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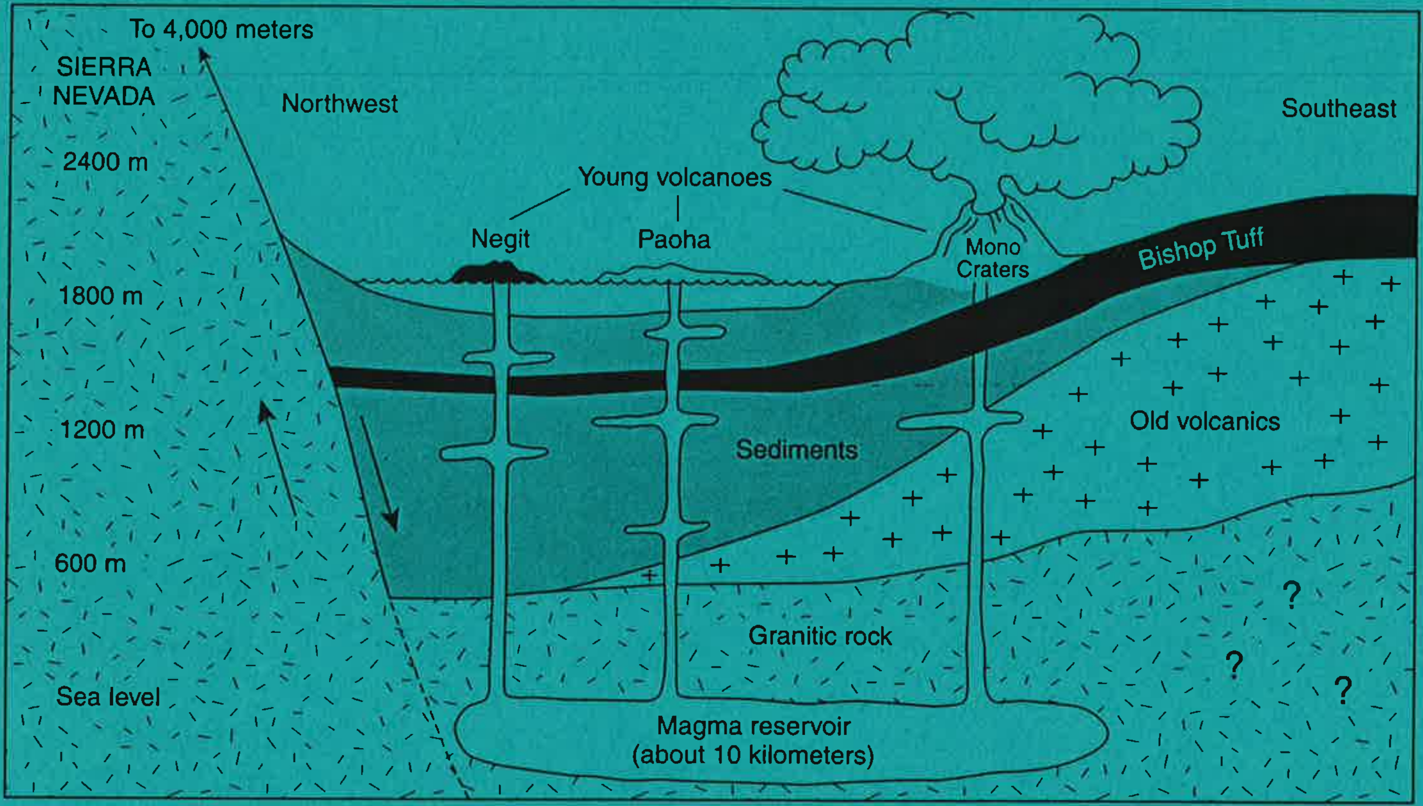
DEPARTMENT OF GEOLOGICAL SCIENCES
CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

FALL FIELD FROLIC TO OWENS VALLEY

Thursday through Saturday, August 26 - 28, 1999



Department of Geological Sciences
California State University

FALL FIELD FROLIC TO OWENS VALLEY

Thursday through Saturday, August 26 - 28, 1999

Tentative Itinerary for Thursday, August 26

Leave CSUN	0815	
Arrive Mojave	0945	
Leave Mojave	1015	
Arrive Red Rock Canyon STOP #1	1045	p.9
Leave Red Rock Canyon	1115	p.25
Arrive Fossil Falls	1200	p.34
Lunch and Fossil Falls STOP #2	1200-0145	
Leave Fossil Falls	0145	
Arrive Mt Whitney Visitor's Center STOP #3	0245	
Leave Visitor's Center	0315	
Arrive Bishop	0430	

Department of Geological Sciences
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FALL FIELD FROLIC TO OWENS VALLEY

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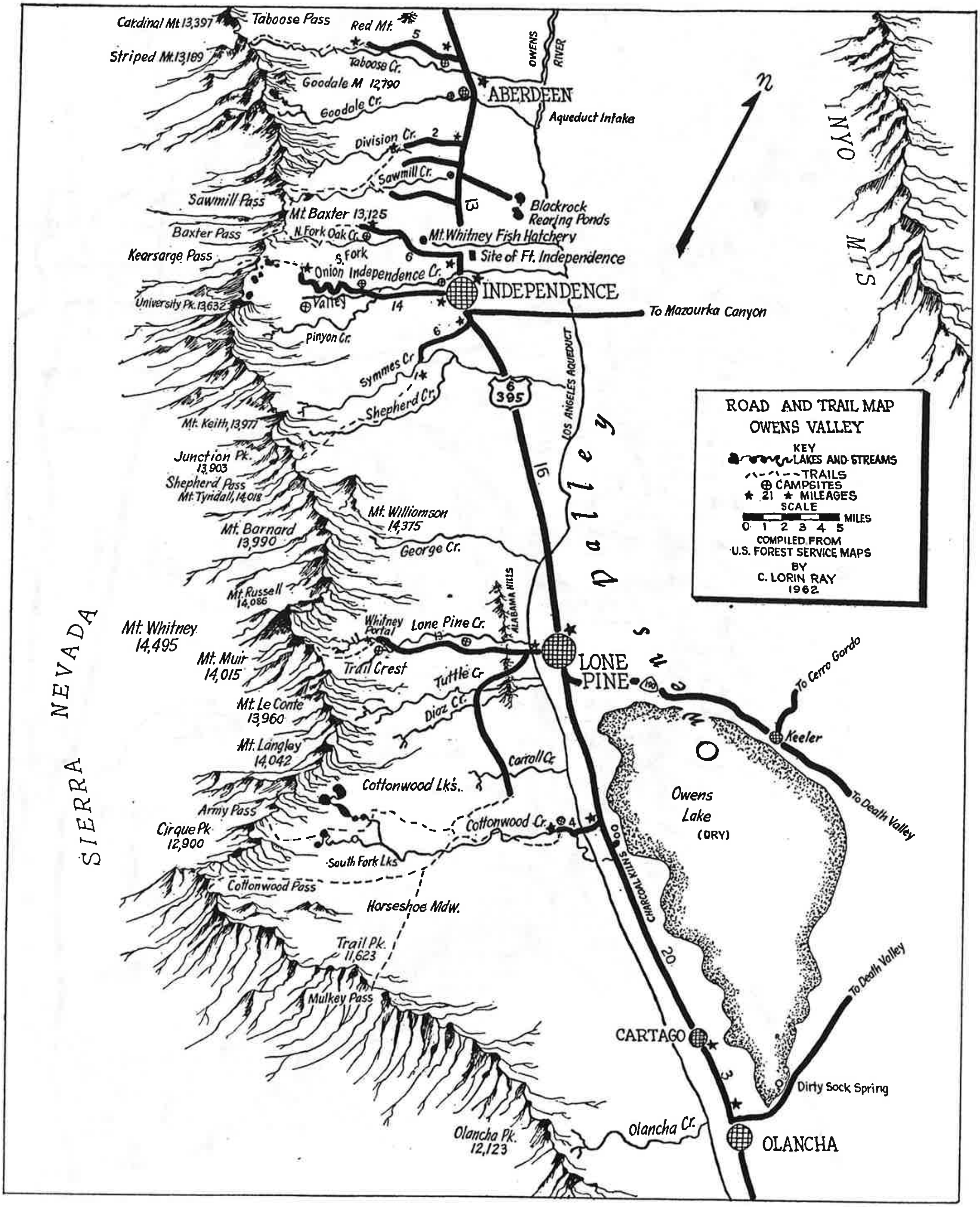
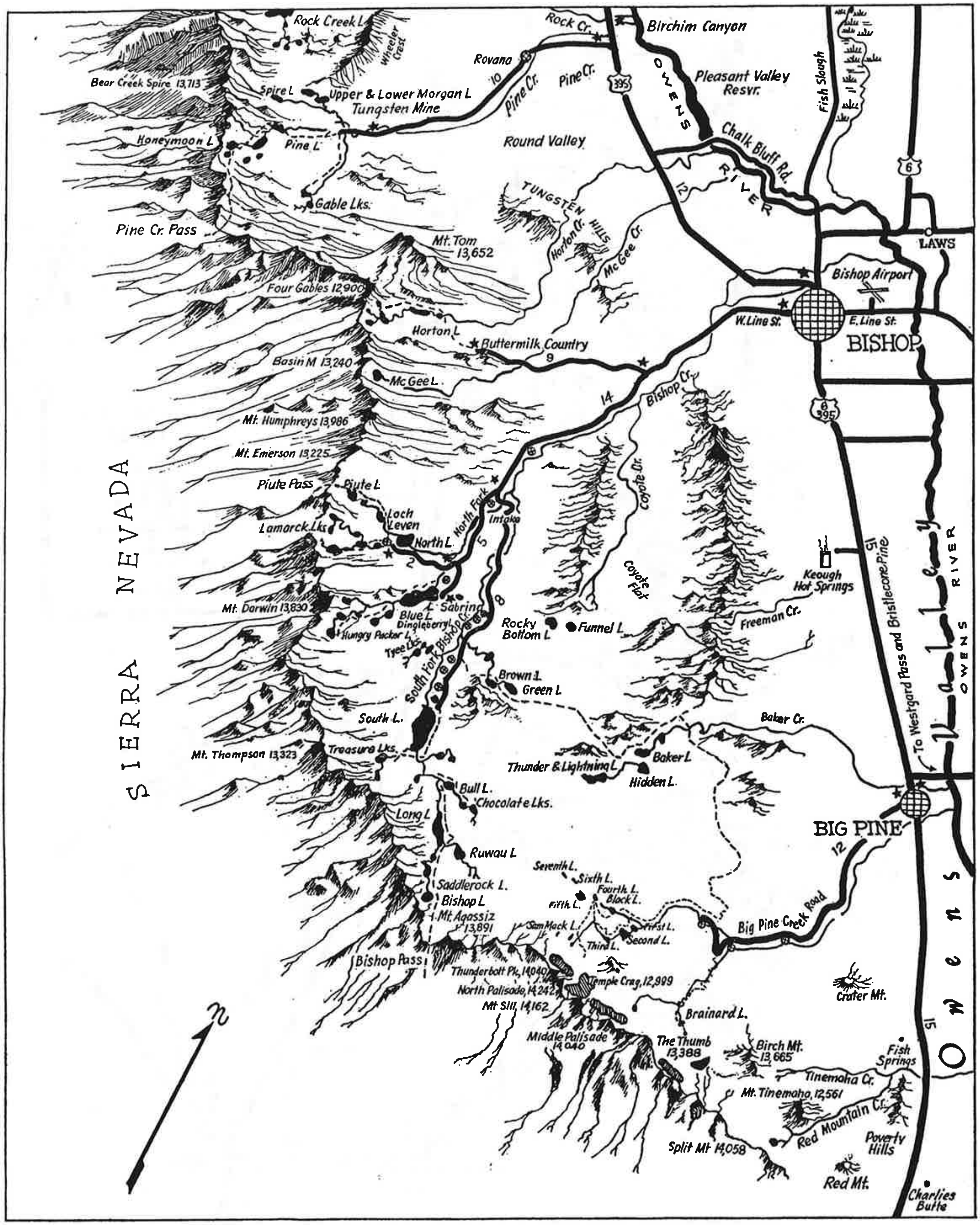
Tentative Itinerary for Friday, August 27

Leave Bishop	0830	p.38, p.55
Arrive Geothermal Plant STOP #4	0915	p.101
Leave Geothermal Plant	1045	
Arrive Mono Lake Visitor's Center STOP #5	1115	p.109
Leave Visitor's Center	1145	
Arrive Tufa Towers	1200	
Lunch	1200-1245	
Tufa Towers STOP #6	1245-0200	
Leave Tufa Towers	0200	
Arrive Obsidian Dome STOP #7	0215	
Leave Obsidian Dome	0300	
Arrive Owen's Gorge STOP #8	0330	p.66
Leave Gorge	0430	
Arrive Bishop	0500	


ROAD AND TRAIL MAP
OWENS VALLEY
KEY
LAKES AND STREAMS
TRAILS
CAMPSITES
21 MILEAGES
SCALE
MILES
0 1 2 3 4 5
COMPILED FROM
U.S. FOREST SERVICE MAPS
BY
C. LORIN RAY
1962
n
INYO MTS
SIERRA NEVADA
Owens Valley
Cardinal Mt. 13,397
Taboose Pass
Red Mt.
Striped Mt. 13,189
Taboose Cr.
Goodale M 12,790
Goodale Cr.
ABERDEEN
OWENS RIVER
Aqueduct Intake
Division Cr.
Sawmill Cr.
Sawmill Pass
Blackrock Rearing Ponds
Mt. Baxter 13,125
Baxter Pass
N. Fork Oak Cr.
Mt. Whitney Fish Hatchery
Site of Ft. Independence
Kearsarge Pass
S. Fork
Onion Valley
Independence Cr.
INDEPENDENCE
University Pk. 13,632
Pinyon Cr.
To Mazourka Canyon
Symmes Cr.
Shepherd Cr.
6 395
LOS ANGELES AQUEDUCT
Mt. Keith, 13,977
Junction Pk. 13,903
Shepherd Pass
Mt. Tyndall, 14,018
Mt. Williamson 14,375
Mt. Barnard 13,990
George Cr.
Mt. Russell 14,086
ALABAMA HILLS
Mt. Whitney 14,495
Whitney Portal
Lone Pine Cr.
Mt. Muir 14,015
Trail Crest
LONE PINE
190
To Cerro Gordo
Tuttle Cr.
Diaz Cr.
Mt. Le Conte 13,960
Mt. Langley 14,042
Keeler
Carroll Cr.
Cottonwood Lks.
Army Pass
Cirque Pk. 12,900
Cottonwood Cr.
South Fork Lks.
Cottonwood Pass
Owens Lake (DRY)
To Death Valley
CHARCOAL KILNS
Horseshoe Mdw.
Trail Pk. 11,623
Mulkey Pass
CARTAGO
Dirty Sock Spring
To Death Valley
Olancha Pk. 12,123
Olancha Cr.
OLANCHA
5
2
13
6
14
6
1
16
13
4
20
3


Rock Creek L
Wheeler Crest
Rock Cr.
Birchim Canyon
Rovana
10
Bear Creek Spire 13,713
Spire L
Upper & Lower Morgan L
Tungsten Mine
Pine Cr.
Pine Cr.
395
OWENS
Pleasant Valley Resvr.
Fish Slough
Honeymoon L
Pine L
Round Valley
Chalk Bluff Rd.
RIVER
6
12
TUNGSTEN HILLS
Gable Lks.
Pine Cr. Pass
Horton Cr.
McGee Cr.
Mt. Tom 13,652
LAWS
Bishop Airport
Four Gables 12,900
W. Line St.
E. Line St.
BISHOP
Horton L
Buttermilk Country
9
Basin M 13,240
McGee L
14
Bishop Cr.
6
395
Mt. Humphreys 13,986
Mt. Emerson 13,225
SIERRA NEVADA
Piute Pass
Piute L
Loch Leven
North Fork
Intake
Coyote Cr.
Lamarck Lks
North L
2
5
Coyote Flat
Keough Hot Springs
15
To Westgard Pass and Bristlecone Pine
8
Mt. Darwin 13,830
Blue L
Sabrina
Dingleberry L
Hungry Packer L
Tyee Lks
Rocky Bottom L
Funnel L
Freeman Cr.
OWENS RIVER
South Fork Bishop Cr.
Brown L
Green L
South L.
Baker Cr.
Mt. Thompson 13,323
Treasure Lks.
Thunder & Lightning L
Baker L
Hidden L.
Bull L.
Chocolate Lks.
Long L
BIG PINE
12
Ruwau L
Seventh L.
Sixth L.
Saddlerock L.
Bishop L
Fifth L.
Fourth L.
Black L.
Mt. Agassiz 13,891
Sam Mack L.
First L.
Second L.
Third L.
Big Pine Creek Road
Bishop Pass
Thunderbolt Pk. 14,040
North Palisade 14,242
Temple Crag 12,999
Mt Sill 14,162
Crater Mt.
Brainard L.
Middle Palisade 14,040
The Thumb 13,388
Birch Mt. 13,665
Fish Springs
Tinemaha Cr.
Mt. Tinemaha 12,561
Red Mountain Cr.
Split Mt 14,058
Poverty Hills
Red Mt.
Charlies Butte
OWENS
15
N

GEOL 414
IGNEOUS PETROLOGY

OWENS VALLEY QUIZ

1. Near what avenue is the San Andreas Fault?
2. Where is Avenue A?
3. With what does Avenue A coincide?
4. What's at Willow Springs?
5. How far apart are the alphabet avenues in Antelope Valley?
6. Where is Little Pine?
7. Where is the Tungsten Mine?
8. In what type of ore body is tungsten found?
9. What is the chemical symbol for tungsten?
10. What is the common tungsten mineral?
11. What three towns anchor the south west corner of Owens Lake?
12. Where is Aberdeen?
13. What distinctive color was the Little Lake Hotel?
14. How far north on Rt.395 can you still see Mt. Whitney?
15. For what does KIBS stand?
16. What are the names of the two resevoirs in the Owens Valley?
17. What hills are west of Lone Pine?
18. What hills are southwest of Big Pine?
19. Where is Dolomite?

5

20. What is dolomite?

21. What is Winnedumah? Where is it?

22. Where is First Lake?

23. Where is Lake Sabrina?

24. Where is Gilbert Lake?

25. What range lies east of Red Rock Canyon?

26. Who was Vasquez?

27. When was the Owens Valley earthquake and how many people died?

28. How high is Mt. Whitney?

29. Name the southernmost Sierran glacier. Where is it?

30. What is the name of the first trans-Sierra road north of Bishop?

31. What is the name of the first trans-Sierra road south of Bishop?

32. Where does Rt.14 run into Rt.395?

33. Where is Dunmovin?

34. When was the most recent Coso vulcanism?

35. Where is Pearsonville?

36. Where is Indian Springs Valley?

37. What is the age of the Sherwin Till?

38. Where is the Sherwin grade?

39. Where is Tom's Place?

40. Where is Mt. Tom?

42. How high is Mammoth Mountain?

43. How many ski lifts are on Mammoth Mountain?

44. When was the most recent vulcanism in the Mammoth region?

45. How far did the Bishop Tuff travel?

46. What is the relief between Death Valley and Mt. Whitney?

47. Where is the longest stretch of straight road between Los Angeles and Lee Vining? How long is this stretch?

48. What canyon has no name?

49. Where is Westgard Pass?

50. How do you get to the Bristlecone pines?

51. Where is Montgomery Pass?

52. Where is the lake that makes you think of prisoners?

53. What lake partly fills Long Valley?

54. Where is Cerro Gordo?

55. What was Cerro Gordo?

56. What does the Spanish name mean?

57. How did the Cerro Gordo ore get to market?

58. What is the name of the island in Mono lake?

59. How did the tufa towers form in Mono lake?

60. What creatures live in the briny Mono lake waters?

61. How do you get to Devil's Postpile?

62. Of what is the Devil's Postpile made?

63. Of what is Obsidian Dome made?

64. How did the Indians use obsidian?

65. Where is Jawbone Canyon?

66. List three hot springs areas between Mojave and Lee Vining.

67. To where did waters from Owens Lake used to flow?

68. What was mined in the Owens Lake?

69. Where is Movie Flats?

70. Where is Diaz Lake?

71. Why is Diaz Lake where it is?

72. When was the recent Mammoth earthquake swarm?

73. What are the names of the major roof pendants along the Sierran crest?

74. Where can you get a shower in Lone Pine? How much does it cost?

8

Field Guide to the Geology of
Red Rock Canyon and the Southern El Paso Mountains
Mojave Desert, California

by

David P. Whistler

Earth Sciences Division
Natural History Museum of Los Angeles County
900 Exposition Blvd.
Los Angeles, CA 90007

Red Rock Canyon, with its colorful and scenic cliffs, has been an area of public curiosity for over 100 years. The geologic and paleontologic significance of the area began to be realized with detailed studies by geologists in the early part of this century (Baker, 1912; Merrian, 1919), a process that continues (Cox and Diggles, 1984; Burbank and Whistler, 1985, 1986; Loomis and Burbank, 1987; Whistler and Burbank, 1987).

The following guide highlights some of the more obvious features of areas which are accessible by paved highways. Several side trips are also described, and considerably more awaits those who venture off the main thoroughfare. Much of the area described is within Red Rock Canyon California State Park, thus collecting, even hand specimens, is prohibited. Geographic place names are in a state of flux, however, the names currently applied by the California State Park are used in this report.

Road distances are given in miles in deference to United States auto odometers; all other measurements are metric. The data presented is taken from observations and extensive geologic mapping by the author and published and unpublished reports (Masters and Doctoral theses). All photographs are by the author.

GENERAL GEOLOGY

The geology of Red Rock Canyon and the southern El Paso Mountains is fairly straight forward, although it spans an interval of time from Late Precambrian to Holocene (Dibblee, 1952; Carter et al., 1981). Major depositional episodes occurred in the later Paleozoic, Paleocene, Miocene and Quaternary, and plutonic intrusion occurred during the latest Permian and Mesozoic (Dibblee, 1952; Cox and Morton, 1980). The area is tectonically active and arid, thus exposures are excellent.

The bulk of exposures in Red Rock Canyon, and those described herein, document the later Miocene through Holocene history of the area (Whistler, 1982; Loomis and Burbank, 1987). The area is under major structural control by the Garlock and El Paso Faults (Carter, 1980; Loomis and Burbank, 1987).

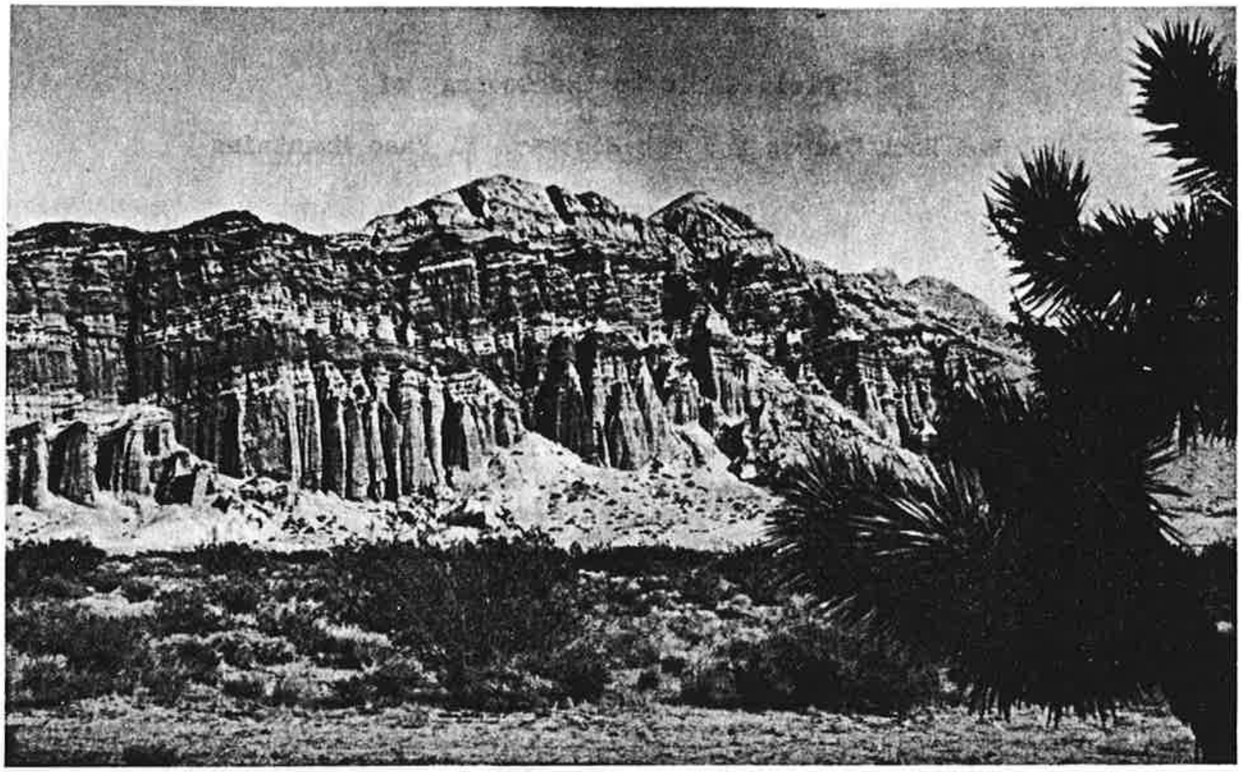


Figure 1 - Typical exposures of Ricardo Formation at Red Cliffs Natural Preserve east of California Highway 14. Section is interbedded channel sandstones (dark beds), overbank deposits (light, thin-bedded bands) and massive, floodplain deposits (gray). Cliff is capped by resistant, pink lapilli tuff breccia.

The oldest rocks exposed in the El Paso Mountains are the highly metamorphosed chlorite-quartz-albite-sericite Mesquenite Schist. This Precambrian schist forms the basement on which the slightly metamorphosed, Late Paleozoic, marine Garlock Formation has been deposited (Dibblee, 1952; Christiansen, 1961). The Garlock Formation is composed of shales, cherts, quartzites, limestones, conglomerates and submarine volcanic flows that are not exposed in Red Rock Canyon, but they are the dominant lithologies in the northeastern El Paso Range.

The Garlock Formation and the Mesquite Schist have been intruded by a complex of plutonic rocks ranging in composition from hornblende-quartz diorite to granite. One of these intrusive units, a highly fractured and jointed granophyre plug, surrounds the gorge at the entrance to Red Rock Canyon.

The Paleozoic and Mesozoic rocks are deeply eroded and are unconformably overlain by the continental Goler Formation of Paleocene age (Cox, 1982), a thick succession composed primarily of conglomerates and sandstones. Occasional finer-grained rocks in the Goler Formation have produced sparse, but diagnostic, vertebrate fossils (McKenna, 1960), which are the oldest records of fossil mammals in California. The Goler Formation is not exposed in Red Rock Canyon, but some thin exposures are present on the eastern side of Scenic Canyon (called Iron Canyon on Figure 1).

The dominant exposures in Red Rock Canyon are Middle and Late Miocene volcanics and clastics lumped together as the Ricardo Formation by Dibblee (1952). More current interpretations would subdivide the older, dominantly volcanic rocks and the overlying, dominantly fluviatile rocks into two formations (Loomis et al., 1983; Loomis and Burbank, 1987). Because the new formational names have not yet been published, the term "Ricardo Formation" will be used here for all these rocks.

The Middle Miocene volcanic rocks at the base of this sequence (Ricardo Members 1 and 2 of Dibblee) are coarse pyroclastics and andesite flows that are most prevalent in Last Chance Canyon in the west-central El Paso Mountains. They also form most of the rocks of Black Mountain in the northwestern El Paso Mountains (including the Black Mountain Basalt which Dibblee considered Quaternary). Radiometric age determinations from interbedded basalt and andesite flows yielded a range of dates from 15 to 19 million years (Cox, personal communication). These volcanic rocks are probably related to the Middle Miocene Tropico Group volcanics which blanketed much of the western Mojave Desert at that time (Dibblee, 1967).

The Middle Miocene volcanics are overlain by 1800 meters of primarily fluviatile and lacustrine, later Miocene sediments (Ricardo Formation Members 3-8 of Dibblee, 1952). These form the scenic, multicolored badlands in Red Rock Canyon (Figure 1). The lower 800 meters of this succession contain numerous volcanic ash falls, two thick lapilli tuff breccias and two basalt flow sequences (Whistler, 1969). A volcanic ash near the base of Dibblee's Member 3 yielded a radiometric date slightly in excess of 10 million years (Evernden et al., 1964), but subsequent radiometric and paleomagnetic analyses support an older age of at least 12.5 million years (Loomis and Burbank, 1987; Whistler and Burbank, 1987). The fluviatile sandstones and conglomerates in this part of the section have an easterly source area (Loomis, 1984). The common pebbles and boulders are nearly all porphyritic volcanics and dark metamorphics, not plutonics, which would be expected because of the dominantly granitic nature of the source area today. The upper 1000 meters of later Miocene sediments are generally coarser grained and, in them, Sierran-derived plutonic clasts become more common.

The later Miocene part of the Ricardo Formation has yielded a diverse vertebrate fossil record spanning over 5 million years based on radiometric and paleomagnetic studies (Whistler, 1969; Burbank and Whistler, 1986). This fossil assemblage is currently being proposed as a biostratigraphic standard for the Clarendonian North American land mammal age in southwestern North America (Whistler and Burbank, 1987).

The Ricardo Formation is overlain by several episodes of Quaternary alluvial deposition derived primarily from the emerging Sierra Nevada. These deposits demonstrate a complex history of down-cutting and terrace and pediment development, all probably related to periodic uplifts in the Sierra Nevada. Unpublished radiocarbon evidence from the author's files suggests an age of approximately 10,700 years for at least some of these deposits.

STRUCTURAL CONTROL

The dominant structural feature of the area is the Garlock Fault and its major splay, the El Paso Fault. The Garlock Fault is a major transform fault which separates the relatively stable Mojave Block to the south from the major crustal extensional area of the Basin and Range Province to the north

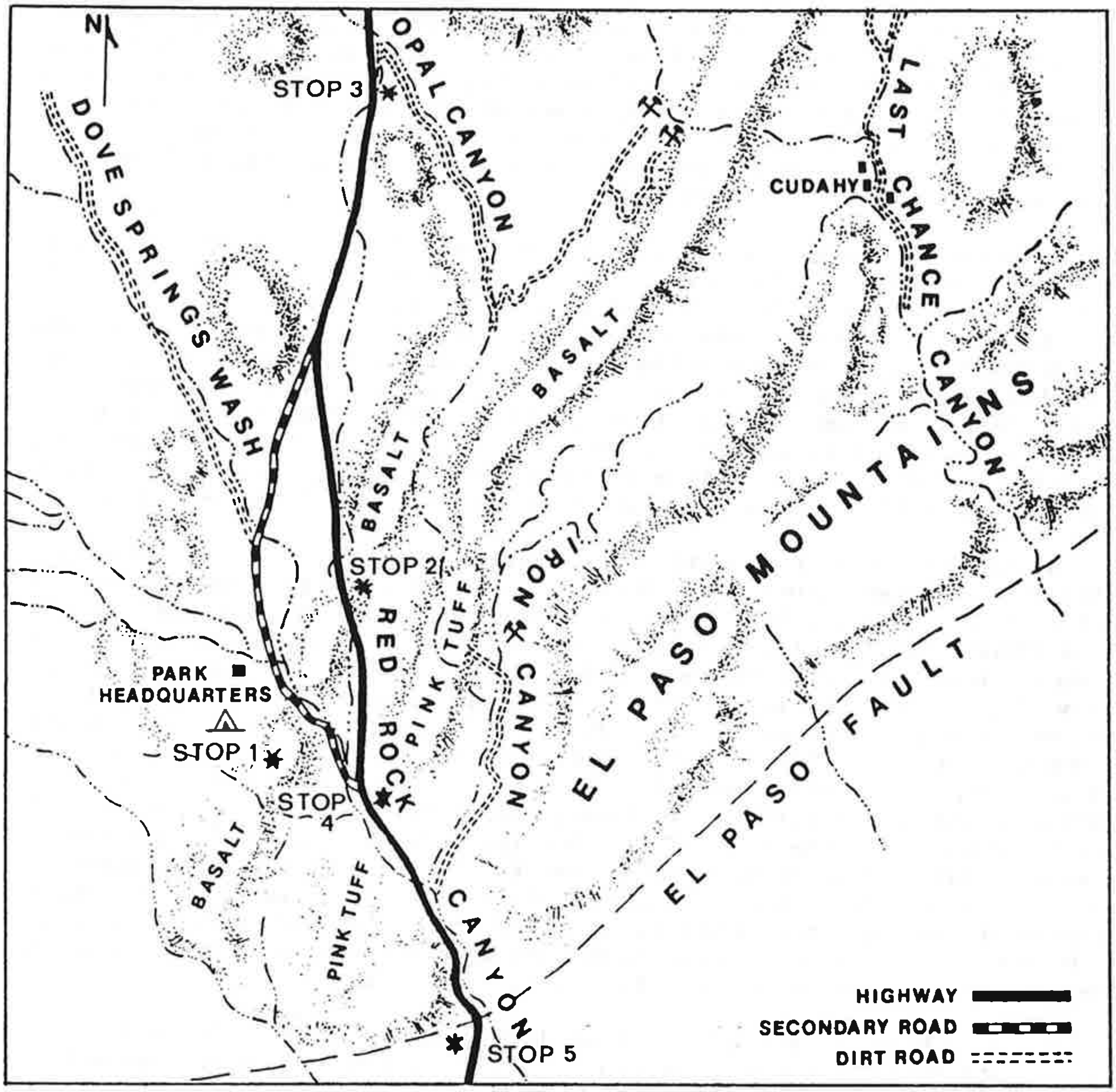


Figure 2 - Index map of the Red Rock Canyon area showing stops discussed in text.

(Davis and Burchfiel, 1973). Both the Goler and Ricardo formations were deposited in elongated troughs, similar in morphology to the Fremont Valley today, that probably formed along the trace of the Garlock Fault. A cumulative left-lateral displacement of 48 to 64 kilometers has been demonstrated for the Garlock Fault zone (Smith, 1962; Chen and Moore, 1979). Alluvial fans that are offset from their source canyons along the front of the El Paso Mountains indicate at least 18 kilometers, or roughly one-third of the cumulative displacement, has occurred during the past 1.5 million years (Carter, 1980).

Major uplift of the El Paso Mountains, with a cumulative total in excess of 15 kilometers, has taken place primarily on the El Paso Fault and this movement is responsible for uplifting the rocks exposed in Red Rock Canyon.

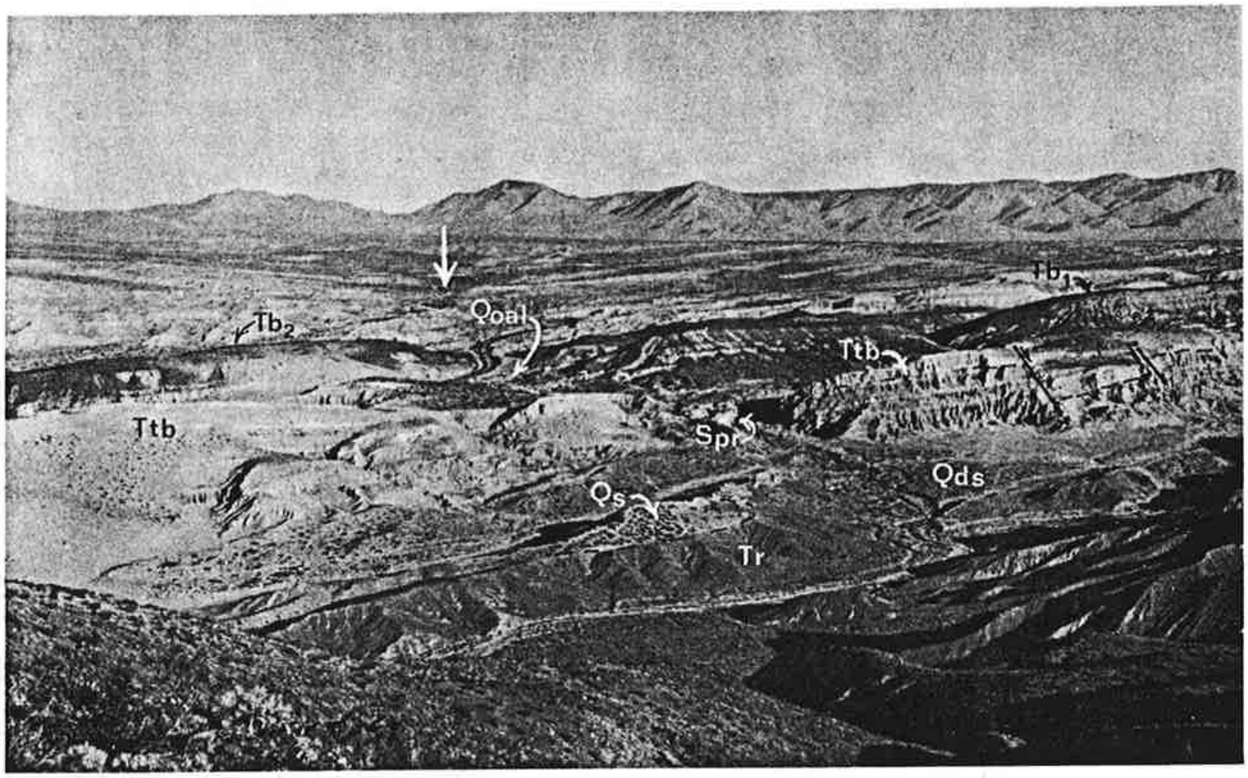


Figure 3 - View looking northwest from top of El Paso Mountains of lower Scenic Canyon and part of Red Rock Canyon. Sierra Nevada on horizon with pediment fans extending eastward from base. Hogback ridges in middle distance are formed by basalts interbedded within Ricardo Formation (Tb_1 and Tb_2). Large white arrow points to Dove Springs Wash. Closer, light colored ridges are capped by pink lapilli tuff breccia (Ttb) which displays offset from faulting in right center of view (see Figure 8 also). Alluvial infilling (Qoal) of ancient stream valley shown in detail in Figure 4 in middle distance with Sullivan Springs (Spr) at eastern end. Unconformity between flat-lying Quaternary deposits (Qs) and underlying Ricardo Formation (Tr) prevalent in middle foreground (see Figure 7).

This fault forms the eastern boundary of the range. There are a few minor faults which traverse diagonally across the El Paso Mountains and cut the overlying Miocene clastics and volcanics, but none appear to have been active in the Quaternary.

ACKNOWLEDGEMENTS

The author has benefited from the participation of many people in field work in the Red Rock Canyon area over the past 20 years. I wish to especially thank R.H. Tedford who turned over all of his mapping and other studies. Since its formation in 1970, all the staff of Red Rock Canyon California State Park have provided assistance and amenities that greatly facilitated field work. Although too numerous to name, several deserve special recognition for their direct participation in field work: Rangers Mark Faul, Stuart Alexander, Joe McCummins, Alan Wilkinson, Vic Maris and Buck Graham, several of their wives, Sue McCummins, Lynn Alexander and Barb Wilkinson, and

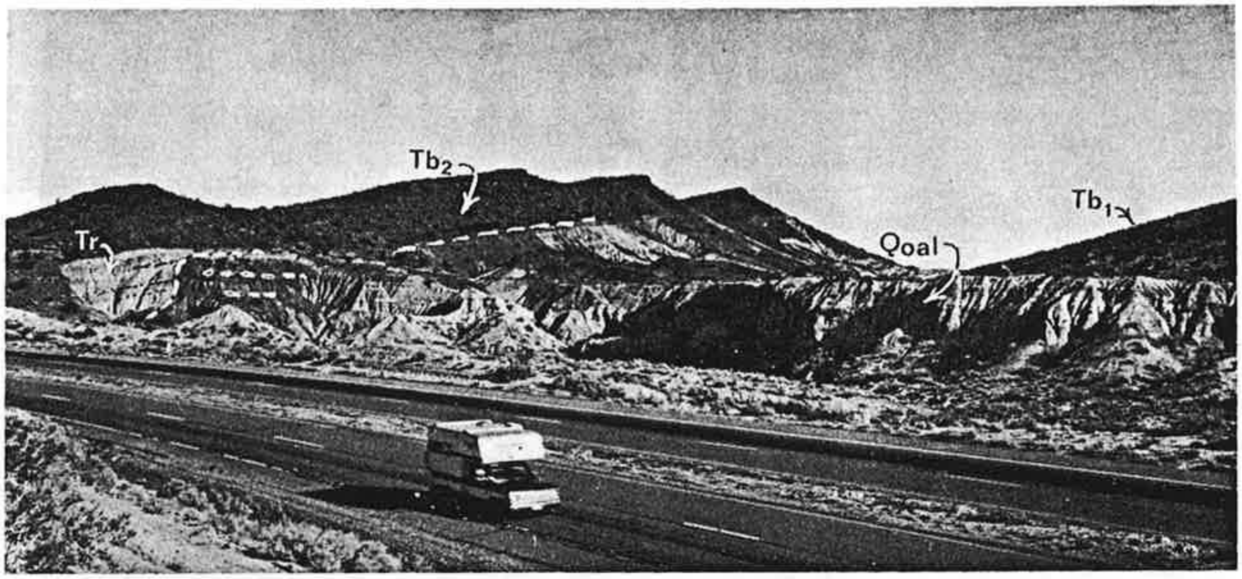


Figure 4 - Field trip STOP 2 - Infilling of alluvium (Qoal) into an older Quaternary channel cut into Miocene Ricardo Formation. This alluvium is part of fan, stream and pond deposits which blanketed area between Sierra Nevada and El Paso Mountains except for high-standing ridges of Ricardo Formation volcanics (Tb_1 and Tb_2). Note the angular unconformity between Ricardo Formation (Tr) on left and alluvium on right. This alluvium has been dissected by latest Quaternary and Holocene erosion caused by stream capture in Red Rock Canyon and continued uplift of El Paso Mountains and Sierra Nevada.

