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EIGHTH ANNUAL SPRING FIELD FROLIC
GEOLOGY OF THE EASTERN MOJAVE DESERT

GEOLOGY AND EARTH SCIENCE FIELD TRIP
Department of Geological Sciences
California State University, Northridge
January 23-25, 1991

Peter W. Weigand, Coordinator

Wednesday, Jan. 23 - Meet at the Monterey Hall parking lot at **7:00 AM**. See the attached list for things to bring. It is **not** wise to leave cars at the University during the duration of the trip. Several have been broken into during past trips, so try to arrange a ride to campus. If you must leave a car, you can park it near the Police Station on Halstead. Map on pg. 3.

1. **Kramer Borate Deposit** . . . . p. 6
   This sodium borate ore body of Miocene age is located just north of Boron and supplies much of the world's boron. We will get a talk from Frank Gonzales and a tour of the pit from geologist Joe Sietke, both of U.S. Borax.

2. **Calico Early-Man Site** . . . . p. 11
   This site contains evidence that suggests human occupation 200,000 years ago; this represents the earliest date in the Western Hemisphere. We'll get a tour from Yvonne Lipking.

3. Afton Canyon (maybe)

4. **Zzyzx Desert Field Station** . . . . p. 27
   This Center is a CSU facility located about 11 mi SW of Baker and is situated on the edge of Soda Dry Lake at the end of a 4.5 mi dirt road. These are our accommodations for the next two nights. We will meet first with caretaker Rob Fulton, then figure out the logistics of unpacking, sleeping arrangements, and eating.

Thursday, Jan. 24 - We'll rise at 6:00 AM and try to be off by 8:00 AM. Map on pg. 4.

5. **Cima Volcanic Field** . . . . p. 66
   We'll look at some spectacular petroglyphs, search for some lower crustal xenoliths, explore a lava tube, and talk about the origin of the lavas.

6. **Late Proterozoic and Lower Cambrian Basement** . . . . p. 36
   We'll look at some of the basement rocks near the town of Kelso, perhaps hunt for some trilobite fragments, and listen to Dr. Dunne talk about the structures and tectonic history of the eastern Mojave.

7. **Kelso Dunes** . . . .
Here we can play on the dunes and build up our apatites.

Friday, Jan. 25 - Again, up at 6:00 AM and off by 8:00 AM. Map on pg. 5.

8. **Miocene Volcanic Rocks** . . . . p. 59
The Peach Springs Tuff is an important, widespread 18.3 Ma correlatable unit in the eastern Mojave. We'll look at it a few miles SW of Cima. Then we'll look at the Wild Horse Mesa Tuff at Hole-in-the-Wall Campground.

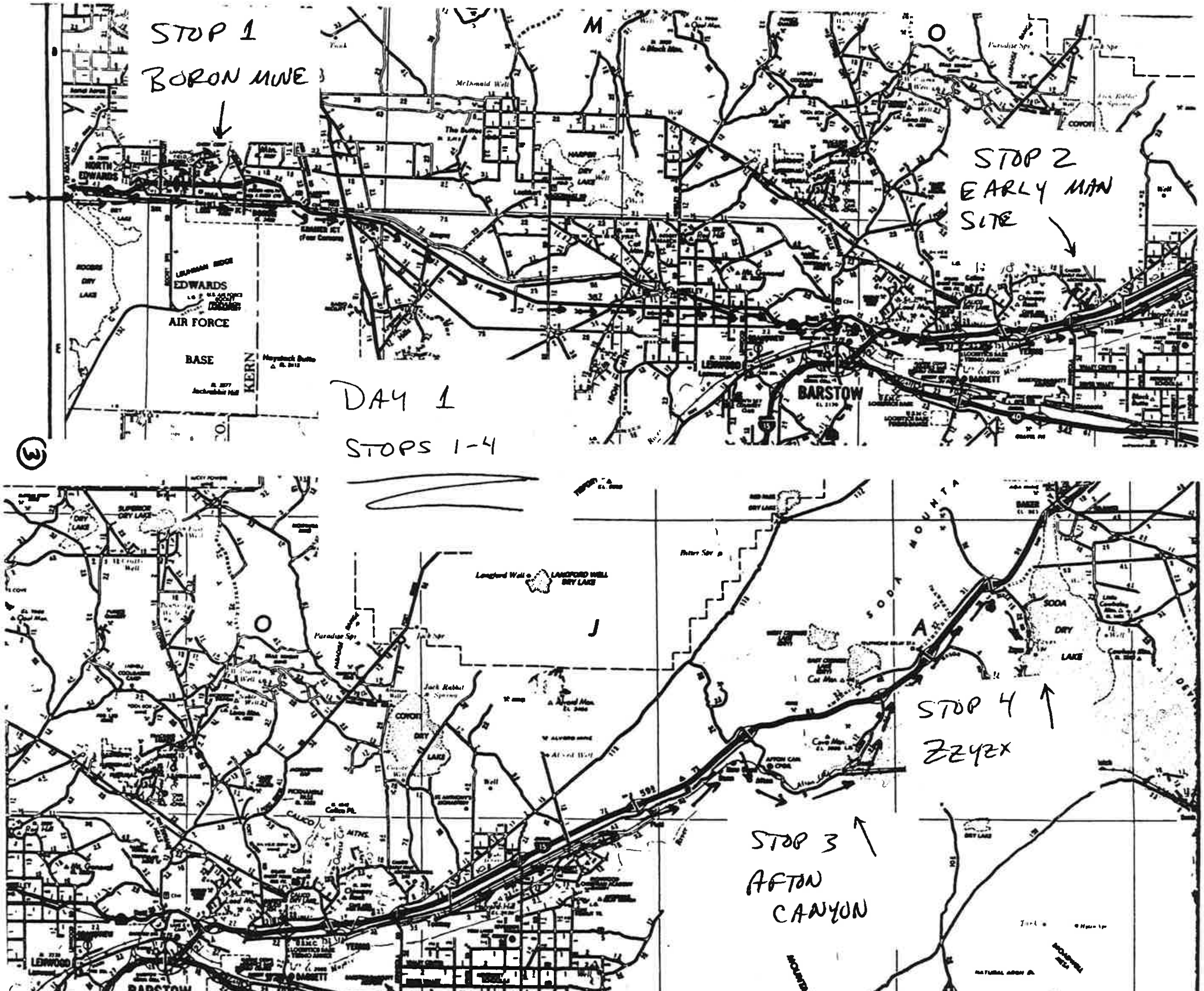
9. **Mitchell Caverns** . . . . p. 65
Our last stop will include a private tour of the caverns that have developed in Paleozoic limestone.

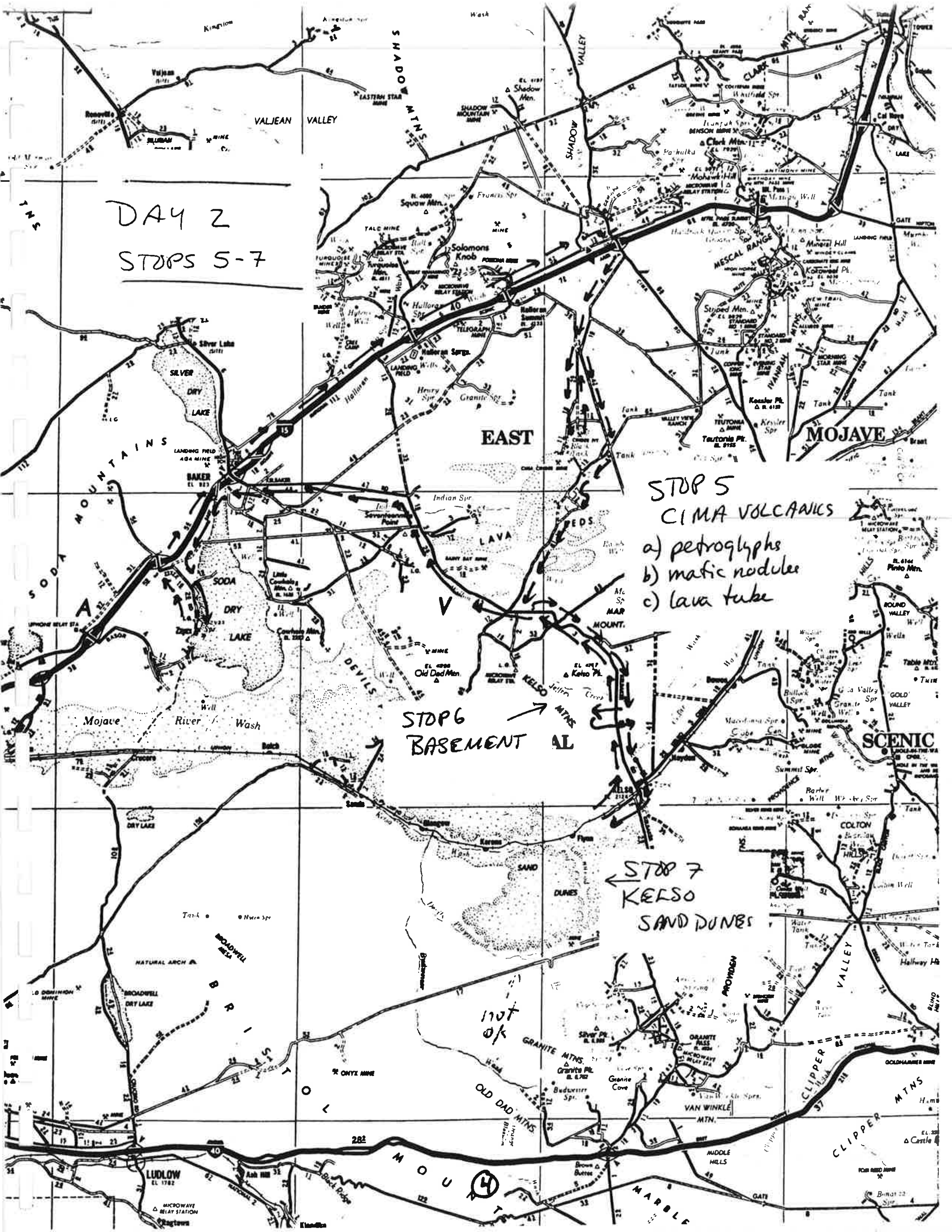
Weather - Winter in the desert can be **extremely** variable. Pay close attention to weather reports and plan accordingly. Normal temperatures at this time of year might be 45° during the day and 25° at night. It might be very windy.

