all folks! (End of Kern Plateau Transect)

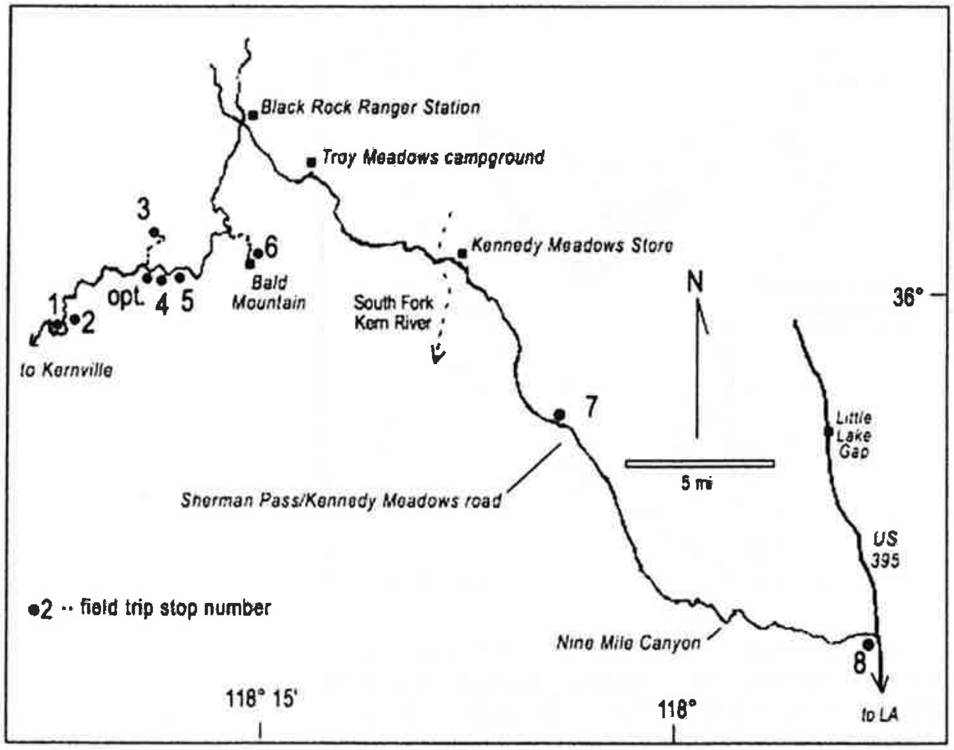

Figure '0'

Route of travel, numbered field trip stops, and selected cultural and geographic features.