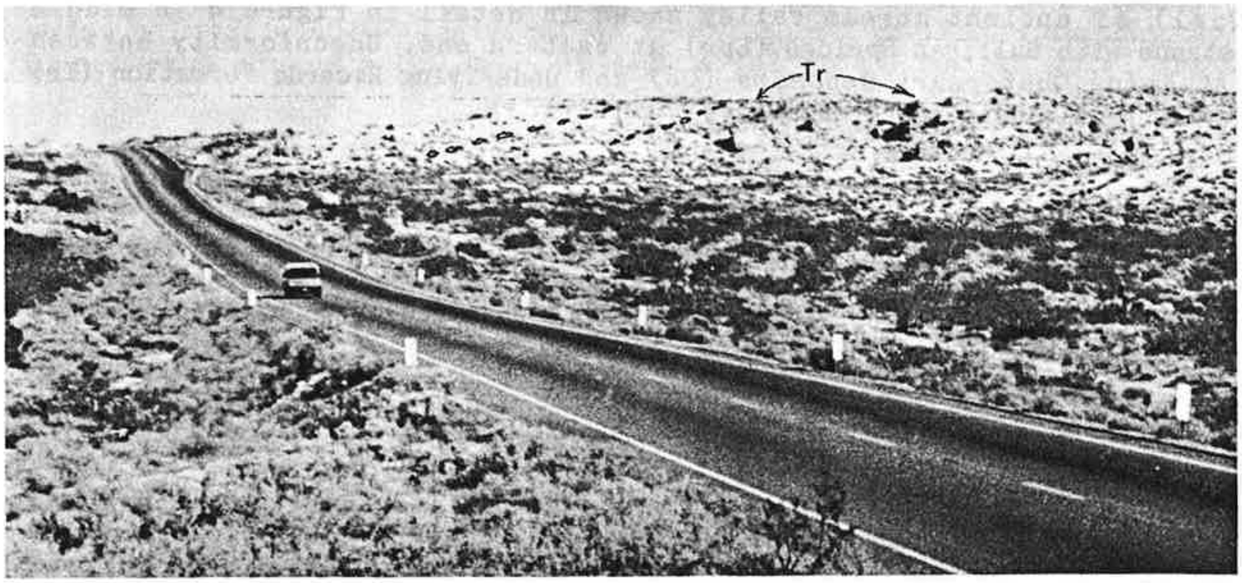


Figure 5 - Field trip STOP 3 - Paleosoil and siliceous (opal and zeolites) hardpan deposits prevalent in the upper 400 meters of Ricardo Formation (Tr) on the east side of highway, 3 miles north of Park Headquarters.

seasonal rangers Colleen Helton and Jennifer Fletcher. Collecting permits have been granted by the California State Department of Parks and Recreation and the United States Department of Interior, Bureau of Land Management. John Harris and Lawrence Barnes provided helpful comments on this manuscript. Support for field work has been provided by an Annie Alexander Fellowship from the University of California, Berkeley, Museum of Paleontology and the Center for Field Research (Earthwatch). Funding for paleomagnetic and fission trackway studies was provided by NSF Grant EAR 8305874. Additional support was provided by NSF grants BMS 7202014 and BSR 8218194.

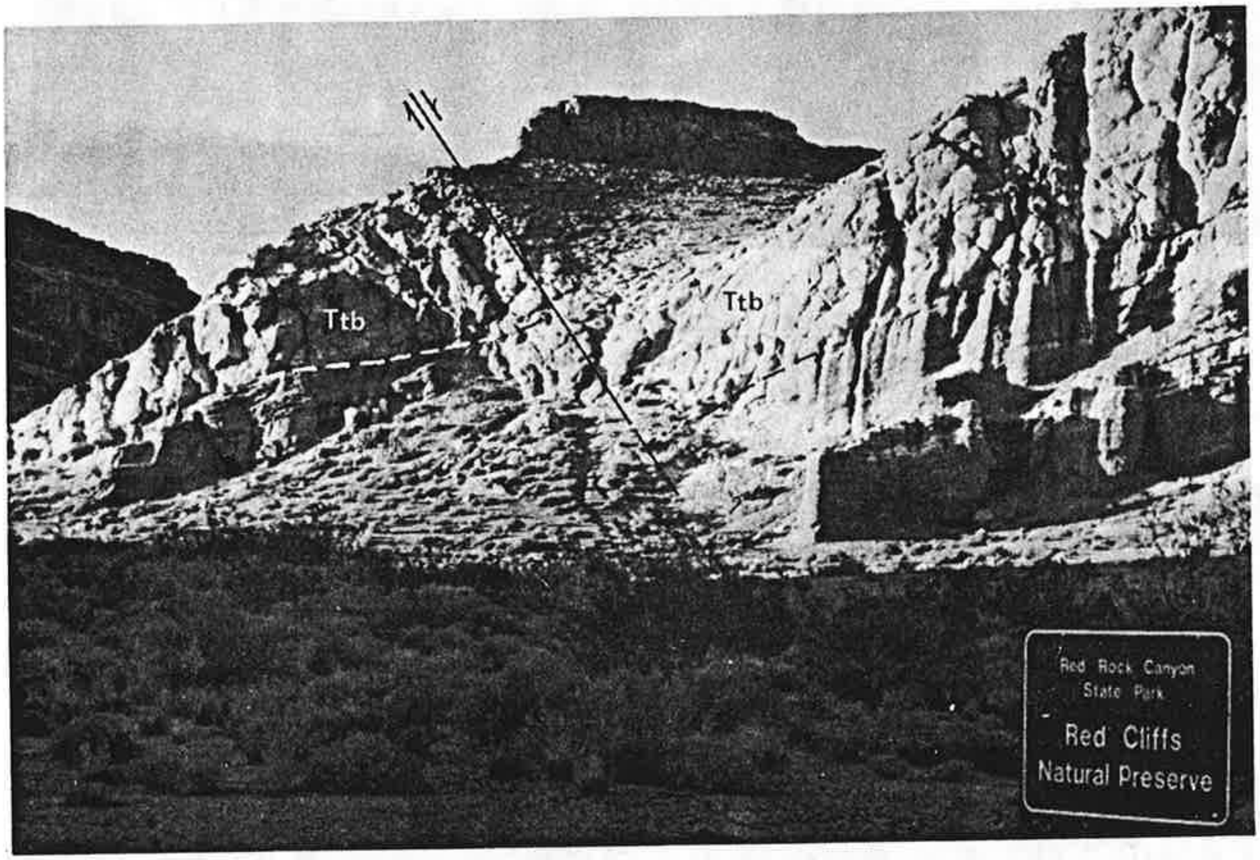


Figure 6 - Field trip STOP 4 - Small fault cutting pink lapilli tuff breccia in Ricardo Formation immediately east of Highway 14 at west end of Red Cliffs Natural Preserve.

FIELD TRIP ROAD LOG
Figure 2

STOP 1 -- Starting point is at the Red Rock Canyon State Park Headquarters about one mile west of Highway 14 on Abbott Drive. The ranger station is adjacent to ridges formed by a sequence of basalt flows interbedded within the Ricardo Formation. These flows are clearly exposed in the road cut on Abbott Drive where vugs and veins are filled with white opal, chalcedony, and zeolites and a green alteration mica, celadonite. From the Ranger Station, walk south about 1 kilometer on the Campground Road and up the nature trail to the top of the basalt ridge for a panoramic view of the entire southern El Paso Mountains, southern Indian Wells Valley, Red Rock Canyon, Fremont Valley and Mojave Block beyond to the south. The lower portion of the Nature Trail traverses pebble and boulder conglomerates. Note that the pebbles, cobbles and boulders are mostly well rounded volcanics and metamorphics, not

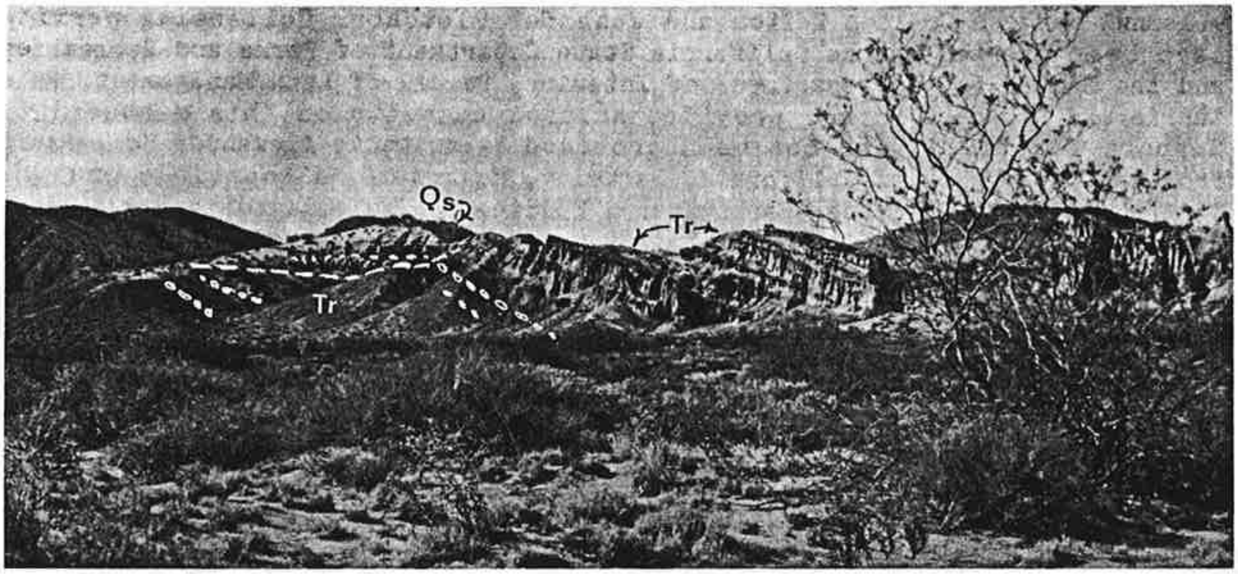


Figure 7 - Part of flat-lying Quaternary sands and clays (Qs), an extension of same deposits described in Figure 4, unconformably overlying basal Ricardo Formation (Tr). View is in lower Scenic Canyon (see Figure 3 also).

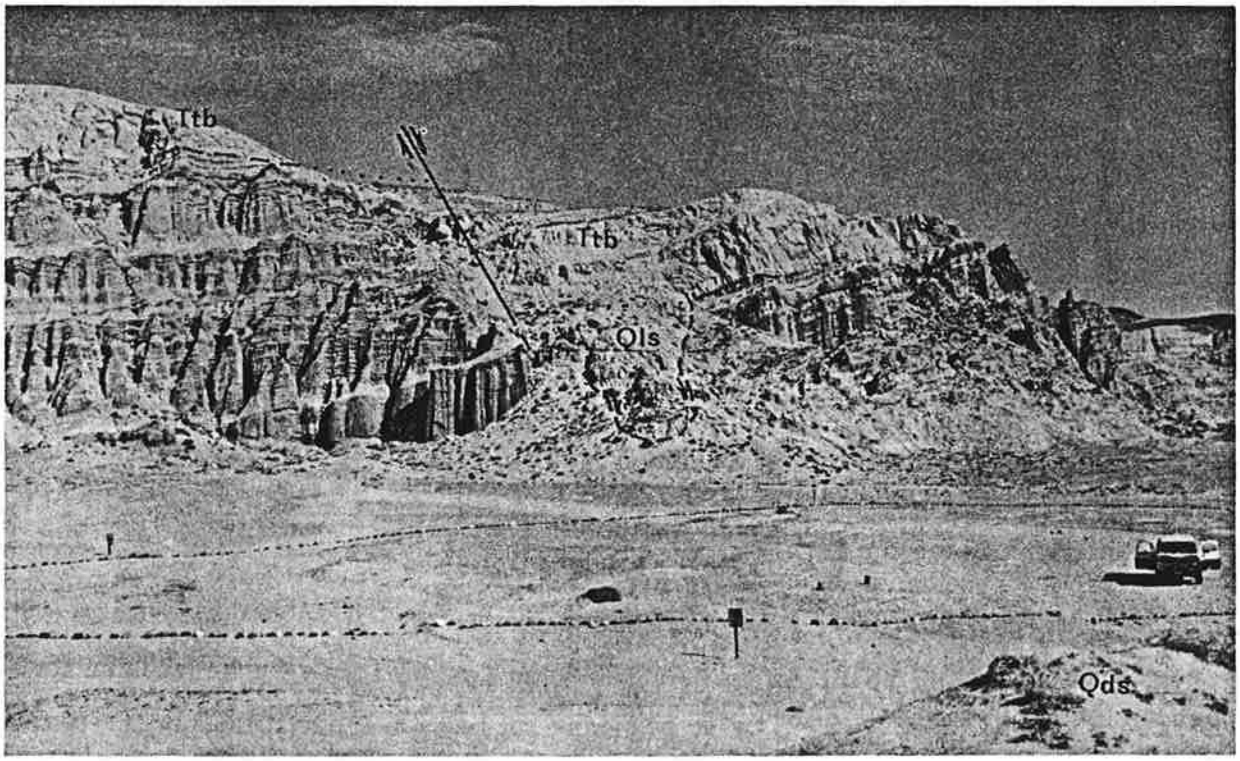


Figure 8 - Faulting and landsliding in lower part of Ricardo Formation at Scenic Cliffs. Note offset of pink tuff breccia (Ttb) capping cliffs and landslide block (Qls) of tuff breccia extending to flats in foreground. Actual plane of fault is nearly vertical and it strikes parallel to bluff face. This fault can be traced several kilometers up Scenic Canyon where it offsets and repeats Middle Miocene volcanics underlying the Ricardo Formation. Photo taken from top of stabalized sand dune (Qds) formed in wind gap in tuff breccia to west.

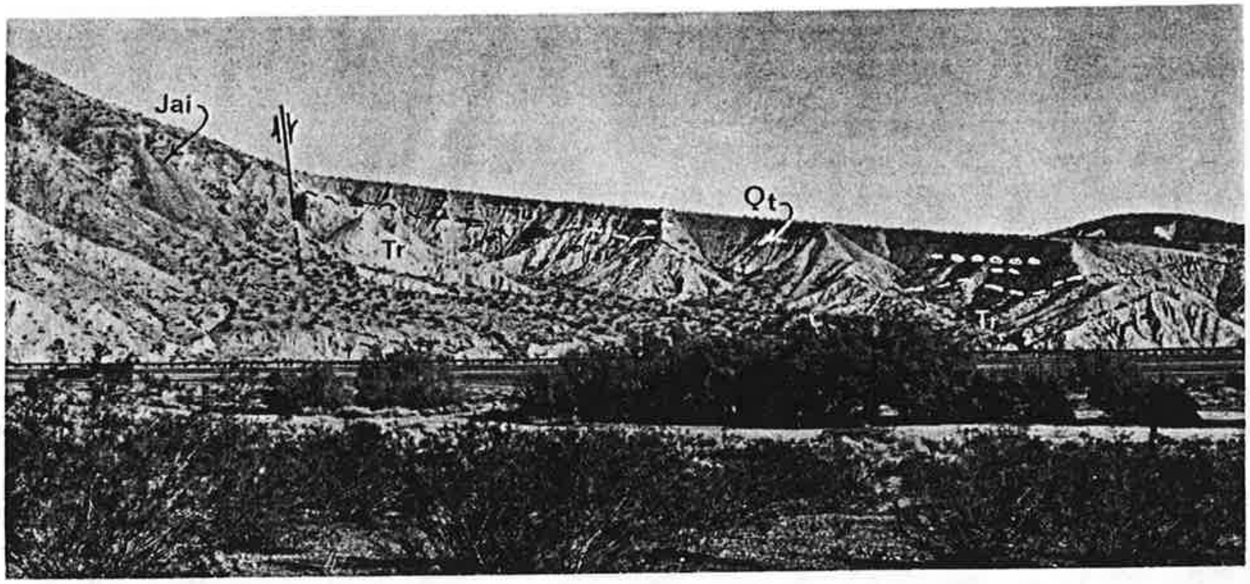


Figure 9 - Field trip STOP 5 - View at entrance of red Rock Canyon of El Paso Fault separating Mesozoic granophyre (Jai) from dipping Tertiary clastics (Tr) and overlying Quaternary alluvial terraces (Qt). Latest Quaternary and Holocene uplift on El Paso Fault and stream capture in the adjacent Red Rock Canyon gorge has produced the downcutting which exposes the section.

plutonics. Further up the hill, the trail traverses a dip-slope on top of the basalt flow sequence which is highly vesiculated and displays some rudimentary columnar jointing.

To the northwest is the southern end of the Indian Wells Valley covered with alluvial fans spreading eastward from the granitic Sierra Nevada (Figure 3). The Sierra Nevada is uplifted along the high angle Sierran Front Fault that is evident to the southwest where there is an escarpment at the foot of the steeper granitic hills. Badlands in the near distance are formed in clastics of the upper portion of the Ricardo Formation. To the east is the crystalline core of the El Paso Mountains which has been uplifted and tilted to the west. Beyond is the deep trough of the Fremont Valley which formed between the Garlock Fault on the west and the Cantil Valley Fault on the east. Beyond the Fremont Valley is the elevated, flat, granitic Mojave Block which extends 50 miles to the south where it is truncated by the San Andreas Fault and the San Gabriel Mountains (only visible on a clear day).

The El Paso Mountains extend to the northeast where their western slopes are covered with western-dipping deposits of Middle Miocene volcanics. These volcanics also form most of Black Mountain, the high peak on the horizon directly to the north. In the near distance are dissected badlands in the western-dipping homocline of the interbedded clastics and volcanics of the lower portion of the Ricardo Formation. Note that the lower of the two basalt flow sequences in the foreground pinches out before crossing Abbott Drive and starts up again north of the main highway. Both basalt sequences thin and eventually pinch out to the northeast.

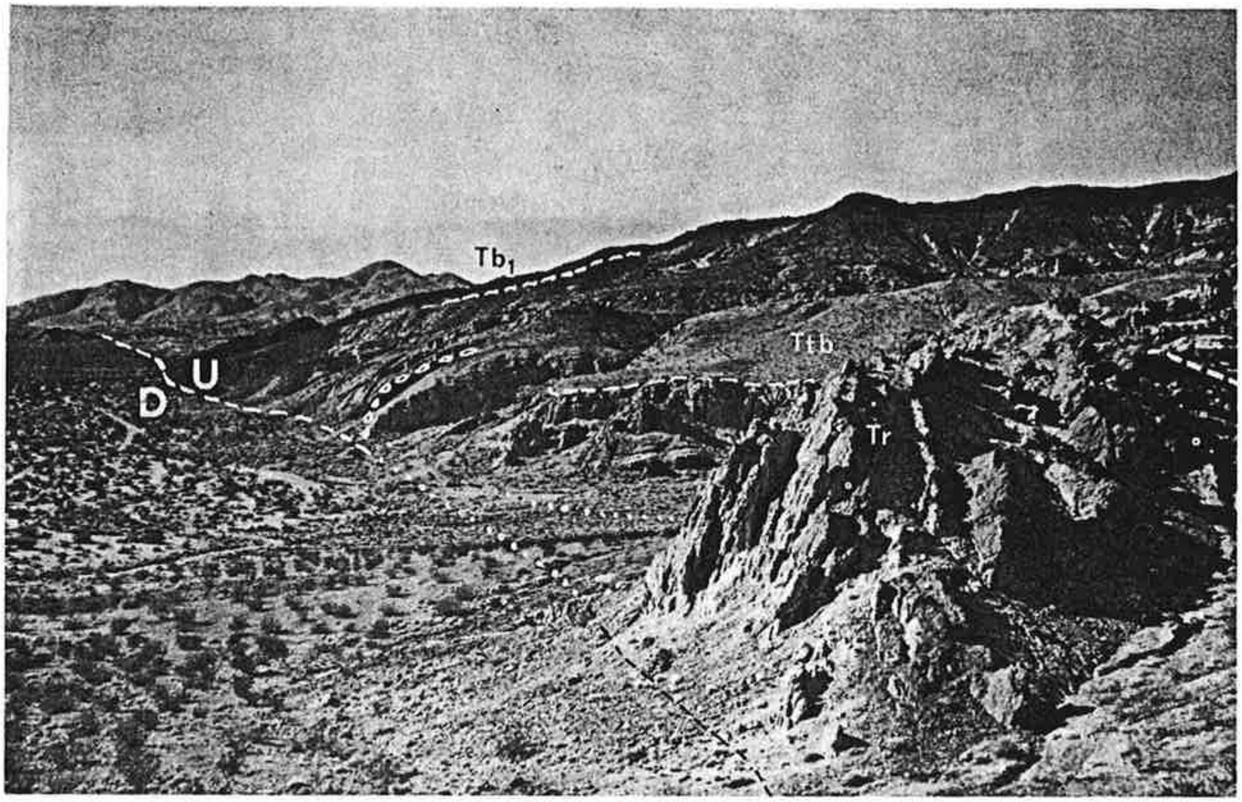


Figure 10 - Field trip STOP 5 continued - El Paso Fault separating Ricardo Formation (Tr) from alluvial plain at Red Rooster, 1 kilometer west of Highway 14 west of entrance to Red Rock Canyon. Ricardo Formation on right has been uplifted at least 1 kilometer relative to the alluvial plain. Note nearly vertical dipping outcrops of Ricardo Formation in fault-wedge in foreground, more gently dipping outcrops in background and drag folding of thin-bedded sandstones in mid-distance.

Return to the Park Headquarters and proceed southeast (right) on Abbott Drive. At 0.3 miles the road crosses the lower basalts. On the right at 0.5 miles is a thin, white ash bed interbedded within orange and light gray channel sandstones and siltstones of the Ricardo Formation. This ash thickens dramatically to the northeast and becomes the 6 meter thick ash in upper Last Chance Canyon that was mined for abrasives for the first half of this century by the Dutch Cleanser Company. Turn north (left) on Highway 14. On the right is a dip slope within a massive pink lapilli tuff breccia, at 1.3 miles are badlands in channel sandstones and conglomerates overlying the tuff breccia. At 1.7, miles turn out at a small siding on the right, opposite a sand dune flowing down from the basalt-capped ridge on the left.

STOP 2 -- Walk north on the right side of the highway and observe dissected Quaternary sands and conglomerates partially filling the canyon which was cut into the Miocene Ricardo Formation (Figure 4). Note that the upper surface of these deposits is flat and that the interbedded boulders are mostly light-colored granites derived from the Sierra Nevada, not basalt boulders derived from the immediately adjacent ridges. These bouldery sands were deposited in an ancient stream course that traversed directly eastward through the resistant ridges of the underlying Ricardo Formation and then

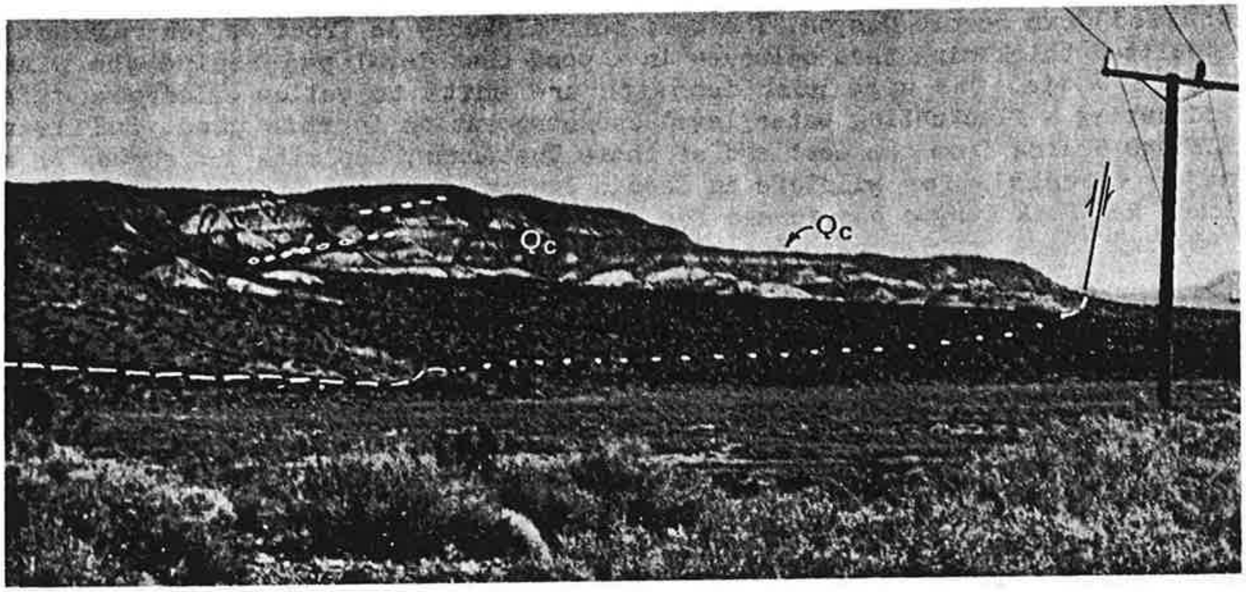


Figure 11 - Field trip STOP 7 - Quaternary lake and alluvial fan deposits (Qc) uplifted by Garlock Fault at mouth of Mesquite Canyon. Due to fault uplift, sediments which were originally dipping gently to right are now dipping 10 degrees to left.

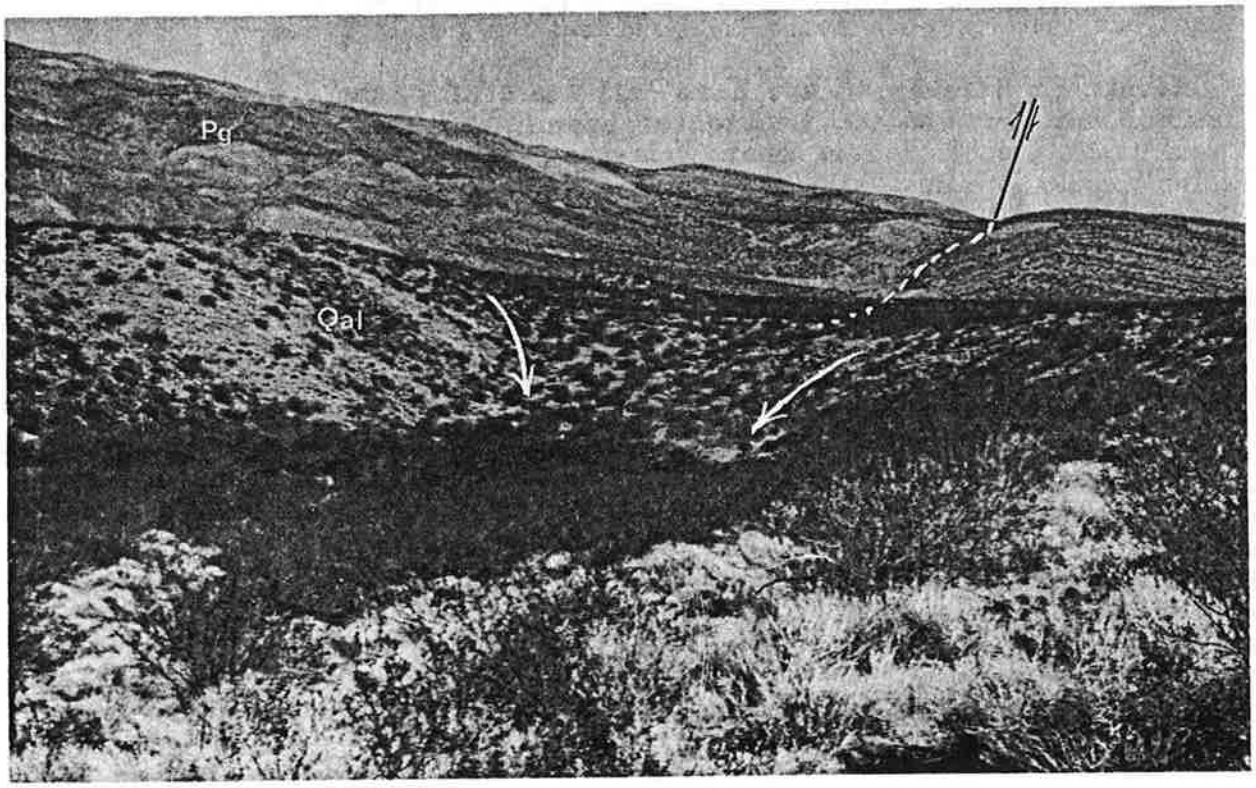


Figure 12 - Field trip STOP 7 - Graben (white arrows) formed in alluvium along trace of Garlock Fault below Goler Gulch. Note fresh escarpment on left in alluvium (Qal). Mountains in left background formed in Late Paleozoic Garlock Formation (Pg). Notch in hill in background continuation of trace of Garlock Fault.

drained down Scenic Canyon. The sediments directly in front of you represent localized thickening that occurred in a pond that developed behind the pink tuff breccia. The uppermost deposits are white to yellow calcareous tufa indicating a fluctuating water level and evaporation in this pond. Sullivan Springs drains from the east end of these Quaternary deposits and serves as a major waterhole for wildlife in Scenic Canyon. Subsequent stream capture in lower Red Rock Canyon has formed the current drainage which is now rapidly removing these poorly consolidated Quaternary deposits.

Return to the highway and drive north. The highway traverses a long projection of Quaternary fan sediments overlying the Ricardo Formation. At 4.4 miles you pass gently dipping white beds on the right that are paleosoils and authigenic siliceous (opal and zeolites) hardpan deposits common in the upper part of the Ricardo Formation (Figure 5). Turn out to the right at 4.6 miles at a sign that says "Opal Canyon" (or just "Opals").

STOP 3 -- From this vantage point there is a good overview (to the south) of the flat, upper surface of the pediment fans extending eastward from the Sierra Nevada. It is apparent that the present-day badlands of Red Rock Canyon are dissecting these fans. From here a side trip can be taken down Opal Canyon. The road traverses the upper part of the Ricardo Formation down to the upper basalt where it turns north toward the opal mines. The Ricardo Formation is finer grained and contains many interbedded cherts in this general area because you are close to the center of the Late Miocene depositional basin. The fire opal mines are privately owned, but open to the public for daily mining on a fee basis. The opals are formed in vesicles, vugs, and veins where a small fault crosses the basalt flows.

Return to Highway 14 and turn left (carefully, the view to the right is restricted). Drive to the junction of upper Abbott Drive at 6.2 miles and turn right (west). Follow Abbott Drive back toward Park Headquarters. At 6.9 miles you cross a dry wash (Dove Springs Wash), the major drainage from the Sierra Nevada into Red Rock Canyon. Flash floods are common in this drainage, as may be evident from the freshly plowed piles of sand where the road crosses the wash. On the right (west) are sandstones and siltstones of the Ricardo Formation that produced the earliest vertebrate fossil collections between 1906 and 1920. Continue down Abbott Drive past Park Headquarters, retracing your earlier travel, but turn right (south) on Highway 14. Turn left (east) across the highway at 9.3 miles at Red Cliffs Nature Preserve.

STOP 4 -- The colorful bluffs surrounding the parking area are stream channel and overbank deposits of the lower part of the Ricardo Formation (Figure 1). The bluff is capped by a massive, pink, lapilli tuff breccia containing many angular lithic fragments. A prominant break (and color change) in this unit in the cliffs to the west represents a baked zone between two successive falls. These tuff breccias are over 200 meters thick here, but they thin rapidly and pinch out 4 kilometers to the northeast. Walk west around the base of the cliffs to observe a small fault which offsets the contact between the tuff breccia and the underlying clastics (Figure 6).

From this stop there is an easy side trip by foot up Scenic Canyon and Nightmare Gulch, the latter name applied to the upper drainages of Scenic Canyon (see Figures 7 and 8). This hike will provide close-up views of the sediments and volcanics of the lower part of the Ricardo Formation in a spectacular setting of deeply dissected cliffs and badlands.

Return to the highway and turn left (south). Clearly visible on the right (west) side of the canyon are the basal conglomerates of the Ricardo Formation lapping onto older crystalline rocks. The planed-off upper surface of the crystalline basement on which the Ricardo Formation is deposited appears to dip to the west at the same angle as the overlying sediments and to project eastward toward the top of the El Paso Mountains. The road crosses the bridge and proceeds through a deep gorge cut through highly jointed, fine-grained, quartzose granophyre. Directly after leaving this gorge turn right (west) into a Tamarisk grove at 10.6 miles.

STOP 5 -- Walk about 200 meters to the west to the top of a small alluvial terrace extending (south) from the hills on the right. The view to the east across the mouth of Red Rock Canyon displays the steeply dipping plane of the El Paso Fault between crystalline rocks on the left (north) and younger clastics to the right (south) (Figure 9).

The El Paso Fault can be traced through a series of fresh escarpments across the base of the steep hills to a point directly under foot. The older, clastic sediments (possibly Ricardo Formation - Samsel, 1962) south of the fault dip 25 degrees toward the fault. The overlying Quaternary deposits have developed a nearly flat upper surface, indicating a period of depositional stability prior to the erosion that formed Red Rock Canyon. You are standing on a remnant of the same Quaternary sediments.

The view to the west (Figure 10) shows the continuation of the El Paso Fault with the Ricardo Formation on the right and a flat alluvial plane on the left. The fault can be traced nearly to the base of the granitic core of the southern Sierra Nevada to the west where it is truncated by the Sierran Front Fault. The latter is clearly visible near the mouth of Jawbone Canyon, 4 miles south on Highway 14. The steeply dipping sandstones directly in front of you are bounded by two branches of the El Paso Fault. Drag folding of interbedded orange and white conglomerates of the Ricardo Formation is clearly visible in middle distance. The dark ridge in the distance is capped by the lower of the basalts within the Ricardo Formation.

Return to Highway 14 and turn right (south). At 11.4 miles, the road climbs through a ridge (the local name is "Windy Gap", an apt name if it is at all windy) which is capped by a flat-topped remnant of Quaternary fan deposits. From this vantage point there is a good view to the south of the Fremont Valley, with the Garlock Fault occurring at the base of the eastern face of the northern Tehachapi Mountains on the right. The eastern side of Fremont Valley is limited by the fault-bounded Rand Mountains. In certain low-angle lighting, there is an obvious escarpment tracing this fault that is visible between the crystalline rocks of the southwestern Rand Mountains and the outwash alluvial plane to the southwest. Turn hard left at 13 miles at Randsburg-Red Rock Road. The highway traverses perched Quaternary terraces and then along the bases of alluvial fans extending eastward from the El Paso Mountains on the left. Note fresh scarps of the Garlock Fault along the base of the El Paso Mountains on your left. Koehn (or Kane) dry lake, a basin of internal drainage in the fault valley of the Garlock Fault, is on the right. Until the late 1950's, salt (halite) was mined at the abandoned site of Saltdale by evaporating concentrated lake waters. Continue north on Randsburg-Red Rock Road to Mesquite Canyon Road at 24.2 miles.

STOP 6 -- On the left are dissected, Late Quaternary, lakebed and alluvial fan deposits that have been uplifted on the Garlock Fault (Figure 11). These fine-grained muds were originally flat lying and probably were deposited near the present level of Koehn Lake on the right. Nearly 80 meters of uplift has led to a 10 degree upslope dip in these sediments. There are several small springs at the base of these outcrops along the trace of the fault. Continue northward on Randsburg-Red Rock Road 1.1 miles (25.3 miles from start) and turn left on Garlock Road.

You pass the old townsite of Garlock at 26.1 miles. The El Paso Mountains on your left now contain nearly vertical sediments of the Late Paleozoic marine, Garlock Formation composed of partly metamorphosed, fine-grained clastics, limestones and submarine volcanic flows. Continue until you pass the road to Goler Gulch and a distinct elevated escarpment will appear on the left at 30.9 miles.

STOP 7 -- On the left, below the scarp representing the recent trace of the Garlock Fault, is an un-drained depression (graben) which emphasizes the recentness of faulting activity (Figure 12). The northeasterly trace of the fault is clearly visible on the horizon as a notch part way up the slope of the El Paso Mountains. From here, proceed to Highway 395 and return to Ridgecrest.

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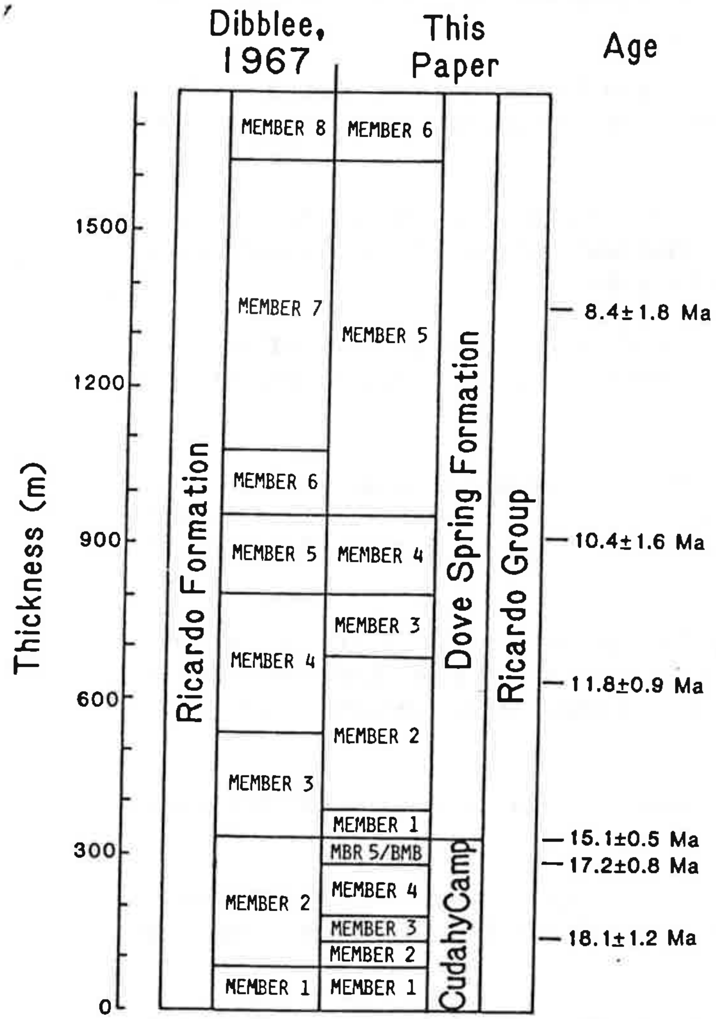

CONCLUSIONS

The Miocene volcanic and sedimentary rocks of the El Paso basin document the following tectonic events: (1) volcanism and north-south tension with no net extension, about 17–15 Ma in the early Miocene; (2) relative uplift about 15–13.5 Ma in the middle Miocene at the same time as absolute tectonic uplift farther west in the San Joaquin basin; (3) initiation of sinistral slip on the Garlock fault about 10 Ma; (4) the onset of east-west extension by at least 9 Ma; and (5) morphotectonic emergence of the Sierra Nevada by 8 Ma. These events can be related through plate-tectonic models to interactions between the North American, Pacific, and Farallon plates at the western margin of North America, and they provide some new age constraints for the uplift of the Sierra Nevada and for initial sinistral motion along the Garlock fault.