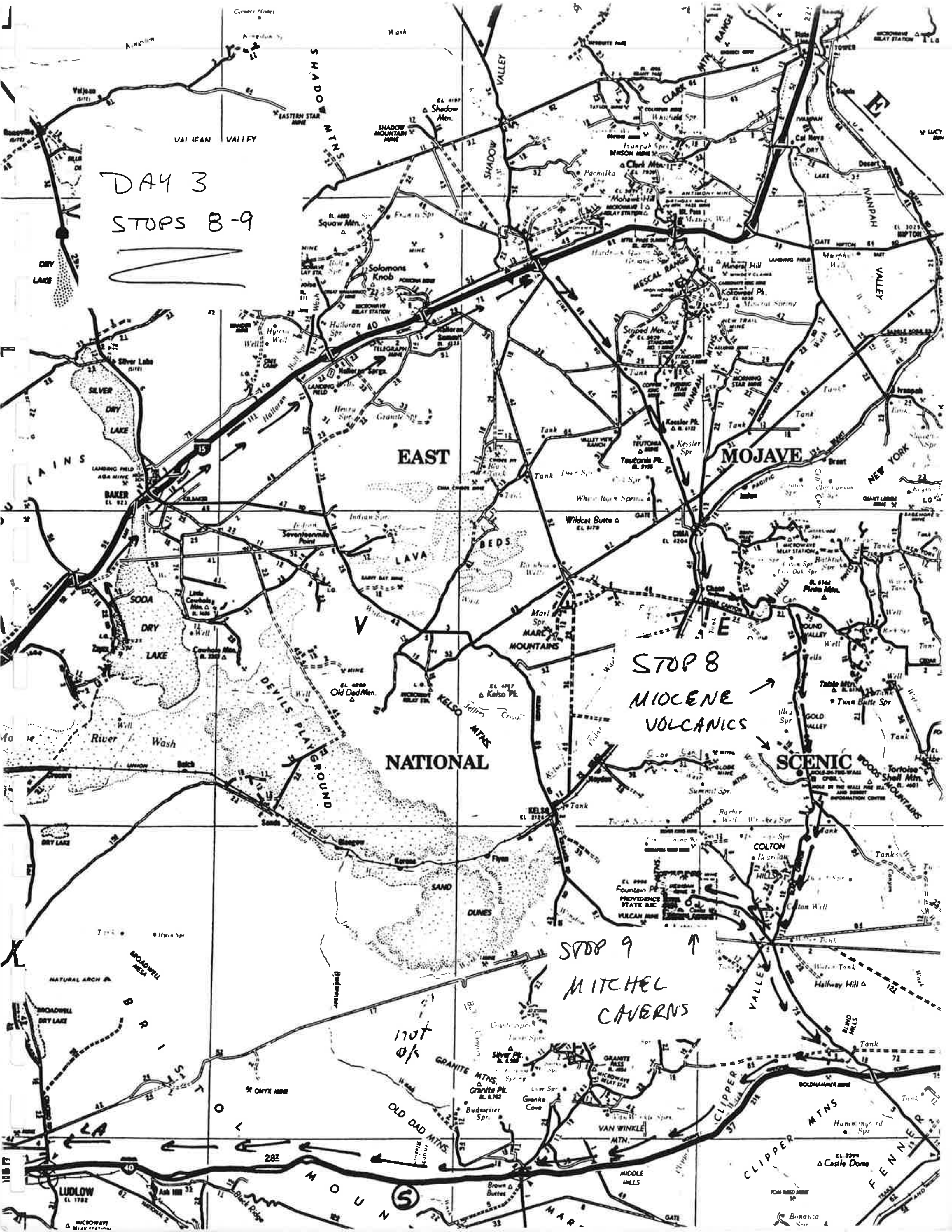
Accommodations - The Desert Research Station is a good-sized and nicely-maintained facility. Sleeping accommodations are dormitory style (i.e. cots and mattresses) with numerous 2-, 3-, and 4-person rooms. Electrical power, drinking water, hot showers, flush toilets and a well equipped kitchen are all available.

What to bring - Be conservative -- we don't have much room. Do **not** bring an ice chest. Suggested items to bring include:

- one lunch for Wednesday (all other meals will be provided)
- warm sleeping bag (no pad required)
- warm clothes for 3 days -- follow the layered philosophy. Don't forget gloves and hat. Tennies are fine.
- towel and toiletries
- plate, bowl, cup and eating utensils
- hammer and hand lens
- camera (and binoculars)
- money for snacks and drinks
- evening liquid refreshments
- hat, suntan lotion, dark glasses
- water bottle, day pack, flashlight


STOP 1
BORON MINE
STOP 2
EARLY MAN
SITE
DAY 1
STOPS 1-4
STOP 3
AFTON
CANYON
STOP 4
ZZYZX
NORTH EDWARDS
EDWARDS
AIR FORCE
BASE
KERN
BARSTOW
LENWOOD
SODA
DRY
LAKE
SODA MOUNTA


DAY 2
STOPS 5-7
STOP 5
CIMA VOLCANICS
a) petroglyphs
b) mafic nodules
c) lava tube
STOP6
BASEMENT
STOP 7
KELSO
SAND DUNES
not o/k
VALJEAN VALLEY
SHADOW MTNS
SILVER DRY LAKE
SODA MOUNTAINS
SODA DRY LAKE
BAKER
EAST
MOJAVE
LAVA
DEVILS
KELSO MTNS
MESCAL RANGE
CLARK MTN
IVANPAH MTNS
SCENIC
Mojave River Wash
SAND DUNES
BRISTOL
GRANITE MTNS.
OLD DAD MTNS.
PROVIDEN
VALLEY
CLIPPER MTNS
LUDLOW
MARBLE
4


DAY 3
STOPS 8-9
STOP 8
MIOCENE
VOLCANICS
STOP 9
MITCHEL
CAVERNS
not
o/k
EAST
MOJAVE
NATIONAL
SCENIC
SHADOW MTNS
SHADOW VALLEY
CLARK MTN RANGE
IVANPAH VALLEY
MESCAL RANGE
IVANPAH MTNS
NEW YORK
LAVA BEDS
KELSO MTNS
DEVILS PLAYGROUND
SAND DUNES
GRANITE MTNS
OLD DAD MTNS
CLIPPER MTNS
CLIPPER VALLEY
PROVIDENCE MTNS
SILVER DRY LAKE
SODA DRY LAKE
BAKER
KELSO
CIMA
LUDLOW
LA
BRISTOL MOUNTAINS
VAN WINKLE MTN.
Old Dad Mtn.
Kelso Pk.
Solomons Knob
Halloran Spr.
Clark Mtn.
Kessler Pk.
Teutonia Pk.
Wildcat Butte
Granite Pk.
Silver Pk.
Castle Dome
Table Mtn.
Pinto Mtn.
Tortoise Shell Mtn.
Fountain Pk.
PROVIDENCE STATE REC
COLTON HILLS
Halfway Hill
NATURAL ARCH
ONYX MINE
BROADWELL MESA
BROADWELL DRY LAKE
MARL MOUNTAINS
Seventeenmile Point
Little Cowhole Mtn.
Cowhole Mtn.
Kelso
Glasgow
Kerens
Flynn
Sands
Baxter
Crucero
Rasor
Dunn
Vulcan Mine
Brown Buttes
Granite Cove
GRANITE PASS
Cornfield Spr.
Budweiser Spr.
Ivanpah
Nipton
Hart
Valjean
Riggs
Squaw Mtn.
Shadow Mtn.
Mohawk Hill
Mineral Hill
Kokoweef Pk.
Striped Mtn.
Halloran Summit
Hytens Well
Silver Lake
Indian Spr.
Wheel Rock Spring
Cima Dome
Marl Spr.
Rock Spr.
Hole-in-the-Wall
Summit Spr.
MIDDLE HILLS
Hummingbird Spr.

Second Symposium on Salt, Northern Ohio Geological Society, vol. 1, p. 133-150, 1966

Stratigraphic and Structural Evolution of the Kramer Sodium Borate Ore Body, Boron, California

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ABSTRACT

The Kramer sodium borate ore body consists of a lenticular sedimentary facies of borax and kernite crystals together with varying amounts of interstitial and interbedded claystone. This sodium borate facies has been divided into seven stratigraphic units. The sodium borate facies is successively enveloped by a ulexite facies, a colemanite facies, and a barren claystone facies. Together, these four facies constitute the Shale member of the Kramer beds. The term Kramer beds is locally used to designate all of the conformable Miocene strata, including the borates, between the base of the Quaternary alluvium and the base of the Saddleback basalt. The borax is believed to have been precipitated in a permanent shallow lake, fed from nearby thermal springs containing anomalous amounts of sodium and boron. AsS and Sb_2S_3 were most abundant in the lake during a late stage of borax deposition. Successive beds of borax crystals protected by layers of mud were progressively deposited as the lake remained structurally low due to movement along a fault scarp at its south edge. The ore body has been deformed by faults and associated folds which developed in several stages. Minor faulting and folding took place in the borax lake contemporaneously with borax deposition. Some of the borax was altered to kernite after burial beneath a great thickness of fluvial sediments. Later, some of the kernite reverted back to borax when regional uplift and erosion and a renewal of local faulting and folding resulted in a reduction of temperature and redistribution of excess water within the ore body.

INTRODUCTION

The Kramer borate deposit is in the northwestern Mojave Desert of California, approximately 100 miles northeast of Los Angeles, immediately north of the town of Boron (Fig. 1). The deposit derives its name from the mining district in which it lies. The deposit is presently being mined from the Boron open pit, which supplies a major portion of United States borate production.

This paper deals with previously unpublished stratigraphic and structural studies of the borate deposit, based primarily on mapping undertaken during the last three years. This basic work is still in progress and will be completed before mineralogic and geochemical studies of a detailed nature are undertaken. The work completed to date has resulted in a series of detailed geologic maps of the ore body which are presently being utilized in open pit design and other mining operations.

The ore body consists of a roughly lenticular crystalline mass of borax ($NA_2B_4O_7 \cdot 10H_2O$), and kernite ($NA_2B_4O_7 \cdot 4H_2O$), containing interbedded claystone, and completely enveloped by ulexite-bearing shales (Gale, 1946). Stratigraphic and structural studies indicate that the Kramer borates were deposited in a small structural, nonmarine basin, elongated in an east-west direction and limited on the south by a fault scarp.

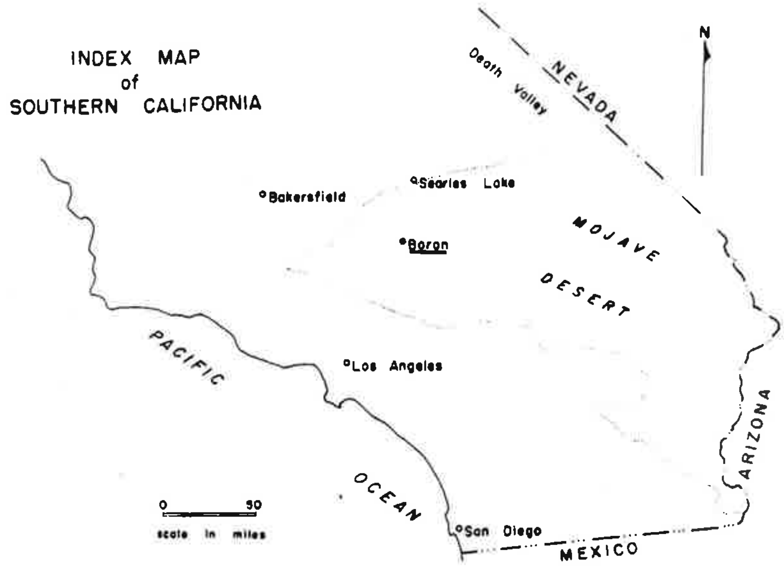


Figure 1. Location map.

Gale (1946) assigned the Kramer borates and associated shales, together with the underlying basalt and overlying arkose, to the Kramer Lake Bed member of the Pliocene Ricardo Formation. This correlation was made on the basis of lithologic similarities and geographic proximity to the Ricardo sediments and volcanics which crop out about 29 miles northwest of the Kramer deposit. The Kramer borates and associated sediments were later placed in the Pliocene (?) upper part of the Tropico Group (Dibblee, 1958).

Recently, however, well-preserved mammalian remains have been uncovered in sediments overlying the borate deposits in the Boron open pit mine. These fossils have been identified as a pre-Ricardo fauna, with an age no younger than early Middle Miocene (Whistler and Tedford, 1964). The term Ricardo can therefore no longer be used for any of the beds associated with the Kramer deposit, and Dibblee's age correlation within his Tropico Group must be revised.

Figure 2. Exposure of the Kramer beds on the north side of the Boron open pit.

GENERAL STRATIGRAPHY OF THE KRAMER BEDS

The term Kramer beds is being used locally by U. S. Borax geologists to designate all the similar dipping Miocene strata, including the borates that lie between the base of the Quaternary alluvium and the base of the Saddleback basalt in the structural basin. The saddleback basalt is unconformably underlain by older Tertiary arkoses, tuffs, and shales.

We have divided the Kramer beds into three distinct members, the Saddleback basalt member, the Shale member, and the Arkose member, in ascending order. Figure 3 is a generalized stratigraphic section of the Kramer beds near the central part of the ore body.