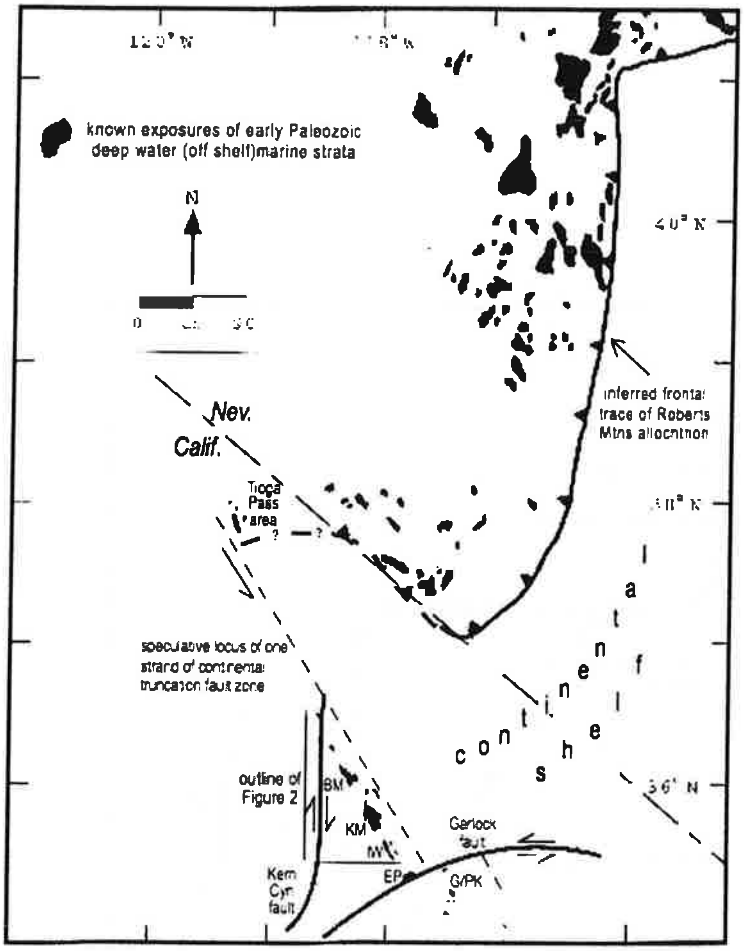

Figure 1

Distribution of actual exposures Paleozoic off-shelf (deep water) strata in Nevada and eastern California. Where studied in Nevada, these strata form the upper plate of the Roberts Mountains allochthon. Principal exposures in field trip region are coded as follows: BM = Bald Mountain pendant; KM = Kennedy Meadows pendant; IW = Indian Wells pendant; EP = El Paso Mountains exposure; G/PK = Goldstone and Pilot Knob exposures. Not shown on this map is an additional strand of the hypothesized continental truncation fault zone which would have lain southwest of the Kern Plateau pendants and accounted for the much larger translation of the Caborca terrain into Sonora, Mexico.

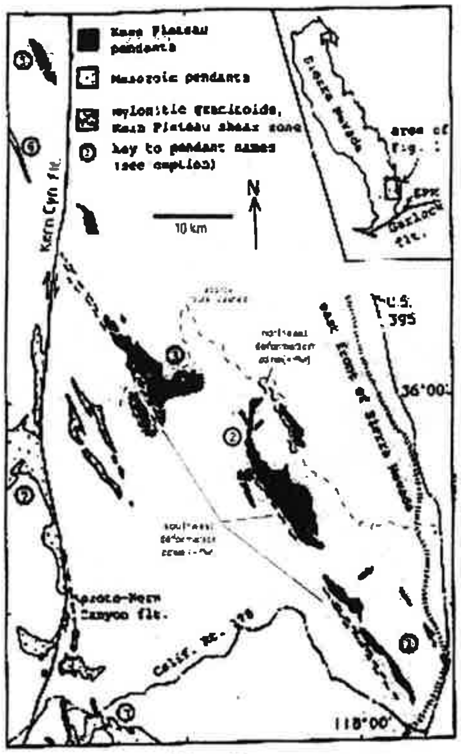

Figure 2.

Geologic sketch of Kern Plateau and vicinity. Key to numbered pendants: 1 = Indian Wells; 2 = Kennedy; 3 = Bald Mountain; 5 = Rattlesnake Creek; 6 = Mineral King; 7 = Isabella