The stratigraphic evolution of the El Paso basin, southern California: Implications for the Miocene development of the Garlock fault and uplift of the Sierra Nevada

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Geology of the Southeastern Sierra Nevada-Revisited
NAGT-FWS Spring Field Conference, 1998

A Brief Survey of the Geology of the Owens Valley From Bishop to Red Rock Canyon

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Introduction

The region east of the Sierra Nevada known as the Owens Valley has been discussed in several excellent books and field guides. This trip will cover the highlights of some locations along Highway 395 discussed in these references. Everyone has his or her favorite spot and I make no attempt to cover them all. If you have a few days and some of the references listed in the bibliography, you can find many interesting off-the-road places. Mileage markers in the text refer to distance from the beginning and distance from the last mileage mark. You should check your mileage frequently to establish a correction factor. Figure 1 is a map of the area covered by this trip with the stops marked.

ROAD LOG

Mileage Cum.	Interval	
0.0	0.0	The field guide begins on Highway 395 on the south side of Bishop at Schober Lane. Set your odometer to zero at this point. The Owens Valley is the western most basin of the Basin and Range province. It is a classic graben or down faulted block between normal faults that form the steep eastern face of the Sierra Nevada range to the west and the western face of the White and Inyo ranges to the east. Beginning a little south of Bishop and extending north the graben is less distinct and the Sierra Nevada face has been warped rather than faulted (Figure 2). This is known as the Coyote warp. This guide covers the more typical graben structure of the southern Owens Valley.
6.4	6.4	Turn off to Keough hot springs. The Keough hot springs are probably the best known of several hot springs found along the western side of the Owens Valley. The springs are named for a pioneer family who operated a small resort here for many years. Some of the resort buildings remain as well as some semi-permanent residents in mobile homes. These springs have remained popular because they do not have the strong sulfur smell associated with most such springs. There are several small pools in the area and this is a nice place to spend an evening looking at the stars. If you wish to visit the springs, turn west on Keough Hot Springs Road. Note that you have no forewarning of the road as you approach from the north. Proceed 0.6 miles to the poorly maintained paved

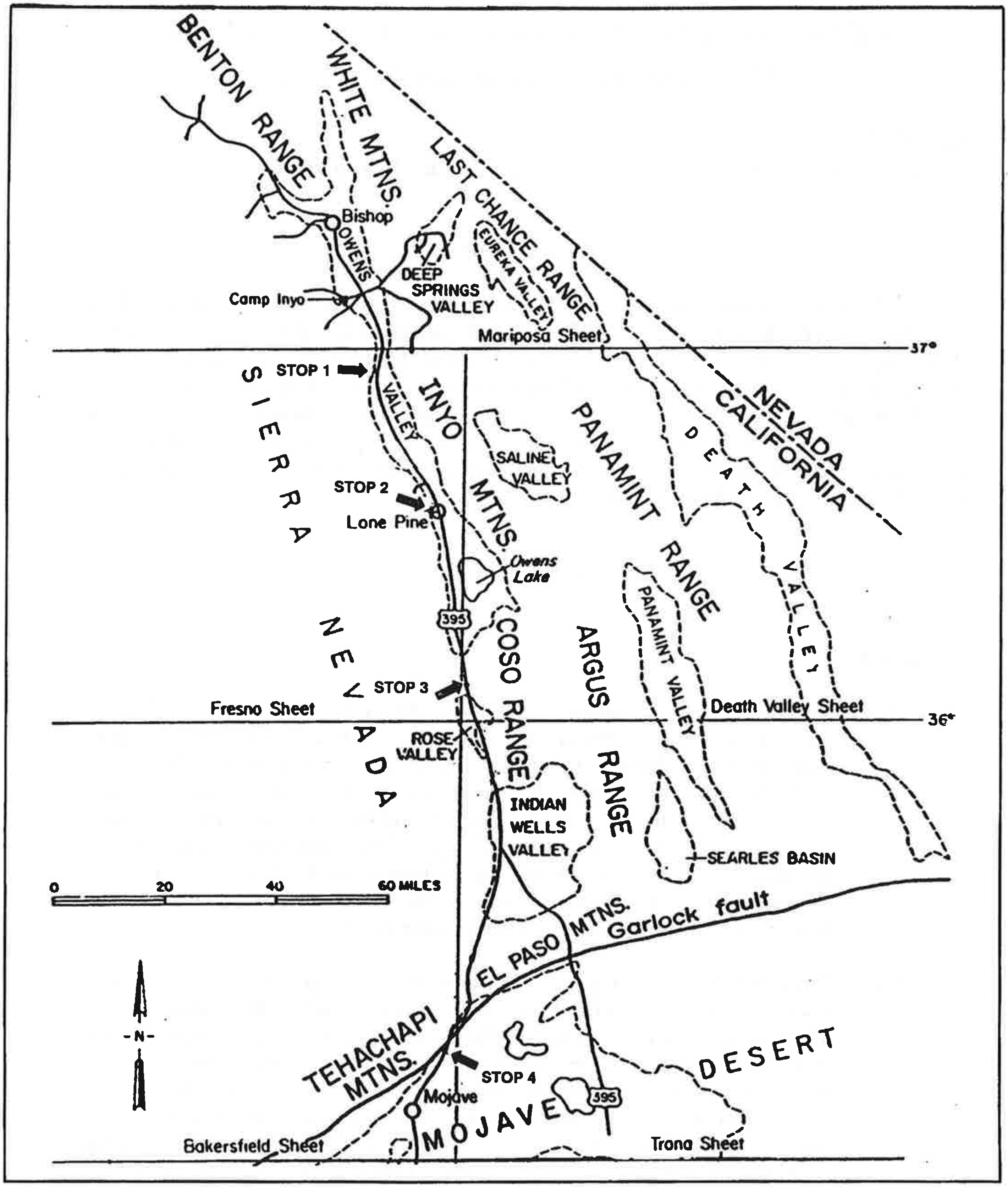

Figure 1. Primitive map of the area covered by this guide.

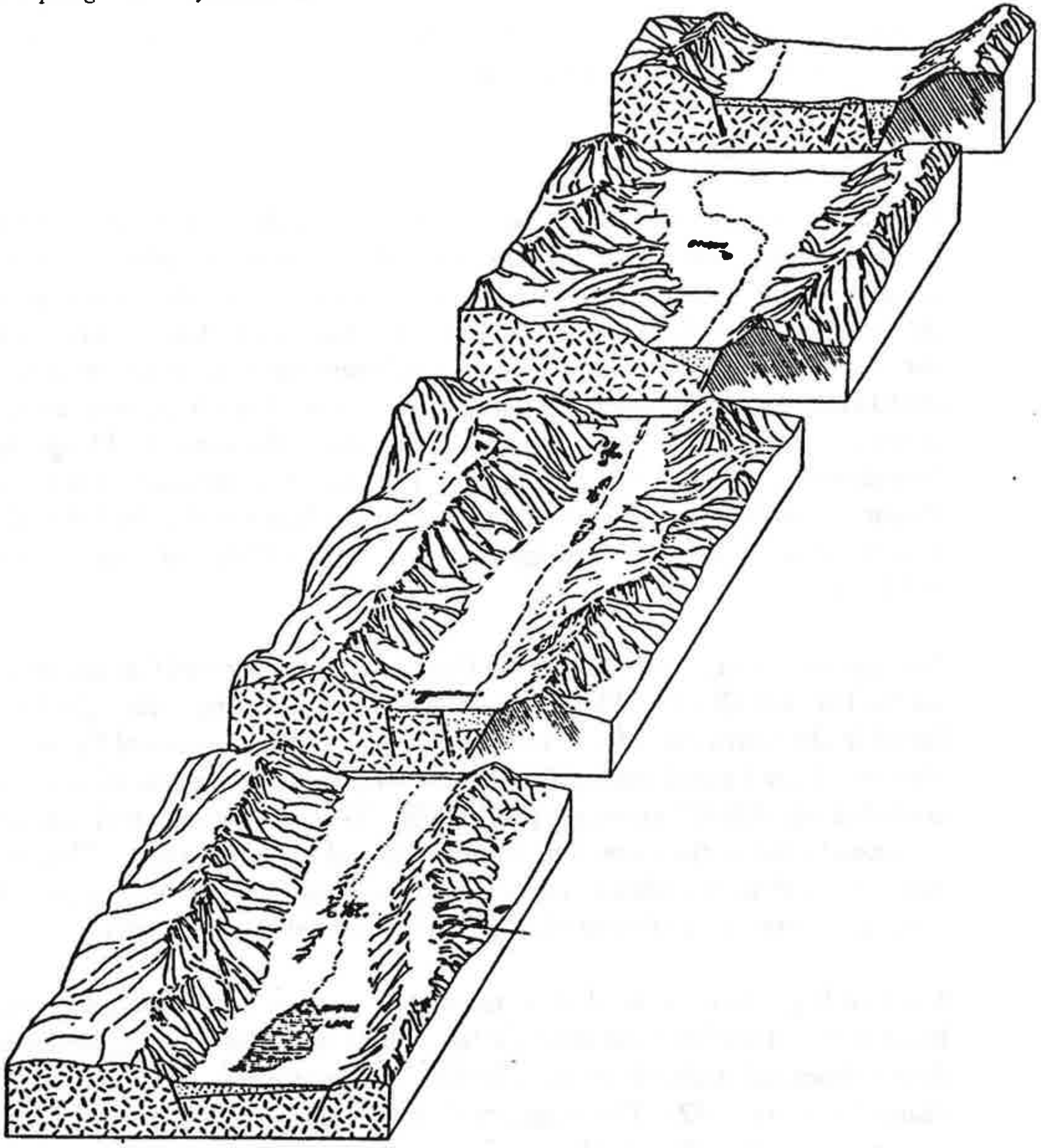

Figure 2. Sketch of the Owens Valley showing the Coyote warp north of Bishop and the graben structure south of Bishop (Schumacher, 1978).

road beneath the power lines. Turn right and go 0.2 miles. The hot pools are on both sides of the road and are fed by a hot creek that flows down across the alluvium.

As we approach the town of Big Pine, you will notice several large, white parabolic dishes on the eastside of the highway. This is the site of the California Institute of Technology radio telescope observatory. A radio telescope "observes" stars that emit electromagnetic radiation in the radio wavelengths rather than the wavelengths of visible light.

The dishes are mounted on rail cars so they can be moved closer or farther apart. In this way the telescope can be focused.

13.7 7.3 Big Pine town limit.

14.0 0.3 Crocker Street is on the right. Do not turn off. A side trip up Crocker Street 1.6 miles to Sugarloaf Road and then right 0.9 miles on Sugarloaf will take you to Bernasconi Center. The Center is the Environmental Education Campus for the Inyo County Schools. It was the site of a fruit ranch that was purchased by the Los Angeles Department of Water and Power for a construction camp when the Owens Valley aqueduct was being built. Some of the fruit trees remain and are still producing nearly one hundred years later. The camp buildings include dormitories, showers, and a dining hall. They can be rented from the Inyo County schools for a minimal fee and make excellent housing for field trips. Reservations can be made through the Inyo County Office of Education at (760) 878-2426.

Nestled in the range front above Big Pine and the Bernasconi Center, you can see the Palisade Glacier. This is the largest of approximately sixty glaciers still found in the Sierra Nevada. These glaciers are not the remains of Pleistocene glaciers. They formed during the "little Ice Age" when a minor climatic dip cooled things 400-500 years ago (Hill, 1975). They are interesting because they are actually below the snow line, the elevation of perennial snow. They exist only on the shady northeast side of ridges and peaks. In the 1870's, John Muir counted seventy-two of these glaciers so they are definitely in retreat.

South of Big Pine for several miles the highway passes through cinder cones and basalt flows of the Big Pine volcanic field. This field consists of approximately a dozen cones and multiple vents. The flows range in age from 10,000 to 100,000 years (Rinehart, 1982). The vents are situated along several faults on both the east and west sides of the highway. The faults provided the basalt a ready avenue to the surface. In several places the cones have been offset by the faults. Field evidence indicates there may have been as much as ten feet of offset on some of these faults in the 1872 Owens Valley earthquake (Rinehart, 1982). The prominent cone west of the highway is Crater Mountain. Its summit is about 2000 feet above the highway but this is not all basalt. The cone rests on a mass of granite and the basalt flows cover the granitic mass like chocolate syrup on a scoop of ice cream.

31.9 17.9 **STOP 1.**
Sawmill Canyon.

Turn right onto Black Rock Springs Road and park. Straight ahead in the face of the range is the deep V-shaped canyon of Sawmill Creek. Observe the dark rock clinging to the sides of the canyon mouth. This is basalt that has been dated at about 100,000 years (Sharp, 1975). Up the canyon out of sight, a glacial moraine is resting on the basalt. Still further up the canyon another moraine lies beneath the 100,000-year-old basalt. These exposures obviously represent two periods of glaciation, one older than the basalt and one younger than the basalt. Using relationships such as these, geologists have been able to account for at least six periods of glaciation in the Sierra Nevada.

38.0 6.1 Fish Hatchery Road turns right. One mile up this road is the Mt. Whitney fish hatchery. This is a very nice side trip, especially on a hot day. The hatchery is a Works Progress Administration project built in the 1930's. The main hatchery building is constructed of alluvial boulders and somewhat resembles an alpine castle. The park-like setting includes a lake filled with large trout that are the brood stock for the hatchery. Grassy slopes and tall cottonwood trees surround the lake. As you enjoy this stop try not to think about what will happen here when the next Owens Valley earthquake occurs.

39.7 1.7 Independence town limit.

40.2 0.5 The Inyo County Court House is on the left. This is the "new" court house building. The original building was destroyed in the 1872 earthquake. It was a two-story brick structure that had been completed only two years earlier for the outrageous sum of $10,000. The fault scarp produced by the 1872 earthquake is about three miles east of Independence. You can find it by driving east on Mazourka Canyon Road that exits the highway on the south side of town.

40.7 0.5 Mazourka Canyon Road turns left.

46.3 5.6 Site of Manzanar internment camp. This site is now part of Death Valley National Park. There is a park ranger on duty here a few days each week.

51.4 5.1 The abrupt change in elevation of the highway is a fault scarp of the 1872 earthquake. There are several scarps along the west side of the highway from here on into Lone Pine. The earthquake of 1872 produced several east- and west-facing scarps in this area. The channel of Owens River was offset and a temporary lake formed east of the highway. You may be able to see a meadow with some dead tree snags protruding from the lake site

Approaching Lone Pine, the Alabama Hills rise to the west of town (Figure 3). Local folklore once advertised these hills as "the oldest hills on earth" and "the mysterious Alabama Hills." They are, however, neither mysterious nor are they the oldest hills on earth. They are largely composed of the same granite as the adjacent Sierra Nevada (Schumacher, 1978). The difference in appearance is due to differences in weathering and erosion. The name for the hills comes from the Confederate cruiser, Alabama. It was applied to the hills by some southern sympathizers during the Civil War. If you are an aficionado of old movies, you might enjoy exploring the Alabama Hills, as they have been the location for many movies. The community of Lone Pine celebrates an annual film festival that features many of these films.

52.9 1.5 Fault scarp west of the highway.

54.3 1.4 Fault scarp west of the highway.

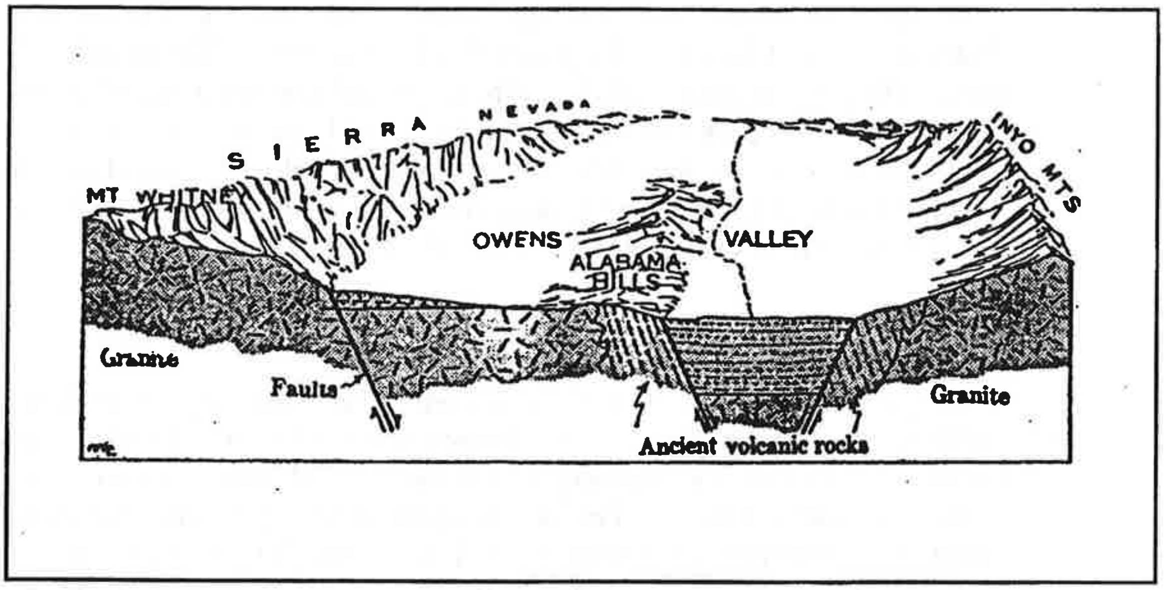

Figure 3. The "mysterious Alabama Hills" near Lone Pine (Schumacher, 1978).

55.0 0.7 **STOP 2.**
Mass grave of 1872 earthquake victims.

Turn off on the right side of the road across from the Lone Pine Cemetery. There is a historical marker for the gravesite shared by the 1872 earthquake victims. Walk up the hill to the monument. The number of people killed in this quake depends on where you get your data. The Inyo Independent, the local newspaper, reported that 25 people were killed. However, several were injured and two of them died later, bringing the total to 27. Even this figure may be a few deaths low. This may not seem like many deaths from so large a quake but it represents about 10% of the population in the area at the time. Imagine if 10% of the population of the Los Angeles basin were killed in one earthquake! This earthquake is generally considered to be the greatest quake in California history. This is based on the vast area where it was felt and the damage done. In Lone Pine, 52 of 59 homes were destroyed. More than 140 miles away, a team of normally sure-footed mules were knocked to the ground.

Any Richter magnitude you may have seen assigned to this event is speculative because there are no records of the event. It was probably middle to high 8 in magnitude.

58.7 3.7 Diaz Lake. This lake occupies a small graben between east- and west-facing scarps produced in the 1872 quake.

61.6 2.9 As we approach Owens Lake, you can see former high-water marks here along the north shore. Owens Lake is one of several basins in southeastern California that were filled during the Pleistocene ice age. It still had water until diversions of the Owens River to Los Angeles began in the 1920's.

75.5 13.9 Cartago. This small town site was most recently a location where evaporites were mined from the dry lake-bed. In the late 1800's, it was a shipping point for silver ingots from the Cerro Gordo mine. The Cerro Gordo mine is located across the lake basin in the Inyo Mountains. The ghost town is still there today and is accessible by jeep trail from Keeler. The silver was milled and poured at the mine site. It was then hauled to Keeler where it was loaded on a boat and shipped to Cartago. Wagons would then finish the haul to Los Angeles. At its pinnacle, the mine produced silver ingots faster than they could be hauled away. As the silver accumulated at Cartago, the guards reportedly built shelters out of the silver bricks.

100.3 24.8 **STOP 3.**

Turn left at Cinder Road. Be very careful as you cross the two northbound lanes of traffic. On the left is Red Hill cinder cone. It is mined for "red rock" to be used as road base. Proceed on Cinder Road for 0.5 miles to where the road branches. Turn right and go 0.3 miles then turn left and drive 0.3 miles into the parking lot for "Fossil Falls." The BLM has recently done some grading of new roads in this area to access the parking lot. The route described is the simplest. Park and lock your car. At the south end of the parking area a trail leads to the "Fossil Falls." This is an easy 0.25-mile-walk.

During the Pleistocene, a series of interconnected lakes filled the currently dry lake-basins known as Owens Lake, China Lake, Searles Lake, Panamint Lake, and Lake Manly (Death Valley). As each basin in the series filled, it overflowed into the next and so on until they all were filled. In this area, the Owens River connected Owens Lake with China Lake which filled the Indian Wells Valley to the south. Beginning approximately 400,000 years ago basaltic lava flows from vents in the Coso Mountains to the east repeatedly blocked and diverted the Owens River channel (Duffield and Smith, 1978). At this location the river channel was blocked and the river cascaded over the lava forming a waterfall that was 150-200 feet high. Gradually the river cut back into the lava forming this gorge that is known as the "fossil falls." This is an excellent location to observe the power of water as an erosional agent. On the upstream side of the falls the basalt has been polished. This is probably due to the river carrying a heavy sediment load from glacial meltwater. There are numerous deep potholes produced by rocks that became trapped in the turbulent currents, whirled around, and drilled holes into the basalt.

This must have been a spectacular place when water was roaring over the falls. The local Indians certainly thought so. Obsidian flakes in the vicinity are an indication that they spent considerable time in this area. During periods of heavy precipitation, water still flows through this channel although at a considerably reduced volume from the Pleistocene torrent. Return to Highway 395. Once again use extreme caution as you cross the northbound lanes and turn on to the southbound lanes. Mileage resumes as you turn on to Highway 395 south.

101.5	1.2	On the east side of the highway, the basalt flows that “ fossil falls” are well exposed. Good examples of columnar jointing can be seen all along this section.
102.9	1.4	Little Lake. In this area and toward the south, the basalt flows forced the Owens River against the base of the Sierra Nevada to the west. The river gradually cut back to the east and formed the steep escarpment along the eastside of the highway (Duffield and Smith, 1978).
103.1	0.2	The highway now passes into Indian Wells Valley. This valley was occupied by one of the interconnected Pleistocene lakes. It drained to the east into the Searles Lake basin.
120.3	17.2	Highway 395 exits to the southeast. We will continue south on Highway 14 toward Mojave.
141.7	21.4	Highway 14 begins to descend into Red Rock Canyon. This is another location that has been popular for movie making. The Red Rock Canyon area is covered in the NAGT-FWS publication from the spring meeting, 1987.
145.1	3.4	As Highway 14 exits Red Rock Canyon and the El Paso mountains into Cantil Valley, the Garlock Fault may be seen where granite is exposed against alluvium on the east side of the highway.
149.2	4.1	Jawbone store.
149.7	0.5	**STOP 4.**

Pull to the shoulder of the highway and park. The Garlock fault extends in an east-west direction along the base of the El Paso Mountains. Look north up the canyon cut into the face of the range. The reddish rocks on the eastside of the canyon are the middle and late Miocene, volcanic-derived, lacustrine sediments of the Ricardo Formation seen in Red Rock Canyon. On the west side of the canyon are the late Mesozoic granitic rocks of the Sierra Nevada batholith. The contact between these two units is the Sierra Nevada frontal fault. Somewhere near where you are standing the frontal fault intersects the Garlock fault.

END OF ROAD LOG.

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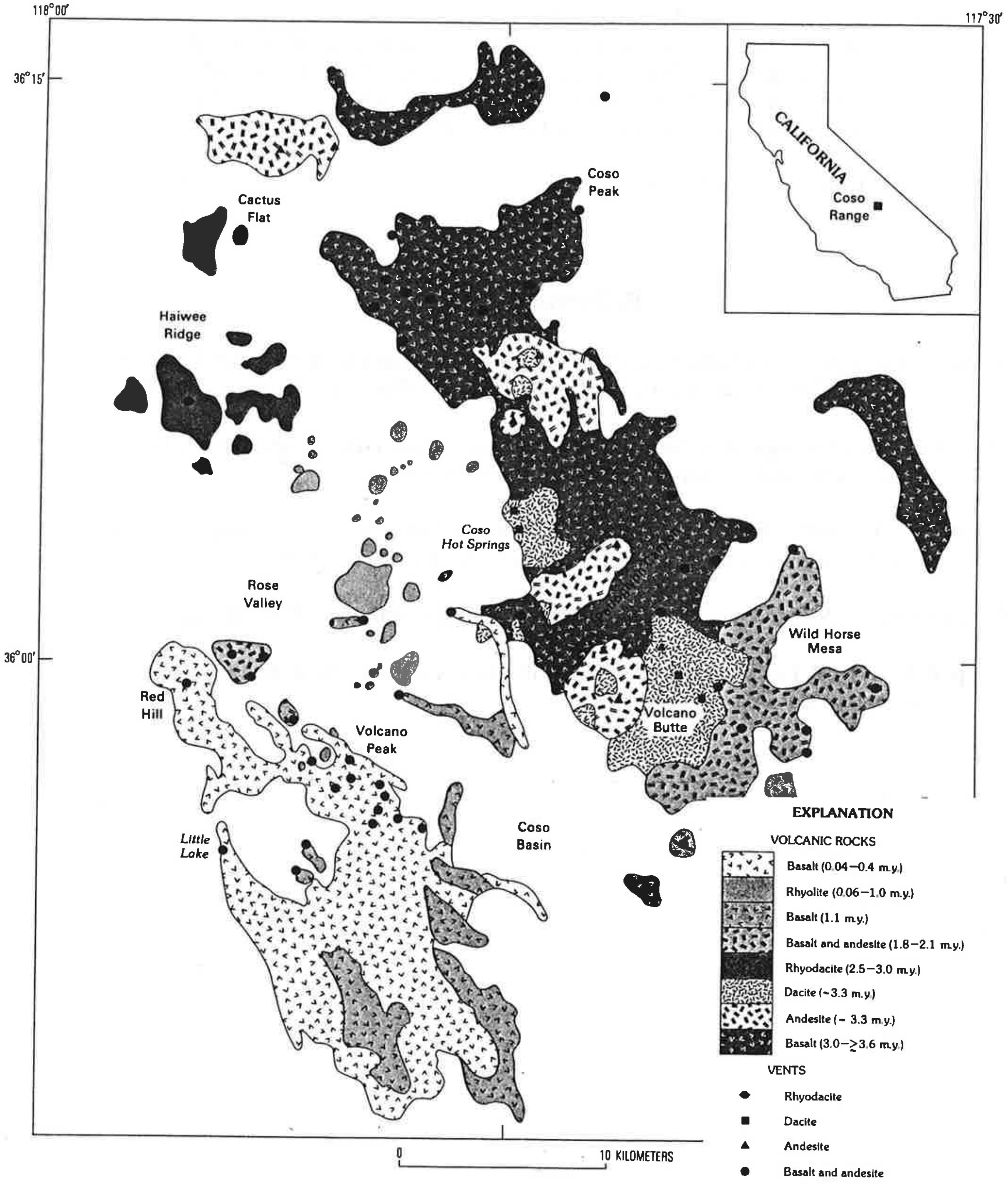

Figure 1.—Simplified geologic map of the Coso volcanic field (modified from Duffield and Bacon, 1981). Faults omitted for clarity.

GEOLOGY & EXPLOITATION OF THE COSO GEOTHERMAL RESERVOIR

by M. C. Erskine & J. L. Moore

INTRODUCTION

The Coso geothermal power development is located in the Coso Range of eastern California (Figure 1). The Coso Range, the first mountain range east of the southern Sierra Nevada, is about forty miles north of the northern Mojave Desert. California Energy Company, Inc. generates electrical power from geothermal fluids derived from wells drilled into fractures in the basement rocks of the Coso Range. The electricity is delivered to the Southern California Edison Company grid at Inyokern, California. The current output of the Coso geothermal development is 240 megawatts.

The Coso Range is one of the western-most ranges of the Basin Range physiographic province. It is located in the southwestern-most portion of the Great Basin region of internal drainage and just south of an imaginary eighty-mile-long line that connects Mount Whitney, the highest elevation in the continental United States, with Badwater in Death Valley, the lowest elevation in the United States. The average topographic gradient represented by this relief is about 180 feet per mile in a southeasterly direction across the entire region.

The Coso Range is separated from the Sierra Nevada on the west by Rose Valley, the southern extension of Owens Valley. The Range is bound on the east by Darwin Wash and the Argus Range. It is bound on the north by Owens Lake, which is a saline playa courtesy of Los Angeles Department of Water and Power. Owens Lake is a closed basin and the

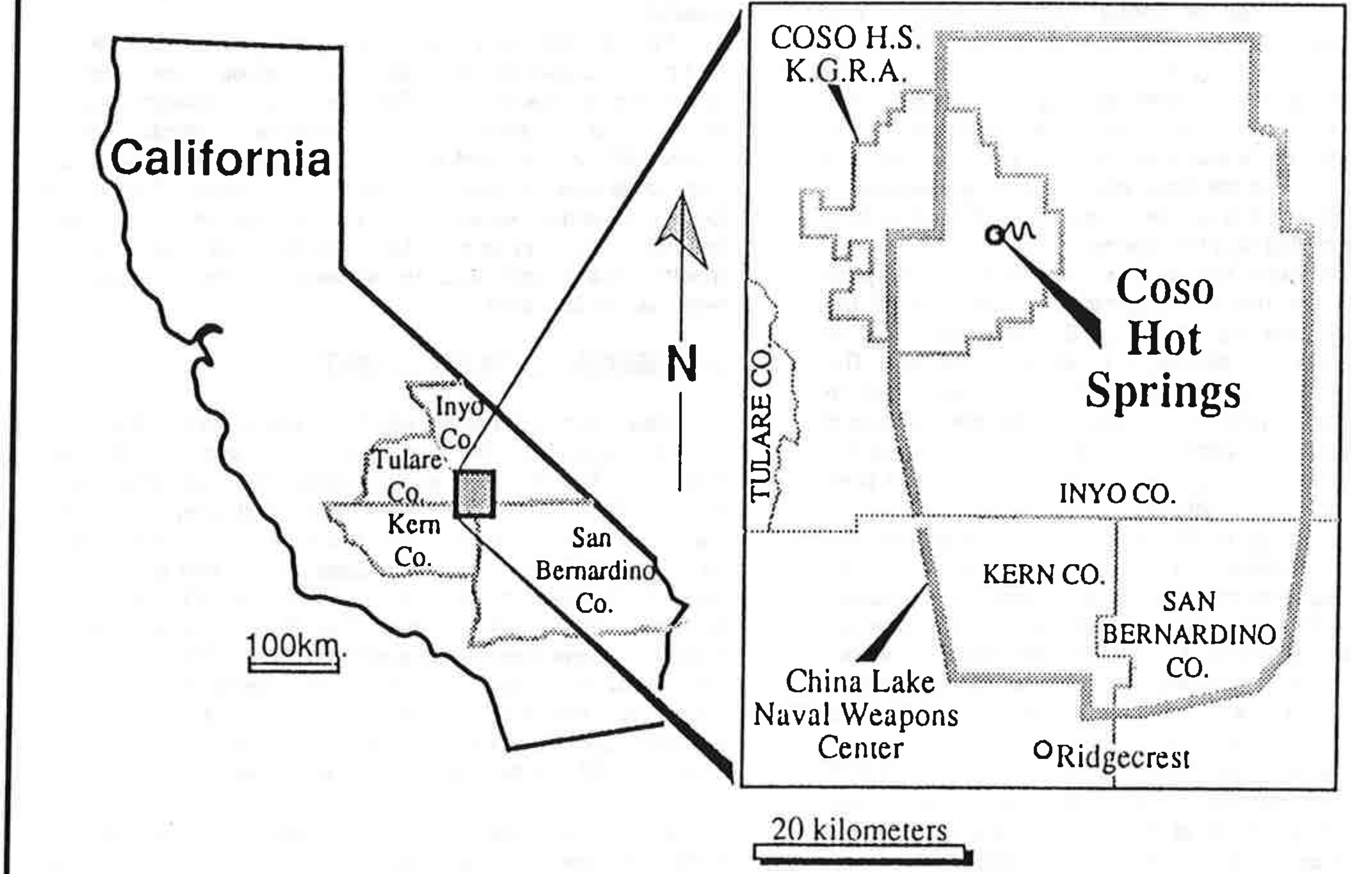

Figure 1. Location map of the Coso geothermal system.

southern terminus of the modern Owens River. The southern boundary of the Coso Range is Indian Wells Valley, a deep structural valley that contains two playas, Airport Lake and Searles Lake, that were fed by the ancestral Owens River during the glacial-pluvial periods of the last three million years.

The bedrock of the Coso Range consists of Mesozoic crystalline igneous rock and metamorphic rocks similar to the adjacent Sierra Nevada. This bedrock outcrops over most of the Range, but is locally covered by Neogene continental sediments of the Coso Formation or by Pliocene to Recent volcanics of the Coso Volcanic Field. The geothermal system is spatially associated with the youngest rhyolite domes (0.06 to 1.00 million years) of the Coso Volcanic Field at the surface. However, at reservoir depths, intrusives associated with the young volcanics are rare and where encountered, do not appear to directly support the present geothermal system.

The Coso geothermal reservoir consists of fractures in crystalline basement rocks and the produceability of the thermal resource is dependent upon the productivity of this fractured regional hydrologic system. To make reasonable estimates of the reserves and rate of economic produceability of the system it is necessary to understand where the water is coming from, where it is heated, and how the fractures control convective heat transport to bring the heated water to within economic reach of the drill.

GEOLOGY OF THE GEOTHERMAL RESERVOIR

The Coso geothermal reservoir consists primarily of complexly fractured Mesozoic igneous and metamorphic rocks of the Sierran basement complex. The igneous rocks range in composition from alaskite granite to diorite to gabbro. The more mafic rocks appear to "float" as irregularly shaped small to large bodies in more abundant, more siliceous rocks. Contacts may be diffuse and irregular or sharp, structural and irregular. It is only from the small scale averaging viewpoint of aeromagnetic data that a sense of overall northwest striking compositional banding may be observed.

The rhyolite dome field and associated volcanic ejecta cover much of the basement complex in the area of the reservoir. It is generally less than 200 feet thick and at reservoir level, related rhyolite dikes or sills are rather rare. The rhyolites intersected at reservoir levels do not appear to be directly related to the present hydrothermal system. Chemical and thermal gradients within the reservoir suggest that the hydrothermal system is very young, much younger than even the youngest of the rhyolite domes.

The thermal energy produced at Coso is carried from the reservoir to the turbines by hydrothermal fluids. These hydrothermal fluids are meteoric water (normal groundwater) with 5,000 to 10,000 parts per million of total dissolved solids that have been heated by flowing through fractures in hot rocks. The source of the heat for the geothermal fluids is assumed to be the same silicic magma reservoir that sourced the young Coso rhyolite dome field.

The hydrothermal alteration most closely associated with present production consists of abundant deposition of vein carbonates, although much of the vein carbonate deposition appears to pre-date the present high temperature regime. The non-condensable gases in the hydrothermal fluids are very high in carbon dioxide. The concentration of carbon dioxide in the fluids at the high-temperature south end of the reservoir reaches over 15,000 parts per million. Silica veining is conspicuous by its rarity.

REGIONAL HYDROLOGY

A topographic gradient of nearly 140 feet per mile exists between the high-precipitation groundwater recharge area on the Kern Plateau of the Sierra Nevada and the desert playa of Panamint Valley. The groundwater gradient between the Kern Plateau and the top of the Coso geothermal reservoir is about 235 feet per mile. The Coso Range reaches an altitude of 8,160 feet at Coso Peak in the headwaters of Coso Wash. The vegetation density seen on thematic mapper images suggests that this higher country also has significant precipitation. The chemistry of the reservoir fluids from the geothermal reservoir suggest that magma heated normal groundwater, but did not significantly interact chemically with it. This means that heat from the magma was conductively transported to the groundwater system. This in turn means that the groundwater must have had long contact with fracture surfaces in rocks conductively heated by the magma to temperatures about 345° C, which is the highest measured reservoir temperature, but at temperatures low enough to allow the rocks to maintain significant open fractures. Deep, long-distance circulation of groundwater controlled by local and regional topographic heads seems well established in purely sedimentary regimes both in a theoretical sense and in the measurements within the Great Basin. Fractured crystalline basement, however, seems to give some geologists serious mental indigestion. The existence of the Coso geothermal reservoir, currently producing 240 megawatts, seems to indicate that the question should be how does it happen, rather than whether it is possible.

Perhaps the most important hydrologic point to make is that heat transport to the geothermal reservoir is controlled by hydrologic permeability. The geothermal reservoir exists where it does because the more-or-less-vertical fracture permeability in this local area is adequate to allow significant convective heat transport by fluids in the fractures. Exploration for geothermal resources in this environment then must become a search for local, deep-penetrating, more-or-less-vertical fracture systems in the post-magma groundwater flow path.

COMMERCIAL DEVELOPMENT

Steam fumorales and recent volcanic activity in the Coso Range suggested the presence of a large geothermal resource. The discovery well at Coso, 75-7, was drilled to a depth of 1,329 feet in December, 1981, and completed "open hole" from the steam cap. Subsequently, five confirmation wells were drilled to establish Coso as a viable geothermal field. Testing of these wells in 1982 established the existence of a reservoir sufficient to meet the Department of Defense electrical requirements of 30 megawatts at the Naval Weapons Center, China Lake. After several years of additional negotiations with the Navy, and the passage of two pieces of enabling legislation, contracts were finally let in February of 1986 to build the first commercial geothermal powerplant at Coso.

Ground was broken for the first Coso plant in March of 1986. Sixteen months later, on July 15, 1987, the first geothermal power was delivered to the Inyokern Substation from the Coso geothermal field. Currently, nine turbine generator units deliver in excess of 240 megawatts of electrical power to the Southern California power distribution network at delivery points in Inyokern and Kramer.

The facility consists of approximately 100 production and injection wells distributed over some nine square miles of project lands. It is interesting to note that the best producing wells lie nearly one mile from the fumorales which first drew attention to the area.

Reservoir pressure decline has been as expected and the replacement/infill program has been able to maintain production at levels in excess of plant design. Step-out wells located easterly of the primary development area proves the existence of what appears to be a large undeveloped reservoir. Development in the eastern area is planned to provide supplemental make-up steam for the existing surface installations. Additional surface generating facilities may be constructed based on continuing resource performance.

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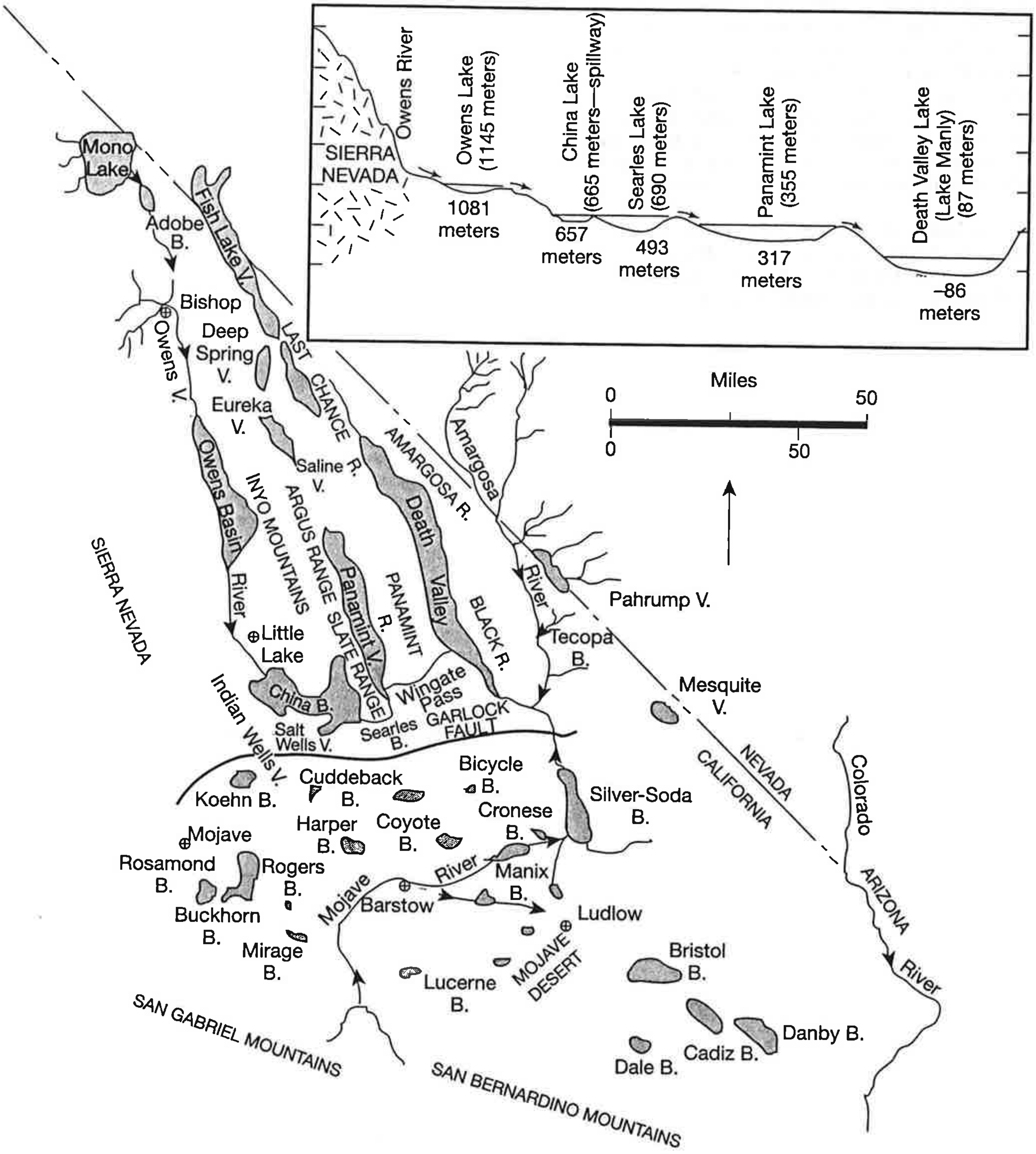

Fig. 6-17 Basins filled by Pleistocene lakes in southeastern California. *Inset* shows the connected system during times of overflowing lake levels. Today only Mono Lake remains. (Source: Used with permission of California Department of Conservation, Division of Mines and Geology. In Blackwelder, E. 1954. Bulletin 170.)