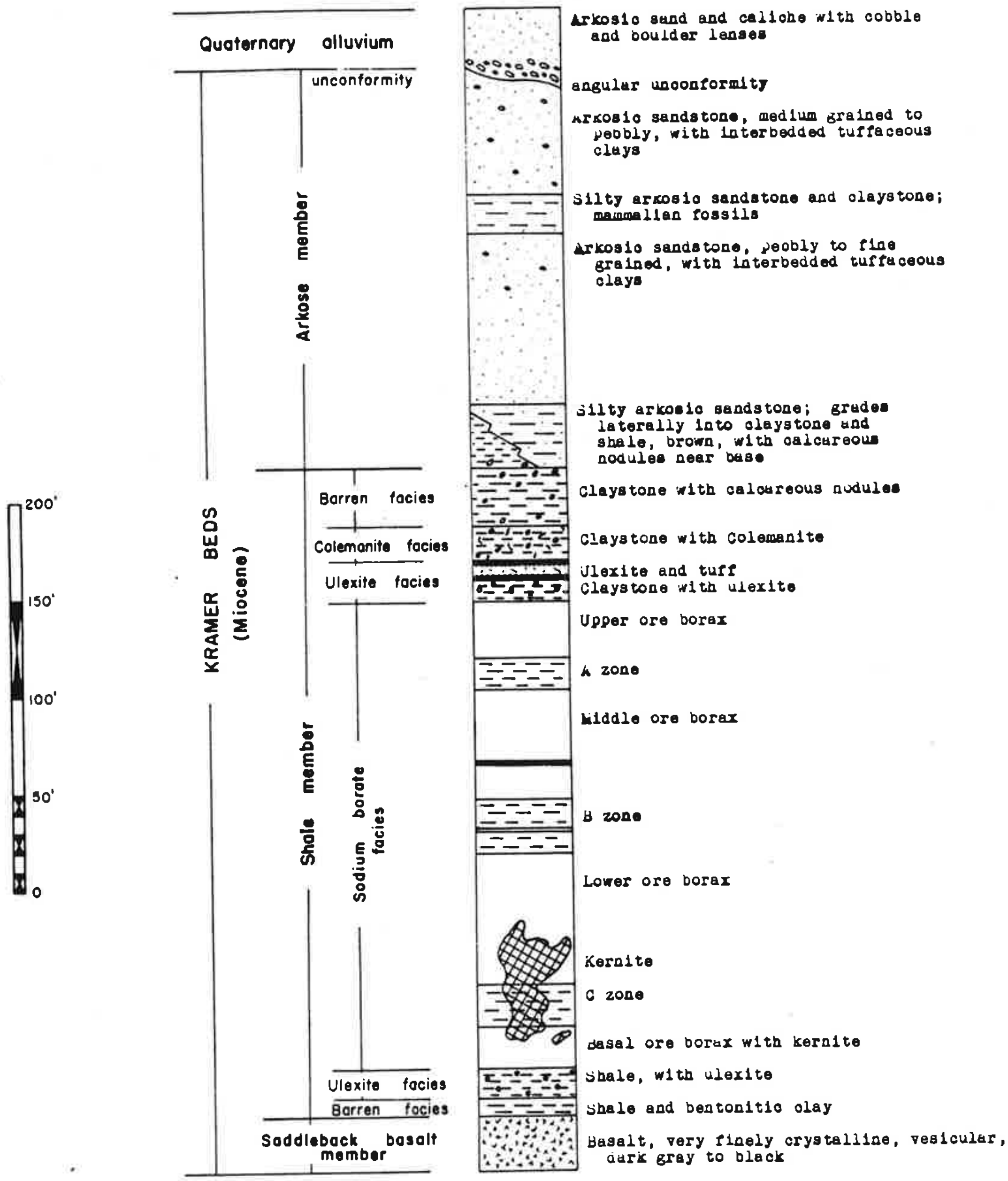
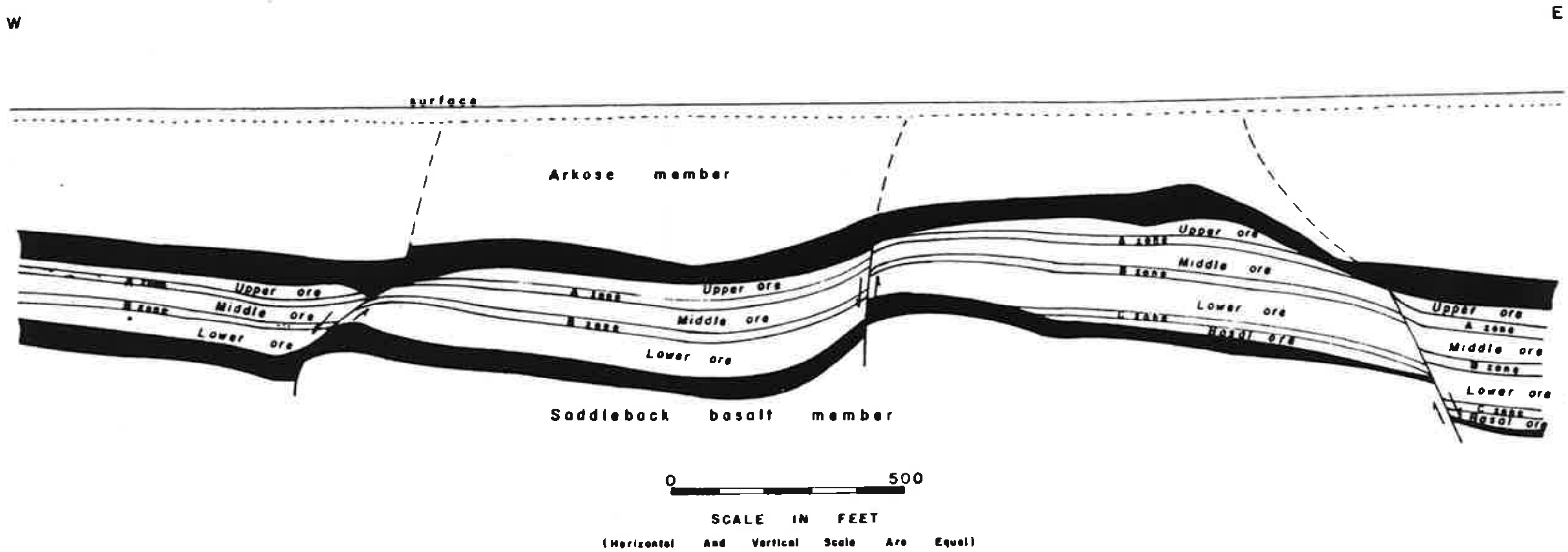


Figure 3. Generalized stratigraphic section of the Kramer beds.



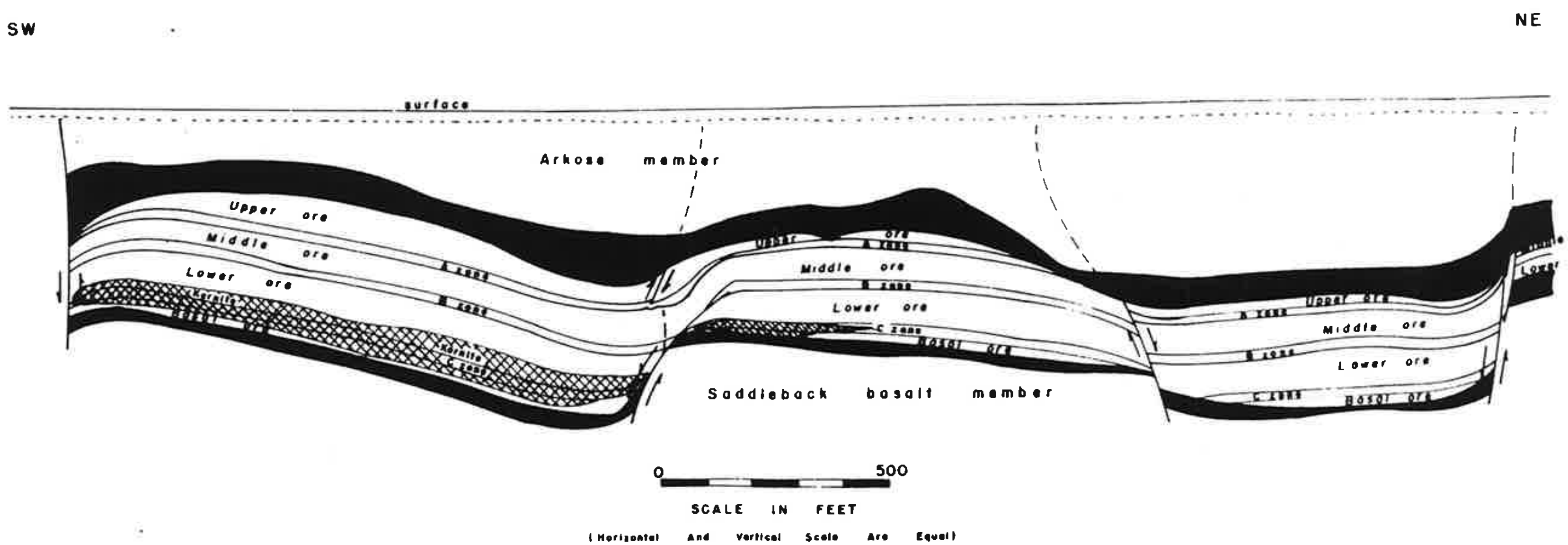


Figure Cross sections of parts of the Kramer borate deposit. Lines of section shown on Figure 8. Darkened areas above and below the ore body represent the ulexite, colemanite, and barren claystone facies.

STRUCTURAL AND DEPOSITIONAL HISTORY AND ITS EFFECTS UPON THE SODIUM BORATE FACIES

Our detailed stratigraphic and structural studies to date have led to the following conclusions regarding the history of the Kramer beds, and particularly the sodium borate facies:

Events immediately prior to and during the deposition of borax.

No later than early Middle Miocene, the Saddleback basalt was extruded on older Tertiary sediments in the area of the future borate basin. This area was already topographically low due to downward movement along the "Western Borax" Fault immediately to the south. Soon after the extrusion of basalt, the topographically low area became a playa basin. The deepest part of the basin was close to its southern border, which was formed by the fault scarp. To the north, east, and west the rise out of the basin was more gradual.

In the structural setting described above, boron and sodium, derived from local thermal springs, combined with calcium from surface water and formed ulexite in the playa muds. (A local thermal spring source for the borate deposits at Kramer has been suggested by Gale, Muessig, and others.) This belief, which we support, is based primarily on the presence of volcanic rocks in the Kramer beds, the association of syngenetic arsenic and antimony sulphides with the borax, the limited suite of evaporitic minerals, and the observation of recent borax deposition at other localities.

A permanent shallow lake soon developed in the central portion of the playa basin. The lake, fed almost entirely from the local thermal springs, contained a great abundance of sodium and boron. The cooling lake brine became saturated with respect to borax, which was precipitated in great abundance in the muds. Muessig (written communication, 1956) has suggested that borax, whose solubility is much more sensitive to temperature changes than other evaporites, probably crystallized at times of decreased temperatures. The solubilities of other salts such as NaCl are not much affected by small temperature changes, and if present in the lake, they remained in solution in the surface waters until they were removed by overflow at a low outlet. The primary precipitation of borax in the lake probably occurred at temperatures in the range (25°-35° C (Christ & Garrels, 1959, p. 517).

During the period of borax, ulexite, and lake mud deposition, the local basin remained structurally low as a result of continued downward movement along the "Western Borax" Fault to the south. Thus, successive beds of borax crystals protected by layers of mud were progressively built up as the basin sank. In the outer portions of the playa, the lake water mingled with calcium-bearing surface and ground waters, resulting in the precipitation of ulexite rather than borax along the margins of the central borax lake.

At three different times during the deposition of borax, temporary slight climatic changes or slight decreases in available boron resulted in the formation of the low-grade A, B, and C zones. During deposition of the B zone, and again during the early deposition of Middle ore, layers of arkosic to silty volcanic ash settled in the borax lake.

The center of borax deposition shifted and the size of the lake varied as the basin was filled with sediments and borax. The first borax deposition was restricted to the southern and eastern portions of the ore body. The borax lake probably reached its maximum development in area in "Lower ore time." During "Middle ore time," the lake retracted slightly from the south and east and shifted slightly farther north. The area covered by the lake was considerably reduced in "Upper ore time," having retracted from the east, south, and north.

From time to time anomalous amounts of AsS and Sb_2S_3 were precipitated in the lake along with the borax. The greatest precipitation of AsS and probably of Sb_2S_3 occurred during the late stages of borax deposition. The local thermal springs were probably the source of arsenic and antimony.

Minor faulting and folding along northwest trending lineaments took place in the borax lake contemporaneously with borax deposition. These vertical movements resulted in less deposition of borax adjacent to faults, especially on the upthrown side.