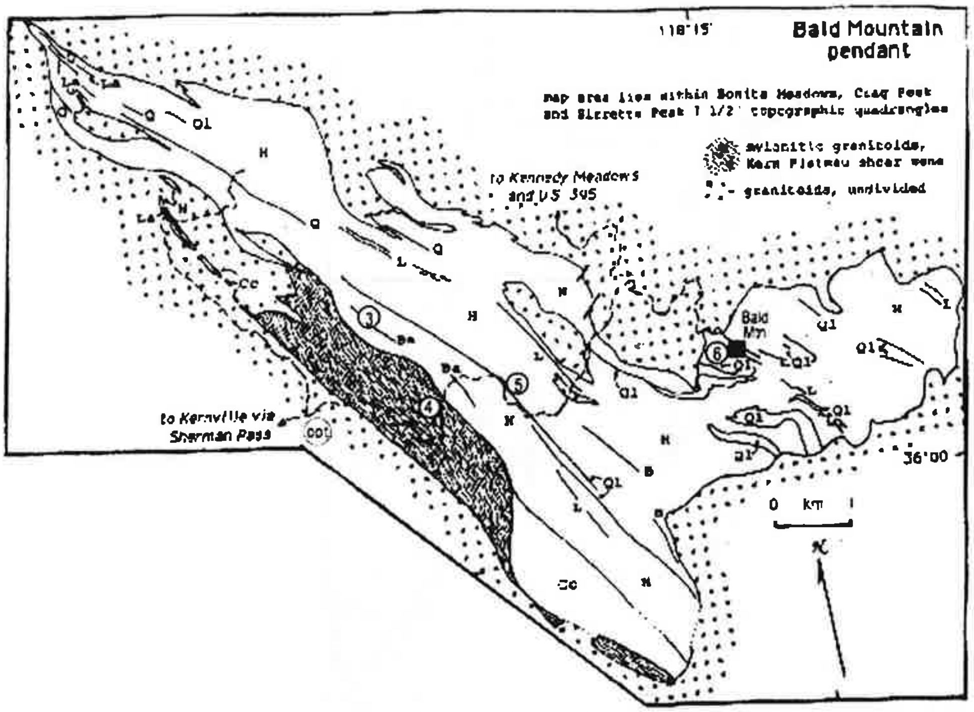

Figure 3.

Geologic sketch map of Bald Mountain, showing distinctive marker lithosomes such as limestone and basalt that are set within a repetitious host lithosome composed of protolith rocks such as shale, mudstone, quartz siltstone, and fine-grained quartzite.Letter code for lithosomes is: H= host lithosome; Q = quartzite; L=limestone; Ql=sandy limestone; B=basalt; Ba=barite; Cc=capping conglomerate.

Stop 7: Northeastern Deformation Zone of the Kennedy Pendant

At this stop we examine some features of the deformation zone that lies on the northeast side of the main Kennedy pendant (Figure 4). The overall deformational fabric here is broadly similar to that of the main part of the Kern Plateau shear zone located along the southwest side of the pendants. Metasedimentary rocks caught up in this more northeasterly zone are incongruent with rocks in the main part of the Kennedy pendant in terms of protolith, metamorphic grade, and style of deformation. At least three distinct, lens-like suites of metasedimentary rock have been recognized, including highly migmatized amphibolites (quartz+oligoclase+diopside+hornblende), lower granulite-facies schists (quartz+hypersthene) and albite-epidote hornfels (clinozoisite+quartz). The higher grade rocks occupy the northeastern band of metasedimentary rocks whereas the lower grade rocks occupy the southwestern outcrops. The higher grade rocks have no known counterparts in the main Kern Plateau pendants, which were everywhere metamorphosed to upper greenschist and lowest amphibolite grades. Generally speaking, likely protoliths of these metasedimentary slivers include significantly more dolomitic rocks and shaly limestone than have been recognized in the main pendant.

The metasedimentary suites are separated and internally intruded by ~0.25- to 0.75-km-wide bands of variably deformed granitoids representing three intrusions. The oldest and most deformed granitoid, underlying a hill southwest of the paved road (see Fig. 4) has experienced intense dynamic recrystallization followed by a more static recrystallization, resulting in a very fine-grained, only locally foliate rock resembling massive metasandstone, an identity applied by the earliest mappers in this area. It has yielded a U-Pb date of ~185 Ma. This rock was subsequently intruded by the Sacatar Quartz Diorite, which is mildly to moderately foliated and lineated, but clearly less deformed than the older intrusion noted above. The Sacatar has yielded a ~177 Ma Rb/Sr date and a 171 U-Pb date in this area. Both of these intrusions were intruded by a small body of mildly foliate porphyritic granite that has yielded a U-Pb date of between 155 Ma and 158 Ma. All of the above intrusions have been intruded by bodies of undeformed gabbro and diorite assigned to the Summit mafic complex, which has yielded a U-Pb date of ~155 Ma. These relationships suggest a multi-episode deformational history for this northeastern deformation zone: a strong episode following 185 Ma but prior to emplacement of the Sacatar at between 177 and 171 Ma, another episode (or ongoing deformation) following emplacement of both the Sacatar and of the porphyritic granite, with observable deformation ended by the time the Summit mafic complex was emplaced ~155 Ma. In sum, deformation in this northeastern zone could have been entirely coeval with deformation in the southwestern.

At present, the slip sense (or senses) of this northeastern zone are essentially unknown, and thus in need of further study. As you look at exposures of the deformed Sacatar quartz diorite, what do you note about possible linear and/or planar deformational fabric elements? Are they similar to those observed in the Dark Canyon gneiss or different?