Glacial and Paleoclimate Record of the Sierra Nevada, Bishop to Mono Lake

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ROAD LOG

Begin trip at Whiskey Creek at Bishop, California.

Be sure you have enough gas for today's ~ 90 mile trip.

Note: In this road log, many frequent landmarks are described because the odometer on the vehicle used to establish the mileages apparently adds about 5% to actual distance.

Stops for this road log were planned during heavy snow pack. Undoubtedly, some stops will need to be ommited, and mileages adjusted accordingly due to prevailing weather conditions during the NAGT meeting. The particulars of the trip alterations will be announced at the first stop. Because of this flexible nature in the schedule, descriptions of the geology are given in an abbreviated fashion here. More detailed description will be provided for the stops which actually occur.

Mileage Cum.	Mileage Interval	
0.0	0.0	FROM WHISKEY CREEK, TURN NORTH onto 395. Proceed through Bishop north on 395.
0.4	0.4	Intersection of Hwy 395 & Hwy 6. STAY TO THE LEFT and continue on Hwy 395. At 10 o'clock, there is a view into the Buttermilk Country (Tungsten Hills are in the Buttermilk Country) and the glacial deposits of Bishop Creek.
3.0	2.6	65 MPH sign. At 2 o'clock a view of the Bishop Tuff is in the mid ground. At 11 o'clock, glacial deposits of Little McGee Creek (the next major drainage north of Bishop Creek) come into view.
4.2	1.2	The road makes a sweeping right hand turn, at 10:30 view of the Pine Creek moraines, which will be our first stop.
9.2	5.0	Mill Creek Road crossing. Note the houses up against the Bishop Tuff East of the highway. Move into the left lane, and prepare to turn.

14.8	0.8	Cross over Pine Creek. Note the high Tahoe left lateral moraine at 1 o'clock.
15.6	0.8	Enter Inyo Nat'l Forest.
16.2	0.6	Windy Road sign - Range front fault at 10 o'clock.
17.3	1.1	Huarte Creek sign - note truncated fan remnants at the mouth of Huarte Creek.
18.0	0.7	Jointed granite dipping to the south dominates the north wall of Pine Creek.
18.7	0.7	Power lines pass back over the road, and there is a green building on left. Turn around here and drive back down Pine Creek.
20.9	2.2	Upper end of lateral moraines represent the paleo-ELA.
21.9	1.0	Leave Inyo Nat'l Forest.
22.7	0.8	Cross back over Pine Creek. Note Bishop Tuff in Rock Creek Gorge (10 - 1 o'clock).
23.3	0.6	TURN RIGHT onto Vanadium Ranch Road.
23.5	0.2	**STOP 2.** **A view of rock weathering, soils, remote sensing, and geomorphic processes.** Park off the road for short hike up the moraine (Figure 1). We will investigate the rock weathering differences between deposits of Tioga age and those of Tahoe age. To the south side of the moraine complex are a series of debris flows which have as their source the former glacier that extended above the moraine crest. The soil development of these debris flows, as determined in backhoe pits, is similar to the soils we will see exposed in stream cuts at stop 3 (Fred Fischer, personnel communication, 1994). Remote sensing techniques have been successfully applied at this location to reveal the complex nature of moraines, showing an older buried soil capped by the much younger Tioga age materials. Return to cars, and proceed down fan on Vanadium Ranch Road.
25.0	1.5	Stop Sign — Turn Left on Round Valley Road.

25.6 0.6 Stop Sign - Proceed straight (across Pine Creek Road).

25.7 0.1 **STOP 3.**
Late Pleistocene and Holocene alluvial deposits of Pine Creek.

Park off Pavement to the Right — gather just across Pine Creek bridge for short discussion of alluvium (Figure 1).

Fan deposits exposed by the incision of Pine Creek have soil profiles similar to those of the debris flow fan deposits viewed at stop 2. The debris flow fans of stop 2 were clearly deposited in glacial times because the source for those fans appears to be the former ice surface. The fans here along Pine Creek can be traced up stream to outwash terraces giving rise to the conclusion that these deposits are also related to times of glaciation. The sequence of alluvial fans along the Sierra Nevada bajada in Owens Valley are the subject of ongoing studies to determine the contribution of tectonics and/or climate to their formation.

Return to vehicles continue north on Round Valley Road.

26.7 1.0 Turn right on Birchim Lane.

27.9 1.2 At the Stop Sign, turn left onto Old Sherwin Grade - Lower Rock Creek Rd.

28.1 0.2 Another exposure of the Bishop tuff, which erupted from Crowley Lake ca. 0.76 Ma (Sarna-Wojcicki et al.,1997).

31.2 3.1 As we approach the new housing development, note the rounded stones which have come down Rock Creek.

31.7 0.5 Sharp left corner at the Paradise town sign - watch road cut on the right, and note the exposure of Bishop Tuff. This location exposes the Bishop Tuff over lain by rounded, glacially-derived (?) weathered boulders.

32.5 0.8 Fire station on right, enter public lands. Note the numerous "hillocks" on the right that represent gas vents of the Tuff emplacement.

33.2 0.7 Note the Bishop Tuff exposure in the Rock Creek gorge at about ~3 o'clock.

34.2 1.0 Off to the East, Rock Creek Gorge exposes cooling fractures of the Bishop Tuff.

35.0 0.8 Inyo Natl. Forest Boundry.

35.0 0.7 Note spectacular jointing in the Cathedral Peak and Wheeler Crest Plutons (Bateman, 1965) of the Sierra Nevada at 9 o'clock.

36.2	0.5	Enter Rock Creek Drainage.
36.9	0.7	Cross Rock Creek.

37.5 0.6 **STOP 4.**
Buried Pre-Sherwin soil exposure.

CAREFULLY CROSS THE ROAD AND PARK ON THE LEFT SIDE FACING TRAFFIC for exposure of pre-Sherwin soil (Figure 1).

In a rare exposure, here we see the bottom of the Sherwin till resting upon a weathered diamicton. This deeply weathered red zone was first described by Sharp (1968) as most likely being a buried soil formed in a pre-Sherwin till. Work by Birkeland et al. (1980) confirmed the buried soil hypothesis, and supported Sharp's suggestion that the lower diamicton is most likely a till in excess of 1.0 Ma.

Return to cars, CAREFULLY cross back over road, and continue up Rock Creek gorge.

38.2 0.7 Note exposures of Sherwin till on the hillslopes.

39.5 1.3 **STOP 5.**
A view of the relation between the Bishop Tuff and the Sherwin Till.

PARK IN LARGE PULLOUT ON RIGHT and remove hats for this revered site (Figures 1 and 2).

Assemble in the pullout to observe the Big Pumice Cut.

This somewhat remote view of the Big Pumice cut provides an excellent over view of this benchmark outcrop along U.S. Highway 395. Having first been described in detail by Sharp (1968), the details of the road cut are exquisitely provided by the same author (Sharp, 1987) in the Cordilleran Centennial Field Guide of the Geological Society of America. The cut reveals the stratigraphic relation between the ~0.76 Ma Bishop tuff (refined ages reported by Sarna-Wojcicki et al., 1997) and the underlying Sherwin Till. A soil formed on the till (Birkeland et al., 1980) prior to burial supports Sharp's original age estimate for the till of ca. 1.0 Ma. The tuff has a magnetization direction which is normal (Dalrymple et al., 1965), and therefore has been a major control on the timing of the Brunhes-Matuyama magnetic boundary. Clastic dikes which cut the tuff and terminate in the till are filled with rounded gravels, and their origin remains somewhat of an enigma.

39.8 0.3 At the Stop Sign, CARFEULLY TURN LEFT (North) onto Hwy 395.
40.2 0.4 The view to the left is into upper Rock Creek where you can see multiple ages of moraines.

40.7 0.5 Continue past Tom's Place. Excellent view of Banner and Ritter Peaks on the skyline.

42.2 1.5 Enjoy the excellent road cut through the Bishop Tuff.

43.7 1.5 View of moraines in the McGee Creek at ~11:30.

44.2 0.5 Continue past turnoff to Crowley Lake.

45.2 1.0 **STOP 6.**

The Sierra Nevada Range front fault, McGee Creek glacial deposits, and the Long Valley Caldera (Crowley Lake).

PULLOUT IN THE SCENIC POINT ON RIGHT SIDE OF ROAD (Figure 2).

This vista point permits an excellent view of the Hilton Creek fault, a segment of the Sierra Nevada Range front fault system, where it cuts glacial deposits of Tioga, Tahoe, and pre-Tahoe age at the mouth of McGee Creek. Recent work by Berry (1990) yields slip rates on the Hilton Creek fault of 1.3 mm/yr for the past 25 ka, and 1.0 mm/yr for the past 140 ka. To the east is Crowley Lake, the "center" of the caldera that resulted from the eruption of the Bishop Tuff. Shorelines of a lake which temporarily filled the caldera can be seen in the distance. The lake was drained when the rising resurgent dome cause the lake to overflow and cut the Owens Valley Gorge to the south (Bailey, 1987).

CONTINUE NORTH ON HWY 395.

46.7 1.5 At 10 o'clock - excellent view of the range front fault north of McGee Creek.

47.2 0.5 Pass the turnoff to McGee Creek.

48.6 1.4 Pass the Crowley Creek Drive Exit

49.9 1.3 Srike and Dip sign indicates the turnoff to Mt. Morrison - the Minarets, Banner and Ritter on the skyline (11 o'clock); at 3 o'clock the Convict Lake moraines dominate the foreground.

51.4 1.5 Pass the turn off to Convict Lake - note the difference in moraine smoothness - old moraines south of the Convict Lake road, young (Tioga age) moraines north of the Convict Lake road.

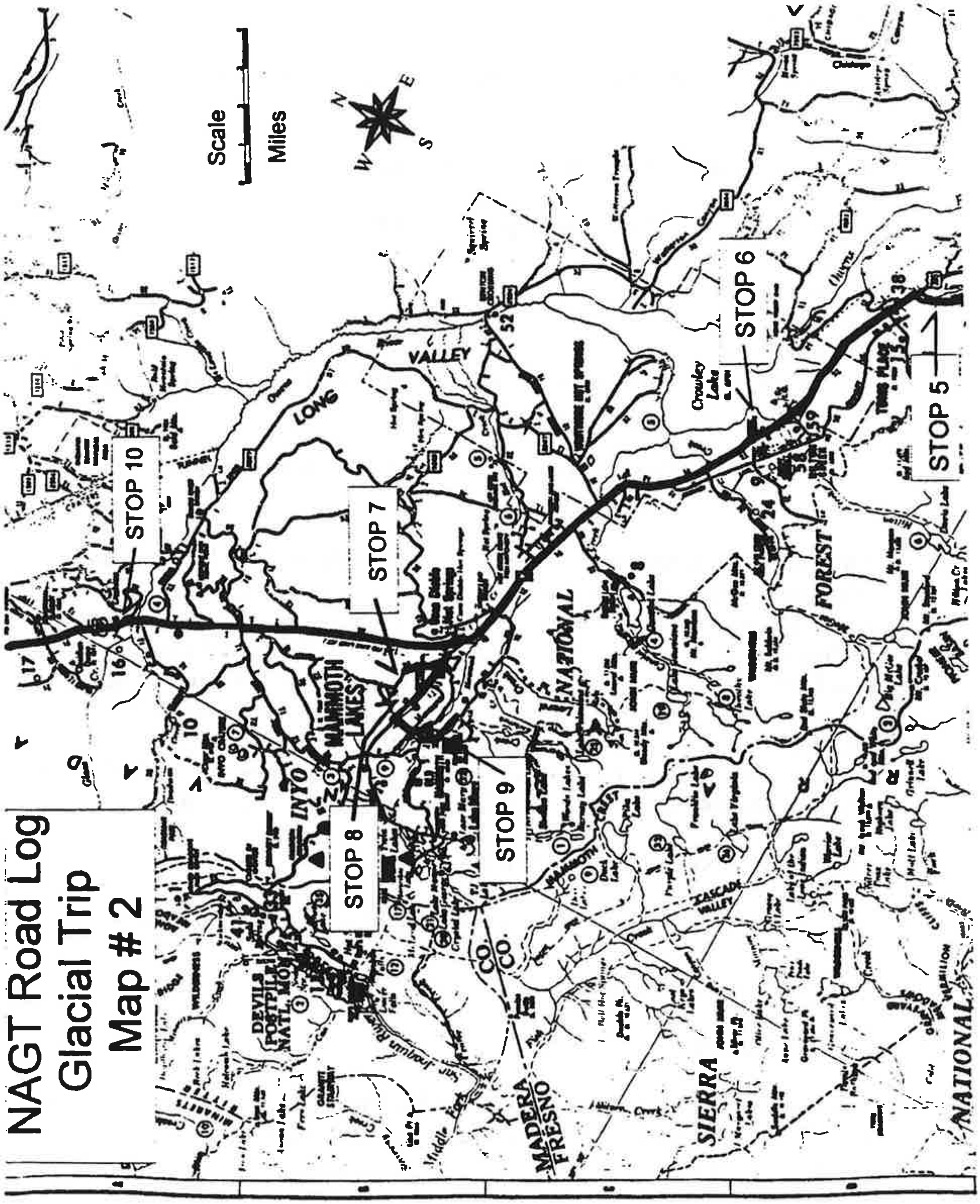

Figure 2. Glacial and Paleoclimate Trip map 2, field stops 5, 6, 7, 8, 9, and 10.

52.8 1.4 Pass the Hot Creek Hatchery Road, note Mammoth Mtn. in the near foreground at 11 o'clock - the forested moraines of Sherwin Creek at 10 o'clock and the non-forested moraines of Laurel Canyon at 9:30. These differences will be discussed at Stop 7. You may be able to see steam from the Casa Diablo Hot Springs Geothermal plant at 12:30.

56.4 1.8 Pass the Sherwin Creek Road.

55.6 1.0 EXIT HWY 203 TO MAMMOTH LAKES / DEVIL'S POSTPILE. TURN LEFT AT THE STOP SIGN, TOWARD MAMMOTH LAKES.

56.2 0.6 **STOP 7.**
Type locality Casa Diablo Till.

TURN RIGHT UP A SECONDAR ROAD, CONTINUE ~0.5 MILES AND PARK ALONG THE ROAD (Figure 2).

Get out of cars for a short walk and a discussion of the age relation of the Casa Diablo till with nearby volcanic units.

If free of snow by mid-April, we will walk to the type locality Casa Diablo till of Curry (1968, 1971). This till is in contact with overlying and underlying basalt flows allowing an excellent opportunity for age numerical age control on the Sierra Nevada glacial sequence. In addition, the till is downvalley from, and therefore older than the bulk of Mammoth Mountain. Curry's original K/Ar dates suggested an age for the Casa Diablo of nearly 400 ka, but re-dating by Bailey et al.(1976) limit the age of the till to about 150 ka. Burke and Birkeland (1979) suggested on the basis of relative dating that the Casa Diablo till is correlative with the Tahoe till.

Return to Hwy 203.

57.2 1.0 TURN RIGHT toward Mammoth Lakes.

58.0 0.8 Enter the town of Mammoth Lakes.

58.6 0.6 Proceed across Meridian Blvd.

59.4 0.8 TURN RIGHT into the Mammoth Visitor Center.

59.5 0.1 **STOP 8.**
Mammoth Lakes Visitor Center (restroom stop).

Return to Hwy 203 (Figure 2).

TURN RIGHT ONTO THE HIGHWAY AND IMMEDIATELY GET INTO THE LEFT HAND LANE.

60.0 0.5 TURN LEFT at the stop light onto Old Mammoth Road.

60.3 0.3 Meridian Blvd. - PROCEED STRAIGHT through the stop light. Low hills in the foreground are the Mammoth Lakes moraine complex.

60.7 0.4 When the road takes a sweeping right, TURN LEFT onto Sierra Meadows Ranch Road. Continue beyond USFS pack station approximately 0.5 miles to large gravel area where we will turn around.

~61.3 0.6 **STOP 9.**
Soil development and rock weathering of Tioga Age moraine.

Line-up and park on the right side of the road. Stop to view Tioga age soil and weathering (assuming the snow has melted enough to see it). (Figure 2)

Here we hope to view a typical soil profile of Tioga age and walk the crest of a Tioga moraine to study the weathering features of Tioga age boulders. The A/Bw/Cox soil profile is developed to a depth of 165 cm and only 10% of the boulders on the moraine crest are considered weathered (Burke and Birkeland, 1979).

Return to Old Mammoth Road.

62.0 0.7 TURN RIGHT (back toward Mammoth).

62.3 0.3 TURN RIGHT at stop light onto Meridian Blvd.

62.5 0.2 Stop sign - CONTINUE STRAIGHT.

63.6 1.1 TURN RIGHT on Hwy 203 East (toward Bishop) - again note moraines of Laurel Creek, Sherwin Creek & Convict Lake (3 o'clock).

64.5 1.1 On the left side of the road, the type locality Casa Diablo till is sandwiched between two basalt flows.

65.2 1.6 Get into left lane and go under Hwy 395, and turn left onto Hwy 395 North.

66.9 1.7 Rest Area 5 miles sign - passing through a large Jeffery Pine forest.

68.5 1.6 Crossing Smokey Bear Flat (is it a pumice filled lowland?).

70.6 2.1 Pass the Mammoth Lakes "scenic loop" turnoff .

72.4 1.8 Rest Area to the Left - continue north on Hwy 395.

73.8 1.3 Turnoff to Deadman Creek Road -

74.2 0.6 **STOP 10.**
Optional - Overview of Deadman Summit.

At the Cal Trans Crestview maintenance station, begin to climb out of the Long Valley Caldera (Figure 2).

75.7 1.5 Note Holocene plug dome at 10 o'clock

76.2 0.5 Deadman Summit elevation 8036' at 12 o'clock is Wilson Butte, a Holocene Plug Dome (note treefall angle - possibly a result of the eruption of a neighboring dome?).

79.2 3.0 Roadcut through a moraine which exposes a buried soil and a fault.

79.8 0.6 Pass the turn to Pumice Mine Road, CONTINUE NORTH on Hwy 395.

80.2 0.4 Pass the turnoff to June Lake Loop Road. Note Mono Crater plug domes and obsidian flows at 3 o'clock.

81.6 1.4 Bishop Tuff exposures on right - to the left are right lateral moraines surrounding Grant Lake. Grant Lake is impounded by an end moraine of Tioga age which can be seen from June Lake Loop Road. When the June Lake Loop Road is snow-free, the drive is a spectacular view of glacial depositional and erosional features, and a short, scenic diversion from Hwy 395.

84.3 2.7 Pass West Portal Road.

85.2 0.9 At 9 o'clock, note the moraine complex of Walker Creek - 8 o'clock the moraine complex of Parker Creek.

85.9 0.7 **STOP 11.**
The type locality of the Mono Basin Moraines.

TURN RIGHT toward Benton and IMMEDIATELY PULL INTO THE PARKING AREA on the right for discussion of moraines and Mono Craters plug domes (Figure 3).

If snow and road conditions don't allow us to actually hike on the classic type locality Mono Basin moraines as defined by Sharp and Birman (1963), this overview will suffice to provide a backdrop for a discussion on relative dating vs. numerical dating techniques of glacial deposits. This morainal sequence has been the focus of much research, but we will concentrate on the mapping discrepencies between the work of Burke and Birkeland (1979), and that of Phillips et al. (1990).

Return to vehicles.

Depending on snow and road conditions, and time of day, we will either (1) end the trip here, or (2) continue to the type locality Mono Basin morianes (STOP 11B), where we will end the trip.

END OF ROAD LOG.

Acknowledgements

I would like to acknowledge a variety of people and organizations for making this trip possible. For the field discussions, research efforts, and years of cooperative exchange, I thank: John Ballantine, Fred Berman, Margaret Berry, Paul Bierman, Pete Birkeland, Doug Clark, Malcom Clark, Bob Curry, Fred Fisher, Alan Gillespie, Jeff Herrick, King Huber, Doug La Farge, Fred Phillips, Linda Reynolds, Bob Sharp, Diane Sutherland, Clyde Wahrhaftig, Skip Wollenburg, Paul Zehfuss, LADWP, USFS, and the BLM.

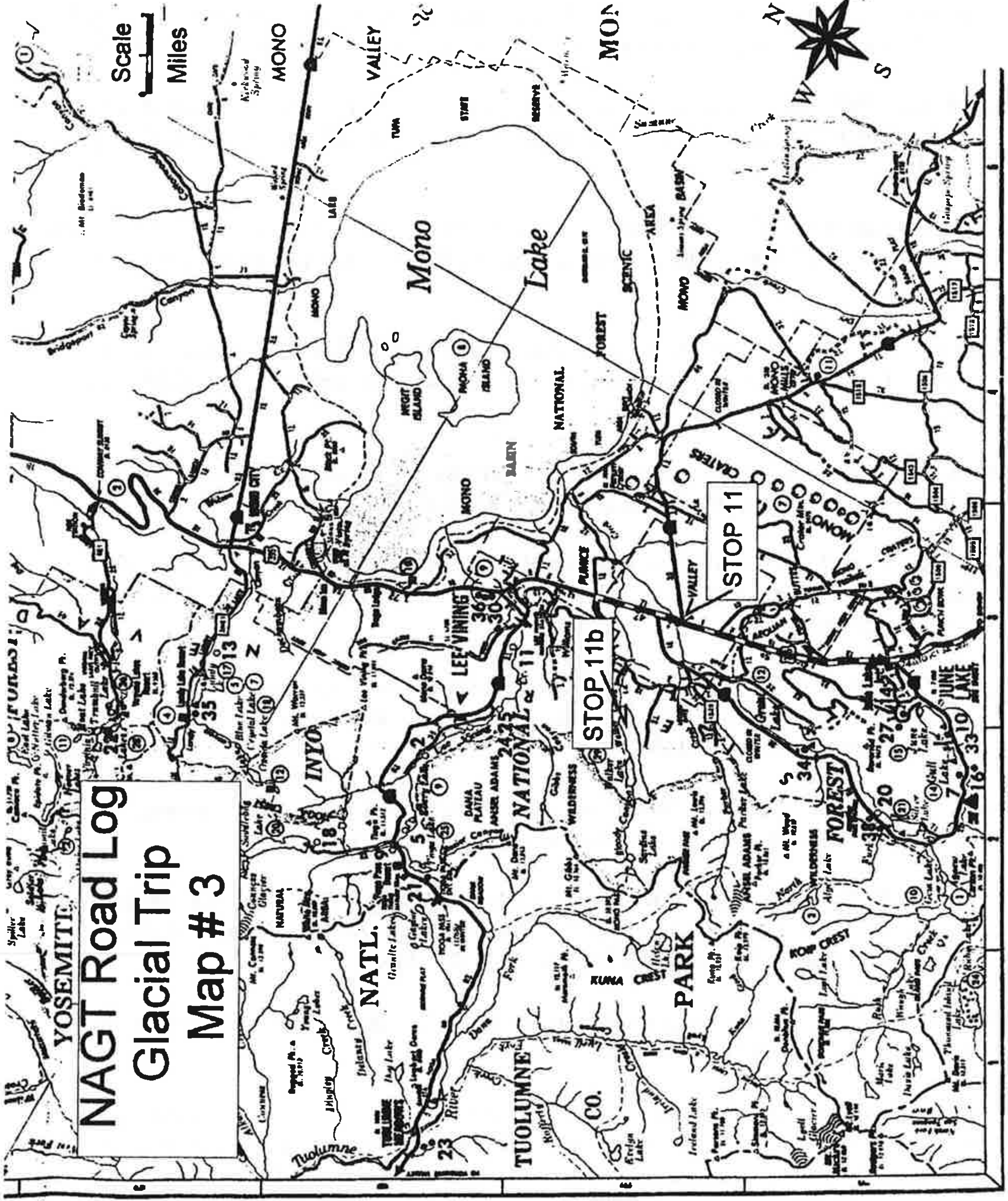

Figure 3. Glacial and Paleoclimate Trip map 3, field stops 11 and 11b.

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Quaternary Volcanism of the Long Valley Caldera and Mono Craters Region, California

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Introduction

This field guide is a broad overview of the history of Quaternary volcanism in the eastern Sierran region between Bishop and Mono Lake. Because this field trip (Figure 1) is a half-day event, discussions of the volcanic activity and the rocks that resulted from the volcanism will necessarily be limited in scope. This volcanic history is discussed at considerably more depth in a number of publications, including Russell (1889), Gilbert (1938), Bailey and others (1976), Wood (1977b), Hildreth (1979), Sieh and Bursik (1986), Bailey (1989), and Sharp and Glazner (1997). In particular, the Quaternary history of Long Valley caldera has been deciphered primarily by Roy Bailey. Parts of this field trip guide are excerpted and updated from an earlier guidebook (Lipshie, 1976).

Another limitation of this field guide is that it is written for a mid-April meeting, at which time much of the region can be blanketed by snow–a situation that is splendid for skiing but not so desirable for geologizing. Because of the unpredictability of snow conditions at the time of the trip, we are including several alternative stops, some of which are likely to be inaccessible in mid-April.

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Summary of the Volcanic History of the Long Valley-Mono Craters Region

The Quaternary volcanic history of the region between Bishop and Mono Lake is primarily the history of the Long Valley caldera and its relation to the Mono Craters chain (Figure 2). The oldest volcanic rocks that are associated with the Long Valley magma chamber are the rhyolite flows of Glass Mountain, which were extruded in the northeast sector of the not-yet-formed caldera between 2.1 and 0.8 million years (m.y.) ago (Metz and Mahood, 1985). The next major event in the formation of the caldera was the extrusion of the Bishop Tuff about 0.76 m.y. ago. The eruption began from a vent area along the south-central margin of the proto-caldera immediately

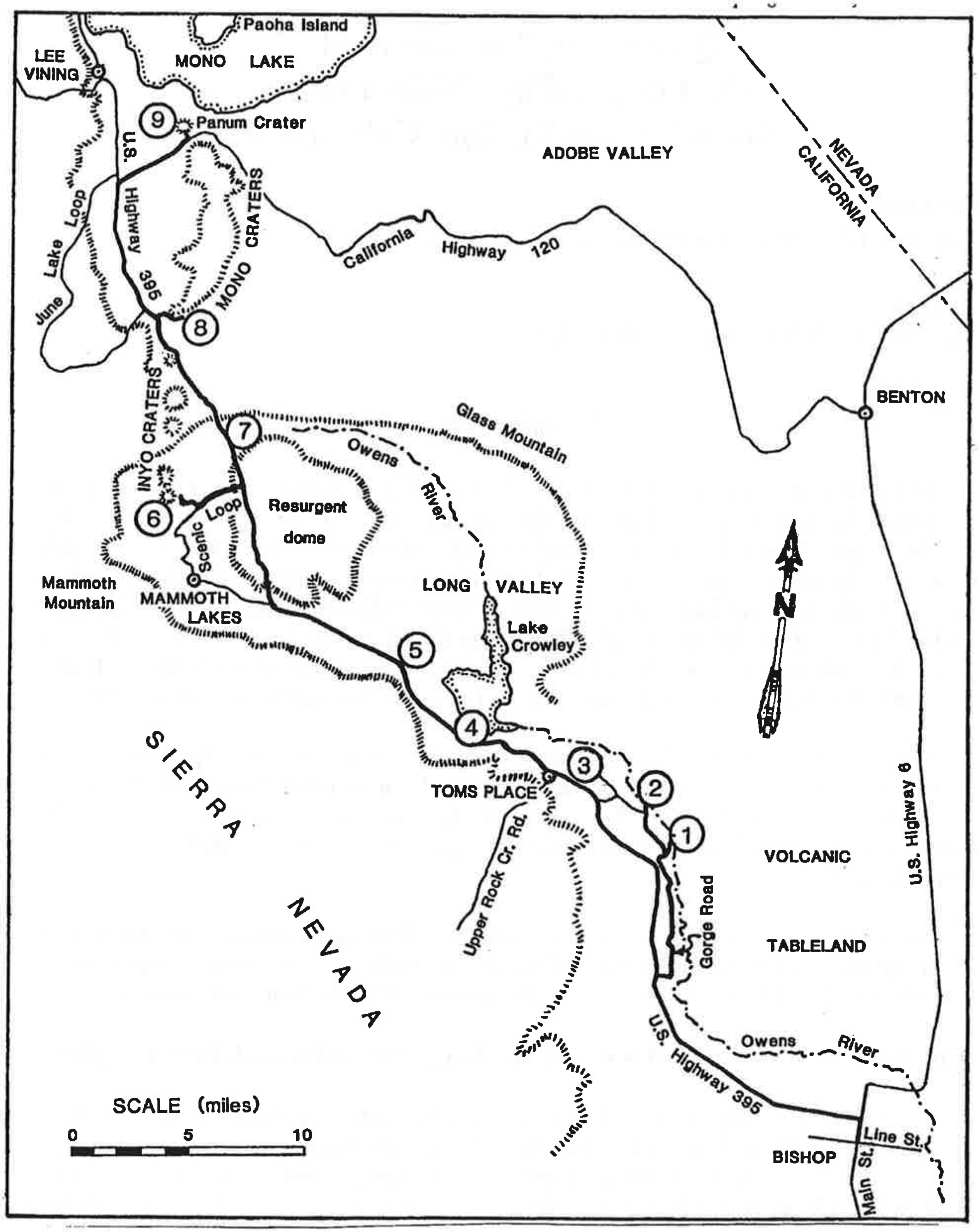

Figure 1. Route of field trip. Locations of stops are denoted by circled numbers, and the roads traveled during the trip are indicated by heavier lines. Hachures show boundaries of areas of higher elevations.

west of the Hilton Creek fault (Hildreth and Mahood, 1986). As the eruption proceeded and the caldera began to subside, multiple vents developed along a ring-fracture system. As the ring fracture propagated around the subsiding caldera, the earlier ash flows erupted toward the east, southeast, and southwest, and the later, hotter ash flows erupted toward the north (Hildreth, 1979). About 125 cu mi (500 cu km) of Bishop Tuff were emplaced over a very short time span, perhaps only a few days or weeks. The eruption also produced about 75 cu mi (300 cu km) of air-fall ash, which was carried as far east as Kansas and Nebraska. The tuff covers about 450 sq mi (1170 sq km) between Bishop and Mono Lake, with the Volcanic Tableland north of Bishop (Figure 2) comprising the largest part of the outcrop area.

As eruption of the Bishop Tuff partially emptied the magma chamber, its roof collapsed and formed the Long Valley caldera, an elliptical depression measuring 10 miles (16 km) from north to south and 18 miles (29 km) from east to west. Caldera subsidence totals 2 miles (3 km), of which one third is reflected in present topographic relief and the other two thirds are represented by post-caldera basin fill. Exploratory geothermal drilling within the caldera showed that at least 4100 ft (1.25 km) of Bishop Tuff accumulated in the eastern part of the caldera (Bill Smith, Republic Geothermal Corp., oral communication, 1976).

Shortly after formation of the caldera, the central part underwent resurgent doming (Figure 3), during which rhyolite flows (the so-called "older rhyolite") and rhyolitic tuff breccia were extruded (Bailey and others, 1976). The rhyolite was emplaced from at least 12 vents during an interval of perhaps 100,000 years, between 0.73 and 0.62 m.y. ago (Mankinen and others, 1986). Doming and rhyolite extrusion in the central region of the caldera was probably completed by 0.5 m.y. ago, thus producing what Smith and Bailey (1968) called a "resurgent cauldron" with an uplifted central dome surrounded by a low-lying "moat."

The next phase of volcanism involved the emplacement of marginal (moat) rhyolites in three discrete episodes: 0.5, 0.3, and 0.1 m.y. ago. The moat rhyolites ("younger rhyolites"), which were emplaced on the periphery of the central dome (Figure 3), are probably related to ring fractures around the resurgent dome. A later stage of volcanism produced rim rhyodacites from at least ten vents in the western part of the caldera. The main mass of these hornblende-biotite rhyodacite flows is Mammoth Mountain, which consists of flows ranging in age from about 220,000 to 50,000 years. At the same time that Mammoth Mountain was being formed, basalt and andesite flows were extruded in the west moat of the Long Valley caldera. The potassium-argon (K-Ar) ages of the flows range from 239,000 to 64,000 years (Mankinen and others, 1986). Near the town of Mammoth Lakes, basalt flows are interbedded with pre-Wisconsin glacial deposits.

Bailey and others (1976) reported a decrease in silica content with decreasing age of the extrusive rocks derived from the Long Valley magma chamber:

Glass Mountain rhyolite	77 percent silica
Bishop Tuff	76
Older (resurgent dome) rhyolite	75
Younger (moat) rhyolite	72
Hornblende-biotite rhyodacite	64 - 70

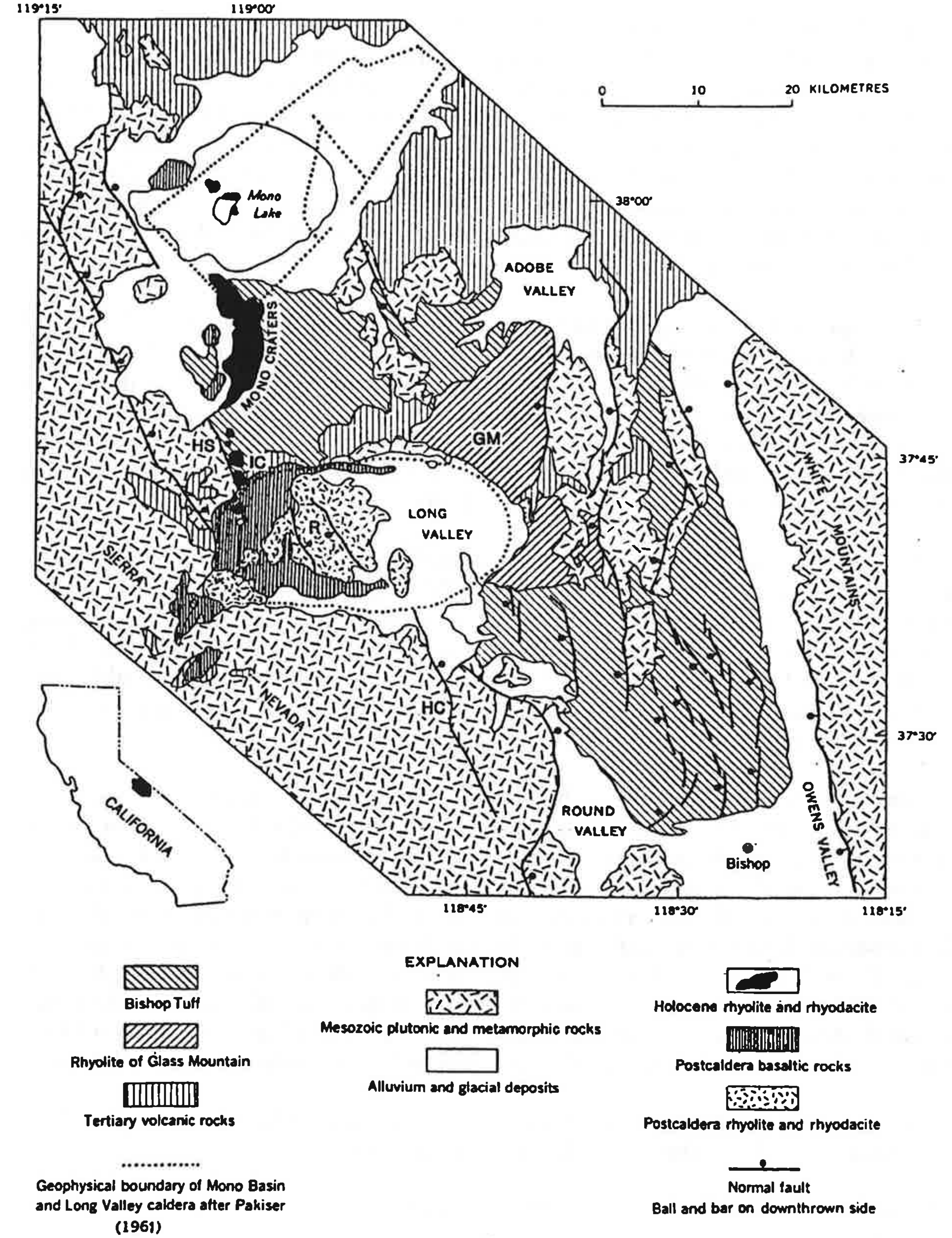

Figure 2. Generalized geologic map of the Long Valley-Mono Basin region. The Volcanic Tableland is the area of Bishop Tuff between the Long Valley caldera and the town of Bishop. GM = Glass Mountain Ridge; HC = Hilton Creek fault; HS = Hartley Springs fault; IC = Inyo Craters; R = resurgent dome of the Long Valley caldera and its medial graben. (Modified from Bailey and others, 1976, Jour. Geophys. Research, © Amer. Geophys. Union)

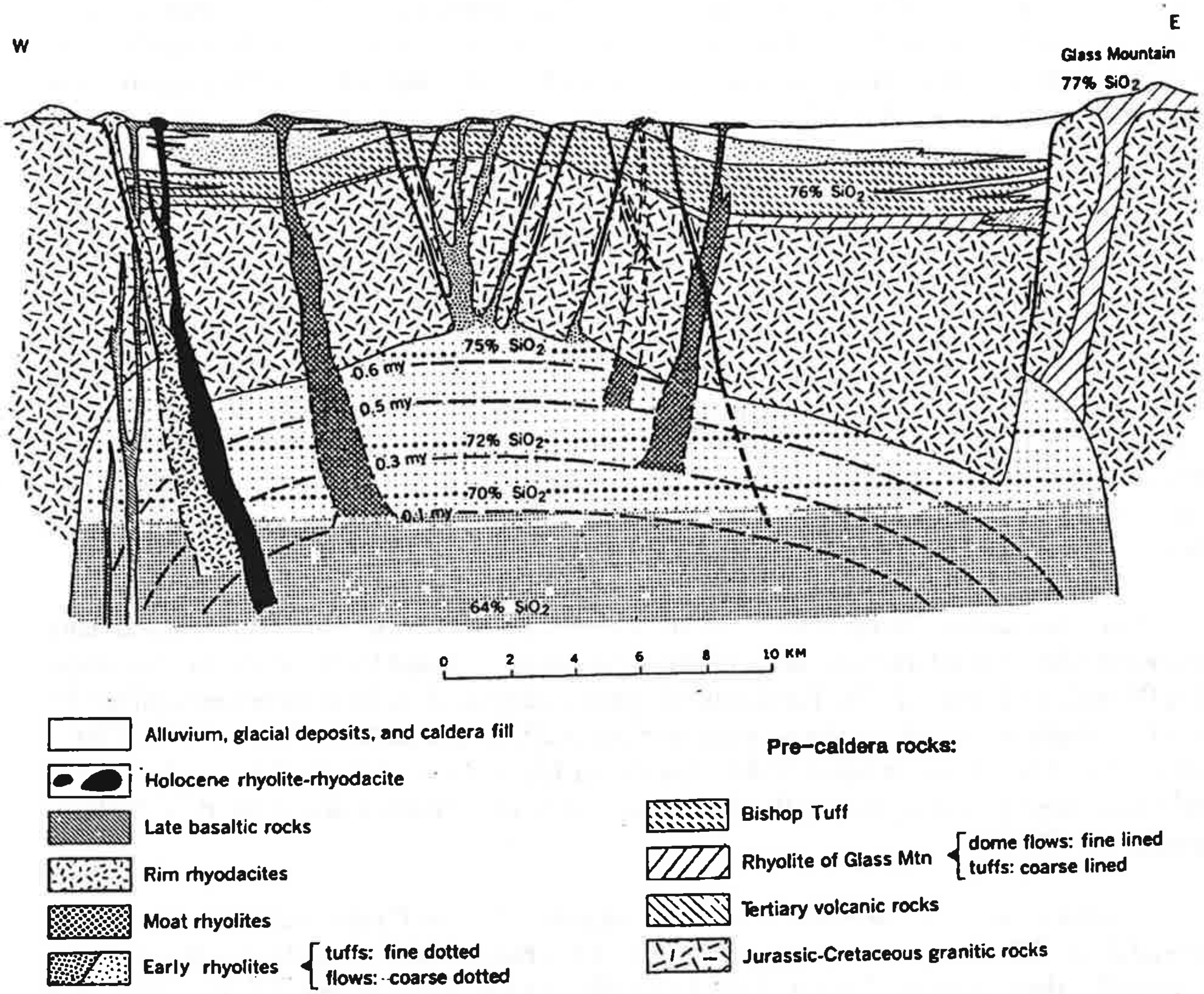

Figure 3. Schematic east-west cross section through Long Valley caldera and its subjacent magma chamber. Heavily dotted part of chamber is rhyodacite magma; lightly dotted part is rhyolite magma. Horizontal dotted lines show silica gradient in vertically zoned chamber. Curved dashed lines show depth to residual magma at specified times. Because the diagram is intended to be a simplified rather than precise representation and because of gaps and uncertainties in subsurface data, the vertical scale is unspecified. Pre-Cenozoic metamorphic rocks are included with granitic rocks in the cross section. (From Bailey and others, 1976, Jour. Geophys. Research, © Amer. Geophys. Union)

They interpreted this decrease in silica content of successive eruptives as indicating progressive downward crystallization of a zoned magma chamber that is more silicic in its upper part. Most of the basalt and andesite flows have silica content between 48 and 56 percent, which is significantly different from that of the contemporaneous rhyolitic rocks. Bailey and others (1976) suggested that the basalt and andesite were derived from a much deeper source than the Long Valley magma chamber and that the mafic and silicic magmas did not interact to any great extent.