A CALICO PRIMER

BY JANE BRAKHAGE

INTRODUCTION

Calico. The word was coined early in the Nineteenth Century when the town of Calicut, India on the Arabian Sea started exporting inexpensive cotton cloth to England and America. At first it was white. Then they started printing it on one side in bright colors. Soon England and America were making it themselves just at the time the pioneers were settling the west. It became a symbol of the domestic pioneer woman. Bolts and swatches of it bounced in every Prairie Schooner. Bright-colored female cats started being called "calico cats." Naturally, when miners saw the dry hills in the Mojave Desert with multicolored patches of dirt, they named them The Calico Hills and the Mining town in those hills was called Calico.

Then in 1964, on November first, an archaeological dig was begun on an alluvial fan that welled out from the Calico Hills, and of course that dig was called Calico too.

Archaeology is about as young as the word "calico," though it emerged slowly out of antiquarianism, scientific minds becoming fascinated with treasures looted from exotic graves, human bones found among those of extinct species, beautifully knapped stone tools and carved bones dug up in southern France. Naturally, traditional ideas of human dignity, even religous precepts fought against the developing science and many scientists who dared to believe what they found were booed into their graves.

Anthropology is the study of humanity. Archaeology is the study of old man-made things.

In 1931, two anthropologists, Dr. Louis S. B. Leakey and his wife Mary, began digging in Olduvai Gorge because

they found stones there which, although they weren't nearly as sophisticated as those in southern France, seemed to have been knapped, made into tools, by human or hominid hands. Again, the world scoffed, the scientific community oppposed, friends and family pleaded and a few scattered people supported the possibility. It wasn't until 1959, twenty-eight years later, that Mary found the bones which proved their case. From that moment on, the Leakeys, Olduvai Gorge and Africa as the cradle of humanity became central to archaeology.

THE MIDDLE MIOCENE IN SOUTHEAST CALIFORNIA

Ten to twenty million years ago, where the wind now sweeps across the Mojave Desert, palm trees flourished interspersed with the still waters of swampy lakes. The period was lively with volcanic activity, mostly in the form of lava flows but also there were volcanoes spewing ash which, if it falls thickly into water, solidifies into a soft light rock called tuff. Here and there in those still waters, concentrations of silica dioxide settled and formed into a gel in pockets on the bottom. Other places, blue-green algae lived and died on rocks in the shallows of the lake, leaving behind organic lime which across many centuries grew, exquisitely complex like a tiny coral, into another kind of soft light rock called tufa. When a palm tree died, sometimes a piece of it was buried quickly enough to be preserved. Some of those pieces of buried palm wood were in places where water full of silica dioxide could seep into them and replace each cell of the wood as it rotted away with silica gel which hardened to stone.

This was the Miocene Epoch. During the Miocene, a type of rhinoceros waded in American waters, gigantic long-necked camels browsed treetops, there were three-toed horses and pigs that stood six feet high at the shoulder. There were giant armadillos.

Two to three million years ago, during the Pliocene Epoch, weather patterns changed and the swampy lakes dried up. Animal and plant forms changed radically across a few thousand years. The silica that had gelled under the water dried when the water was gone and hardened into solid, flat-topped formations of chalcedony and chert.

THE TIME OF LAKE MANIX

Half a million years ago, a dramatic geological event occurred which is called the Pasadena Orogeny (Orogeny means the process of the formation of mountains). Over several thousand years, thousands of square miles of the American west bulged up and then some of it sank back, leaving these small mountain ranges which now grace our Mojave Desert. It may well have been at that time also that hot springs steamed east of the new Calico Hills long enough to form plates of jagged sparkling quartz crystals.

It was during this era of activity that Lake Manix was formed. There was water here then, some of it snowmelt from the San Bernardino mountains. The Ice Ages kept the area cooler and wetter. At least it wasn't the stark desert it now is. The Calico Hills were furred with pinyon pine, juniper and live oak and dancing with mountain sheep. The Newberry Range across the valley had white fir. Lake Manix crawled with freshwater clams, snails, stickleback and chub. Flamingos stood in reeds and cattails. White pelicans swarmed up startled into flashing swirling swarms when a herd of giant bison thundered toward them or a dire wolf approached. Various ducks, loons, grebes, coots, cormorants, sandpipers, phalaropes, gulls, eagles and cranes made much use of Lake Manix. Dire wolves, coyotes, mountain lions, scimtar cats and two kinds of bears thrived. There were mammoths here. Three sizes of ground sloth, two sizes of horse. Two types of camels, two sizes of llama. Antelope. Jackrabbit. Mouse.

There were essentially three types of environment here during the Pleistocene Epoch, the lake, the hills, and the vast grassland valley-floor. Streams poured out of the hills then and beside those streams and in marshes, various bushes grew. The succulent-leaved goosefoot was common, and several types of grasses. The oversize bison and the mammoths, the horses, camels and antelope grazed and browsed. To feed mammoths, there must have been plenty of vegetation. Elephants eat a lot. The mountain-lion-size scimtar cat has been considered to have loved nothing better than a meal of young mammoth. The large ground sloth seems to have lived mostly on grasses. The smallest kind lived in caves, ate bark, leaves, berries, tubers. The middle-sized sloth browsed on bushes near water. Camels were abundant. They lived in the dryer places, ate thorny things and dried grasses. A kind of big sagebrush called Ambrosia grew here then. There seems to be some evidence that the llamas reached up with their long necks like giraffes do and ate out of the trees. Coyotes scrounged carcasses, chased birds and jackrabbits, and probably howled. And at some point during this time, Calico Early Man arrived and stayed for probably thousands of years.

THE ALLUVIAL FAN

At some time during the Pleistocene Epoch, there were flows of mud, rock and debris down Mule Canyon East and out fan-shaped across the little hills near the hot springs. These flows built up, layer upon layer, for up to about 10,000 years, certainly less than 20,000 years. Some flows roared down rolling rounded nodules of chalcedony and chert that had broken off from outcrops in the hills. Other flows came more gently, smoothing and filling in with finer gravel and sand. Water erosion started to work in the flow immediately. Gullies carved into it going outward in every direction, leaving ridges splayed out. This formation is called an alluvial fan and can grow out for miles across foothills and plains. This particular alluvial fan is eight miles long and five miles wide. It is called the Yermo Fan. The surface of the middle part of the fan where the Calico dig is located seems to be older than the north and south sections. At some point during the time of its building, a fault slip seems to have occurred, plummeting the outlet of Mule Canyon East down perhaps as much as seventy-five feet, making a trough which then sent the later flows north toward Coyote Lake and south toward the Manix Basin. The Calico dig cuts through layers of flow down at one point into the lake bed sediments from the Miocene Epoch. On the north and west walls of Master Pit 1, the history of that alluvial fan is laid out in sedimentary layers which tell the tale of the growth of the fan like tree-rings show the life and times of the tree. Unfortunately, there aren't so many such concise cuts into an alluvial fan as there are into ancient trees so the geologists, looking at that wall, have more questions in their minds than the layman does. That layer of hardened sand, for instance, could be a little stream

which ran for a number of years or it could have been laid down in a day or a week of comparatively lighter rain. The age of the alluvial fan is still unsure. Calcrete from the lower levels of Master Pit 1 has been tested and the answers averaged out to about 200,000 years. This result displeases Calico site Director Ruth deEtte Simpson (but everyone calls her "Dee") who would prefer an age for the Yermo Fan of 100,000 years. "The artifacts of Calico Early Man are more like Neanderthal workmanship than that of Homo erectus," she says, " but that's what the tests averaged out to, so we have to live with it." Some geologists are now thinking that the fan is even older, maybe as old as 500,000 years, but no scientific evidence has as yet been brought forward to refute the earlier tests.

Calico Early Man's tools were deposited in the Yermo Fan during most of its formation. However, the top few feet of Master Pits 1 and 2 are barren of his artifacts and for that reason we assume that he died off or left the area before the flow stopped.

THE DEATH OF LAKE MANIX

Lake Manix covered about 150 square miles, more or less. It had, across its history, four major shorelines and these can still be seen here and there in the desert and on some hillsides, particularly around Afton Canyon. It was roughly in a T-shape, the long part of the T reaching down to Afton Canyon eastward where it overflowed into Lake Mojave near the present town of Baker, California. The dry remnants of Lake Mojave are called Soda Lake and Silver Lake today. At the top of the T, the Mojave River ran on the surface, bringing in water from the San Bernardino

Range summer and winter, keeping the waters of Lake Manix fresh.

About 19,000 years ago, the lake waters overflowed, eroding away the natural dam, then drained, it seems, catastrophically into Lake Mojave in a matter of a few days or weeks, leaving behind two isolated lakes which had formed the two arms of the T, Troy Lake, eight miles south of the Calico site, and Coyote Lake, two miles to the north. Those two lakes, having no outlet, soon turned brakish and ephemeral (i.e. wet after rains but otherwise dry).

Then, 12,000 to 10,000 years ago, the last ice age ended and enormous changes occurred around the world. The Bering Strait and the continental shelf were covered over with ocean. Weather patterns changed and the stark, dry Mojave Desert replaced the grasslands. The Mojave River runs on the surface for only part of the year now, but wells drilled near its seemingly dry bed produce remarkable amounts of water.

The world-wide changes in climate caused tremendous changes in flora and fauna everywhere. Many of those animals which had inhabited the Manix Basin as well as many other areas in North and South America, i.e. the camels, horses, sloths, mammoths, scimtar cats and many others, became extinct. Some of those which survived, such as the antelope, bison and wolf, changed their body forms radically, moved into different areas and adjusted to different lives.

A group of people whose work we call the Lake Manix Lithic Industry lived here during the latter part of the last great ice age and into the warmer modern times (called the

Holocene Epoch), i.e. from between 33,000 and 8,000 years ago. Their chipping stations and their stone tools lie on the surface of the Yermo Fan. Similar tools have been found at San Diego, in Wyoming, Mexico, Brazil, Chile, Canada and many other places in the Americas.

About 14,000 to 11,000 years ago, some of the most sophisticated projectile points in the history of the world were being made in the Americas. These are called the Clovis and Folsum projectile points.

THE MOJAVE DESERT

The Mojave Desert has an undeniable stark beauty. Sunsets and sunrises can sometimes be overwhelmingly colorful and go on for over an hour. Pinks go to reds and reds to lavender and green which darken down to olive, opal, deep purple. Small dry treeless mountain ranges rise hard and steep throughout the Mojave. It is what's called a high desert, ranging from 2,000 feet to mountain peaks over 5,000 feet in altitude. The full moon brings out the eerie vastness of it all and the predatory life. During the day, the sun cannot be ignored. Temperatures in the summer rise often to 115 or 120 degrees Fahrenheit. In the winter, days range from the 70's down to the 20's at night. Across an average year, four to six inches of rain will fall, mostly in early spring, bringing to life thousands of tiny plants which hasten to bloom and be done if the moisture of the soil lasts. Wind from the Pacific Ocean dumps almost all its moisture onto the San Bernardino Mountains which form the southern edge of the Mojave Desert and the Tehachapi to the west then sweep dry eastward across it. Storms, which elsewhere are torrential, in the Mojave are in the form of dry raging winds. Dust devils have nothing to stop them. Wind over the centuries from the west has blown

much of the sand away eastward and the surface tends to be more hard and rocky than sandy.

Because of the wind and because of the often freezing temperatures in the winter, there are none of the giant cacti of the Sonoran Desert southeast of the Mojave. Small, low cacti, creosote bush, desert holly, etc. sparsely dot the dry alkaline gullies and protected hillsides of the Mojave. Tiny birds chatter here and there. Lizards skitter about catching insects. At night, kangaroo mice hop about and the poisonous Mojave rattlesnakes dart after them. Roadrunners dash at speeds up to thirty miles per hour after the lizards, sleep on the ground beside a bush or a projecting rock. In the morning, they bare their sparsely-feathered backs to the sun and bask sleepily for sometimes well over an hour. Coyotes, bobcats and various hawks find enough to eat. The desert tortoise is very rare now because of roads and other human intrusions on their lives. But those same human intrusions have brought in ravens and crows by the hundreds to scavenge roadsides and garbage dumps.