Finally, it is interesting to speculate about the possible significance of this deformation zone, given its similarities and differences—the latter primarily in the nature of the metasedimentary rocks caught up within it—with the southwestern deformation zone. Your trip leaders will guide some discussion of this last point as you wrap up this field trip stop.

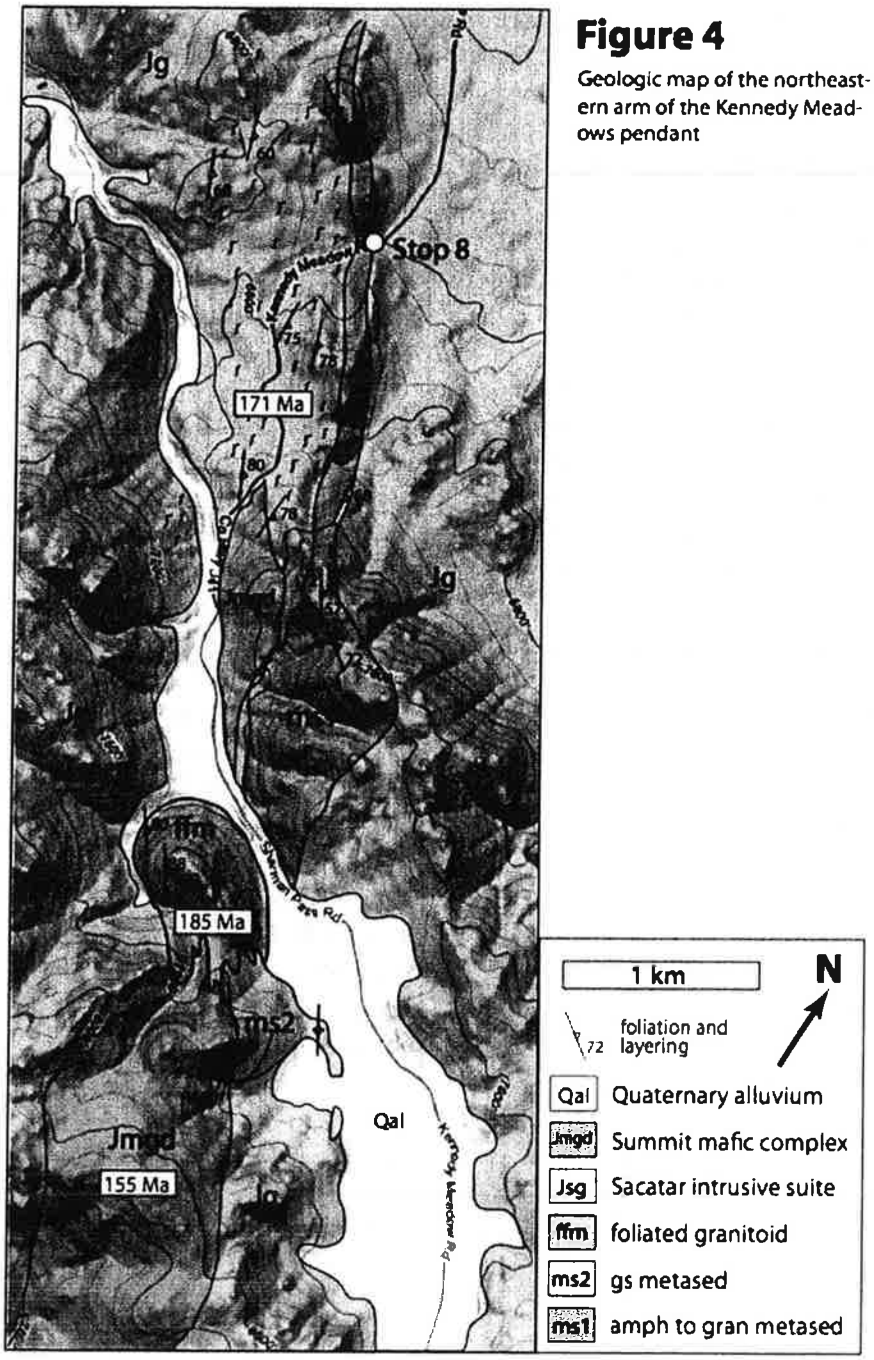

Figure 4

Geologic map of the northeastern arm of the Kennedy Meadows pendant

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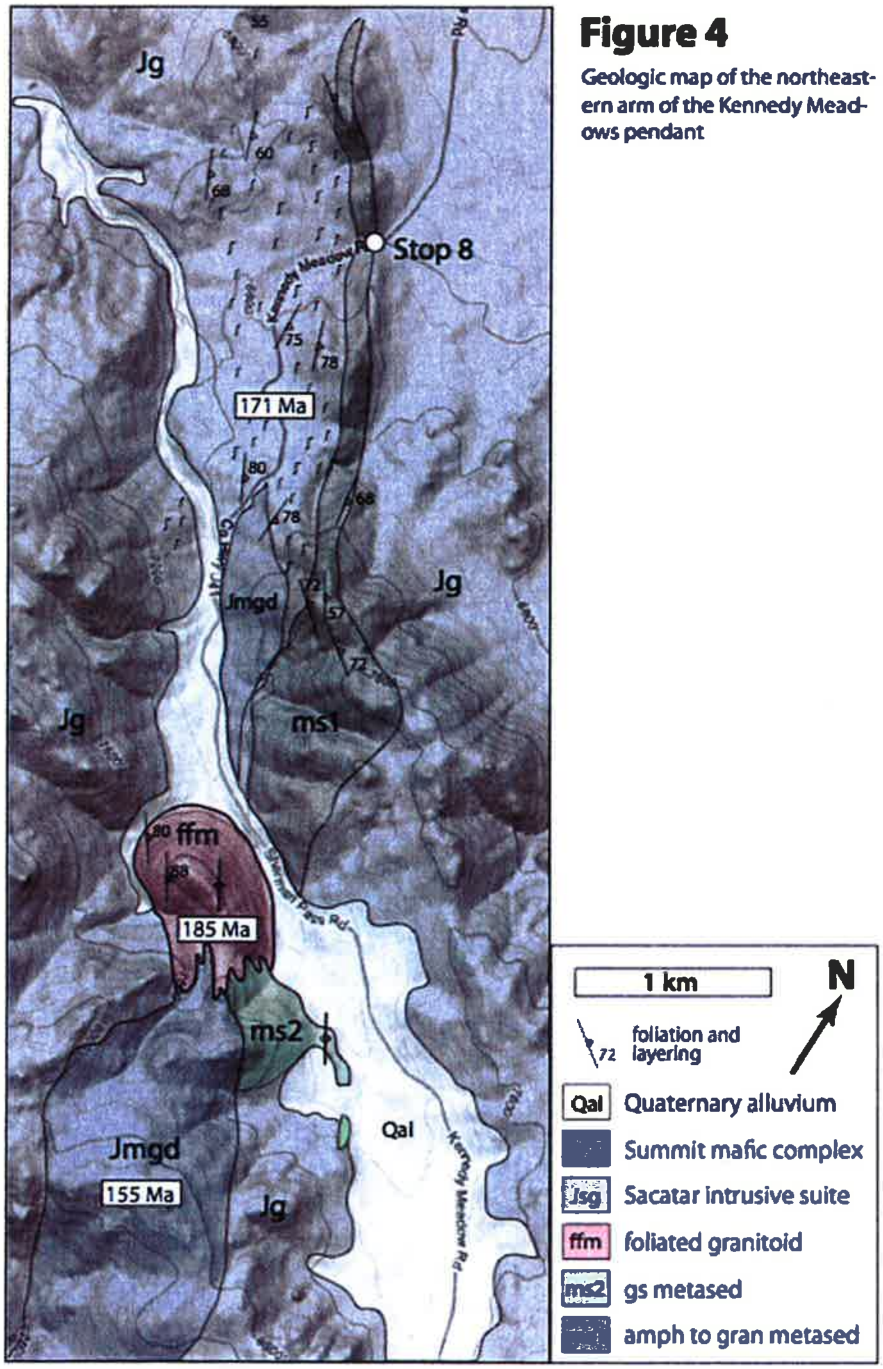

Figure 4

Geologic map of the northeastern arm of the Kennedy Meadows pendant