More recent volcanic activity has occurred north of Long Valley, in the Mono Craters region near Mono Lake. Rhyolitic magma began erupting in the Mono Craters about 40,000 years ago, and eruptive episodes continued until about 600 years ago (Wood, 1977b). The Mono Craters volcanism ultimately produced more than thirty domes, craters, and flows (coulees) that lie along a concave-westward arc. The Mono Craters rocks are rhyolitic in composition, and the exposed materials consist primarily of pumice, obsidian, and ash deposits. The trace-element chemistry of the rhyolite indicates that the Mono Craters lavas were not derived from the Long Valley magma chamber. Kelleher and Cameron (1990) suggested that, based on variations in trace elements and accessory minerals, the Mono Craters rhyolites were derived from multiple magma bodies.

The most recent volcanism in the Mono Craters has been at the north end of the arcuate chain, where the Panum Crater dome formed between A.D. 1270 and 1350, based on radiocarbon dating (Wood and Brooks, 1979). Farther north, Paoha Island is thought to have been uplifted by subsurface emplacement of a volcanic plug between A.D. 1660 and 1850 (Stine, 1984). This is based on the observation by Stine (1984) that Paoha Island does not have the strand line that should have been produced during the highest recent level of Mono Lake (6456 ft or 1968 m) around A.D. 1720 ± 60.

Almost contemporaneously with the formation of Panum Crater, volcanic activity also occurred along the Inyo Craters chain to the south. The chain lies along a north-trending fracture that straddles the northwest margin of the Long Valley caldera (Bailey and others, 1976). The fracture is subparallel and east of the Hartley Springs fault (Figure 2), which extends northward from the caldera to the south end of the Mono Craters chain. The Inyo Craters chain consists of a series of craters and domes that range in age from about 6000 to 550 years (Wood, 1977b).

Drilling of four slanted borings along the Inyo Craters chain in the 1980's showed that the north-trending fracture postulated by Bailey and others (1976) is associated with a rhyolite dike. Eichelberger and others (1988) concluded that the dike system tapped more than one magma chamber along its length, resulting in chemical differences among the Inyo dome rhyolites. Bailey and others (1976) had suggested that the Inyo Craters rhyolite formed by mixing of magmas from the Long Valley and Mono Craters magma chambers. This suggestion was confirmed by subsequent geochemical studies (Sampson and Cameron, 1987).

Although no volcanic eruption has been reported in the region for hundreds of years, the region is still volcanically active. (An alleged volcanic event at Mono Lake in 1890 can safely be discounted.) Hot springs and fumaroles abound within the caldera, particularly along the south and east margins of the "resurgent dome" and, to a lesser extent, at Mammoth Mountain. Seismic activity that began in 1978 and continues today is associated with about 1.6 ft (0.5 m) of dome-shaped uplift in the western part of the resurgent dome that occurred between 1975 and 1987 (Goldstein and Stein, 1988). Whether the seismic activity is a volcanic or a purely tectonic manifestation is still a topic of controversy that remains to be resolved. An observation that Mark Twain (1872) made about the volcanic islands of Mono Lake over a century ago can just as well be applied to the Long Valley-Mono Craters region today: Although this crater has gone out of active business, there is still some fire left in its furnaces.

A Brief Note on Rhyolitic Volcanism

Volcanic domes and flows of the Long Valley caldera can be divided into two categories on the basis of topographic expression: rhyolite and rhyodacite flows have moderate to steep relief and are up to 1000 ft (300 m) high, whereas basalt and andesite flows have low, gentle relief, typically measuring between 15 and 100 ft (5 and 30 m). Part of this topographic dichotomy is due to the dependence of volcanic flow behavior on the physical properties of magmas: thick, stubby flow masses of rhyolite and rhyodacite cooled from very viscous, high-silica magma, whereas the thin, sheetlike flows of basalt and andesite formed from less viscous, low-silica magma.

A rhyolitic volcano undergoes a complex sequence of eruptive events during the course of its evolution (Putnam, 1938). Its birth is heralded by explosive eruptions that blanket the surrounding area with pumice ash and lapilli and form a tephra ring around the newly created crater (stage 1 of Figure 4). As the magma rises along the vent, it forms a stiff, cylindrical, nearly solid plug of obsidian-an incipient dome-in the floor of the crater. If the rhyolite plug continues to grow, it builds a bigger and bigger dome that eventually fills the crater and engulfs the surrounding tephra ring (stage 2 of Figure 4). Continued outpouring of rhyolite magma causes the domal mass to spill over its tephra ring and form a stubby flow called a "coulee" (stage 3 of Figure 4). Coulees are blocky, steep-faced flows that were extruded in a highly viscous state (although probably less viscous than dome-forming magma). A surface crust that hardens as the lava flows is broken up to form the irregular, blocky surface that is characteristic of rhyolite domes and coulees.

Each rhyolite flow includes a distinctive suite of rocks associated with solidification of a viscous flow of high-silica magma: breccia, obsidian, pumiceous rhyolite, flow-banded rhyolite, and massive rhyolite. The outer part of the flow is churned and brecciated by the moving flow as it cools. Within the initially fluid interior of the flow, the outer zone cools rapidly and chills to form rhyolite glass, the relatively degassed magma chilling to form obsidian and the more gas-charged fraction forming pumiceous rhyolite. The slower-cooling core of the flow crystallizes to form lithoidal (stony) rhyolite, which is massive to flow-banded in appearance (Roy A. Bailey, oral communication, 1972).

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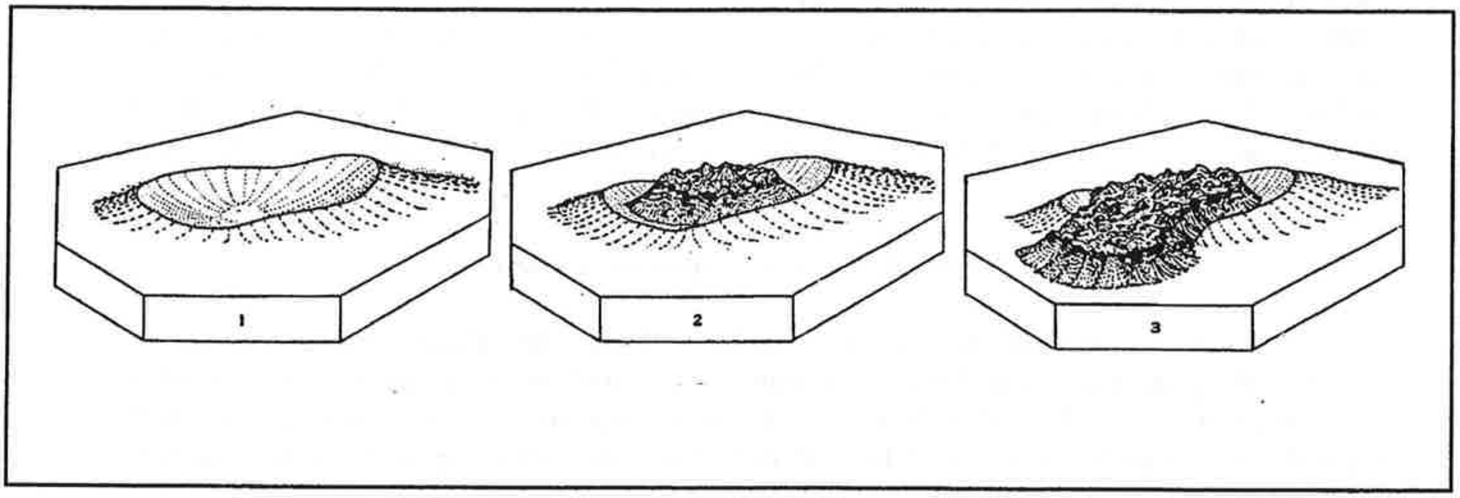

Figure 4. Sequence of eruptive events in the development of a rhyolitic volcano. Eruptive forms may evolve through three stages during the growth of the volcano: (1) explosive eruptions form a shallow crater rimmed by a tephra ring; (2) a rhyolite dome is emplaced within the crater and may fill the crater and engulf the tephra ring; (3) if extrusion of magma continues, the dome may form a coulee that spills over the tephra ring as a thick, stubby lava flow. (From Putnam, 1938; © Amer. Geographical Soc.)

ROAD LOG

This field guide begins at the intersection of Main and Line Streets, in the heart of downtown Bishop (Figure 1). Main Street is U.S. Highway 395, which is the main route between Los Angeles and Reno. The town, which was founded in 1864, and the creek were named for Samuel A. Bishop, who in 1861 moved from Fort Tejon to Owens Valley and started a ranch there. However, after trouble began between the settlers and the native Paiute inhabitants of the valley, Bishop decided to go back to more tranquil Kern County. Despite its inauspicious beginnings, Bishop today is the largest town in Inyo County and a major gateway to the Eastern Sierra and its recreational attractions.

Mileage		
Cum.	Interval	
0.0	0.0	Start at traffic signal at Line Street intersection and HEAD NORTH on Main Street.
0.4	0.4	Traffic signal at intersection of Main and Park Streets. The Bishop City Park and tourist information center are on the right, south of Park Street.
0.8	0.4	As U.S. Highway 395 (Main Street) curves to the left (west), U.S. Highway 6 is on the right. This is the west end of Highway 6, which heads north across Montgomery Pass into Nevada and then swings eastward, eventually terminating on the Atlantic seaboard at Cape Cod. On the left side of Main Street are the Tri-County Fairgrounds, where the Tri-County (Inyo, Mono, and Alpine Counties) Fair is held each summer.
2.9	2.1	Intersection with Brockman Lane. The group of big trees on the north side of Highway 395 is reputed to be the site where two of the escaped convicts involved in the 1871 shootout that gave Convict Lake its name were lynched.
5.6	2.7	Ed Powers Road on left (south), which connects with Bishop Creek Road. U.S. Highway 395 parallels the southern margin of the Volcanic Tableland, an ash-flow deposit of Bishop Tuff that extends southward and southeastward from the Long Valley caldera. The southern margin is so abrupt that it looks like a fault scarp. However, the "escarpment" is apparently an erosional feature, as is indicated by the small outlying butte of Bishop Tuff north of Highway 395 and west of Ed Powers Road.
6.3	0.7	Small plug or flow of Pleistocene(?) basalt on right (north).
6.4	0.1	The north side of the Tungsten Hills is on the left (south). The hills consist mostly of Cretaceous plutonic rocks that range from quartz monzonite to hornblende gabbro (Bateman, 1965). The Tungsten Hills are aptly named, because the first tungsten ore to be reported from the Bishop mining district was found here in 1913.
7.1	0.7	Isolated outcrops of Bishop Tuff occur on both sides of the highway in this vicin-

ity. These outcrops show that the southern edge of the Volcanic Tableland is of erosional, rather than tectonic, origin. Bishop Tuff is also found in shallow water wells at least as far south as Big Pine (Clem A. Nelson, oral communication, 1974). Straight ahead is the impressive escarpment of Wheeler Crest, which consists mostly of Wheeler Crest Granodiorite (formerly called Wheeler Crest Quartz Monzonite; see Stop 2).

10.8 3.7 Pine Creek Road is on the left. Continue straight. If you want to make a side trip to the Pine Creek tungsten mine, turn left here and drive 10.5 miles (17 km) to the mine. However, the mine, which once billed itself as the "second-largest tungsten mine in the free world," has been shut down since 1990. The mill is still in operation, though, because the operators have found that it is more economical to bring tungsten concentrate from Asia and mill it here than it is to mine ore locally and process it at the site. In its heyday, until the mine was shut down, the Pine Creek operation employed over 400 people, a number of whom lived in the company town of Rovana, about halfway between Highway 395 and the mine.

11.8 1.0 Roadcut (one of many to come) in Bishop Tuff.

12.4 0.6 Begin the long climb up Sherwin Grade. Highway 395 ascends 2500 feet (750 m) over the next 10 miles (16 km). The grade is named for James Sherwin, who started a ranch in Round Valley in 1859. In the 1870's, during the brief flurry of gold mining activity at Mammoth Lakes, he built a toll road up the grade along Rock Creek. For many years, U.S. Highway 395 followed the route of Sherwin's toll road, until the four-lane highway was built along its present alignment between Round Valley and Toms Place in 1956-57.

12.5 0.1 Roadcut in typical Bishop Tuff, on right. If you have the time, this is a good spot to park and look at the unit. Bishop tuff is a rhyolitic ignimbrite consisting of ash deposits that grade downward from sillar (tuff in which induration is due to recrystallization rather than welding) into true welded tuff. The tuff at this exposure is typical sillar-porous, light in weight, and containing uncollapsed fragments of pumice. Abundant phenocrysts of quartz, sanidine, and minor plagioclase, biotite, augite, and hypersthene are contained in a vitroclastic matrix that has largely been crystallized to a mixture of sanidine and cristobalite or tridymite (Wes Hildreth, written communication, 1976). Small xenoliths of basalt, hornfels, quartzite, and granitic rocks are included locally in the tuff and serve to indicate the nature of the basement rock along the ring-fracture segment from which the ash flow was extruded (Hildreth and Mahood, 1986). In the welded part of the unit (not exposed here), the tuff is dense and locally glassy (although most of the glass has devitrified), and it contains flattened pumice fragments and deformed glass shards.

12.85 0.35 TURN RIGHT at Gorge Road, which goes to City of Los Angeles Dept. of Water and Power (LADWP) powerhouses in the Owens River Gorge. The road to the left goes up the Sherwin Grade along lower Rock Creek, following the old toll road route.

13.55	0.7	Turn left (north) at T-intersection. The road is paved and maintained by the LADWP, but the condition of the pavement varies from year to year, depending on how long ago it was last resurfaced. The big pipeline that parallels the road is a penstock (water conduit) that carries Owens River water from LADWP Tunnel No. 3 to Powerhouse No. 3 in the gorge.
13.75	0.2	Note the small "fumarolic mounds" about 50 to 100 feet (15 to 30 m) high that dot the surface of the Volcanic Tableland on both sides of the road. These low, rounded mounds on the Bishop Tuff surface are believed to be the sites of formerly active gas vents. The temperature increase due to the escaping hot gases enhanced vapor-phase crystallization near the vent (Sheridan, 1970). The tuff near fumaroles thus became more highly indurated and less susceptible to weathering. Subsequent erosion has stripped 50 to 200 feet (15 to 60 m) of the surface of the Volcanic Tableland (Sheridan, 1971), leaving the more resistant rocks at sites of former gas vents as low mounds. Sheridan (1970) reported that fumaroles were aligned along early joints in the tuff, which indicates that jointing occurred after compaction but before the completion of cooling.
14.15	0.4	Roadcut through a fumarolic mound. This is a nice spot to see a tuff that has undergone some hydrothermal alteration. The white, altered tuff in the vapor-phase zone of the mound consists largely of cristobalite, tridymite, and alkali feldspar (Sheridan, 1971).
14.8	0.65	Mono County line.
14.95	0.15	LADWP surge tank straight ahead. Surge tanks are empty enclosed tanks that are designed to absorb the energy of the first surge of water that comes through the line when valves are opened. Energy is dissipated by compressing the air in the tank. Surge tanks are placed at the downflow ends of LADWP tunnels to absorb the energy that would otherwise damage the penstock valves.
16.8	1.85	Paved road on right goes to LADWP Powerhouse No. 2 in the Owens River Gorge. This is one of three hydroelectric plants built by the LADWP in the gorge between 1949 and 1953.

18.2 1.4 Fumarolic mounds dot the surface of the Bishop Tuff on both sides of the road. The vapor that was released at fumaroles was primarily steam, produced when the hot ash flows overrode and buried streams and lakes during the eruption. A similar phenomenon occurred in the graphically named Valley of Ten Thousand Smokes in southern Alaska, when Novarupta and Mount Katmai erupted in 1912 (Curtis, 1968). By comparison with that eruption, the Volcanic Tableland was probably "the Valley of a Million Smokes" while the Bishop Tuff was cooling.

19.2 1.0 Road crosses a small gorge cut into the Bishop Tuff.

19.6 0.4 Paved road forks. TAKE RIGHT FORK. Left fork will eventually take you to the LADWP surge tank near Stop 2 of this road log.

19.8 0.2 Road is blocked by a locked LADWP gate. PARK along the side of the road and walk about 150 ft (50 m) down the road past the locked gate. If the gate is open, park outside the gate anyway, or you may come back and find your car locked in.

STOP 1.
Radial (rosette) columnar jointing in Bishop Tuff.

At this locality, the Owens River Gorge is carved entirely in Bishop Tuff. The unit generally is 400 to 500 ft (120 to 150 m) thick but locally is up to 800 ft (240 m) thick (Gilbert, 1938; Rinehart and Ross, 1957). The gorge here is about 450 ft (135 m) deep, which provides a minimum thickness for the tuff. The lower, more highly welded tuff is generally massive with irregularly developed jointing. The upper, unwelded part of the tuff, however, has strikingly unusual columnar joint ing that commonly forms radiating sets (Figure 5). Column diameters typically range between 3 and 5 ft (1 and 11/2 m), and columns have diverse orientations ranging from horizontal to vertical. If you want to photograph the rosette jointing, visit this locality in the afternoon.

The Bishop Tuff in the roadcut near the locked gate is a sillar that consists of very light gray to pale pink, agglutinated but only slightly welded, vitric pumice ash that weathers a distinctive grayish orange pink. The tuff contains abundant pumice fragments, generally equidimensional, as well as plentiful phenocrysts of sanidine, quartz, and plagioclase. The lower, more highly welded tuff can be seen by walking farther down the road into the gorge. It is darker in color (pale red purple to medium gray on fresh surfaces) and noticeably denser than the sillar by the locked gate. Pumice fragments in the denser tuff are considerably flattened in the plane of bedding. Granitic and metasedimentary xenoliths can be found in the lower part of the tuff.

Putnam (1960) and Sheridan (1970) observed that radiating columnar joints commonly occur beneath fumarolic mounds. Sheridan noted the similarity of the radial jointing pattern to the heat flow pattern during cooling around a gas

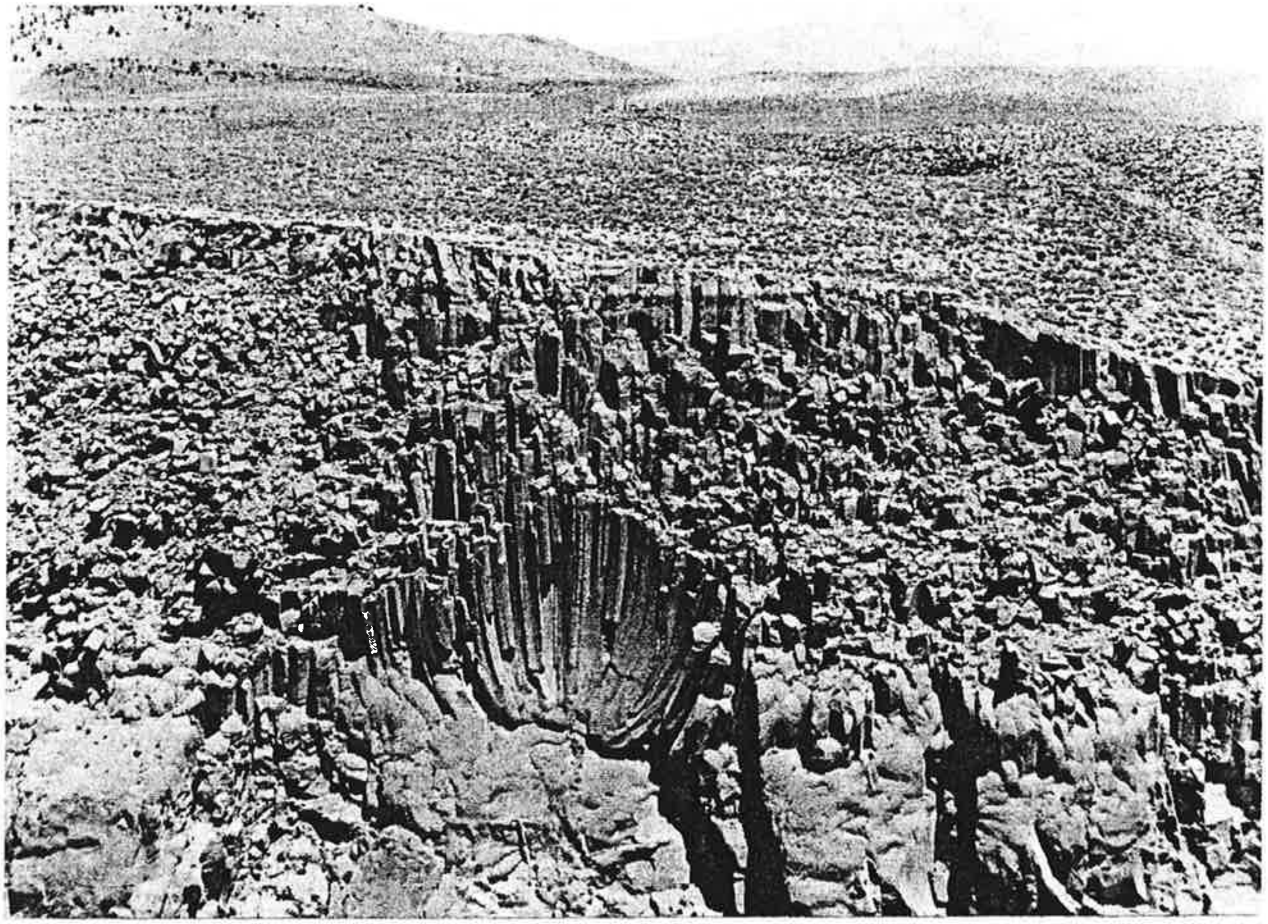

Figure 5. Radiating (rosette) columnar jointing in Bishop Tuff at Owens River Gorge (Stop 1). The upper, more highly jointed part of the tuff is poorly welded to unwelded; the lower, less jointed part is more highly welded. (Photograph taken in July 1976)

vent-the heat would flow radially outward and upward from the vent. This similarity suggests that jointing formed normal to isothermal surfaces around vents, and Sheridan used this relationship to reconstruct thermal regimes in the tuff during cooling. An example of the rapidity with which joints form is provided by ash-flow tuff that was deposited in the Valley of Ten Thousand Smokes, Alaska, during the 1912 eruption. Within forty years of the eruption, a gully had eroded to a depth of 100 ft (30 m) in the tuff, exposing well-developed vertical columnar joints, 20 to 50 ft (6 to 15 m) in length, in the upper part of the unit (Curtis, 1968; see especially his Plate 6, Figure 1).

20.0	0.2	Return to junction of two paved roads. TURN RIGHT SHARPLY at road junction and head northward. This road is posted by the U.S. Forest Service as route 4 S 43.
20.55	0.55	Dirt road to the right goes to the LADWP's Mesa Gorge emergency telephone, which is used for reporting trouble in the LADWP hydroelectric system in the gorge.
21.8	1.25	Fork in paved road. TAKE LEFT FORK (i.e., go straight). The right fork goes to a point on the gorge overlooking the penstock that carries water from LADWP Tunnel No. 1 to Powerhouse No. 1 in the gorge below.
22.2	0.4	Road intersection at which pavement ends. GO STRAIGHT, bearing just to the left of the LADWP surge tank. Forest Service route 4 S 43 turns left (west) at this intersection.
22.25	0.05	If your vehicle cannot clear the rocks in the road ahead, park off the road on the right.
22.3	0.05	Road ends in a small turnaround loop. PARK HERE for Stop 2. The surface of the Bishop Tuff at this elevation (about 7000 ft or 2100 m) is forested with pinyon pine (round, stiff needles about an inch long that grow singly, not in bundles) and juniper.

STOP 2.
Owens River Gorge overlook near Powerhouse No. 1.

The geology of the gorge near LADWP Powerhouse No. 1 is shown on the geologic map by Rinehart and Ross (1957). Four lithologic units are exposed in the wall of the gorge here (Figure 6). The oldest rock, which comprises the lower half of the wall, is Wheeler Crest Granodiorite, which is of Late Triassic age, having been dated at between 207 and 217 m.y. (Bateman, 1992). Outcrops of this unit are scattered along the eastern flank of the Sierra Nevada from Bishop to Mono Lake. The unit was originally named the Wheeler Crest Quartz Monzonite (Bateman, 1961) but was renamed because the widespread adoption of

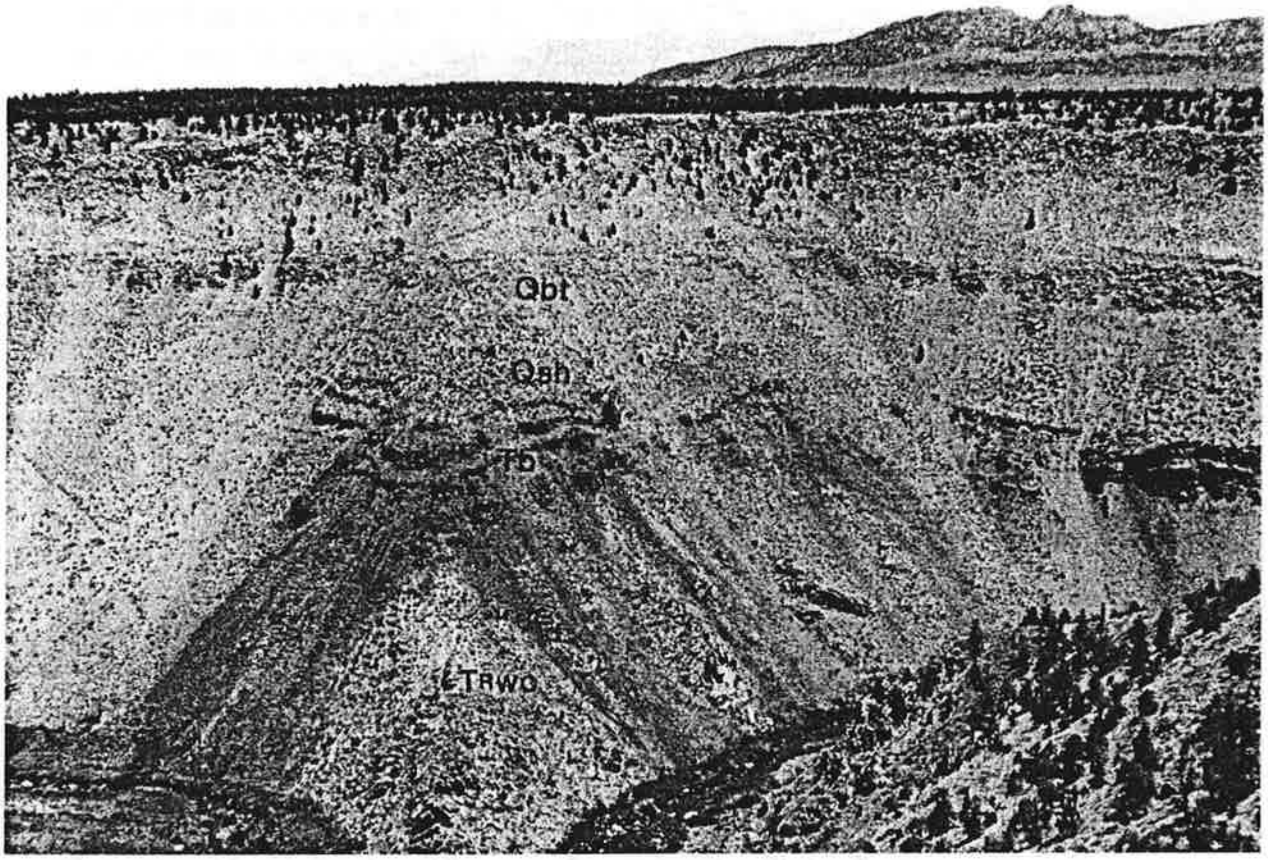

Figure 6. Owens River Gorge (Stop 2) above LADWP Powerhouse No. 1. Stratigraphic units exposed in gorge wall are (from oldest to youngest) Wheeler Crest Granodiorite (TRwc), late Pliocene basalt (Tb), Sherwin till outwash (Qsh), and Bishop Tuff (Qbt). Casa Diablo Mountain, which rises as an island of mostly Wheeler Crest Granodiorite in a sea of Bishop Tuff, is in the distance at upper right. A trail that switchbacks into the gorge (left margin of photo) was made, probably around 1920, to provide access to a small hydroelectric power plant in the gorge. The plant, the remains of which are along the river below, was built to provide power to a gold and silver mining operation at Casa Diablo Mountain (E.C. "Rocky" Rockwell, U.S. Forest Service, oral communication, 1978). (Photograph taken in June 1976)

the Streckeisen (1973) classification system for plutonic rocks displaced the old petrographic nomenclature (Williams and others, 1954) that we learned in school. Such are the vagaries of geologic terminology.

Overlying the granodiorite in the gorge are basalt flows that have been potassium-argon (K-Ar) dated at 3.2 ± 0.1 m.y. (Dalrymple, 1963). The basalt is overlain by a thin, discontinuous layer of glacial debris, which can be recognized from here (if you have the eye of a believer) by its light-colored granitic cobbles and boulders. This material is Sherwin Till outwash (Sharp, 1968), derived from glacial deposits west of the gorge.

The stratigraphically highest unit exposed in the gorge is the Bishop Tuff, which here is about 200 ft (60 m) thick and consists of rhyolitic ash-flow deposits that grade downward into welded tuff. The unit has a basal zone of non-welded pumice ash which is mostly concealed by talus in the gorge but which can be found locally (Wes Hildreth, written communication, 1976). The non-welded zone includes both the basal air-fall ash and the lower part of the ash-flow sequence; we will see this zone at Stop 3. The more highly welded zones form cliffs, whereas the unwelded or partially welded parts of the unit, although indurated by vapor-phase crystallization and agglutination, form slopes on the gorge walls.

Upstream from here, most of the gorge wall consists of Wheeler Crest Granodiorite that has been uplifted on the west side of a north-trending fault (Rinehart and Ross, 1957). Note the thinning and disappearance of the basalt farther up stream; the lava flowed across an irregular topographic surface on the granodiorite, filling in the low-lying areas and flowing around the higher elevations.

Putnam (1960) studied the origin of the Owens River Gorge and concluded that it formed by headward cutting of the Owens River across the Volcanic Table land. He argued that headward growth of the south-flowing river captured the Long Valley drainage and provided an outlet for the Pleistocene lake (Long Valley Lake, discussed at Stop 4) that once filled the valley. But Wahrhaftig (1965a) advanced several objections to Putnam's hypothesis: (1) the present gorge is at the lowest point on the rim of the Long Valley hydrographic basin, where one would expect overflow to occur; (2) only streams that drain areas outside the Bishop Tuff have incised deep canyons across the tuff, which suggests that gorge cutting by headward erosion of a stream within the area of the tuff is unlikely; and (3) the gorge has incised meanders reaching nearly to the canyon rims and having a wave length and amplitude appropriate for the stream's present flow, rather than for that of a much smaller stream. From this evidence, Wahrhaftig (1965a) concluded, as had Rinehart and Ross (1957) concluded that the Owens River Gorge formed when Long Valley Lake was drained by overflow at the lowest point on the rim of its basin, leading to downcutting of the gorge by the Owens River.

22.4	0.1	Return to road intersection near surge tank. Go straight (south), retracing your route on the paved road back to U.S. Highway 395 at the base of Sherwin Grade. However, if the dirt road that goes to the right (west) from this intersection is free of snow, you can take that road and save over 16 miles of driving. It will take you to Highway 395 near Sherwin Summit, a driving distance of 2.5 miles. Just follow the main road, and take the left fork 1.45 miles from this intersection. If you use this shortcut, adjust your mileage accordingly when you get to Highway 395.
26.4	4.0	Along this stretch of road is a good view of glacially carved Pine Creek Canyon at 1:00 (letting 12:00 be straight ahead along the road, looking south). The canyon has the U-shaped cross-section that is characteristic of glacially carved valleys. Composite lateral moraines of Tahoe and Tioga glacial deposits are conspicuous at the mouth of Pine Creek Canyon. Mount Tom is the prominent peak to the left of the canyon, at 12:30.
30.8	4.4	TURN RIGHT (west) onto paved road that connects with Highway 395.
31.5	0.7	TURN RIGHT (north) onto U.S. Highway 395 and begin the climb up Sherwin Grade. James Sherwin (see mileage 12.4) also has a hill, a till, a creek, a summit, and a group of lakes named after him. He apparently had a very good publicity agent.
32.8	1.3	Mono County line. On the left is a fine view of Wheeler Crest, which rises about 6000 ft (1800 m) above Round Valley. Wheeler Crest was named for Lt. George M. Wheeler, U.S. Army Corps of Engineers, who directed an early geographical and geological survey (the Wheeler Survey) of the West between 1869 and 1873.
37.8	5.0	Entering Inyo National Forest. The national forest, which was established in 1907, includes about 2 million acres of the eastern Sierra Nevada and White-Inyo Range.
39.2	1.4	We are leaving an area of Bishop Tuff exposures and entering an area blanketed by Sherwin Till, which we will see at Stop 3.
40.0	0.8	The rounded hill on the right, with a telephone company microwave relay station on top, is Sherwin Hill, the type locality of the Sherwin Till.
41.1	1.1	The top of Sherwin Grade is marked by Sherwin Summit, which allegedly has an elevation of exactly 7000 ft (2134 m), according to the road sign.
41.2	0.1	Dirt road on right. This intersection is where you would reach Highway 395 if you took the shortcut from Stop 2 that was mentioned at mileage 22.4.
42.0	0.8	PARK on shoulder along right side of highway. Walk to the roadcut west of the parking area.

STOP 3.
The Big Pumice Cut.

This roadcut, named the "Big Pumice Cut" by Sharp (1968), was made in 1957 when the present highway was constructed to replace the steep, winding road that follows Rock Creek along the Sherwin Grade. The Big Pumice Cut (Figure 7) is famed in storyand song and revered by geologists throughout the land because it finally laid to rest the controversy regarding the relative ages of the Bishop Tuff and Sherwin Till. The till, which here clearly underlies the tuff, is one of the oldest Pleistocene glacial deposits yet recognized in the Sierra Nevada, being exceeded in age only by the McGee Till. Because the till appears to have undergone about 50,000 years of weathering and the overlying tuff has been dated at about 760,000 years, the Sherwin Till is thought to be around 800,000 years old (Sharp and Glazner, 1997).

If you want a photograph or a good overview of the geologic relationships between the tuff and the till at this stop, the best vantage point is the parking area on the other side of the highway. However, crossing the highway with its sporadically heavy traffic can be extremely hazardous to your health. One option is to drive to Lower Rock Creek Road (0.3 mi to the west), make a left turn, and turn around and return to the parking area on the south side of the highway.

The Big Pumice Cut has a number of notable geologic features-something for everyone (unless you are interested only in the pre-Quaternary underburden). The contact between the boulder-laden till and the overlying pumice-ash tuff is very well defined. Boulders in the till are highly weathered and have largely decomposed to grus. The basal 15 ft (5 m) of the tuff consists of air-fall ash and lapilli, whereas the overlying material is an ash-flow deposit that presumably was emplaced as a nuée ardente (Sheridan, 1971). Within the tuff, layering in the air-fall ash unit is parallel to the surface of the Sherwin Till, whereas layering in the ash-flow unit is roughly horizontal. You should be able to see the angular unconformity between the two tuff units, although each year the condition of the roadcut deteriorates. To see the effects of roadcut degradation, compare the present condition of the roadcut with the 1976 photograph.

The tuff here is cut by a conspicuous series of clastic dikes that are nearly perpendicular to layering and extend into the till (Figure 7). The dikes, which were derived from boulder gravel deposited on the tuff at the top of the cut, consist of unconsolidated material that becomes finer grained downward. Wahrhaftig (1965b) suggested that the gravel originated as outwash of the Tahoe or an older glaciation and that it slumped into fissures that formed in the tuff after deposition of the gravel. The fissures may be related to the broad warping of the tuff, which has given the southwestern part of the Volcanic Tableland a gentle southwestward tilt.

42.3 0.3 Intersection with Lower Rock Creek Road on the left. Until 1957, Lower Rock Creek Road was U.S. Highway 395.

43.3 1.0 Toms Place turnoff is on the left; Owens River Gorge Road is on the right. Toms Place is named for Tom Yerby, who built a general store and cabins here in 1917. This is also the turnoff for numerous campgrounds to the south along Rock Creek, as well as the road to the trailhead for the Mono Pass trail in the John Muir Wilderness area.

44.2 0.9 Wheeler Crest Granodiorite is on the left (south), and Bishop Tuff is on the right (north).

45.6 1.4 Passengers (but not drivers!) can look back to see reasonably well developed vertical jointing in Bishop Tuff on the north side of the highway. Eastbound traffic gets a better view of the jointing.

46.8 1.2 Hilton Creek and Lake Crowley turnoff on right. The creek is named for Richard Hilton, who had a dairy ranch along the creek in the 1870's and supplied some of the mining camps with butter.

47.6 0.8 PARK in the paved parking area for the Lake Crowley vista point.

STOP 4.
Lake Crowley and an overview of the Long Valley caldera.

This is a good vantage point for an overview of the lake and the caldera in which it is situated. Although a large lake once filled Long Valley during Pleistocene time, the present Lake Crowley dates only from 1941, when the LADWP built Long Valley Dam at the head of Owens River Gorge. The reservoir was named for Father John J. Crowley, who helped organize the Inyo-Mono Association to promote tourism in the region after its economy was decimated by Los Angeles's acquisition of most of the area's water rights.