The fascination of the Mojave Desert is great and has spawned a form of humanity called the "desert rat." Desert rats roam these forbidding lands in four-wheel-drive vehicles and on foot, their clothes usually ragged, faces dark and weathered by sun and wind, grimly determined to find silver or precious stones or artifacts or perhaps only silence and solitude and that sense of ones own smallness in an immense world that is so intense in a desert. Some of these desert rats die early on. The desert is a harsh habitat. Some of them learn a lot about it. It was one of these, Ritner Sayles, who worked for the Southwest Museum of Los Angeles scouting for finds and sites, who first brought the concentration of crudely-made artifacts on an alluvial

fan jutting out from the Calico hills to the attention of Dee Simpson, then Curator of the Southwest Museum and of Gerald Smith, its director. Dee Simpson and Gerald Smith decided to go with Sayles and see what he had found.

DESERT PAVEMENT

Up on the ridges, the wind has blown sand and other fine stuff away, leaving the rock behind. Years, centuries, actually thousands of years of dry wind has blown across these ridges, taking the fine stuff off and not replacing it. Sand, silt, organic matter, anything light enough for the wind to pick up, it will do so and carry it for miles perhaps across the land. If there's a rock under another rock, the upper rock will eventually roll off the lower one to lie beside it. After these thousands of years, the wind has arranged and laid out evenly all the rocks from the top few feet of ridge surface till they're packed together like cobblestones. In some places the surface seems almost smooth enough to rollerskate on.

Then, when the rocks are that close together, the wind drops fine silt down between those rocks and, with the help of the average of four to six annual inches of rain, packs that silt tightly into something resembling cement which then holds those closely-knit stones in place.

ROCK VARNISH

The silt that blows in and the soil that it mixes with are both highly alkaline. Calcium and iron are plentiful here. As these rocks then sit for thousands of years cemented into one spot, the iron oxidizes on the buried surface of the

rocks and turns it a characteristic rusty orange color. Many of the rocks on the desert pavement surface are orange on the bottom where they have spent centuries developing that iron oxide layer.

And many of those rocks are shiny black on top. The black upper surface is formed by another process, a very complex process involving many lives.

On the black upper surface of each of those rocks dwells a forest of tiny algae inhabited by a type of bacteria which, while it lives, collects, concentrates and exudes that black manganese oxide. These living things are dependent upon a neutral environment, i.e. neither acid nor alkaline. The Mojave Desert's few inches of rainfall keeps these surfaces cleaned enough of the alkaline soil to provide that neutral environment. Pick up any one of these orange and black rocks and you hold in your hand an entire ecology, a world of plants and animals in a splendid and stable balance which has continued for centuries upon centuries unchanged except for one thing. The layer of manganese oxide left behind by the bacteria while they live sticks to the rock, gradually thickening across the centuries. These two common deposits on desert rocks, the orange iron oxide and the black manganese oxide are called "rock varnish."

FLINTKNAPPING AND EARLY MAN

The first thing we relate to in the search for the origins of Homo sapiens is the manufacture of tools. The few societies remaining today based on the hunter-gatherer economy have tools of many materials — fire-hardened wooden spears, digging sticks, bags made of woven net, leather or animal stomachs, clothing of leather, vegetable fiber, homes of hide, sticks, leaves. One could go on and on naming various manufactured goods and finally come to something made of stone. The stone tools of a society have probably always been a small percentage of our ancestors' total tool kit. But, unlike all the other equipment, stone survives.

Who knows what wood, leather or vegetable fiber was being used and for what by whatever hominid first took a cobble and broke it in half to get that edge? Later they started breaking those halves in half again for a straighter, sharper edge. And later yet, they invented flaking. This was a big step. Life was stable then. Things didn't change fast. To make a quartered cobble takes two hard blows on the rock. To make a flake takes precise sweeping blows with a hammerstone. To make a core tool, one has to remove many flakes. It takes a knowing eye, a certain amount of learning and skill, and it takes knowing your rocks. For many centuries, the flake and core tool industry developed. Flakes and cores of different types gradually emerged into distinguishable tools. These hominids learned to remove the rough cortex of the rock, they learned that a platform with an acute angle was the best place to strike, they learned how to prepare a core before striking the blow that could make the tool they needed.

That particular sweeping blow leaves its sign on the flake and on the core it came from. It leaves a bulb on the flake and a negative bulb on the core from which anyone can see just where that blow struck. Beyond the bulb, concentric ripples, force lines, circle out from the bulb like the ripples on a still lake when one drops a rock in. Sometimes an overdone blow will make a hinge, one of the force lines

curving through the flake to the other side to make a smooth rounded end to the flake.

Gradually the tool kit became more complex. Gradually these hominids developed edge-flaking or retouching, the process of straightening, sharpening or saw-toothing the edge of the flake to achieve particular results such as a smooth scraping edge, resharpening a blade that had gotten dull, or forming the edge into a sawblade. This edge-work was originally for thousands of years achieved with a light blow by a small hammerstone or perhaps the blunt end of a bone or antler across the edge.

Then the process called pressure-flaking was discovered, in which the flintknapper, instead of striking the rock with a hammer-stone, presses on the edge with a pointed tool like the tine of an antler or a sharpened bone.

By the time edge-flaking developed in the Americas, we have come to about a quarter of a million years ago. The species may have been Homo erectus which had been living on earth for over a million years. He stood erect, lived in family bands and had discovered the tremendous value of fire.

We can decipher what their life was like only from the few tools that have survived across the millenia. And of course those few tools are all of stone. What these tools were for, we can only make educated guesses.

SILICIOUS ROCK

To understand what early man was working with, we should know the nature of silicious rock. And also to

understand one of the basic controversies whirling about the Calico site, we should study how silicious rocks break and the shapes they tend to make under different circumstances.

Silicious rock was the material used by early mankind for toolmaking because of its ability to break into different shapes from different blows and also because it could be made to be very sharp. All the various kinds of quartz, flint, agates, chalcedony, chert, obsidians and other rock types around the world used in flintknapping are basically silicon.

Unless the chalcedony or chert is still in its original flat-topped place of origin, it tends to be rounded. There are thousands of silicious boulders that have rolled into the Yermo Fan, all bulbous, nodular, i.e. rounded by nature into lumpy round shapes, all surfaced with a rough, pitted cortex. Nature tends to round off silicious rocks. It tumbles them about with bouncing and rolling action, it sandblasts the surface, fills the tiny holes with dirt and sand and living things which, across the centuries, grind the holes bigger and deeper till to look at one of these rocks, one would find it hard to realize the deep smooth inside of it.

Early man knew to look for just that kind of round rough rock, to then chip away the cortex with sharp percussive blows. One great thing about silicious rock is that the kind of blow that breaks it is so clearly recorded in the break. Those bulbs on the flakes broken off, the negative bulbs left on the core, the force lines, all record the percussive blow that flintknappers the world over used for thousands of years in making their tools.

DID NATURE MAKE THESE ARTIFACTS?

Nature can make bulbs and negative bulbs too. Here and there on the Yermo Fan, one can find an example of this, where some rock was struck just right by another rock and two or three flakes with bulbs and force lines stand stacked together at one end of a piece of chert like sliced bread. However, it's not a very common occurrence. The slopes of the alluvial fan are smooth and rocks tend more to roll than to fly through the air to make such a percussive blow.

There are other ways too in which nature can achieve a similar result, especially in a hot desert. If a chalcedony boulder sits for hours in the hot sun and then is struck by a drop of water, sometimes the instant evaporation of that drop of water will shatter out a round chip. However, in that case, the shape of the chip and its scar on the boulder differ from those made by percussion. It tends to be more scooped and to have no force lines.

Sometimes a cloudburst will come on a very hot day and a silicious rock will shatter into many pieces and one or two of those pieces may look like a good chopper or blade. In that case, however, almost all of the pieces are blocky rather than flaked and also the shattered rock sits in a clump rather than the scattering of sharp flakes left by a flintknapper.

Then there is the question of edgeflaking and use-wear. Well, sure. Nature can do those things too. Say one of the pieces of the shattered stone was scraped just right against another stone, there at that spot would be an edge-flake scar. Or maybe a blade-like piece happened to have occurred in the shattering of a rock and somehow as it lay on the ground it got rubbed and rubbed just on the sharp edge.

But this is beginning to sound far-fetched. What if ten or twenty or fifty edgeflakes were made on a single rock? What if hundreds of these rocks show use-wear? What if there's alternate edge-flaking? What if there are thousands of examples of rocks found in a small area that have been flaked by percussive blows, trimmed and edge-flaked into the shapes of tools made by early man in Africa, Asia, Europe? These are some of the questions that the Calico Early Man collection present.

The most likely explanation seems to be that humans or hominids made both sets of artifacts of the Calico site, the 200,000-year-old Calico Early Man artifacts from below the surface and the Lake Manix Lithic Industry which dates from about eight thousand to thirty thousand years ago. Stone tools akin to the Lake Manix Lithic Industry have been found in sites in Alaska and Wyoming, in Texas and Mexico, among mammoth bones in Brazil, in the Atacama Desert of Chile and several other places across North and South America.

So why is Calico still a controversial site? That's easy. Bones of animals from early ages have been dug out of the ground in South Dakota, Nebraska, Wyoming, here and there all across the Americas. Just a few miles down the road from Calico at Camp Cady, a serious and well-documented paleontological survey was made and it is from George Jefferson's work, including abstracts from that survey that we know as much as we do about the fauna of the Lake Manix times. But at none of these digs has a single human bone been found that can be dated conclu-

sively older than at the most ten to twenty thousand years old. Until ancient human bones are found — anywhere in the Americas — these stone tools are an enigma that scientists find it difficult to deal with. Archaeology wants to be absolutely sure of its facts.

The Bering Strait was open off and on for the last 500,000 years up until about 10,000 years ago. It was open 250,000 years ago. It was open 100,000 years ago. It was open many times in that vast era of history. And every time it was open, the continental shelf was open too. Cold summers when snow never melted near glaciers and icefields enlarged them, thickened them. The icecaps became as thick in what is at the moment called Wisconsin and Montana as the ice now is in Antarctica — one to three miles thick. Less spring run-off ran down into the sea. All the seas shrank as much as 350 feet world-wide. The Pacific continental shelf was a lush, fairly level walkable environment between the mountains and the Pacific shore, including the 80-mile-wide Bering Land Bridge. Certainly, early man would have wandered across on foot. All we need to prove it is his datable bones.

THE CALICO DIG

Dee Simpson and Gerald Smith followed the museum scout, Ritner Sayles, to the top of the ridge and walked a long way. And they saw embedded in the desert pavement stone tools like those they had seen in books and reports from Africa, Asia and Europe. These stones were obviously worked but they had none of the sophistication of the spearpoints and arrowheads that the American Indians were making since ten or twelve thousand years ago. Dee went back to the place again and again, showed samples to other

archaeologists, most of whom scoffed. The stones were too crudely knapped, they said. Since they lacked the fine workmanship of the Indian flintknappers, either they were blanks or they were the result of natural processes. In vain she showed them edgeflaking or compared the stones to pictures and discriptions of Dr. Leakey's finds. They all said she'd have to get sub-surface finds. Their final argument would always be that everyone knows that there had never been humans on these American continents primitive enough to have made them.

Then one day in 1958, Dee arrived at the ridge and found a bentonite prospector digging in a gully with a bulldozer where she had seen the stone tools the thickest. At first, she was horrified but then she realized this was an opportunity to see if there were any of these artifacts below the surface. She waited till he went away and then looked along the wall of the cut he had made. And she found stone tools and she took them, packed them in a suitcase and went around to every institution in America that might be able to finance a dig. And one after another they all said that humans hadn't been here that early and the stones must therefore have been chipped by nature.

So she took her suitcase full of stones to Europe and in Europe everyone had seen stones knapped like that, they even had samples in their collections of tools that matched those that she brought. They were all very excited and encouraging. They were sure she could find backing in America. No, they couldn't afford to finance a dig. She went to London and managed to get an appointment with Dr. Louis S. B. Leakey himself. And Dr. Leakey was very excited because the stones she showed him were very like some of the tools he had been digging out of Olduvai

Gorge. "I'm extremely impressed," he said, "This will be one of the most important excavations in the Americas! Next time I come to America, I'll want to visit your site."

Dee came home knowing she had something wonderful, knowing she must somehow find a way to get a dig going on this spot, to find what was buried here and try to decipher what it meant. She contacted again every institution that might back such a dig. And soon she was receiving her answers. All in the negative. For five years she watched the bentonite prospector busily tearing into the hillside, unable to dig there herself with the careful ways of the archaeologist. That prosopector continued to dig until his death although the bentonite was of poor quality and he never sold any.