During part of the Pleistocene, a lake which Mayo (1934) called Long Valley Lake filled much of the Long Valley caldera. Shoreline terrace deposits can be found on the flanks of the resurgent dome in the central part of the caldera at elevations as high as 7600 ft (2320 m). Bailey and others (1976) concluded that the lake at its highest level reached an elevation of 7800 ft (2380 m) and that this occurred sometime before 0.63 m.y. ago. On the basis of K-Ar dating of Long Valley volcanics associated with terrace deposits, they inferred that the level of Long Valley Lake was near 7500 ft (2290 m) between 0.51 and 0.47 m.y. ago and 7300 ft (2230 m) after 0.47 m.y. ago, dropping below 7000 ft (2135 m) by 0.1 m.y. ago. The Pleistocene lake disappeared sometime in the last 100,000 years when the outlet at Owens River Gorge was cut deeply enough to drain the lake.

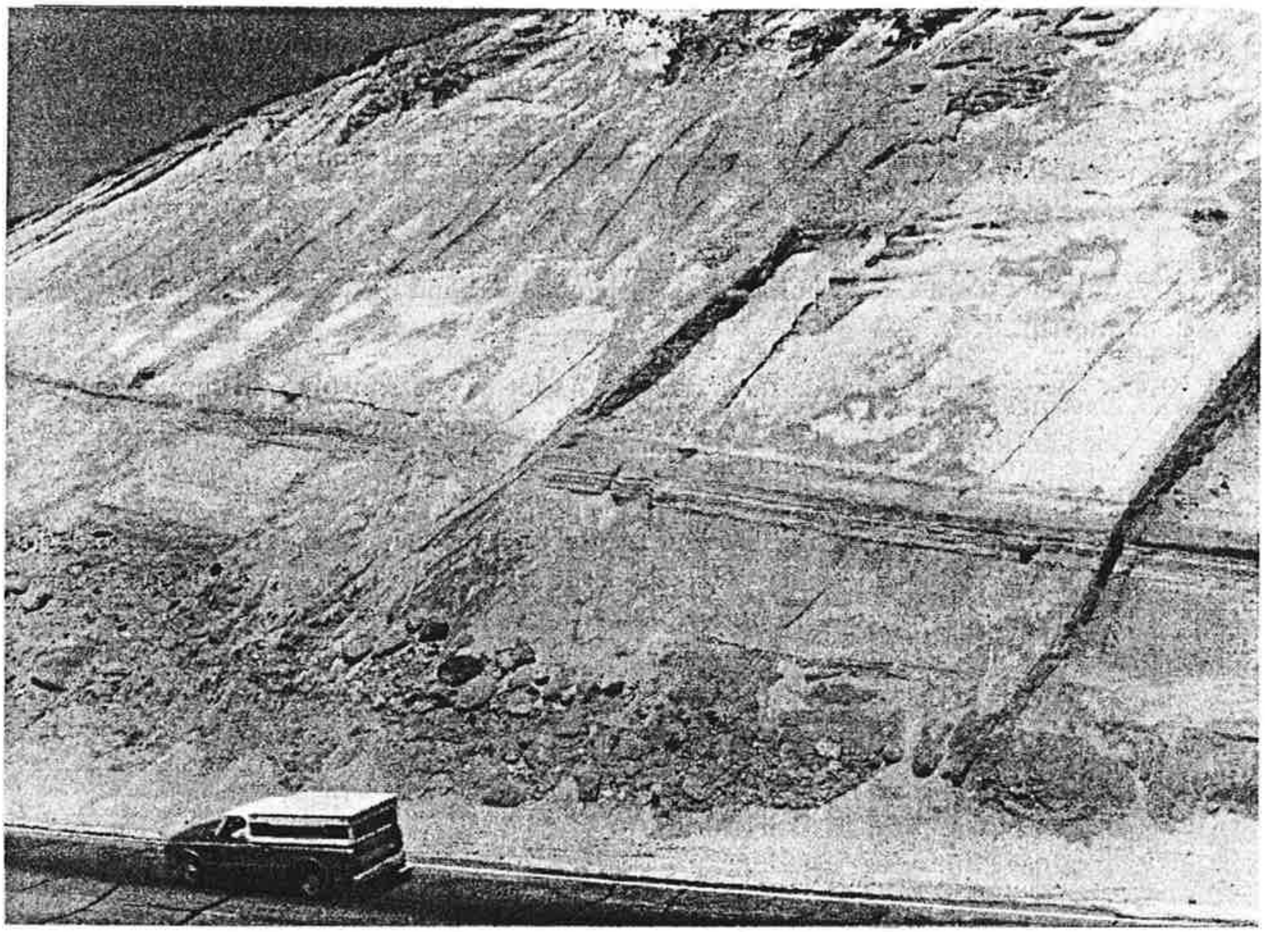

Figure 7. The Big Pumice Cut along U.S. Highway 395 (Stop 3). Bouldery Sherwin till is overlain by Bishop Tuff. The basal 15 ft (5 m) of the tuff is air-fall ash, which is overlain by ash-flow deposits. Between the two tuff units is an angular unconformity. Clastic dikes of sand and gravel cut the tuff and extend downward into the till. (Photograph taken in July 1976; the highway was widened to four lanes in 1977)

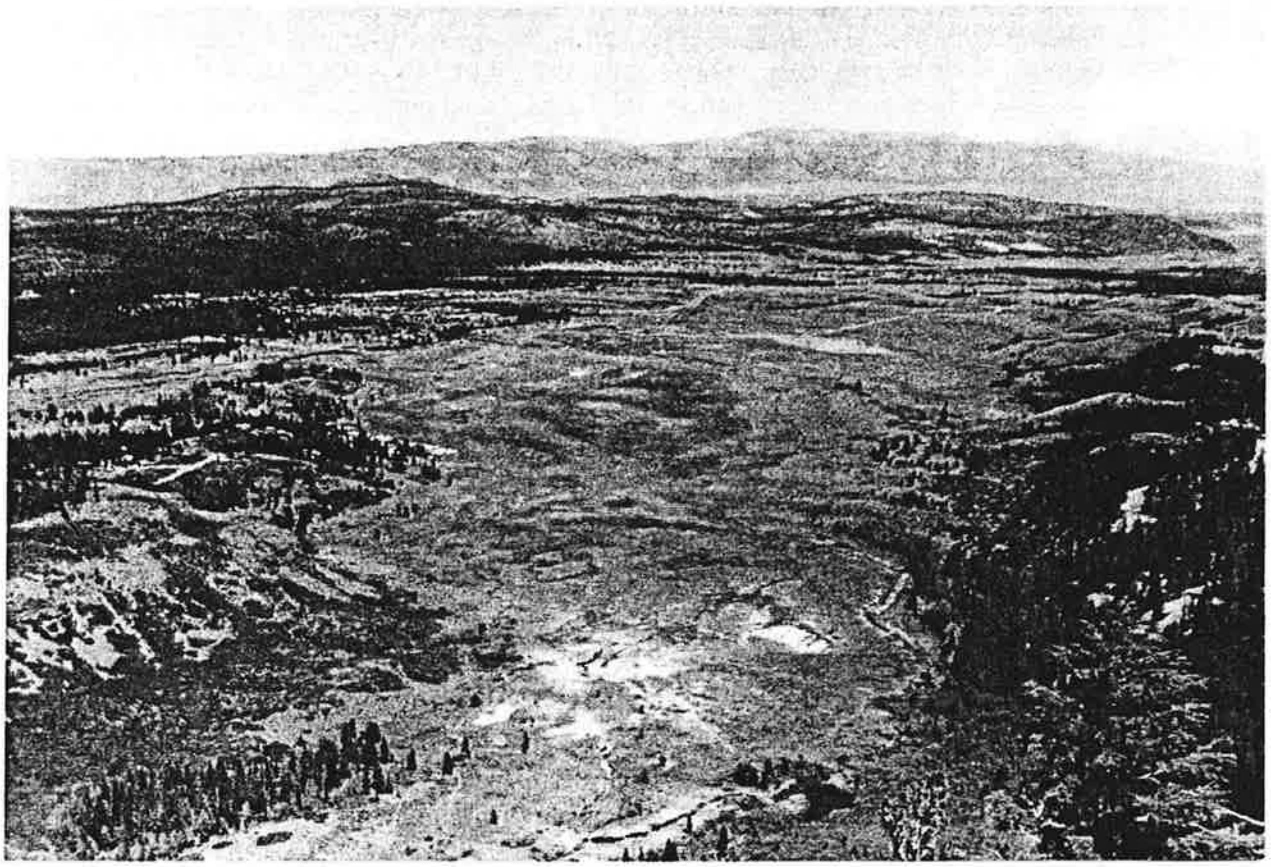

Figure 8. View east-northeast across Long Valley caldera from Gold Mountain, above Mammoth Rock. View is toward Glass Mountain Ridge, which forms the far rim of the caldera, on the skyline 18 mi (29 km) away. In the middle distance are the tree-covered low hills and ridges of older rhyolite that form the resurgent dome of the caldera. The brush-covered ridge at the lower left is a rhyodacite spur of Mammoth Mountain. Arcularius Meadow, the area in the center foreground, is now a golf course and condominium development. A series of low, subdued glacial moraines covers the caldera floor on the near side of the resurgent dome. These glacial deposits, mostly of Wisconsin age, overlap Pleistocene basalt and andesite flows that erupted in the "south moat" of the caldera. (Photograph taken in August 1978)

The mountain mass to the north, across Lake Crowley, is Glass Mountain Ridge, which forms the northeastern boundary of the Long Valley caldera (Figure 8). The forested area east and southeast of this stop is the Bishop Tuff surface that extends southward from the caldera rim to form the Volcanic Tableland north of Bishop. If we let Highway 395 to the northwest be 12:00, the McGee Creek lateral moraine, which consists of Tahoe and Tioga glacial deposits, is between 10:30 and 12:00. Looking toward 9:00, one can see the Hilton Creek "dump moraine" (terminal moraine complex), which appears to override an older, bouldery debris flow.

Between about 9:30 and 12:00, the trace of the Hilton Creek fault is near the base of the range. The fault is particularly conspicuous in the mid- to late afternoon, when it is highlighted by shadows resulting from the declining sun angle. Where it crosses the Tioga lateral moraines along McGee Creek, the fault has formed a well-preserved scarp 50 ft (15 m) high, which you can see (and drive across) if you drive about 2 mi (3 km) up the McGee Creek Road. This scarp was formed in the last 20,000 years, since the Tioga glaciation. McGee Creek and McGee Mountain, the big peak that overlooks Highway 395 west of the creek, were named for the three McGee brothers, early pioneers and cattlemen who settled along McGee Creek in the 1860's.

49.7 2.1 McGee Creek Road on left. If you want to view the Hilton Creek fault scarp where it crosses the McGee Creek moraines, the best time to do so is in the late afternoon when the low sun angle produces a shadow along the scarp. The road also affords a panoramic view of Lake Crowley and Long Valley.

51.1 1.4 Crowley Lake Drive on left. A former route of Highway 395 can be seen to the left, paralleling the present highway.

52.1 1.0 PARK on right shoulder of highway, along low roadcut.

STOP 5.
Overview of Long Valley caldera and nearby mountain ranges.

This is a good location for viewing a variety of caldera-related features, as well as some of the pre-caldera rocks of the surrounding regions. The best place from which to survey the scenery is on top of the roadcut alongside the highway. If the area is buried under snow, as is likely in mid-April, this is probably as good a view as you are likely to get of many of these features. For directional purposes, let Highway 395 to the northwest be 12:00. Lake Crowley is then situated between about 4:00 and 6:00.

Between 2:00 and 4:00 are the pre-caldera rhyolite flows of Glass Mountain Ridge along the northeast boundary of the caldera. Between about 5:00 and 7:00 is the Bishop Tuff, which is outside the southeastern boundary of the caldera. The low, steep-sided hills between 12:30 and 2:00 are flows of hornblende-biotite rhyolite that have a K-Ar age of about 0.3 m.y. Bailey and others (1976) identified five volcanic centers that are associated with this flow mass, which probably represents a late magma extrusion of moat rhyolite along ring fractures that bound the resurgent dome of the caldera.

Mammoth Mountain, the isolated massive edifice at 11:00, is a composite volcano, now quiescent, that rises to an elevation of 11,053 ft (3370 m). The tephra-mantled mountain comprises multiple flows of hornblende-biotite rhyodacite and hypersthene-augite rhyodacite and vitrophyric rhyolite. Bailey and others (1976) described Mammoth Mountain as a "cumulo-volcano" that consists of many individual domes and coulees. They identified at least 10 eruptive vents on the mountain from which magma was extruded. A number of K-Ar dates have been published for the Mammoth Mountain volcanic rocks (Dalrymple, 1964; Huber and Rinehart, 1967; Curry, 1971; Bailey and others, 1976; Mankinen and others, 1986). They suggest that the emplacement of Mammoth Mountain lava flows probably spanned an interval of about 170,000 years, beginning around 220,000 years ago and ending 50,000 years ago. The volcano has been active since then, as is indicated by widespread Holocene tephra falls that probably came from Mammoth Mountain (Robert Koeppen and Spencer Wood, written communications, 1976). Volcanic activity on the mountain, although dormant, continues to manifest itself today in the form of geothermal activity and release of volcanic gases. Fumaroles have been reported on the summit and south flank (Huber and Rinehart, 1967) and on the northwest flank (Curry, 1971), and the release of carbon dioxide near Horseshoe Lake has led to a major tree kill and the closing of a campground.

In the Sierra Nevada west of the caldera, Mount Ritter (left) and Banner Peak (right) are the prominent peaks on the skyline at 11:30. If you look in the opposite direction, you can see the White Mountains on the skyline. Boundary Peak (the highest point in Nevada at elevation 13,140 ft or 4006 m) and Montgomery Peak (13,441 ft or 4098 m) are at 4:00, and White Mountain Peak (the second highest mountain in California, at 14,246 ft or 4343 m) is at 5:00.

Before you leave, look at the back (northeast) side of the low hill on which you are standing. The back side of the hill is a somewhat degraded fault scarp that lies along the Hilton Creek fault. The hill consists of older alluvial deposits of Pleistocene age, which indicates that the fault has been active in Quaternary time. This is in keeping with the observed recency of faulting where the fault crosses McGee Creek (see Stop 4).

52.8	0.7	Road to Whitmore Hot Springs and Benton Crossing on right, just past the church.
53.0	0.2	The steep-sided hills on the right, just north of Highway 395, are the hornblende-biotite rhyolite flows dated at 0.3 m.y.
53.8	0.8	Convict Lake Road on left.
55.3	1.5	Road on right goes to the Mammoth Lakes airport, Hot Creek, and the State fish

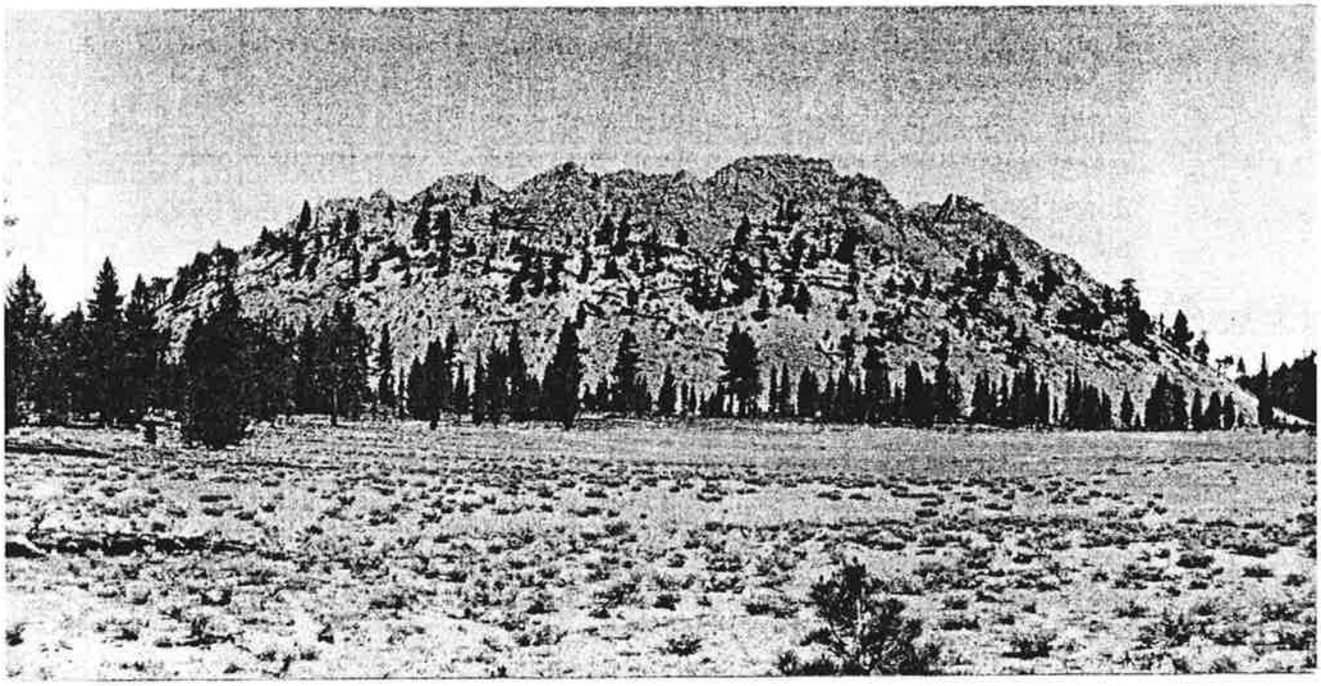

Figure 11. Wilson Butte, a Holocene rhyolite dome between the Inyo and Mono Craters chains. Wilson Butte is 0.4 mi (0.65 km) across and has 500 ft (150 m) of relief. In the left foreground and on the dome itself are uprooted trees with tops pointing eastward. These trees were probably uprooted in the 1920's, when major rainstorms were followed by violent winds. (Photograph taken in July 1976)

		northwestward from the Long Valley caldera into the Mono Basin about 0.76 m.y. ago.
81.8	0.5	TURN RIGHT at Pumice Mine Road (Forest Service route 1 S 40), which goes to the east side of the southern Mono Craters chain.
82.2	0.4	TURN LEFT onto main unpaved road, which will take you to Devil's Punch Bowl; the road straight ahead is a dead-end road.
82.75	0.55	BEAR RIGHT at four-way intersection, keeping on main unpaved road. Dirt road that goes straight ahead is a side road along the west side of the southern Mono Craters chain.
82.9	0.15	Volcanic dome straight ahead is Wilson Butte.
83.15	0.25	Bishop Tuff is exposed in the steep walls of a volcanic explosion crater situated in the tephra-blanketed valley south of the Mono Craters chain. It is one of several craters that lie along a line between the south end of the Mono Craters and the north end of the Inyo Craters chain. They are presumably associated with the north-trending fracture system that controls the alignment of the Inyo Craters. The wall of this crater has been breached by gullies in two places. The large V-shaped gully on the northeast side was formed in only a few hours, when a pipeline broke during construction of the Los Angeles aqueduct (Smith, 1976).
83.55	0.4	TURN LEFT onto minor side road that angles off of main road.
83.6	0.05	PARK at oblique crossroad intersection.

STOP 8.
Devil's Punch Bowl.

This stop at the southern end of the Mono Craters chain provides an opportunity to see several different stages in the eruptive sequence of rhyolite volcanoes in this region. (See Figure 4 and accompanying discussion of rhyolitic volcanism.) Right next to the intersection is the Devil's Punch Bowl itself, an explosive crater containing a small protrusion of pumiceous rhyolite. The dome to the southwest, which was dated by the obsidian hydration-rind method at between 9500 and 7900 years (Wood, 1977a), completely filled its crater and engulfed the tephra ring. The dome northeast of the Punch Bowl, however, did not entirely fill its crater, so its tephra ring is still preserved, separated from the dome by a small "moat." The road that bears northeast, heading upslope from this intersection, goes onto the tephra ring and eventually dies out. This dome also has a summit crater, indicating that it had a second episode of explosive activity. Farther to the northeast, the next dome (not visible from here) has been completely eviscerated by a subsequent explosive eruption. The remaining shell of the dome affords a good view of the internal flow structure of a rhyolite dome. The eviscerated dome has an estimated age of 6500 to 5200 years, based on obsidian hydration-rind dating (Wood, 1977a).

Note the abundant granitic pebbles and cobbles in the tephra ring of the Punch Bowl and on the flanks of the adjacent domes. These clasts probably were derived from overlying glacial outwash or stream gravels at the site that were incorporated into the deposits produced by the explosive eruptions. Trees in the vicinity of the parking area are almost all Jeffrey pine, but lodgepole pines are more common on other parts of the crater walls.

83.65 0.05 TAKE RIGHT FORK at intersection and descend to main road. TURN SHARPLY RIGHT at main road and retrace route back to Highway 395.

84.55 0.9 BEAR LEFT at four-way intersection and stay on main road.

85.1 0.55 TURN RIGHT at T-intersection with paved road. The paved road used to be part of Highway 395 until the highway was straightened out and widened to four lanes in the late 1970's or early 1980's.

85.5 0.4 TURN RIGHT onto U.S. Highway 395.

85.9 0.4 June Lake Loop (California Highway 158) on left (west), at South June Lake Junction. The town of June Lake, about 2.5mi (4 km) southwest of Highway 395, is a popular vacation area that, like Mammoth Lakes, offers fishing in the summer and skiing in the winter. Most of the bedrock in the June Lake vicinity is Granite of June Lake, which is of Late Cretaceous age (Bateman, 1992).

Rocks in the vicinity of the road junction are the Basalt of June Lake Junction, a late Pleistocene lava flow that is sandwiched between Tahoe till below and Tioga deposits above (Putnam, 1949). Bursik and Gillespie (1993) correlated the basalt, in which they recognized two lava flows, with two radiocarbon-dated basaltic ash layers northwest of Mono Lake that have adjusted ages of 25,200 years and 30,700 years.

86.1 0.2 Highway passes through Tioga end moraines for the next half mile (0.8 km). The massive, lightly forested lateral moraine buttressed against Reversed Peak (on the left at about 10:00) is a Tahoe glacial deposit.

87.0 0.9 Outcrops to left (west) of highway are Basalt of June Lake Junction; outcrops to right (east) are Bishop Tuff.

87.6 0.6 Outcrops on right (east) are Bishop Tuff. The tuff here is highly porphyritic (quartz and feldspar phenocrysts), and part of the unit is rhyolite tuff breccia. The tuff is mantled by rounded, presumably glacial, metamorphic and granitic cobbles and boulders.

89.0 1.4 Exposure of Bishop Tuff in gully wall on right. This dry wash probably drained the June Lake basin before Tioga end moraines sealed the basin's northern outlet and diverted drainage into Reversed Creek. The gully wall is a good place to examine Bishop Tuff of the Aeolian Buttes area in hand specimen. The tuff contains abundant quartz and feldspar phenocrysts and angular, pebble-sized pumice fragments. Widespread flattened vesicles contribute to the unit's distinctive weathering pattern here, so that the outcrops along the gully closely resemble the Bishop Tuff outcrops along Rock Creek Gorge near Toms Place.

Phenocrysts are noticeably more abundant in the tuff here than in the tuff of the Volcanic Tableland, which suggests that the Bishop Tuff near the Aeolian Buttes was erupted later than that of the Volcanic Tableland. Hildreth (1981) concluded that the difference in phenocryst abundance is not due to crystal settling but rather to upward enrichment of volatiles in the magma chamber, which depresses the temperature below which crystals nucleate; this leads to fewer phenocrysts in the upper part of the chamber, despite the lower temperature there.

89.7 0.7 On the right (east) are the Aeolian Buttes, which consist mostly of Bishop Tuff on top of Quartz Monzodiorite of Aeolian Buttes (Bateman, 1992). The latter unit was K-Ar dated at 85 to 88 m.y. (Evernden and Kistler, 1970), which indicates a Late Cretaceous age for the pluton. Only a few small outcrops of the granitic rock are exposed; elsewhere the unit is concealed by Bishop Tuff. The Aeolian Buttes were named by Russell (1889) for the outstanding examples of wind erosion developed in the tuff here.

90.0 0.3 Leaving Inyo National Forest.

90.7 0.7 Off to the right (east) is a panoramic view of the Mono Craters chain (Figure 12), which we will soon view more closely. The low Tioga end moraines on the left impound Grant Lake, a reservoir in the LADWP aqueduct system.

91.5 0.8 TURN RIGHT (east) at California Highway 120, which goes to Benton, where it connects with U.S. Highway 6 to Bishop or Montgomery Pass (and Cape Cod).

91.7 0.2 This stretch of Highway 120 is a good place from which to get a broad overview of the arcuate, convex-eastward Mono Craters chain. Russell (1889) gave the Mono Craters their name in his classic study of the Quaternary geology of the Mono Basin. The center of the chain is dominated by three rhyolite domes (Figure 12), of which the central dome is the highest (elevation 9172 ft or 2796 m). To the south (right), the huge South Coulee (Figure 13) flowed westward toward the Aeolian Buttes. Just north of the three domes in the center of the chain, the North Coulee flowed eastward, away from us. Toward the north end of the chain, almost straight ahead along the highway, is the Northwest Coulee, which flowed both eastward

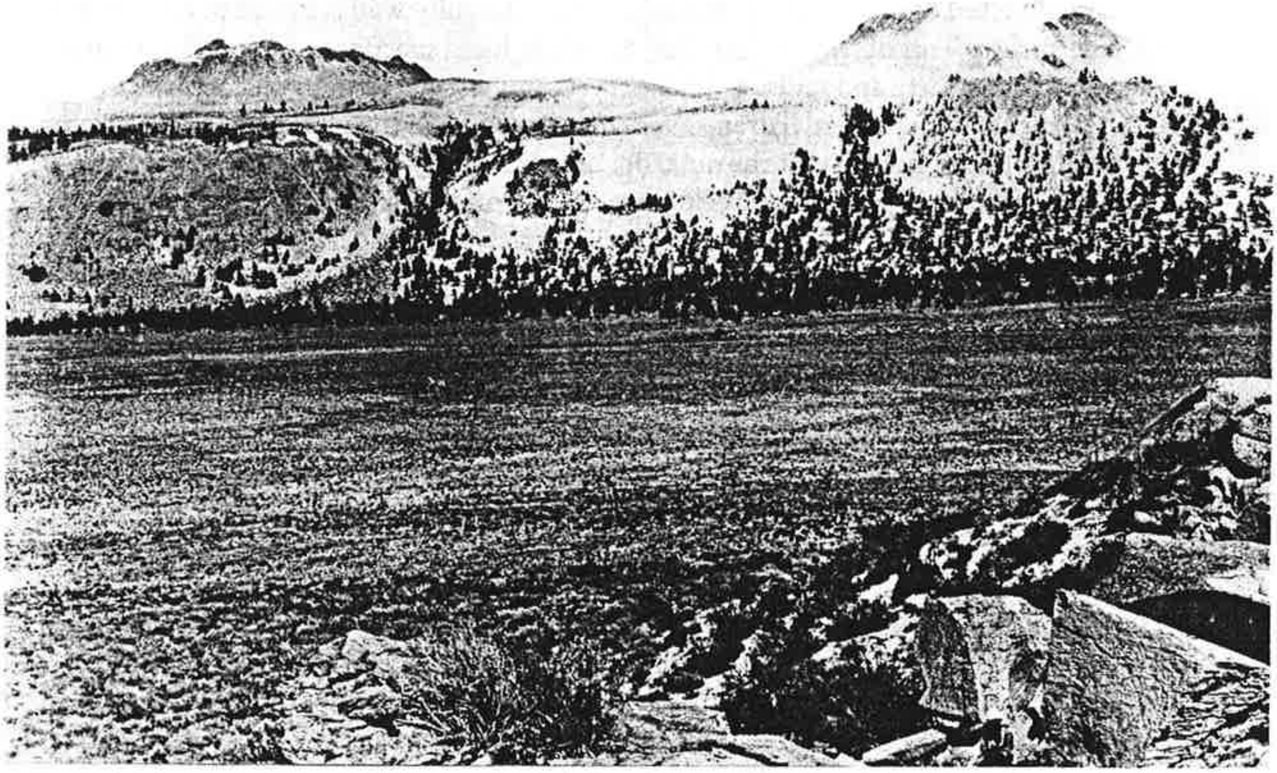

Figure 12. View east toward the central part of Mono Craters from the Aeolian Buttes, looking at the largest rhyolite domes in the chain. The high dome on the left (Crater Mountain, elevation 9172 feet or 2796 m) was obsidian-hydration dated at between 3900 and 2900 years, and the high dome on the right (unnamed, 9121 feet or 2780 m) was dated at between 8200 and 6300 years (Wood, 1977a). For scale, a man wearing a white pith helmet is sitting in front of large blocks of Bishop Tuff at the right lower edge of the photo. (Photograph taken in 1882 or 1883 by Israel C. Russell, U.S. Geological Survey)

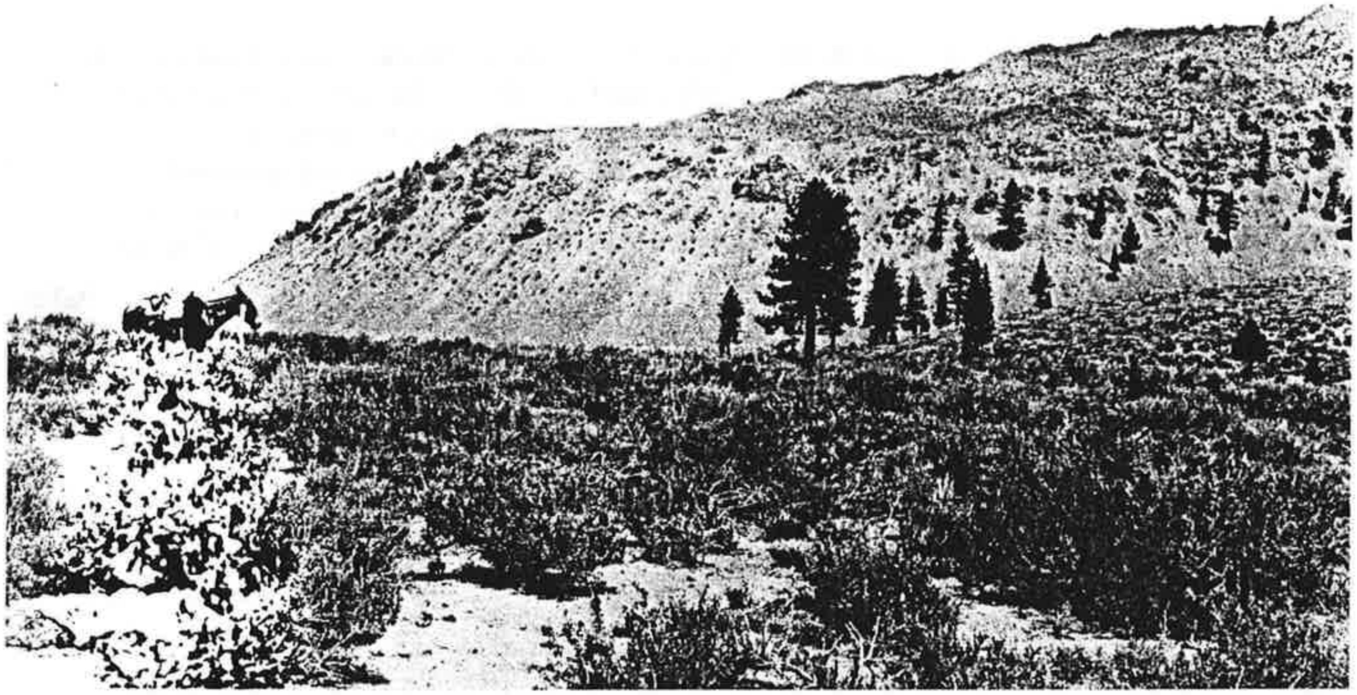

Figure 13. View north toward South Coulee, a rhyolite lava that flowed westward from a vent in the Mono Craters. Note the great thickness and steep sides that are characteristic of viscous flows of silicic lava. The coulee was dated by the obsidian hydration-rind method as being around 2500 years old (Wood, 1977b). (Photograph taken in 1882 or 1883 by Israel C. Russell, U.S. Geological Survey; his horse is on the left)

and westward from its source vent or vents. Farther north, on the other side of California Highway 120, is the isolated tephra-ringed dome of Panum Crater (Stop 9). Geological and geophysical evidence indicates that the Mono Craters magma chamber is smaller, deeper, and younger than that of Long Valley (Hill and others, 1985).

Wood (1977a) used the obsidian hydration-rind method to date many rhyolite domes and flows of the Mono Craters. He found that the earliest rhyolite dome is between 32,000 and 40,000 years old, and that another major extrusive event occurred about 24,000 years ago. He noted that eruptive activity increased noticeably about 10,000 years ago and that the rate of extrusion has "increased dramatically" in the last 2000 to 3000 years. The most recent dated eruption in the Mono Craters chain is associated with Panum Crater (see Stop 9). The most recent noneruptive volcanic activity in the Mono Craters appears to be at Paoha Island, where shallow intrusion of magma raised the island above lake level sometime between A.D. 1660 and 1850 (Stine, 1984).

93.5 1.8 Paved road on left goes to Mono County dump at Pumice Valley.

94.6 1.1 TURN LEFT (north) onto dirt road to Panum Crater; follow main road. Another dirt road, on the right side of Highway 120, goes along the west side of the Mono Craters.

95.2 0.6 Complicated intersection of 3 roads. GO STRAIGHT, heading toward Panum Crater.

95.25 0.05 Road forks. TAKE RIGHT FORK.

95.4 0.15 TURN LEFT at T-intersection.

95.5 0.1 TURN RIGHT AND PARK in parking area. Walk up the path onto the tephra ring and, if you are so inclined, cross the crater moat to the rhyolite plug (Panum Dome). Note: Collecting of rocks, or of anything else, is prohibited here by the Forest Service.

STOP 9.
Panum Crater and Dome.

Panum Crater (Figure 14) was named by Russell (1889) for the Indian word "panum," meaning "lake." The crater is a textbook example of an explosion pit in which the subsequent rhyolite plug extrusion was not voluminous enough to engulf the surrounding tephra ring. The crater represents a further advance in the sequence of eruptive events (Figure 4) beyond that of the Devil's Punch Bowl (Stop 8), where the plug formed only a small protrusion in the floor of the crater.
The tephra ring of Panum Crater, which has a maximum rim-to-rim diameter of

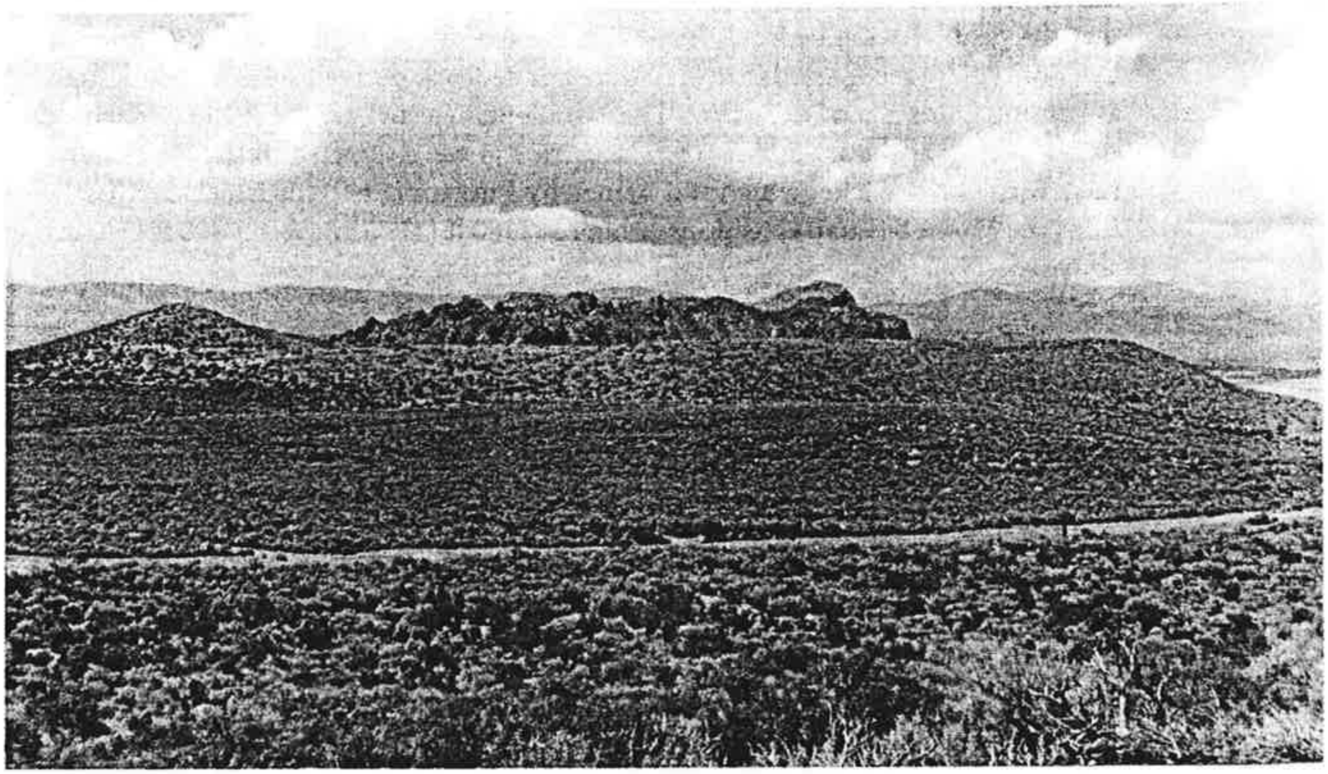

Figure 14. View north toward Panum Crater, at north end of Mono Craters chain. The crater contains a jagged composite dome of rhyolite, which is surrounded by a tephra ring. At the far right is Mono Lake in the distance. (Photograph taken in June 1976)

4000 ft (1220 m), consists of pumice ash and lapilli, obsidian fragments, and "accidental ejecta." Most of the latter are well-rounded granitic pebbles; such pebbles can also be found on the tops of most Mono Craters domes. Whitney (1865) thought that the pebbles were bedrock fragments ejected by the explosive eruptions, but LeConte (1879) recognized that they were not bedrock-derived and identified them as coming from glacial deposits. The "accidental ejecta" are most likely derived either from glacial outwash or from lacustrine gravel deposited in the Pleistocene Lake Russell. The lake, which was named by Putnam (1949) for Israel C. Russell, filled the Mono Basin to elevations as high as 7180 ft (2190 m), about 800 ft (240 m) above the 1990 lake level.

Rhyolite of Panum Dome consists of light gray pumiceous rhyolite and black obsidian and includes all gradations between these two rock types, including rhyolite breccia with angular, pebble- and cobble-sized clasts. "Breadcrust" texture, tension gashes formed in the outer "skin" during cooling of the rhyolite lava, is common. Most of the rhyolite is flow-banded, and the flow banding of the dome provides a good picture of the internal flow structure of a typical rhyolite plug. Note that most flow banding dips steeply; Williams (1932) speculated that the magma built a levee as it flowed from the vent, thus constraining later extrusions to keep rising vertically and preventing them from spreading laterally. As the magma rose, it cooled and hardened; by the time that it was able to spread laterally, it had solidified enough that it fractured into blocky rubble instead of flowing. Many of the Mono Craters domes are capped by jumbled, blocky debris that probably formed in this manner.

Russell (1889) observed that Panum Crater, although situated well below the high stands of the Pleistocene lake, was never subjected to wave erosion. Putnam (1950) correlated high shorelines of Lake Russell with the Tioga glaciation (about 20,000 years ago), indicating that Panum Crater (and most of the Mono Craters chain) postdates the Tioga glaciation. Wood and Brooks (1979) used radiocarbon dating to determine an age of 640 ± 40 years for Panum Crater. Sieh and Bursik (1986) recognized various rhyolite tephras, domes, and coulees that they identified with very recent eruptions from at least ten aligned source vents at the northern end of the Mono Craters chain, including Panum Crater. During this event, eruptive activity was contemporaneous over a distance of about 4 mi (6 km), and Sieh and Bursik concluded that the eruptions resulted from shallow intrusion of a rhyolite dike or dikes. They used radiocarbon dating to constrain the age of the eruptions to between A.D. 1325 and 1365, and they suggested that the explosive eruptions lasted no more than a few months and that the entire eruptive episode spanned not more than several years. Using stratigraphy of tephra layers, Sieh and Bursik concluded that the northern Mono Craters eruptions antedate the Inyo Craters eruptions (see Stop 7) dated by Miller (1985), but they suggested that the Mono Craters eruptions occurred only a few years earlier.

Panum Crater has received the attention of a number of geologists, starting with Russell (1889) and including Wood (1977a,b) and Sieh and Bursik (1986). From this accumulated research has come a complicated history of the crater, mostly unraveled by Sieh and Bursik. The first event was the eruption of an unsorted, heterogeneous "throat-clearing breccia," which formed a crater in the lakebeds and stream deposits south of Mono Lake. Then a pyroclastic flow of ash and lapilli erupted, followed by surge beds (nuées ardentes). This was followed by a block-and-ash flow ("block avalanche" of Wood, 1977b) to the northwest, toward Mono Lake; the deposit has angular blocks up to about 10 ft (3 m) across. After the block-and-ash flow was emplaced, a small explosive event produced the crater and tephra ring that we see today. Panum Dome was then extruded into the crater as a composite dome formed of four distinct masses: (1) North Dome is the largest and youngest mass, occupying the northern two thirds of the composite dome; (2) South Dome is somewhat older and bisected by a north-south graben; (3) Southwest and East Domes are small fragments of older domes.

TURN AROUND and return to main road to Highway 120.

95.6 0.1 TURN RIGHT at T-intersection.

95.8 0.2 GO STRAIGHT at complicated 3-road intersection. The steep-sided, lightly forested rhyolite mass ahead at about 11:00 is the Northwest Coulee of the Mono Craters, which has an age between 2300 and 1200 years B.P., based on obsidian hydration-rind dating (Wood, 1977a).

96.4 0.6 TURN RIGHT (west) at paved California Highway 120.

99.5 3.1 END OF FIELD TRIP at junction of California Highway 120 and U.S. Highway 395.

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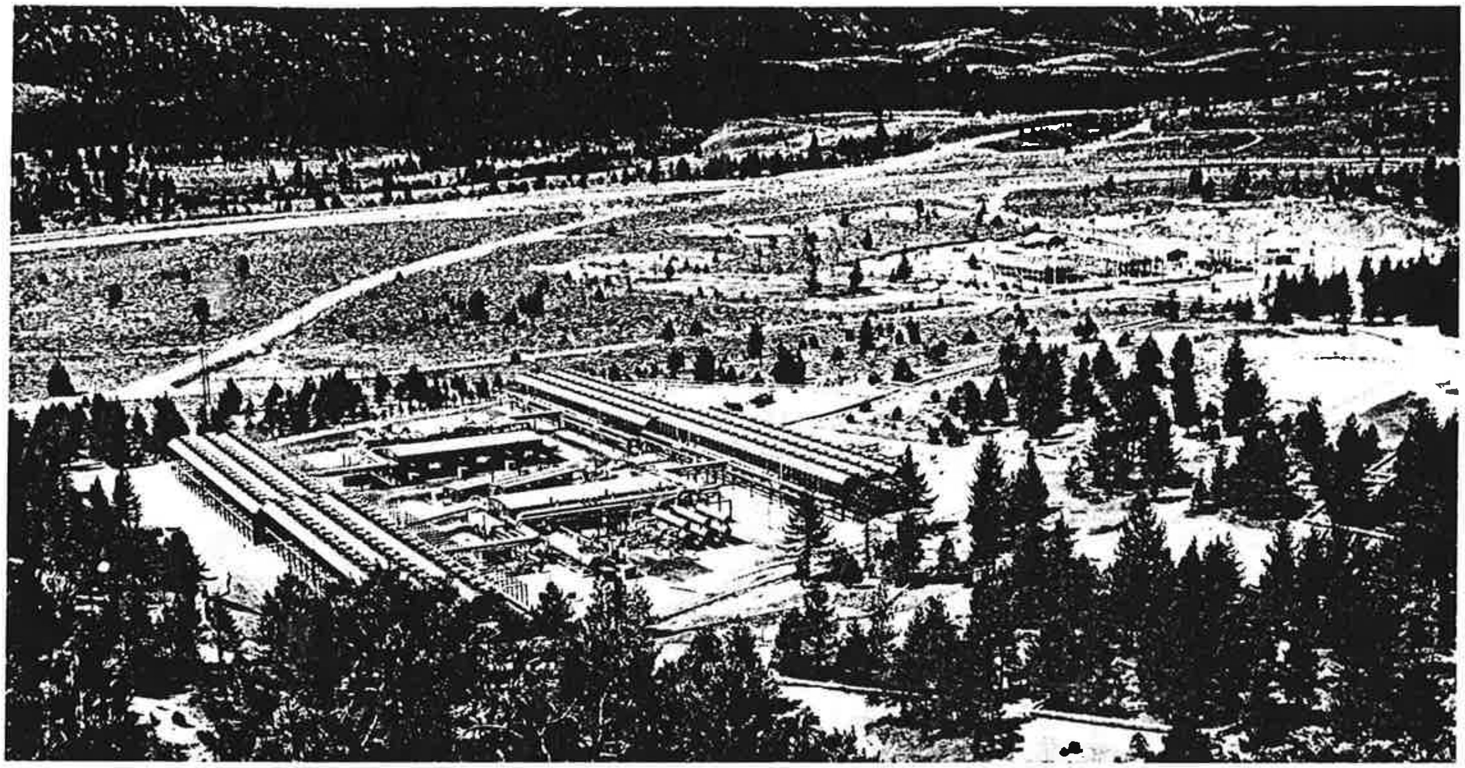
MAMMOTH-PACIFIC GEOTHERMAL DEVELOPMENT

Geothermal Hot Water to Electric Power



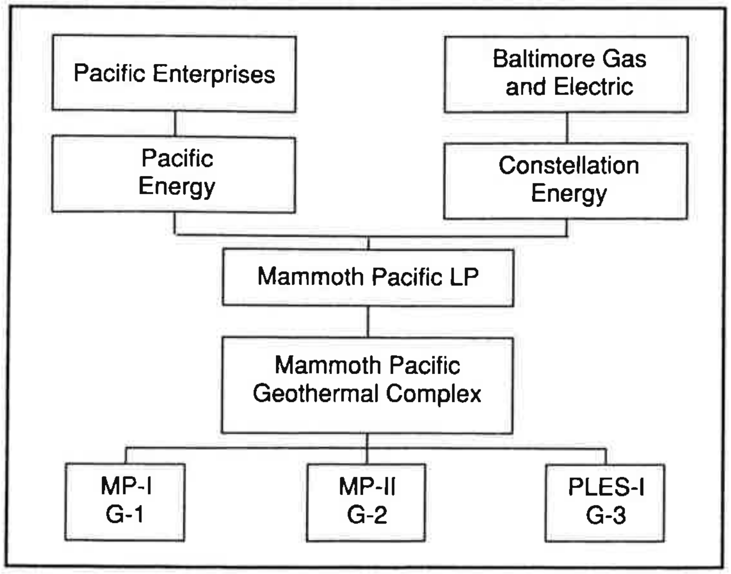
Mammoth-Pacific Geothermal Power Plants G-2 and G-3 shown in foreground, each rated at 15 megawatts; and G-1 shown in background (top right), rated at 10 megawatts.

PROJECT DESCRIPTION

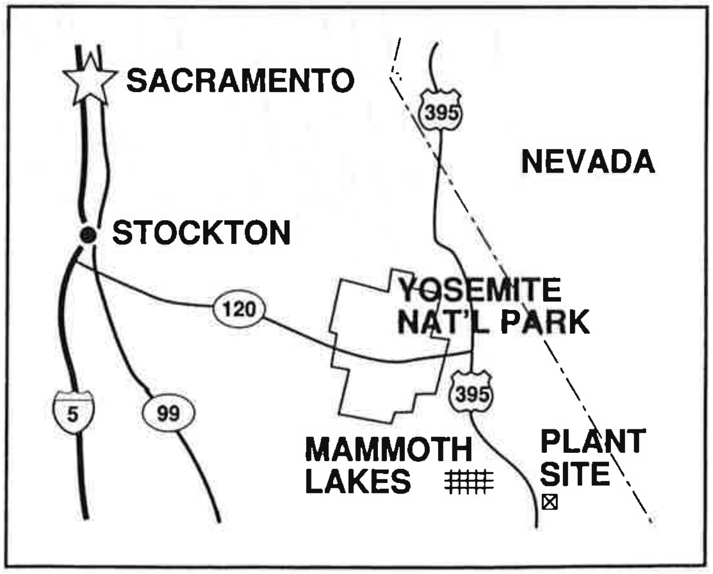
The Mammoth Pacific Geothermal Complex at Mammoth Lakes, California, utilizes geothermal hot water to produce electric energy. The energy is produced by three separate power plants using hot water from the same geothermal resource.

The three plants are: G-1 (MP-I) rated at 10 MW, G-2 (MP-II) rated at 15 MW and G-3 (PLES-I) rated at 15 MW. The combined output of the three plants is enough to serve the electrical needs of about 40,000 homes. In addition, the project provides economic benefit to the community and the county and captures a clean and reusable energy resource that can displace up to 500,000 barrels of imported oil each year.

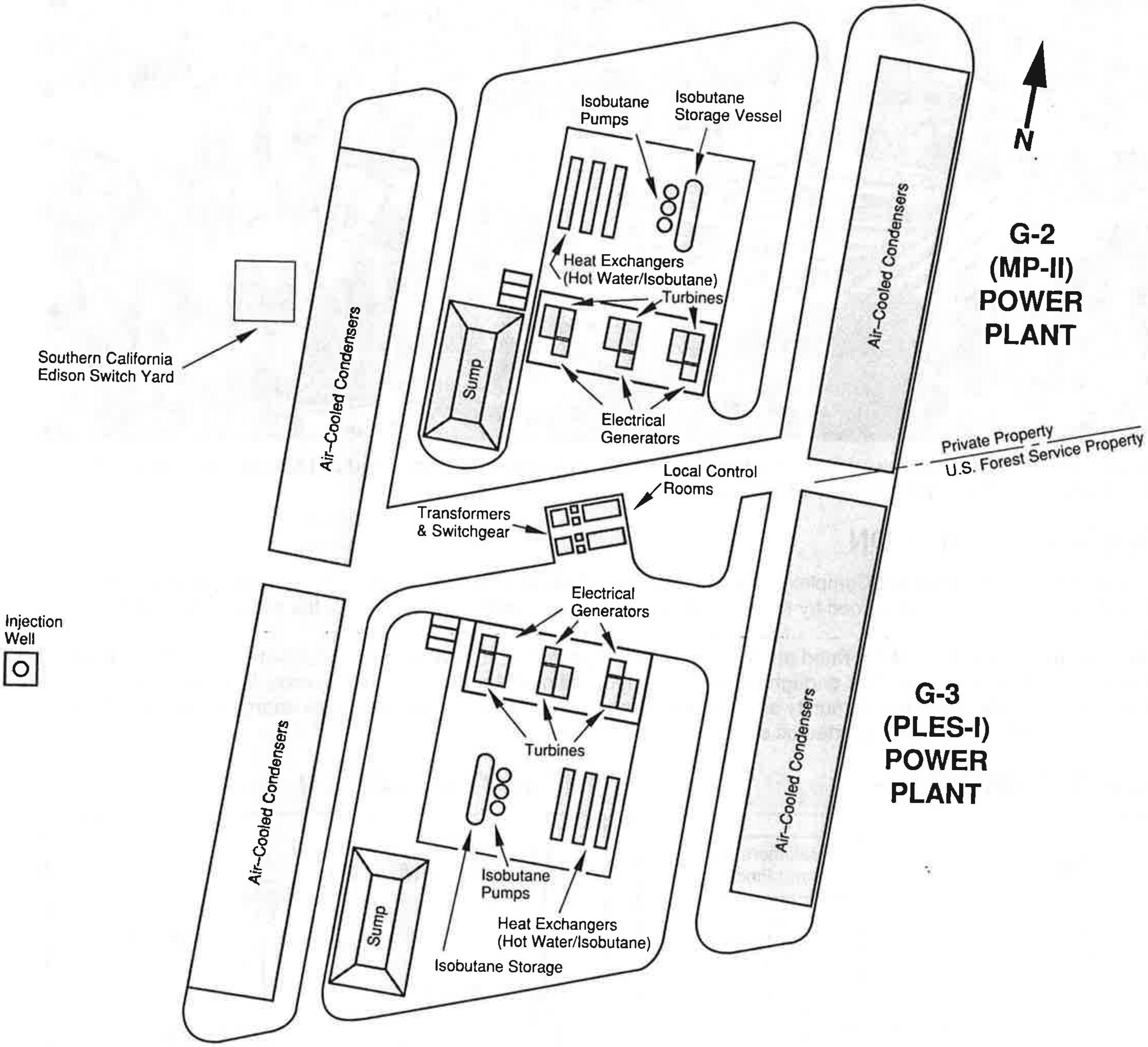
PROJECT OWNERSHIP



PROJECT LOCATION



PLOT PLAN
GEOTHERMAL PLANTS G-2 & G-3



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KEY PROJECT ELEMENTS

The G-2 (MP-II) and G-3 (PLES-I) geothermal power plants, built in 1990, use the same binary design as the orginal G-1 (MP-I) power plant built in 1984. The major components as described below are substantially the same, except in quantity or size:

Geothermal Production Wells

Hot water is recovered from the earth at 500 feet using 12 geothermal production wells. The wells resemble 12 ft. tall green "mushrooms" located on the western portion of the Mammoth development. Each well contains a 450 hp motor which is coupled to a shaft longer than a football field. The shafts extend down the wells to multi-stage centrifugal pumps set in the hot water reservoir located about 500 feet below the surface. Each well can pump up to 2,000 gpm at pressures up to 250 psi. A total of 12 pumps are currently available for use at the plants, although typically only 9 are in service.

Heat Exchangers (Geothermal Hot Water/Isobutane)

There are six heat exchangers per plant and the geothermal fluid and isobutane pass through each one in series. Up to 6,000 gpm of water enters the exchangers at 330-350° F and leaves at less that 150° F. The isobutane enters at between 40 and 100° F and is heated to about 280° F before leaving. The isobutane enters as a liquid and leaves as a high temperature, pressured vapor that drives the plants' turbines.

Turbines (Turbo-Expanders)

The turbines receive the super heated and pressurized isobutane vapor from the heat exchangers and expand it through a 18" radial inlet wheel in the turbine operating at up to 10,000 hp and 11,000 RPM. The vapor is discharged from the turbines at around 150° F and 40-100 psi. The turbine casing is made of steel and the wheel is aluminum alloy. The G-1 plant has two turbines and the G-2 and G-3 plants have 3 turbines each.

Electrical Generators

The generators are coupled to the turbines through a reduction gearbox (11,000 rpm to 1,800 rpm). Each generator produces 5 MW, enough energy to serve 5,000 homes. Total production from all three plants is 40 MW which can serve 40,000 homes.

Air Cooled Condensers

The condensers are the most prominent part of all three plants, being the outermost and largest structures. The condensers cool the isobutane vapor from the turbine back to a liquid for reuse. In doing so,the condensers transfer the heat from up to 2.5 million pounds of isobutane vapor to the air each hour in each of the three plants. Each of the 96 bays of condensers contains three 12 ft. diameter fans.

Isobutane Storage Vessel

Each plant has a large pressurized storage vessel to contain (store) the cooled isobutane from the air-cooled condensers. The G-1 plant has two vessels containing about 12,500 gallons each and the G-2 and G-3 plants each have a vessel with a 35,000 gallon capacity. The normal isobutane inventory at all three plants is enough to fill an Olympic size swimming pool.

Isobutane Pumps

The isobutane pumps pressurize the isobutane liquid from the storage vessel and push it through the heat exchangers at up to 600 psi. The G-1 plant is serviced by two high pressure isobutane pumps for each turbine. The G-2 and G-3 plants have three pumps each, one for each turbine.

Local Control Rooms

The local control rooms contain the starters and controls for all electrical motors and all of the switchgear for each plant. The G-2 and G-3 local control rooms can run the plants, each is used primarily for start-up. The control room at the G-1 facility is used as the main control room for all three plants and is manned on a 24 hour basis.

Geothermal Injection Wells

The hot water exiting the heat exchangers (140° F to 180° F) is immediately returned to the earth at a depth of 2000 feet to 2500 feet through six injection wells located adjacent to plants G-2 and G-3.

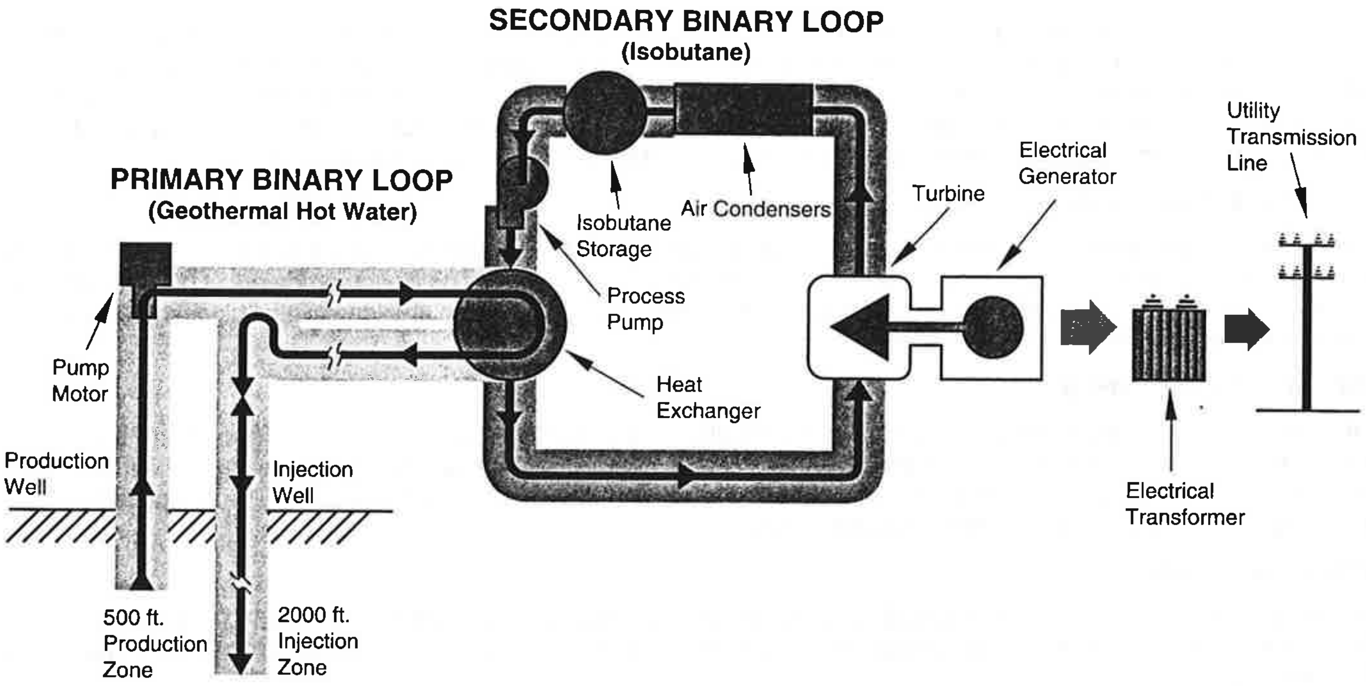
Other Plant Features

An extensive vapor recovery system collects low-pressure isobutane vapor from numerous areas of the plant and injects it into the discharge gas from the turbines, thereby further preventing the discharge of isobutane to the atmosphere. The vapor recovery system can also pump isobutane vapor out of any section of plant piping to allow the opening of equipment to atmosphere for maintenance without the loss of isobutane.

An extensive irrigation system has been installed to ensure the survival of the more than 100 transplanted trees and native plants in revegetated areas.

SCHEMATIC

Geothermal Hot Water to Electric Power



PROCESS DESCRIPTION

The Mammoth-Pacific plants are a world's first—incorporating two closed loop systems called a "binary process" designed to protect the environment and conserve water.

In the "primary binary loop", hot water pumped from the earth passes through heat exchangers (to heat the second loop) and is immediately returned to the earth as warm water with no loss of fluid.

In the "secondary binary loop", a fluid called isobutane is indirectly heated in the heat exchangers to produce a pressurized gas (vapor) that drives the plant turbine-generators to produce electric power. The gas is then cooled back to a liquid by air condensers (cooling fans) and pumped back to the heat exchangers for continued use (recycled).

The key design element is the unique properties of isobutane, the preferred aerosol propellant which vaporizes easily and is environmentally safe. It is used by us all in our homes and offices, in aerosols containing air fresheners, hair sprays, deodorant, baby shampoo, and cooking oil.

DESIGN FEATURES

- Low Profile
- Closed Loop System
- No Water Discharges
- No Water Use
- No Air Emissions

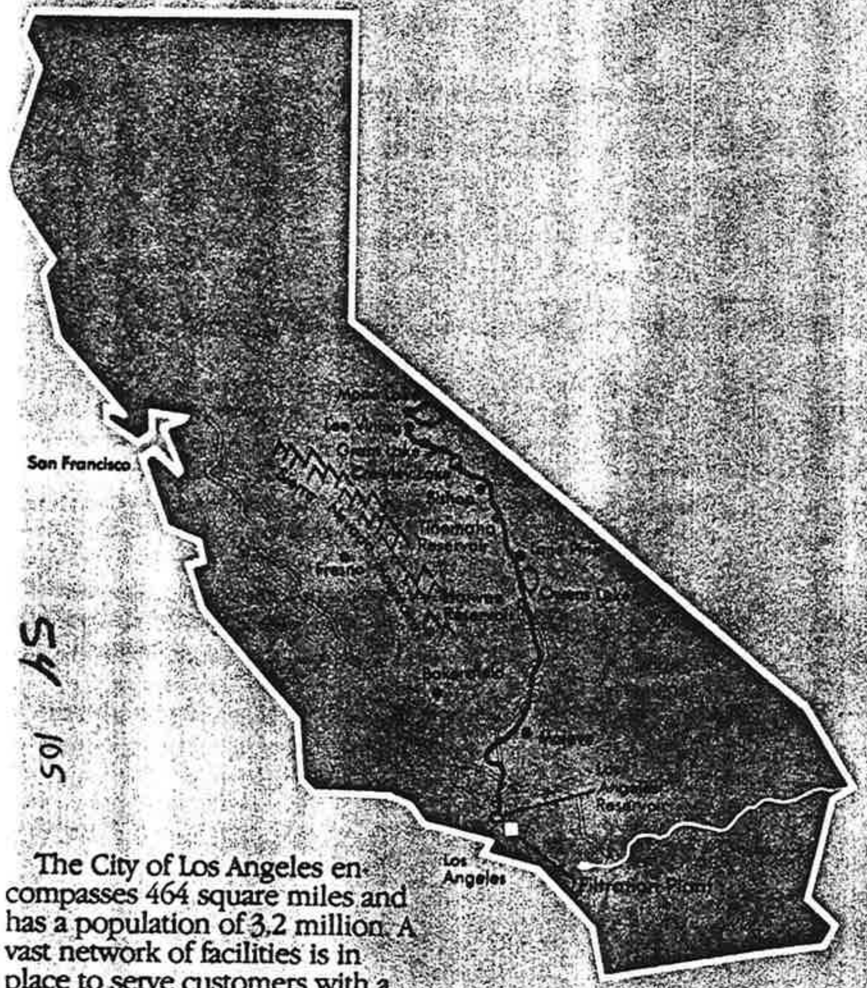
COMMUNITY BENEFITS

- Revenues to County
- Local Employment
- Local Businesses
- Local Housing
- Tourist Attraction

KEY PROJECT DATA

Project Location	Mammoth Lakes, California
Project Site – Area (inc. Wells)	15 acres
Plant Site – Area	10 acres
Number of Production Wells	12 (500 ft. deep)
Number of Injection Wells	6 (2,000 to 2,500 ft. deep)
Hot Water Data	330-350 deg F, 14,000 gpm, 180 psig
Isobutane Data	260-320 deg F, 21,000 gpm, 500 psig
Number of Turbine-Generators	8
Type of Turbine	Single stage, radial inflow
Type of Generator	4,160 V, Sychronous
On-site KW Use	10,000 KW
Net kW to Grid (8 Generators)	40,000 KW maximum
Power Purchaser	Southern California Edison
Equivalent Homes Served	40,000 maximum
Barrels of Oil Saved/Yr.	500,000 maximum
Estimated Project Life	30 Years +

The Los Angeles Aqueduct System



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The City of Los Angeles encompasses 464 square miles and has a population of 3.2 million. A vast network of facilities is in place to serve customers with a reliable supply of water. Approximately 75 percent of Los Angeles' water is imported from the eastern Sierra Nevada and is brought to the city via the Los Angeles Aqueduct System.

The remainder of Los Angeles' water comes from local groundwater wells (15 percent) and purchases of Metropolitan Water District supplies from the Colorado River Aqueduct and State Water Project (10 percent).

The Los Angeles Aqueduct Filtration Plant

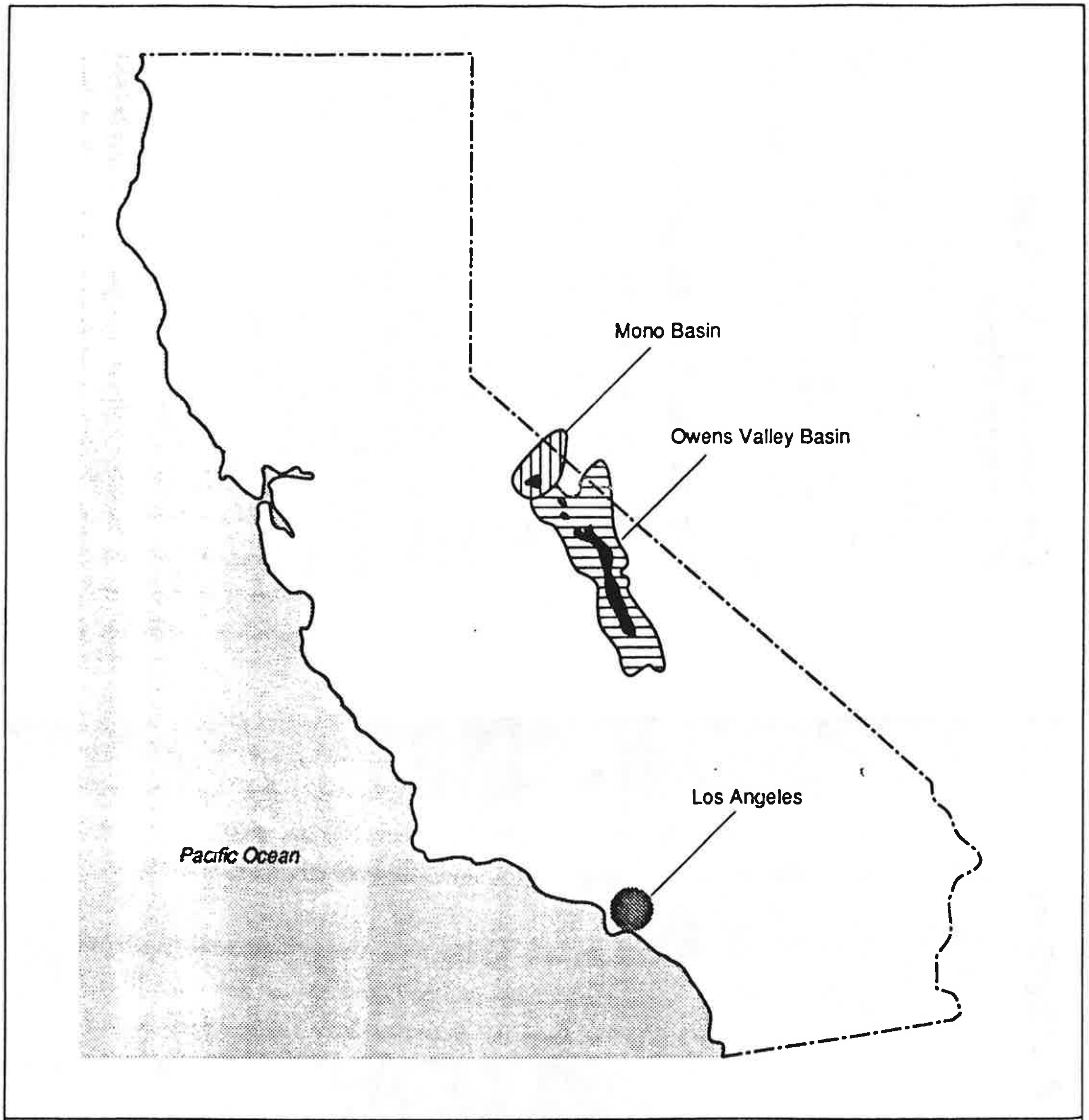
The start-up of the Los Angeles Aqueduct Filtration Plant marks the beginning of a new era in water treatment and quality in Los Angeles. The new filtration plant is one of the largest and most advanced facilities of its kind in the world, treating up to 600 million gallons of water per day. The state-of-the-art technology incorporated into the treatment processes will ensure the efficient delivery of safe, clean water for generations to come.

Water For Los Angeles

Water has played a prominent role in the growth and development of the City of Los Angeles. The City quickly outgrew its local water supplies, and in 1913, the Los Angeles Department of Water and Power (DWP) turned to the Owens Valley to help supply the needs of this thriving metropolis.

Today, 75 percent of the water used in Los Angeles is imported from the Owens Valley and Mono Basin areas of California. High quality groundwater and runoff from the eastern Sierra Nevada mountains flows south through the Los Angeles Aqueduct system, traveling through some 338 miles of pipes, channels, and tunnels to Los Angeles.

Water from the eastern Sierra is of very good quality. DWP sees to it that the water is protected along its route to keep it free from contamination. All fishing and recreational uses of the water are restricted to the northern end of the aqueduct system.



O W E N S V A L L E Y

■ Lands owned by the City of Los Angeles in the Owens Valley and Mono Basin

▤ Watershed Boundary - Owens Valley

▥ Watershed Boundary - Mono Basin

FIGURE S-1
PROJECT LOCATION

SOURCE: EIP ASSOCIATES

MILE 0 .25 .5

88041

Owens Valley Pumped Groundwater

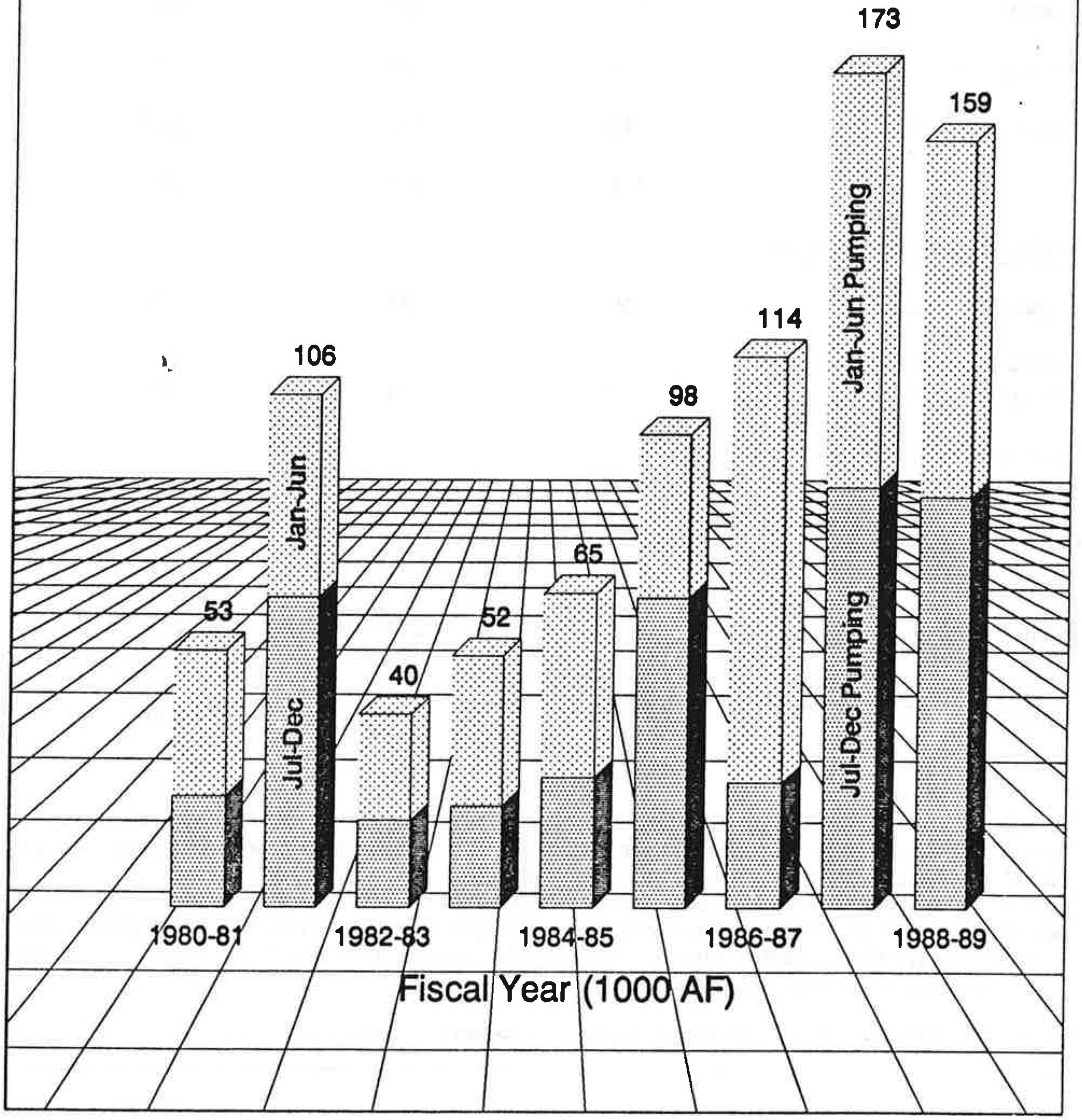


TABLE S-1

LOS ANGELES AQUEDUCT OPERATIONS PRE-PROJECT/PROJECT COMPARISON IN AVERAGE RUNOFF YEARS (1,000s AFY)

	Pre-Project	Proposed Project	
	1945-1970	1970-1990	Agreement[1]
Owens Valley Water Supply			
Runoff[2]	292	313	310
Flowing Wells and Springs	44	17	15
Pumped Groundwater	10	105	110[1]
Total	346	435	435
Water Used in Owens Valley			
Irrigated LA-owned Land	69	53	53
Stockwater, Wildlife, and Recreation Uses	20	23	23
Enhancement/mitigation Project (post 1985)	0	5[4]	30
Other Owens Valley Uses and Losses[3]	127	141	139
Total	216	222	245
Water Exported from Owens Valley to Los Angeles	130	213	190

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[1] Actual pumping will comply with provisions of the Agreement and could be more or less than indicated.

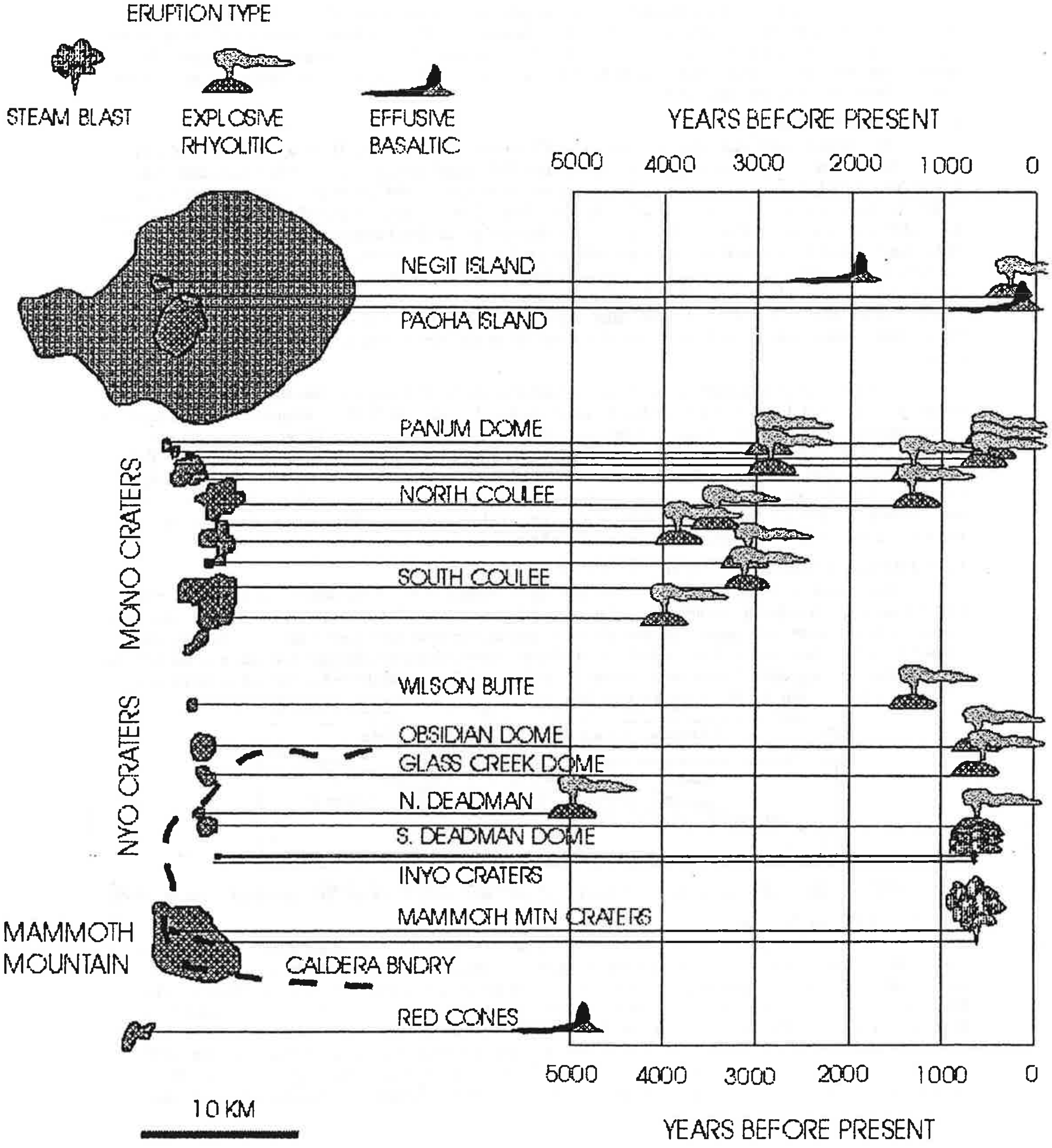
[2] Runoff for the pre-project and 1970-1990 periods is the average runoff recorded for those periods. Runoff for the Agreement is the average runoff recorded to date.

[3] Uses on private land, conveyance losses, recharge and evaporation.

[4] An average of 5,000 AFY was supplied to enhancement/mitigation projects during the 1970-90 period. Due to the implementation of several projects, water supplied between 1984 and 1990 greatly exceeded the average for the entire 1970-1990 period.

Source: LADWP and Inyo County Water Department, September 1990

MONO-INYO CRATERS ERUPTIONS FOR THE PAST 5,000 YEARS



Mono basin and Mono Lake

INTRODUCTION

Mono Lake and its surrounding watershed encompass a unique region in California (Fig. 1). Sagebrush, Jeffrey pines, volcanoes, tufa towers, gulls, grebes, brine shrimp, alkali flies, freshwater streams, and alkaline waters are major components of the ecosystem in this transitional area between the Sierra Nevada and the Great Basin desert. Fourteen ecological zones, with over 1000 plant species and roughly 400 vertebrate species, comprise Mono Lake and its surrounding drainage basin.

TOURIST INFORMATION

The Mono Basin National Forest Scenic Area Visitor Center is located on Highway 395, just north of Lee Vining (Fig. 1). The center features an award-winning film, "Of Ice and Fire: A Portrait of the Mono Basin," an interactive exhibit hall, two art galleries, and a Book Store. As of April 1, 1997, there is a $2 per person fee that enables the visitor unlimited entrance to the Scenic Area Visitor Center exhibits and the South Tufa Area over seven days. Children twelve and under are admitted free, and Golden Age, Golden Eagle, and Golden Access passes will be honored. Scenic Area Annual Passes are available to families for $25 and individuals for $10. A one-day pass is available to tour groups, buses, and vans for $40. School groups are welcome and will be admitted free of charge if their visits are arranged in advance. The Mono Basin Scenic Area is one of 47 National Forest sites throughout the country that are taking part in the Congressionally-initiated Recreation Fee Demonstration Project , in which 80% of fees collected will be returned to the collection site to support resource protection, education, and recreational services.