In 1963, Dr. Louis S. B. Leakey came to the U. S.. to lecture and when he lectured at the University of California at Riverside, she went to hear him. She sat in the very front and was the first one up to speak to him afterward. "Remember me?" she asked. Dr. Leakey had, among all his other considerable abilities, a remarkable memory for faces and years-old conversations. "Of course I remember you!" he said. "How's the survery going?" Then she explained to him that no one would back the project. "Well," he said, "Let's go take a look!"

And the same thing happened to him as had happened to her. "This is remarkable," he said. "This has to be dug." "I've been rejected by absolutely everyone," she said. They were clambering slowly up the steep side of a new cut that the bentonite prospector had just made across the side of the ridge, their eyes barely inches from the ground. "You will be surprised what you're going to find!" he said.

But he didn't explain what he had seen. They got to the top of the ridge and started roving across it. "Dee, dig here!" he said excitedly. He was standing exactly on the spot where Master Pit 1 now is. The idea was to dig where everyone could see that the ground hadn't been disturbed for thousands of years, to do an inmpeccable job, the ultimate in archaeological technique. All by hand. He decided they should leave a witness column where others could dig for themselves if they didn't believe what was found. Besides, new testing techniques are popping up all the time. He walked slowly across the black-varnished desert pavement, his eyes intently sweeping the ground around him as all anthropologists walk, stooping often to look at a stone tool or a work circle, exclaiming, muttering, planning.

National Geographic backed Dr. Leakey as director of this project and on November 1, 1964, they had staked out an area with a "witness column" in the middle of it where no one was to dig. The diggers were each given a five by five foot square of dirt which was their world, their place of work. Some of them returned daily to their squares for years.

DIGGING TECHNIQUE

One quarter of the five- by five-foot square is dug down three inches and a page or two of notes made on that quarter before then the next quarter is begun. The digging tools in Calico are a light rubber hammer and a little awl to break the soil, a whisk broom, a gallon plastic bottle cut into a dustpan and a ten-quart bucket to collect the fine stuff, small stones and dirt.

Exciting finds are triangulated, i.e. measurements are made to show exactly to the half-inch where the tool lay. For such finds, workers use small brushes and dental picks. Levels and tape measures are in constant use in the digs, making sure of the depth. Triangulated finds are mapped on a grid in the notes along with other rocks and boulders found at that level so that a picture of that three-inch layer and everything found in it is recorded.

When the bucket is half-full or so, the worker carries it out to the screens. On a workbench-height stand at the edge of a cliff are stacked three stout hardware-cloth screens, the top one is of half-inch mesh, the middle is quarter-inch, and the bottom one one-eighth inch. The worker empties the bucket onto the half-inch screen and picks out any interesting specimens, tosses the rest down the cliff, does the same again on the quarter-inch screen and again on the eighth-inch screen. Any finds are bagged and labeled with the depth, the code number of the five by five foot square, which quarter they came from, the date, name of digger, and type of find. Much that is found through the screens is what they call debitage, tiny flakes that fly around during flintknapping. Silicious stones from each square which haven't been chipped by early man are saved too and show clearly their rounded and crusted surfaces.

THE MUSEUM BASEMENT

All the specimens are taken to the San Bernardino County Museum. San Bernardino is the biggest county in the United States and has a museum with really impressive natural history exhibits. Naturally, there is a nice display case of the Calico finds. But it's in the basement of that museum where a great deal of work is done on the finds

from the Calico dig. In the basement, every stone from the dig is studied through a magnifying glass and more notes are made in reference to it. Some seem to have been resharpened. There are cores in the collection from which tools have been struck. Hammerstones have been found. Types of blows are noted. Some flakes are concavo-convex, showing that the flintknapper struck twice with the same type of blow at very nearly the same place. Some edges are toothed by being struck first on one side then the other down the length of the edge. This makes a more solid, long-lasting tool with a capacity similar to a ripsaw. And on and on. There are sixty-three different catagories of identification and often several are noted on one artifact.

The stones are kept mostly in boxes labeled according to their position in the dig. Cross-references are kept too so that if one wants to know for instance how many good hide-scrapers were removed from Master Pit 2, which level or square in Master Pit 1 had the most artifacts, who was working the square called Q 19 during May of 1970 or whatever, the answer is readily available.

WHAT HAS BEEN FOUND IN CALICO

Here are some of the catagories and some of their possible uses:

Convex scraper - for cleaning hides.
Concave scraper - to smooth spear shafts.
Reamer - to enlarge a hole, especially in bone.
Anvil - for breaking off stone flakes.
Wedge - to split wood.
Handaxe - for shaping wood, for digging roots out of hard soil.
Chopper - to cut meat or wood.

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Burin - a grooving implement.
Cleaver - for cutting large hunks of meat.
Pointed tool - to shape wood.
Pick - to break hard soil.
Blade, bladelet - sharp.
Sharp flake - very sharp. For fine cutting.
Graver - for woodworking or perhaps for hides.

No one knows positively what these tools were for. These guesses may be wrong. They do suggest that wood and hide were made into useful things. What we do know is that this complex collection of shaped, flaked and sometimes also edge-flaked stones are found repeatedly in sites where Homo erectus and Homo sapiens Neanderthalensis, i.e. Neandethal Man, lived and died. Often a stone will seem to be multi-purpose, a reamer-blade, a scraper-graver, or a chopper-cutter. Surely, many of these tools were used in butchering meat and in collecting and preparing plant foods. Many do seem to be meant for preparing hides, others, like the concave scraper, suggest that wooden spears were probably used to kill large animals. There are no projectile points in the Calico site. If spears were used, the points were of fire-hardened wood.

From the surface of Master Pit 1, the diggers gleaned a few finds. Then for three to five feet, they found next to nothing. Dr. Leakey had prepared them for this possibility. "When you come to a barren stretch, keep digging!" he said. And so they did. He came to visit the site three or four times a year, usually trailing a covey of journalists and photographers. Somehow, he always managed to find time to bake bread in the little gas oven, to look over the finds, to do a little digging in the pit himself, talk with members of the crew, and plan strategy with Dee Simpson.

Below the barren layer, an assemblage of stone tools very different from those that Dee Simpson had been excited about on the surface were found, some better-made than the surface artifacts. They were flake and core tools as were the surface finds, some were edge-flaked, they could be catagorized into the sixty-three identifications, they were made of chalcedony, chert, jasper, petrified palm, they fit nicely into the hand. But the workmanship and the resultant tools were different. They were very very old. Dee Simpson and her crew were wide-eyed. Dr. Leakey arrived and his eyes sparkled. Journalists scribbled, photographers snapped pictures. There was no doubt in his mind but that they had come to a very different people. They named the surface layer of tools the "Lake Manix Lithic Industry" and the very different work below "Calico Early Man." "Keep digging," Dr. Leakey said, "Carefully."

They kept digging, three inches at a time, their skillful hands sweeping and digging, their knowing eyes recognizing bulbs and force lines. The alluvium (underground soil) of every three-inch layer they dug seemed harder than the previous layer. This was, as a matter of fact, true. Age and the weight of the ground above compress and harden the lower deposits into what some call "calcrete," somewhat more crumbly than concrete but not much.

Even underground, the artifacts were not evenly distributed. Chipping stations like those on the surface would emerge in the digging, be described, each stone in its place, copious notes made, then the stones sent to the museum and the digger would dig on. At about a thirteen-foot depth, among fist- to head-size round boulders of silicious rock, the diggers were finding artifacts everywhere. Here it

was also that three small pieces of mammoth tusk were found, the first and, as it turned out, very nearly the only organic remains except pollen to be found in the two Master Pits, the alluvium of that area being so alkaline that it more or less digests (the word is hydrolizes) all organic matter like lime does.

Below the rich boulder layer on the north edge of Master Pit 1, the diggers came to a four-inch layer of hardened sand where it could be that a small stream had once run and below that, there were considerably fewer artifacts. It was at this point that Dr. Leakey felt that another pit should be started forty feet northwest of that wall to see what was going on on the other side of the stream.

It was obvious to them now that the top few feet of soil wouldn't contain what they were looking for now so they began Master Pit 2 with pick-mattocks. Five feet down, they came to rounded boulders of silicious rocks, leveled it off, and started digging in the proper fashion.

Again, there was a witness column and again, they were digging in three-inch layers with the small tools, the three screens, the little brush, the dental picks. And again they found artifacts. Then, at a depth of twenty-three feet, one of the diggers encountered a circle of rocks that seemed to be a fire circle. With infinite care and excruciating patience, she swept and picked until Dr. Leakey told her she must stop. The Calico dig now had a "feature." Digging continued in Master Pit 1 and test holes were being dug here and there for various reasons. Some were searching for places where more organic remains might be found. Others were responding to the many accusations and doubts that the anthropological community and the society at

large presented as to the validity of any of these finds. Controversy swarmed around the Calico dig like biting flies. Louis S. B. Leakey had lived most of his life under such attacks. The Calico dig learned to live with them, to be stimulated by them to the ultimate in archaeological techniques and to finding more if they could. And many tests were made by interested people in several different sciences. (See the section "Experiments and Controversies.")

AFTER 1972

Then, on October 1, 1972, Dr. Louis S. B. Leakey died. Even if we disregard the sorrow of the people of Calico and the loss of his tremendous experience, brilliance, leadership and encouragement to the project, the results of his death were devastating. Immediately, all finiancial support was removed from the Calico dig as well as much of the attention and a great deal of the respect that Dr. Leakey's involvement had drawn. Mary Leakey and her son Richard took a stand against any possibility of authenticity in the Calico finds and complained bitterly to the press that he had been obsessed with Calico the last eight years of his life to the detriment of his other projects.

Dee Simpson told the diggers that she couldn't pay them and they might as well go home. Many of them stayed and worked on as they could for years, even for decades. Some of those original workers still do volunteer work now a quarter of a century later. Dee set out to find a way to preserve the site for future work. The Bureau of Land Management said they would preserve it and provide $9,000 a year with the stipulation that it be open to the public for educational purposes. She started a "Friends of

Calico Early Man Site," a non-profit tax-exempt organization which has been very active ever since, getting enough additional money together to pay a full-time tour guide, encouraging scientific studies and explorations, organizing lectures and gatherings for continued studies, tests and surveys, volunteering their time and various skills to help to keep the Calico site alive. One of the original diggers who worked from the very first day of the dig, Margaret Anthony, has been teaching the digging technique to volunteers one weekend a month. She has led the digging in Master Pit 3, between Pits 1 and 2, down to a depth of more than seventy inches so far.

Dee Simpson helps wherever she can. She guides the volunteer workers in the San Bernardino County Museum basement, helps and encourages those volunteers that Margaret Anthony teaches in the monthly digs. She keeps in touch with archaeologists, geologists, paleontologists around the world who are finding artifacts of early man, learning the processes and histories of earth, rock, ice ages and their effect on the resident life, digging up the remains of long-extinct flora and fauna, discovering different testing techniques. She keeps in close communication too with the Friends group and with the tour guide at the site. She is a respected consultant on early man in the Americas.

EXPERIMENTS AND CONTROVERSIES

Here are some of the tests and studies that have been made to decipher the meanings of finds at the Calico site:

A B C soil profile color tests with a Munsell chart comparing the Yermo Fan matrix with other dated paleosols in the Southwest suggested an era for the creation of the fan of approximately 80,000 to 125,000 BP (i.e. before the present)

Uranium-thorium test on calcium carbonate matrix at twelve-foot depth by James L. Bishoff of the United States Geological Survey and Richard Ku at the Department of Geological Science at the University of Southern California at Los Angeles. From this test, it seemed proper to give the Yermo Fan an age of 200,000 plus or minus 20,000 years BP. At least that was the time of the cementation of the rocks in the calcium carbonate.

Joe Kirschvink and Janet Boley of California Institute of Technology at Pasadena did paleomagnetic analysis tests on the Yermo Fan which seemed to prove that all deposits were laid down since the last major pole reversal, i.e. since 730,000 years ago.

tests on the fire circle:

Vaslav Bucha of the Geophisical Institute of the Czechoslovakian Academy of Science at Prague tested one of the stones from the fire circle (or half of it actually) with a spinner magnetometer. According to the spinner magnetometer, the stone had been heated at one end to somewhere between 350 and 400 degrees Celcius, strongly suggesting that there had been a fire in the circle.