The greatest concentration of these towers is located at the South Tufa grove just off of Hwy 120 East, at the south end of Mono Lake. To reach the South Tufa Area, travel 5 miles south of Lee Vining on U.S. 395 and then 5 miles east on S.R.120 to the marked, short dirt road which leads to the parking area. To protect these fragile formations, at the urging of the Mono Lake Committee the California legislature established the Mono Lake Tufa State Reserve in 1981. VISITORS ARE PROHIBITED FROM COLLECTING OR DAMAGING THE TUFA. A one-mile self-guided nature trail with interpretive panels leads to the lake, and ranger-guided walking tours are led twice daily in summer and on weekends year-round. Parking, toilets, and picnic tables are provided at the site. As noted above, there is a $2 per person entrance fee to the South Tufa Area.

STRUCTURAL GEOLOGY: THE AGONY AND THE ECSTACY

Mono basin is a tectonic basin formed by faulting and downwarping of the earth's crust that began 3 to 4 Ma. The basin has subsided approximately 3000 m and is filled by 500 to 1350 m of glacial, fluvial, lacustrine, and volcaniclastic sediment. Subsidence is asymmetric, like a trapdoor opening downward, with the hinge along the Anchorite Hills on the eastern side of the basin. As the basin subsided and filled, the Sierra Nevada uplifted 2000 m, like a trapdoor opening upward to the west. The combination of uplift and subsidence has resulted in the present 3500 m of relief between the lake and Sierra crest (Fig. 2).

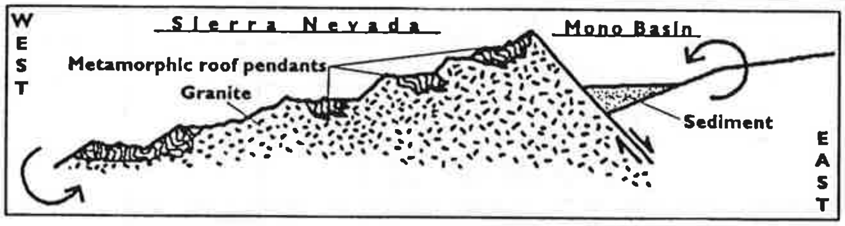
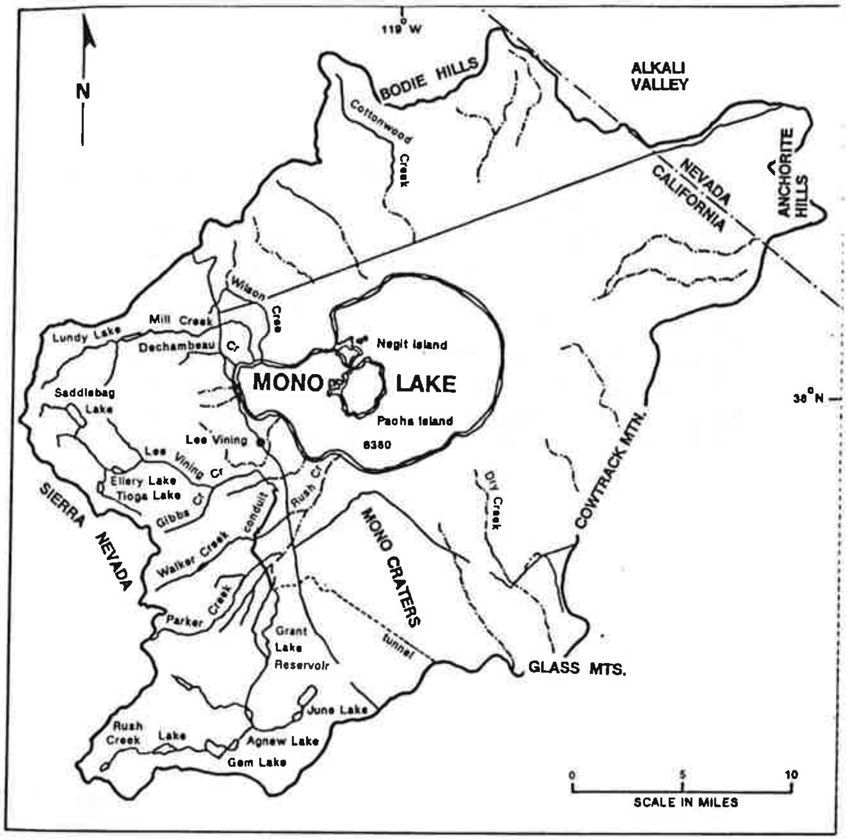
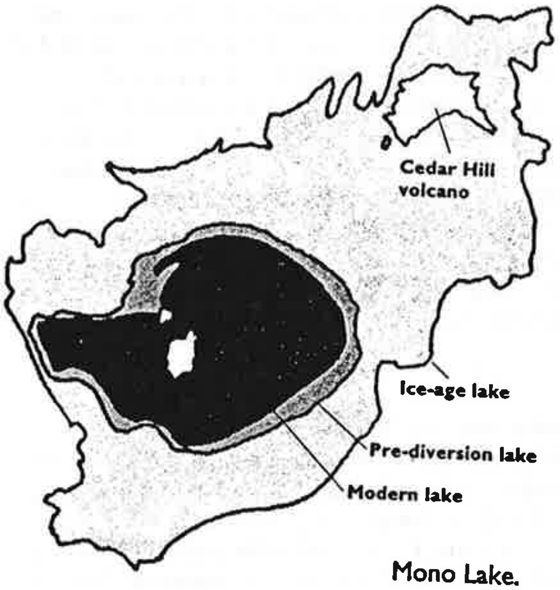


Figure 2. Diagrammatic cross section of the Mono basin and the Sierra Nevada (from Tierney, 1995).

GLACIAL GEOLOGY: COOL

Evidence of five glaciations are preserved in the basin (Table 1). The Sierra highlands were extensively covered in ice. Emergent peaks became narrower and sharper, such as the Minarets near Mammoth Mountain, and stream valleys were widened and deepened by the tremendous erosive power of the moving ice. Modern streams have not yet had enough time to modify the glacial shape of the canyons. Several of the glaciers terminated into a large lake that occupied Mono basin. Rock material gouged by the ice was deposited in moraines along the sides and front of the glaciers. The low, rolling hills at the base of each of the Sierran canyons are remnants of some of these deposits. The lake rose during the cool, wet glacial intervals and fell during the warmer, dry interglacials. During at least the Sherwin and Tahoe glaciations, the lake in the Mono basin overflowed southeastward into the Aurora





Mono Lake.

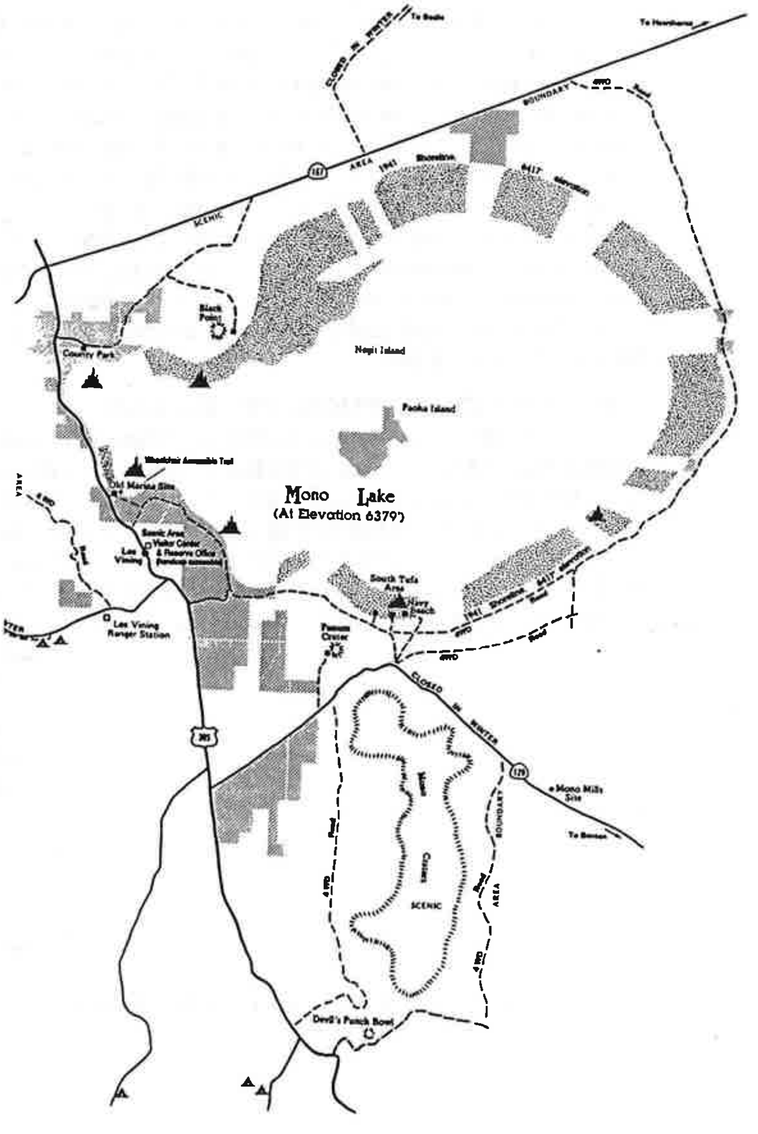


Figure 1. A potpourri of locality maps for Mono basin and Mono Lake.

Valley and was the beginning of a drainage system that ended at Lake Manly, whose remnant is the playa known as Death Valley (Fig. 3).

TABLE 1. GLACIAL HISTORY OF MONO BASIN.

glaciation	age (ka)	magnitude
Tioga	11-21	5 (least)
Tenaya	24-30	4
Tahoe	60-75	2
Mono basin	90-120	3
Sherwin	730-900	1 (greatest)

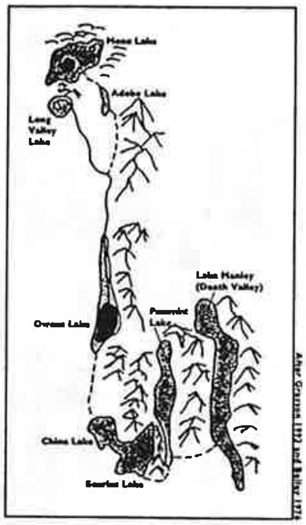


Figure 3. Pluvial drainage system of eastern California.

VOLCANISM: LIVE LONG AND PROSPER

Except for the Sierra Nevada to the west, Mono Lake is surrounded by a volcanic landscape. The oldest volcanic rocks were erupted before the modern Sierra Mountains were uplifted and before Mono basin existed. Most of the basement of the Mono basin is andesitic volcanic rock, formed 28- to 8-Ma during the final phase of arc volcanism as subduction of the Farallon plate ceased in this area. The youngest eruptions of this period form the western portion of the Bodie Hills, such as Mt. Biedeman, Potato Peak and Bodie Mountain. After a hiatus of about 3 m.y., volcanism resumed, associated with Basin-and-Range extension. Lava flows from a widespread network of fissures occurred between 4.5 to 2.6 Ma and formed the large volumes of basalt in the Cowtrack Mountains and the basaltic, andesitic, and rhyolitic eastern portion of the Bodie Hills (Beauty Peak, Mt. Hicks, Cedar Hill). The flows covered an area of about 300 square miles and exceed 200 m in thickness in some places. Volcanism associated with Basin-and-Range extension initially was basaltic, but evolved to andesitic eruptions between 3.0 and 2.5 Ma, such as at Bald Mountain, and finally to rhyolitic composition by 2.1 Ma. Glass Mountain is a rhyolitic volcano formed between 2.1 and 0.8 Ma.

LONG VALLEY ERUPTION: THE BIG BANG

Twenty miles south of present-day Mono lies the northern edge of the 200 square-mile Long Valley caldera, part of a volcanic complex that stretches from Mammoth Mountain to Mono Lake (Fig. 4). About 760,000 years ago, the Long Valley eruption blasted more than 150 cubic miles of earth and ash skyward, burying much of the region in hundreds of feet of volcanic debris. This eruption is thought to have been 2,500 times greater than the Mt. St. Helens blast of 1980. Ash fell as far east as Nebraska, forming a well known marker bed called the Bishop Tuff. The pink tuff, which initially blanketed the Mono basin in a layer 250 to 1500 m thick, is prominent in many natural and man-made exposures in the area.

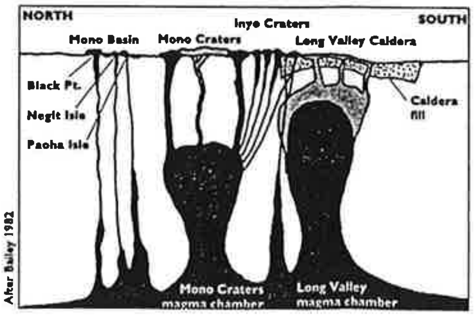


Figure 4. Magma chambers of the Mono basin and Long Valley (from Tierney, 1995).

Geologists have determined the age of Mono Lake from the Long Valley eruption. In 1908, oil prospectors, drilling for oil on Paoha Island, discovered the ash layer from the Long Valley eruption beneath hundreds of feet of lake sediment. Below the ash layer was more lake sediment. No oil was found, but the drilling helped document the great age of Mono Lake. Geologists since determined that Mono Lake has held water since before the Long Valley eruption, making it one of the oldest lakes in North America.

MONO CRATERS: LAST OF THE RED-HOT MAGMAS

South of the lake are Mono Craters. The highest peaks exceed 3,000 m, and this might be the youngest volcanic mountain range in North America. Mono Craters are not actually craters, but a series of 24 plug-dome rhyolitic volcanoes that formed within the last 40,000 years. A plug-dome volcano is a massive dome-like structure formed by cooled lava that has "plugged" a volcanic vent. The last eruption in the Mono Craters chain occurred ~640 years ago at Panum Crater, located just south of Mono Lake, easily reached from Highway 120, 3 mi east of Highway 395.

The two islands that rise above Mono's surface are also volcanic. Negit, a classic black cinder cone, first erupted ~1600 years ago and most recently ~270 years ago. Paoha, the large white island in the center, is <300 years old. Just north of the lake is Black Point, a low mesa of black volcanic rock, formed by subaqueous eruptions about 12,000 years ago, when Mono Lake was five times its current size and nearly ten times its current depth.

There is still a large magma chamber several miles below the Mono basin-Long Valley caldera region (Fig. 4). The U.S. Geological Survey closely monitors the area for warning signs of impending volcanic activity, as earthquakes swarms, hot springs, and steam vents. Maybe if we're lucky, we'll get to see an eruption—or be unlucky and become volcaniclasts.

MONO LAKE HYDROGEOLOGY: LIVING ON A FIXED INCOME

A lake has continuously occupied Mono basin since before the Long Valley eruption, making it one of the oldest lakes in North America. During the Pleistocene, the basin was occupied by pluvial Lake Russell. During glacial intervals, the Laurentide ice sheet advanced to the US-Canadian border and deflected the jet stream southward, bringing high rainfall to the Great Basin. Several times during its history, Lake Russell reached its threshold elevation of about 7200 ft[1] (815 ft higher than today, Table 2) at which point it became an open lake, spilling to the southeast. At the threshold level, the lake was seven times deeper than today and five times larger in surface area. During interglacial intervals, the lake contracted to about 6600 ft.

TABLE 2. LAKE LEVELS, LAKE AREAS, AND SALINITY

Elevation (ft)	When	Lake Area	Exposed Lakebed	Total dissolved solids (seawater=35 g/l)
7,200	25,000 years ago	overflow level (open lake)	+++submerged (1941 ref)	2.5 g/l
6,428	1919, 20th century high	not given	+submerged (1941 ref)	~42 g/l
6,417	1941, just prior to diversions	55,180 acres (86.2 sq. mi.)	0 acres (reference level)	51.3g/l
6,392±6	stabilization level by 2020	48,960 acres (76.5 sq. mi.)	6,000 acres	69.3g/l
6,385	1999	45,900 acres (71.7 sq. mi.)	9,300 acres	78.0g/l
6,372	1982, lowest recorded elevation	36,480 acres (57 sq. mi.)	18,000 acres	99.4g/l
6,355±21	full-diversion level (avoided by legislation)			133 g/l

Mono Lake is a saline, alkaline remnant of Lake Russell, which a current maximum depth 160 ft and an average depth of 58 ft. It is a closed lake, i.e., it has no external drainage. Water leaves the lake only by evaporation. The Los Angeles Department of Water and Power (LADWP) estimate evaporation loss to average 42 inches annually. Total annual inflow to the lake is 230,000 acre-feet, which comes from surface runoff from the Sierra Nevada (187,000 acre-feet) and from direct precipitation onto the lake and from groundwater. The rain shadow of

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[1] Measurements given in references in feet have been retained.

the Sierra Nevada has a dramatic effect on precipitation in the basin, with an average 50 inches at the Sierra crest and 6 inches on the east side of Mono Lake.

The LADWP has rights to divert flow from four streams that empty into Mono Lake, Rush, Parker, Walker, and Lee Vining Creeks. Water diversions from Mono basin began in 1941, after the Owens Valley aqueduct was extended into this area. At that time, lake elevation stood at 6417 ft (Table 2). Between 1941 and 1994, when legislation partially curtailed the diversions, the Lake lost nearly 45 vertical feet of water, or half of its 20th century volume--effectively doubling its salt and mineral content. The ecosystem of the lake was dramatically affected by the increased salinity, stratification of the water column, anoxia of the bottom brine, and episodic connection of the Negit Island to the mainland. Exposure of the tufa columns has stopped their growth and begun their erosion.

A large grass-roots movement has been influential in getting state legislation passed to limit diversion of water by LADWP and to restore lake level to about 6392 ft (Table 2). The Outstanding National Resource Water designation also requires that the salinity be maintained under 85 g/l (the concentration of Mono Lake in May, 1996 and November, 1975). If such restrictions had not been legislated and full diversions continued., lake level would have stabilized at about 6355 ft and salinity at 133 g/l. The yearly average export from the Mono Basin depends on the level of Mono Lake on April 1. Below 6,377, no diversions are allowed. Between 6,377 and 6,380, diversion of 4,500 acre-feet is allowed. Between 6,380 and 6,391, diversion of 16,000 acre-feet is allowed. Once the lake reaches 6,391, a new set of restrictions applies. No diversions are allowed if the lake drops below 6,388. Diversion of 10,000 acre-feet is allowed when the lake is between 6,388 and 6,391. All water in excess of required stream flows (89,000 acre-feet) is allowed to be diverted when Mono Lake is above 6,391. If the lake hasn't reached 6,392 by the year 2014, the State Water Resources Control Board will re-examine the situation.

MONO LAKE CHEMISTRY: JUST YOUR BASIC LAKE

Mono Lake has been a closed lake for 22,000 years. All of the solutes brought in by streams and groundwater during this time have remained in the lake. An estimated 280 million tons of solids are dissolved within the lake, more than double the total dissolved solids per liter than seawater (Table 2). This results in a high density and viscosity of the water (specific gravity ~1.07), so that even those with no body fat (and the rest of us hate you) can float in Mono Lake. Mono Lake also is highly alkaline, with a pH of 9.8, similar to Windex and far more basic than seawater (pH = 8.2) and 1,000 more alkaline than fresh water. Because of the high alkalinity, Mono Lake water tastes bitter and feels slippery. Some claim it feels and behaves a lot like soapy water. However, the water is caustic enough to deteriorate clothing and footwear after repeated soakings. The water of Mono Lake is a $Na-Cl-CO_3-SO_4$ brine, sometimes called a triple water because of the high abundances of the three anions (Table 3). The waters also have an unusually high abundance of B and orthophosphate (~60 ppm).

TABLE 3. CHEMICAL AND PHYSICAL PROPERTIES OF MONO LAKE WATER AND SUBLACUSTRINE SPRINGS AT SOUTH TUFA GROVE (from Bischoff et al., 1993)

	Springs				Navy Beach thermal spring	lake water[3]
	1	2	3	4		
T°C	8	18	15	15	35	5
pH	6.5	6.4	6.5	6.8	6.6	10.0
mg/L						
Na	62	64	132	620	486	30612
K	9	8	12	39	44	1782
Ca	135	111	134	169	125	4
Mg	25	23	37	47	83	33
alkalinity[1]	574	566	845	1280	1891	36201
Cl	18	17	44	296	136	18368
SO_4	26	22	36	387	34	9990
SiO_2	77	81 7 81.7?	81	80	137	14
Fe	4.6	0.6	2.5	7	<0.1	0.8
Mn	1.1	0.4	0.3	2.3	1.5	0.07
B	1.1	1.0	2.6	10.8	7.5	490
TDS[2]	933	894	1326	2938	2945	97494

[1] alkalinity as mg/L HCO_3

[2] total dissolved solids

[3] unpublished analysis by Los Angeles Dept. of Water & Power, 1982 (salinity =95.6 mg/L) - concentrated to represent 1992 salinity of 97.5 g/L

Springs that enter the lake in the South Tufa Grove area include cool-water springs that are recharged through the nearby Rush Creek delta and hydrothermal springs that come from the volcanic complex to the south (Table 3). Mixing of lake water and spring water is neither rapid or homogeneous in the vicinity of springs. Shimmering microstratification and interfingering of the waters is observed extending meters away from the orifices of the springs.

ATTENTION TEACHERS!!!!
You can make a close approximation of Mono Lake water at home or in the classroom. Begin with one gallon of pure water, add 18 tablespoons of baking soda, ten tablespoons of table salt, 8 teaspoons of Epsom salt, and a pinch of borax or laundry detergent (in order to make tufa, just add fresh water containing dissolved calcium chloride).

TUFA FOR THE PRICE OF ONE: THE COST OF LAKE-LEVEL FALL

Tufa is a term that is poorly defined because it has been applied to calcareous deposits that have different physical features and that originate in very different ways. Rocks described as tufa have also been described as stromatolites (laminated microbialites), thrombolites (non-laminated microbialites), travertine (another catch-all term for non-marine limestone, generally used for rather dense, low-porosity limestone formed from springs), and even speleothems. In its broadest sense, tufa is a nonmarine calcareous deposit of abiotic and/or biotic origin. Tufa deposits were common in most of the large pluvial Pleistocene lakes in the Great Basin, such as Lake Bonneville and Lake Lahonton. Mono Lake has Pleistocene tufa >50 m above the modern level of the lake. However, modern tufa formation is far more extensive in Mono Lake than in other remnants of pluvial lakes.

As the lake level began to fall in the 1940s, spires of limestone first emerged above the surface of the lake. These columns composed of calcite and aragonite grew at orifices of sublacustrine springs when lake level was higher than present. Continued regression and exposure of the lake bed has resulted in "groves" of stranded, subaerially exposed tufa towers. Some of the columns are >10 m tall, and several have small springs that issue from their bases. These exposed towers are vulnerable to erosion and meteoric diagenesis (Fig. 5).

Beneath the surface of the lake, tufa continues to form, largely associated with spring discharge (Fig. 5). Some of the springs occur as diffuse seepage from littoral sands, whereas others are artesian from individual orifices or linear fractures. The distribution of tufa towers, shoreline tufa, and $CaCO_3$-cemented beachrock are largely associated with springs. For example, springs discharge on the eastern side of Mono Lake is minimal; and none of these features occur on this side of the island. There are two major type of tufa deposition: 1) columns that form above spring orifices, and 2) stratiform encrustations of hard substrates throughout the lake.

Until publication of a paper by Bischoff et al. (1993), the traditional explanation for the tufa was that underwater springs rich in calcium mixed with lakewater rich in carbonate, resulting in a fluid supersaturated with respect to calcium carbonate. The calcium carbonate precipitates around the spring; and over the course of decades to centuries, a tufa tower grows. Where spring seepage is diffuse, calcium carbonate coats boulders, beer cans, dead vegetation, dead birds, and anything else that ends up in the lake, and cements littoral deposits, forming beachrock. Although the lakewater is supersaturated with respect to calcite, very little of this mineral can form from this fluid because of the very low abundance of Ca in the water (Table 3). Bischoff et al. (1993) have calculated that for precipitation of $CaCO_3$ in Mono Lake, all of the Ca and 53% of the CO_3 are supplied by spring water and that the maximum precipitation of $CaCO_3$ occurs at a mixture of 96 wt. % spring water and 4 wt. % lake water.

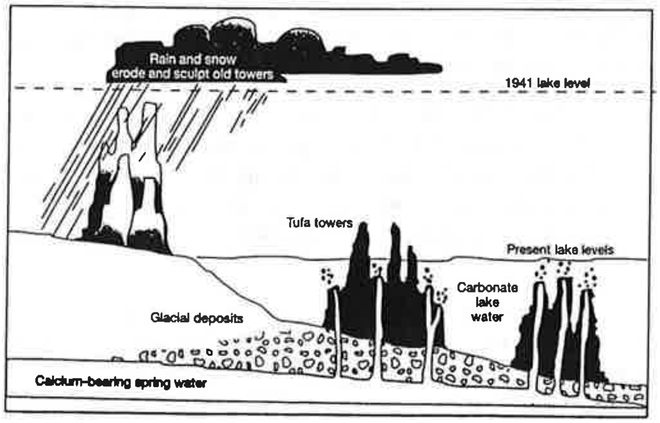

Figure 5. Formation of tufa at Mono Lake (from California Department of Parks and Recreation.

Pupae cases from alkali flies that settle on the tufa are commonly incorporated into the deposit, but it is not correct to say that this is a form of formation of tufa through biogenesis, as described in Tierney (1995) and the Mono Lake Committee web page. However, formation of some tufa might be induced by the microbial activity. Mat-forming communities of cyanobacteria, green algae, and diatoms coat the tufa towers and shoreline sediment in many areas. The photosynthetic activities of these organisms decrease dissolved CO_2, which raises the bicarbonate abundance of the microchemical environment adjacent to the cell membranes of the microbes and enhances the precipitation of $CaCO_3$.

IKAITE COMES OUT OF THE CLOSET: IMPLICATIONS FOR GAYLUSSITE AND TUFA

In December, 1991, the hexahydrate of $CaCO_3$ was discovered in Mono Lake (Bischoff et al., 1993). This mineral, named ikaite because it was discovered in Ika Fjord in Norway, was precipitating as a millimeter-thick coating on littoral sand at sites of diffuse spring seepage and as centimeter-thick crusts (up to 3 cm) on tufa around the orifices of springs. By the following summer, all ikaite crystals were gone. Instead, anhydrous $CaCO_3$ (calcite and aragonite) and gaylussite were found in the same localities.

Ikaite ($CaCO_3 \cdot 6H_2O$) is more soluble than all of the anhydrous forms of $CaCO_3$ at Earth's surface temperatures. In occurrence in nature requires that conditions suppress precipitation of anhydrous forms. Two conditions do this in Mono Lake in the winter. First, the high concentration of orthophosphate poisons the surface sites on anhydrous forms of $CaCO_3$, but does not affect the precipitation of ikaite. Second, anhydrous $CaCO_3$ has retrograde solubility (i.e., its solubility increases as temperature decreases), whereas ikaite precipitation is favored at near-freezing temperatures because its solubility decreases as temperature decreases. Therefore, conditions in Mono Lake are ideal for crystallization of ikaite during winter months. However, as the water heats up in the spring, the metastable ikaite breaks down. Some of this mineral converts to anhydrous $CaCO_3$ and is incorporated in the tufa. Some undergoes the reaction:

$$\underset{\text{ikaite}}{CaCO_3 \cdot 6H_2O} + 2Na^+ + CO_3^{=} \rightarrow \underset{\text{gaylussite}}{Na_2Ca(CO_3)_2 \cdot 2H_2O} + 4H_2O$$

Much of the fragile ikaite is dispersed by waves to the lake bottom, where it eventually dissolves to supply the Ca needed for the widespread formation of gaylussite throughout the lake.

ECOLOGY OF MONO LAKE

Life is in the lake is greatly restricted by the alkalinity and salinity to only bacteria, algae, brine shrimp, and alkali flies. However, this combination produces one of the most productive ecosystems in the world. Nesting birds consist of California Gulls (50,000, 85% of California's breeding population and second largest colony in the world after the Great Salt Lake in Utah) and Snowy Plovers (400, 11% of the state's breeding population). Migratory birds include Eared Grebes (1.5-2 million, 30% of the North American population), Wilson's Phalaropes (80,000, 10% of the world population), Red-necked Phalaropes (60,000, 2-3% of the world population), and 79 other species of waterbirds.

Alkali Flies

Swarms of black alkali flies carpet the shoreline and nearshore on calm summer days, busily feeding on microscopic algae. Alkali flies spend two of their three life stages entirely underwater. The larval and pupal life stages develop within the lake. When the adult fly is ready to emerge from the pupa case its head comes apart! The head separates and a small sac inflates and pops the top off the pupa case. The sac then collapses, the fly's head reassembles itself, and the fly emerges from the case to float to the surface where it then begins its adult life cycle. Eventually adult flies return underwater to lay eggs or feed on algae. Tiny hairs trap a thin layer of air which allows the fly to "scuba dive." On calm days in the summer, you can watch small, silvery teardrop shapes amble along the bottom of the lake in shallow water.

Alkali flies provide more fat and protein than the brine shrimp and so are the preferred fare of most birds. This rich food is used by Phalaropes to grow new feathers before their 3000-mile, non-stop migration to South America. In the mid to late summer, the Wilson's Phalarope can be seen spinning in shallow water, creating a miniature vortex that brings alkali fly larvae and pupae to the surface for easy pickings. You can also watch California Gulls and Brewer's Blackbirds run along the shoreline with beaks open filling themselves with adult alkali flies.

The alkali fly was an important source of food for the Kutzadika'a people during the summer months. Linguistically related to the Northern Paiute peoples, the Kutzadika'a (pronounced Kootz-a'-di-ka-a') lived part of the year in the Mono Basin hunting and gathering. The pupal stage of the alkali fly was collected in shallow water along the lakeshore, dried, and used in stews. The Kutzadika'a even traded this delicacy with neighboring peoples. Don't inquire too closely what is for dinner tonight.

Brine Shrimp

Within Mono Lake's saline waters are trillions of brine shrimp, *Artemia monica*, a species unique to the lake. An estimated 4-6 trillion brine shrimp inhabit the lake during the warmer summer months. Mono Lake shrimp are tiny, about the size of your thumbnail, and by July Mono Lake water looks very much like shrimp soup. Brine shrimp have no practical food value for humans, but birds regard them as haute cuisine. Abundant shrimp provide a feast for the birds, especially the nearly two million Eared Grebes that arrive for "shrimp cocktail" in the fall. The brine shrimp population dies off as the lake cools in the winter. In the late summer and fall, female brine shrimp produce tiny cysts, (dormant, undeveloped embryos), that lie on the lake bottom during the winter. In the spring the cysts develop into tiny shrimp as the lake warms, beginning a new generation of shrimp.

It's for the Birds (You Knew That Was Coming!)

Preying on the shrimp and flies of the lake are the hundreds of species of migratory birds that visit the lake each year, including large volumes of California Gulls, Snowy Plovers, Wilson's and Red-necked Phalaropes, and Eared Grebes. Some of these birds travel from as far off as the Arctic Circle, and stop over only at Mono Lake on their way to wintering grounds in the southern seas as far south as Argentina. Other migratory birds include American Avocets, Western and Least Sandpipers, Snowy Plovers, White-faced Ibises, Dowitchers, along with the occasional rare appearances of Whimbrels, Baird's Sandpipers, Sabine's Gulls, Black Terns, and Parasitic Jaegers. Some of these birds, as well as the many rabbits, mice, and squirrels that live in the basin, will become the meals of hawks, owls, eagles, coyotes and bobcats that frequent the shores of the Mono Lake. Millions of birds arrive and depart Mono Lake between mid-summer and fall, making this a vital stop on the Pacific Flyway for migrating birds. Mono Lake is designated as a part of the Western Hemisphere Shorebird Reserve Network.

Most of the California Gulls, which leave calling cards on your beach towels, were born at Mono Lake. By late spring, anywhere from 44,000 to 65,000 gulls arrive to breed on Mono's lesser-known islands. Most used to nest on Negit Island until 1979, when water diversions lowered the lake level to a point where a landbridge connected the island to the mainland. Hungry coyotes made easy prey of gull chicks, and the adults abandoned the island. As of 1998, no gulls have returned to nest on Negit.

Of all the birds that come to Mono Lake, the Wilson's Phalarope stands out as the hardiest traveler. These small shorebirds, not much larger than a fist, arrive at Mono Lake in mid-summer after breeding in the northern U.S. and southern Canada. At Mono Lake they molt their feathers and double their weight after several weeks. By the middle of August, they depart for South America. The fact that these birds fly over 3,000 *non-stop* miles to South America is amazing enough, but what is truly astonishing is how fast these little birds reach their destination—three days!

The Eared Grebe, a diving, duck-like bird, arrives at Mono Lake in greater numbers than any other species. Aerial surveys have recorded 1.5-1.8 million birds on the lake in the fall, which is a large portion of North America's population! The grebes double, and sometimes nearly triple their weight gorging on brine shrimp. Many grebes end up getting too fat to fly, and must lose weight before departing for winter destinations (go, grebes!!).

The data are incomplete, but there is evidence to suggest that Mono Lake once hosted nearly a million ducks as recently as 1948. In 1986, only 14,000 could be counted. Water diversions to Los Angeles radically changed waterfowl habitat in Mono Basin, but restoration hopefully will increase the numbers of migrating ducks. There is still a wide variety of waterfowl at Mono Lake, mostly in the fall. Canada Geese, Mallards, Northern Shovelers, Northern Pintails, Gadwalls, Ruddy Ducks, Cinnamon Teals, and Green-winged Teals are locally common around the lake. Less commonly, Bufflehead, Lesser Scaup, Snow Goose, and Tundra Swans are sighted.

VEGETATION: SWEET SMELLS AND PESTO

Sage can adapt to extreme cold, heat, sunlight, and drought and so this pungent shrub can be found in almost all parts of Mono Basin. Within the sagebrush community, there is a surprising variety of plants and animals: bitterbrush, desert peach, blazing star, sage grouse, sage sparrows, kangaroo rats, chipmunks, mule deer, black-tailed jackrabbits, coyotes, and the occasional mountain lion. Sagebrush grows slowly, reaching about 2 to 4 ft in height, though some old stands of sagebrush have topped 7 ft. The native Paiutes used sagebrush leaves to make a tea to treat a variety of ailments, and it was hung outside of dwelling places to discourage unkind spirits.

South of Mono Lake is the largest single stand of Jeffrey pines in the world. The aroma of the bark has been described as butterscotch, pineapple, or vanilla, depending on the sniffer. During calm mornings and evenings the sweet fragrance of Jeffrey pines hangs in the air. Related to ponderosa pines, these trees grow large and straight with a thick crown. Valued more for their lumber than their aesthetic presence, Jeffrey pines were heavily logged both during the gold mining heyday of Bodie and more recently under the management of the Inyo National Forest. Though nearly all the big trees have been cut and the forest is crisscrossed by old logging roads, you can still enjoy this stately forest along with its associated community of sagebrush, bitterbrush, monkeyflower, prickly phlox, lupine, mule deer, coyote and great-horned owls.

At scattered locations around the Mono Basin dense stands of pinyon pine thrive. These single-needle pines provide a steady supply of pinon nuts in the autumn feeding birds, rodents, chipmunks, and even people. A well-balanced combination of protein, fat, and carbohydrates make pinon nuts an excellent food source. Growing among the pines you may find Utah juniper, sagebrush, littleleaf horsebrush, phlox, arrowleaf balsamroot, and lupine. The pinyon pines are a favorite hangout for a host of birds like Pinyon Jays, Mountain Chickadees, Blue-Gray Gnatcatchers, and Scrub Jays.

HUMAN HISTORY: HEEEEEERE'S JOHNNY!

Paiutes

The Basin was inhabited by native peoples for more than 5,000 years before white settlers arrived in the mid-19th century. The last of these native groups to live in the Basin, the Kuzedika'a or Mono Lake Paiute, were a small band of hunter-gatherers whose dietary staple of the lake's alkali fly pupae gave both them and the lake their names. In their own language, Kuzedika'a means "fly-eaters", and in the language of their southwestern Yokut neighbors, "fly-eaters" was said as Mono. The U.S. Cavalry, who entered the Mono Basin from the southwest, took their name for the lake and basin from the language of the Yokut. When the snow melted in the mountains, the Kuzedika'a carried heavily laden, elegantly-woven willow baskets over the same ancient Mono Pass trail used by present-day backpackers. They traveled as far west as Yosemite Valley, bartering obsidian, piñon nuts, dried fly pupae, and salt for acorns, manzanita berries and bear skins.

Mountain Men and Miners: the 19th Century Alpha Males

American and English trappers were the first non-natives known to penetrate the Kuzidika'a's homeland. As the routes across the Sierra lay north and south of Mono Lake, the Kuzedika'a saw few of these early travelers. The Kuzedika'a undoubtedly heard of the immigrants crossing the Great Basin and of their treacherous treatment of neighboring tribes. In 1852, Chief Tenaya's band of Yosemite Miwok, pursued by Lieutenant Tredwell Moore and the second infantry, fled across Mono Pass to the shore of Mono Lake, where the Kuzedika'a helped them to hide.

Unfortunately for the Kuzedika, Moore and his men discovered gold-bearing quartz near the lake. When precious metals were discovered in nearby mountains, miners and their "support groups" began flocking to the area to mine gold and silver in camps at Lundy, Bennetville, Dogtown, Aurora, and the infamous Bodie--once the second largest town in California at a population of 10,000, now a deserted ghost town and State Historical Park. A prospector from Indiana by the name of Leroy Vining arrived in 1852 to seek his fortune in gold from the local mountains. He failed in this pursuit, but reaped his fortune instead by opening a sawmill to supply mining towns like Bodie with precious wood for fuel and construction. His legacy remains in the name of the modern lakeside town of Lee Vining.

The mining camps consumed entire forests of piñon and Jeffrey pines for heating, cooking, building and timbering mine shafts. As forests of piñon fell to the ax, the Kuzedika'a lost the pine nuts, an essential winter staple. The cutting of Jeffrey pines drastically reduced the supply of another important food, piuga, the fat, needle-eating caterpillars of the Pandora moth. Wildlife was exploited with good old pioneer rapacity. Mono's gull colonies were robbed of their eggs, which were sold in the mining camps. But as boom towns became ghost towns and Mono's human population dwindled, the gulls were finally left in peace.

Settlers

There also were settlers who were home-seekers, not fortune-seekers like the miners. Several pioneer farms were started along Mono Lake's well-watered, fertile western shore that marketed produce, dairy products, and meat in the burgeoning mining camps. More than 200,000 sheep, herded up the Owens River from the Mojave Desert and San Joaquin Valley, ruined the meadows where the Kuzedika'a gathered seeds, bulbs and roots. The sheep also competed with the antelope, bighorn sheep, sage grouse and other animals. By the turn of the century, antelope and bighorn had been hunted into oblivion, and the once abundant sage grouse had become scarce. The Kuzedika'a were forced from their seasonal camps as the best land was claimed by the settlers, and food supplies dwindled as the settlers clear cut the forests, killed or displaced local game, grazed their stock on wild grasses of the meadows, collected gull eggs by the thousands, and heavily hunted other waterfowl. The Kuzedika'a either became laborers for the settlers or retreated south towards the Bishop Paiute.

Mono's pioneers looked on the lake as a blessing as well as an oddity. They were thankful that it tempered the climate and extended the growing season. They hunted along its shores, picnicked on its islands and swam in its waters. In the 1880's, Mono Lake became a health spa of sorts. Bath houses and accommodations were constructed for "invalids and others who may desire to spend a portion of the summer in reach of the healing waters of the lake". Half a century later, lakeside resorts were still luring guests with therapeutic claims. "Mono salts" were bottled and sold as patent medicine.

Many families continued to till Mono's soil until the hard times of the 1930s and big city water interests intervened. Destitute landowners relinquished their holdings to water barons and others seeking to profit from the water rights they could thereby garnish. Ultimately, the City of Los Angeles came to own much of the water-rich land in the basin, from which it diverted Mono Lake-bound creek water to an aqueduct that would carry it more than 300 miles south to serve the needs of its growing population. So feel a little guilty each time you flush.

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