James Bischoff of the United States Geological Survey tested the stones of the fire circle with the thermo-luminescence technique to determine the presence of heat in the rocks' history. The results were negative. He also did more paleomagnetic analyses with Janet Boley at The California Institute of Technology, Argon-Argon analysis and

an electron spin resonance analysis. All these tests suggested that there had been no fire.

Rainer Berger of the University of California at Los Angeles supervised a mass-spectrometer test on carbon isotopic ratios testing for the presence of carbon in and around the fire circle. The test was inconclusive.

T. M. Oberlander and later R. I. Dorn have both been working to date surface rocks by chemical analyses of rock varnish. Surface artifacts of the type called Lake Manix Lithic Industry have been dated from 8,000 to 33,000 years old by these techniques.

Janet Boley of the California Institute of Technology is working on the X-ray fluorescence "fingerprinting" of cherts. This would make it possible to identify the origins of lithic material, which would help both geology and archaeology.

R. D. Simpson 1989. An introduction to the Calico Early Man Site lithic assemblage: San Bernardino County Museum Association, v. 36, 91p.

AN INTRODUCTION TO THE CALICO EARLY MAN SITE LITHIC ASSEMBLAGE

by Ruth D. Simpson

Introduction

The Mojave River courses northeastward from the San Bernardino Mountains across the Mojave Desert. During the Pleistocene, the river filled Lake Manix east of present-day Barstow; carved Afton Canyon through the Cave Mountains; filled Lake Mohave, where present-day Baker divides the highway traffic headed for Death Valley and Las Vegas; and then flowed northward into Inyo County to join the Amargosa and Owens Rivers in filling Lake Manly in Death Valley (Map 1).

During the pluvial (wet) phases of the Pleistocene, the Mojave Desert and Basin and Range Provinces were well watered. A major waterway of lakes and rivers extended from modern Mono Lake (a remnant of Pleistocene Lake Gilbert) south and east along the Sierra to Death Valley and on to the San Bernardino Mountains. This waterway was fed in part by runoff from Sierra glaciers.

The Pleistocene paleontological record of the Basin and Range Province and Mojave Desert tells us that significant numbers and varieties of animals and birds frequented the region. The archaeological record demonstrates the presence of diverse culture phases of various ages. Both records are incomplete and a great deal of work remains to be done. Each lake basin and river course has a unique contribution to make, yet all relate. The southernmost major lake basin is that of Lake Manix. Here, both the paleontological and archaeological data have been and are being intensively sought and analyzed.

The paleontological story involves mammoths, camels and an abundance of other fauna. Faunal evidence combines with that of tectonic activity, ash from Sierra volcanic action, and lacustrine deposits to present a series of dates extending back more than 185,000 years.

The known archaeological record encompasses early historic and late prehistoric Shoshonean occupation, evidence of trade and trade routes, evidence of Archaic and Paleo-Indian occupation, and evidence of at least two older major lithic industries.

This publication is concerned with these two old industries but predominately with the older, that which involves sub-surface specimens excavated at the Calico Mountains Early Man Site (SBCM 1500, SBr 21-2). The more recent of the two industries has been designated as the Lake Manix Lithic Industry. Artifacts relating to this assemblage are found on surface sites associated primarily with landforms above the Lake Manix shorelines. The Lake Manix Lithic Industry is represented on the large Pleistocene alluvial fan which extends eastward from the Calico Mountains into the western portion of Lake Manix Basin. The Calico Early Man Site also is situated on and within this alluvial fan which has been designated as the Yermo Formation.

The purpose of this publication is to introduce the lithic artifact assemblage from the excavations at the Calico Early Man Site.

Chapter I:
How It all began

In 1954, the Southwest Museum and the Archaeological Survey Association of Southern California began a survey of dunes, recessive shorelines and associated landforms in Lake Manix Basin, a venture soon joined by the San Bernardino County Museum Association. I was selected to lead the survey.

Clusters of camp rocks with pottery sherds, burned food bones, arrowpoints and other lithic artifacts indicated Shoshonean use. Such sites were found in dunes, near the river, and along the shores of modern ephemeral lake playas within the basin.

On higher recessive shorelines and in hollows within the beaches were sites yielding occasional Pinto Basin, Silver Lake, and Lake Mohave atlatl points.

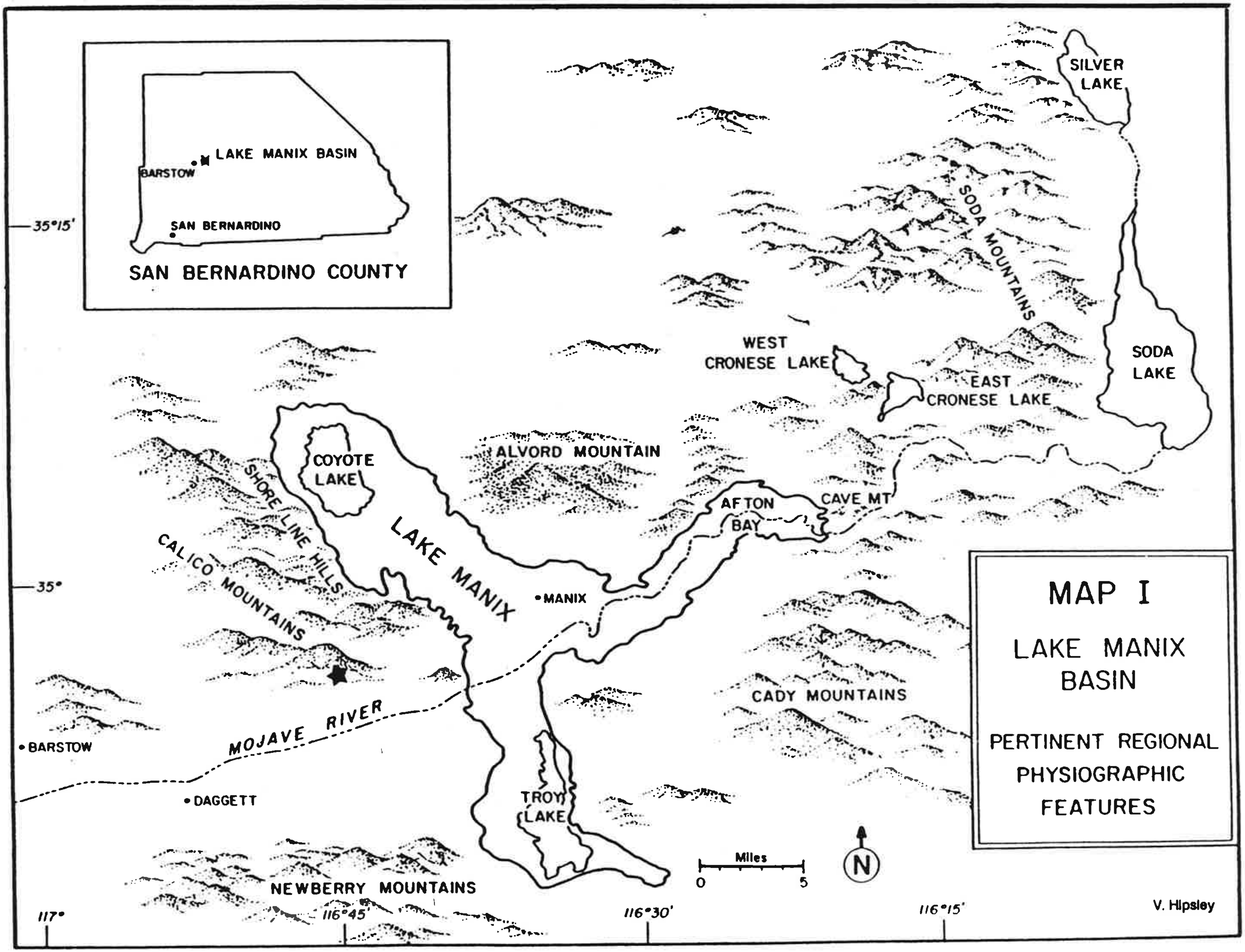
Trails, rock rings, cleared triangles and intaglios were part of the multi-faceted story of the Lake Manix Basin. So, too, was Newberry Cave. Excavated by the San Bernardino County Museum Association in 1953-1956, split-twig figurines, green pictographs, atlatl points and shafts were found. Newberry Cave, with dates circa 5000 B.P., is often designated as Desert Basketmaker.

I wanted to lead the Manix Basin Survey for several reasons. Most important was the fact that, in 1942, Ritner J. Sayles, research associate with Gerald A. Smith and later with the San Bernardino County Museum Association, had brought Dr. Smith and me to sites with seemingly very different artifactual material--sites located on landforms high above the Pleistocene lake beaches in western Manix Basin.

When the survey team began to work above the 1800 foot elevation, we found the kinds of sites and artifacts Mr. Sayles had reported. These sites and the types and quanitites of material were strikingly different than what we had recorded at lower elevations. The sites were mostly large workshops, the artifacts were primarily of local siliceous materials. While workshop debris predominated, well-formed and carefully retouched tools were recorded in workshops and as isolates. No pottery or projectile points were recorded. The definitive tool is an ovate biface foliate. These are the sites and artifacts assigned to the Lake Manix Lithic Industry. Preliminary dates of 15,000 to 22,000 years before present have been obtained from shoreline tufa and by the cation-ratio method of analysis of manganese in the patination on the tools. My present opinion is that this lithic industry was of long duration, occurred widely in the Basin and Range Province and perhaps beyond, and should be designated a lithic tradition.

In 1958, I took Lake Manix Lithic Industry specimens to Europe. Among the scientists who saw them was Dr. Louis Leakey. In 1963 he came to the Lake Manix Basin and saw the archaeological evidence on the alluvial fan designated as the Yermo Formation. He was impressed by the geology exposed in a large commercial excavation and bulldozer cut. Undisturbed stratified deposits in the cut contained pieces of siliceous material suited for use in the preparation of stone tools. Dr. Leakey selected an area immediately adjoining the bulldozer cut as the location for exploratory excavation.

After developing a project design and working on logistical questions with Dr. Smith, geologist Thomas Clements of the University of Southern California, Archaeological Survey Association president John Kettl and me, Dr. Leakey obtained a National Geographic Society grant for the exploratory excavation. Work would be done under sponsorship of the San Bernardino County Museum and under Department of the Interior permit. The site selected is on Bureau of Land Management property in section 22, Township 10 North, Range 2 East. Here we would dig a series of pits and trenches to determine if the siliceous material in the stratified deposits had been used by man to fashion tools. Excavation began November 1, 1964. Funding permitted full-scale excavation until 1972. Work continues on a modest, volunteer basis today.



LAKE MANIX BASIN
BARSTOW
SAN BERNARDINO
SAN BERNARDINO COUNTY
SILVER LAKE
SODA MOUNTAINS
SODA LAKE
WEST CRONESE LAKE
EAST CRONESE LAKE
ALVORD MOUNTAIN
COYOTE LAKE
SHORE LINE HILLS
LAKE MANIX
CALICO MOUNTAINS
AFTON BAY
CAVE MT
MANIX
MAP I
LAKE MANIX BASIN
PERTINENT REGIONAL PHYSIOGRAPHIC FEATURES
CADY MOUNTAINS
MOJAVE RIVER
BARSTOW
DAGGETT
TROY LAKE
Miles
0 5
N
NEWBERRY MOUNTAINS
V. Hipsley
35°15'
35°
117°
116°45'
116°30'
116°15'

Chapter II: A geological perspective

with Dorothy Kasper

Understanding the geologic context of every archaeological site is important; at the Calico Early Man Site it is imperative, for the age of the artifact-bearing beds has been a matter of contention for many years. At the 1970 International Conference on the Calico Mountains Excavations, age estimates ranged from about 70,000 years to 2.5 to 3 million years before present (Schuiling, 1979). More recently, uranium-series and soil-stratigraphic dating suggested an age of about 200,000 years. Regardless, the antiquity of the Calico beds makes the site an exemplary area for the study of early humans in the New World. Thus, regional and local geological investigations are important and ongoing.

Regionally, two areas have a major bearing on the Calico site: the Lake Manix Basin and the Calico Mountains (Map 1).

LAKE MANIX BASIN

The Lake Manix Basin is surrounded by the Calico, Paradise, Alvord, Cave, Cady, and Newberry Mountain Ranges. The Mojave River bisects the basin southwest to northeast; today it is an ephemeral river rarely surfacing. More than fifty years ago, N. Fenneman described it as

> descending from the mountains and pursuing its stealthy course, hiding most of the time beneath its gravel bed and coming to light only when forced to do so by the impervious rock. Like the Humboldt it guides transcontinental railroads. It is lost at last in soda lakes (Fenneman, 1931).

Several climatic factors combined to make the ancestral Mojave River perennial 400,000 to 500,000 years ago, during the Pleistocene. Snow pack in the mountains of the river's head-waters was heavier, and local rainfall was greater. Cloud cover was denser, and evaporation was reduced. The river filled closed basin lakes and maintained them over long periods. Lake Manix lay within the local basin, backing up from the Cady Mountains and into the sumps we know today as Coyote and Troy Lake playas. At maximum, it reached an elevation of 549 meters (m) above sea level and covered an area of 360 square kilometers (Figure 1). Lake Manix is expressed geomorphically by shorelines and stratigraphically by a thick sequence of interfingering lacustrine and distal fan deposits. It has long been accepted that there were three high stands of Lake Manix (Ellsworth, 1932; Blackwelder and Ellsworth, 1936). However, this theory has recently been challenged by N. Meek (Meek, 1988).

Of Lake Manix, paleontologist G. Jefferson writes,

> From about 500,000 to 19,000 years BP, perennial Lake Manix occupied the basin. The freshwater lake was fed by inflow from the ancestral Mojave River system and overflowed to the east in the Afton Canyon area. Lacustrine conditions are confirmed by invertebrate and vertebrate fossil remains. Cyprinid ostracodes occur throughout the light gray to gray-green siltstones and claystones. Local abundant accumulations of freshwater bivalves and gastropods indicate lacustrine, paralimnitic and riverine habitats. The remains of the Tui (Mojave) chub are abundant and distributed throughout the fine-grained sediments. Two-thirds of the extant avian taxa, represented by 80% of the fossil specimens from Lake Manix deposits, presently prefer, or feed exclusively on, small fish; the remaining species feed on a variety of water plants and fresh water invertebrates. These fossil birds as well as extinct avian taxa clearly reflect freshwater lake and lake margin habitats. Judging from food preferences, procurement methods and nesting habits of extant representatives, open water, sandy beach flats and extensive reedy marshland habitats are indicated (Jefferson, 1985b).

These birds include mergansers, mallard, ruddy, and canvas back ducks, flamingos, pelicans, golden and bald eagles, swans, geese, cormorants, grebes, loons, storks, cranes, sandpipers, owls, and seagulls.

Fossil mammalian remains represent a rich Rancholabrean age fauna of ground sloths, mammoths, jack rabbits, mice, dire wolves, coyotes, short-faced and ursid bears, pumas, scimitar cats, horses, camels, llamas, pronghorns, big horn sheep, and bison (Jefferson, 1985a, 1987).

Studies of fossil pollen indicate the presence of piñon pine, juniper, scrub and live oak on the mountains with grasses and scrub vegetation on the valley floor (Horn, 1984).

Lake Manix leaves us a Pleistocene record of animals and vegetation indicating a habitat which would well support a gathering-hunting people. The two most vital human needs, fresh water and food, were abundantly available. This hospitable environment apparently extended to within a few kilometers of the Calico site.

CALICO MOUNTAINS

The Calico Mountains, immediately west of the Calico site, lie in the west and northwest portion of the Lake Manix Basin. They are composed mostly of late Cenozoic rocks. Here, continental sediments are overlain and underlain by multicolored, extrusive volcanic rocks, giving rise to the name "Calico." The middle Miocene Barstow Formation, calcareous clays and mudstones, crops out throughout these heavily faulted and folded mountains. Peak elevations range from about 670 m to 1380 m (Map 2).

Dissected alluvial fans at the eastern end of the Calico Mountains are known informally as the Calico Hills. These fan deposits have elevations of 600 to 700 m and overlie lacustrine sediments of the Barstow Formation. They are now isolated from their source and are generally flanked by highly dissected fans of the younger, late Pleistocene Yermo deposits.

The Barstow Formation is of significance for the discovery of the Calico site. The formation contains a broad variety of lithologies and mineral deposits of economic value. These deposits, including magnesite, borax, bentonite, and silver, have been mined for many years. A bulldozer cut in an attempt at bentonite mining led to the discovery of ancient human tools. Calcareous mudstones of the formation crop out in canyons around the Calico site and are present at the base of the artifact-bearing deposits in the archaeological excavation.

The Calico site is located in the Yermo deposits--mudflows, debris-flows, and fanglomerates that overlie the Barstow Formation. The two units are often separated by an angular unconformity that suggests a significant regional depositional hiatus (Shlemon and Budinger, in press). The Yermo fan deposits have been tectonically separated from their source(s) and have undergone significant faulting and dissections. However, ancient soils (relict paleosols) are still preserved in remnant geomorphic surfaces.

As seen in the archaeological excavations, the Yermo deposits are from about 3 to 11 m thick. Weathered clasts of volcanic tuff and less weathered crystalline igneous clasts occur in a poorly-sorted sandy mudstone matrix that also contains lesser amounts of limestone and chert clasts (Bischoff, 1981). Most of the Calico artifacts were made from chert (chalcedony) clasts (Schuiling, 1972; Budinger and Simpson, 1985).

TECTONICS AND STRUCTURE

Tectonics play an active role in the structure of the Central Mojave Desert that occupies a wedge bounded by the San Andreas and Garlock Faults. The Lake Manix Basin forms a smaller wedge, roughly paralleling the larger (Hamilton, 1982; Keaton and Keaton, 1976), between the east-west trending Manix Fault and the northwest-southeast trending Calico Fault. The west end of the wedge-shaped basin is defined by the junction of these faults. The entire Lake Manix Basin has moved and will continue to move eastward (Budinger and Simpson, 1985). This relative motion was confirmed on April 10, 1947, when a 6.2 magnitude earthquake resulted in 5 centimeters of left lateral displacement and a surface rupture of 3.2 km along the Manix Fault (Buwalda and Richter, 1948).

Recent investigations at the Calico site have located several faults in outcrops, excavations, and trenches (Budinger, personal communication to Kasper; Budinger, 1988).

AGE

Faulting, folding, and subsequent erosion of the Yermo deposits cause the fan to appear to be very old, giving rise to the postulation of a wide range of dates (Schuiling, 1979). There have been many attempts to date the Calico artifact-bearing beds.

A piece of mammoth tusk was submitted for radiocarbon dating. The results were unsatisfactory in that the age of the specimen was beyond the range of the technique at that time (Simpson, 1968).

The bases of cobbles and artifacts from the lower levels of the archaeological excavations are coated with "oyster-shell" laminate rinds of calcium carbonate up to 4 cm thick. In 1979 R. Ku and J. Bischoff selected artifacts covered with these layers of calcrete for radiometric (uranium-thorium) dating. Results of independent work at the University of Southern California and the U.S. Geological Survey, Menlo Park were remarkably close and suggest the artifact-bearing sediments are slightly older than 200,000 years BP (Bischoff and others, 1981).

R. Shlemon assessed the age of the site based on a soil profile at the surface of the Yermo fan adjacent to Master Pit III. He describes a very strongly developed soil, a relict paleosol, estimated to be at least as old as late Sangamon. This interglacial period is generally equated to marine isotope Stage 5, about 80,000 to 125,000 years BP. This date is temporally and stratigraphically consistent with the approximate 200,000 BP dates of R. Ku and J. Bischoff (Shlemon, 1978; Bischoff and others, 1981).

CONCLUDING REMARKS

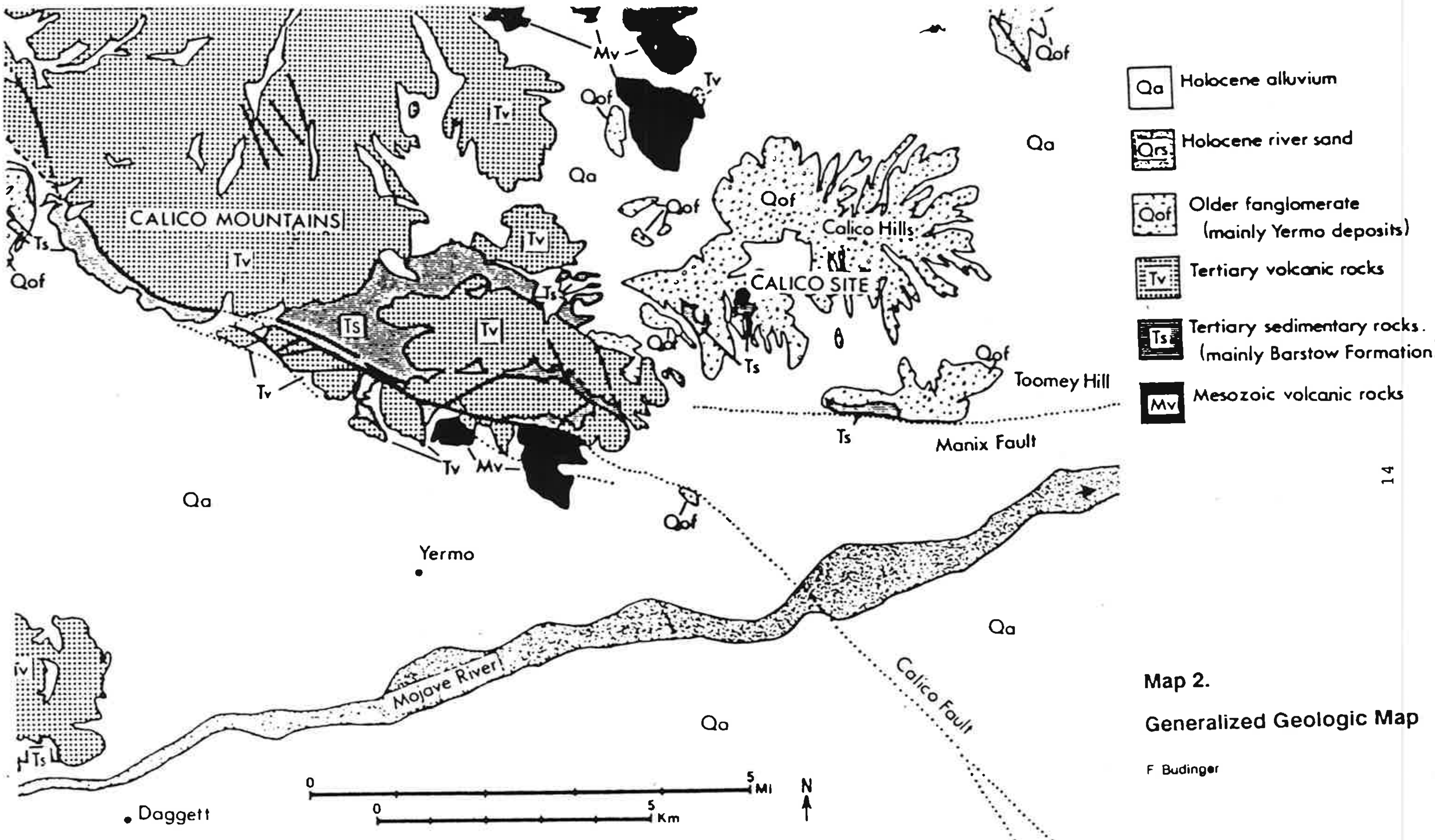
At the 1970 Calico Conference, Louis S. B. Leakey spoke of the enigma of Calico: an apparently very old land form and artifacts. He said these two issues must be addressed and understood

> because truth cannot conflict against truth. The antiquity of the deposits is one fact. The second is that it contains specimens that certainly appear as through they were man-made. What this means in the terms of the age of man in the Americas we've got to resolve. There cannot be a conflict between the geological truth and the artifact truth, we've got to find how to accommodate the two.

Now, nineteen years later, we are still trying to resolve these issues. The artifacts speak for themselves. We continue to work on the geology.

ACKNOWLEDGEMENTS

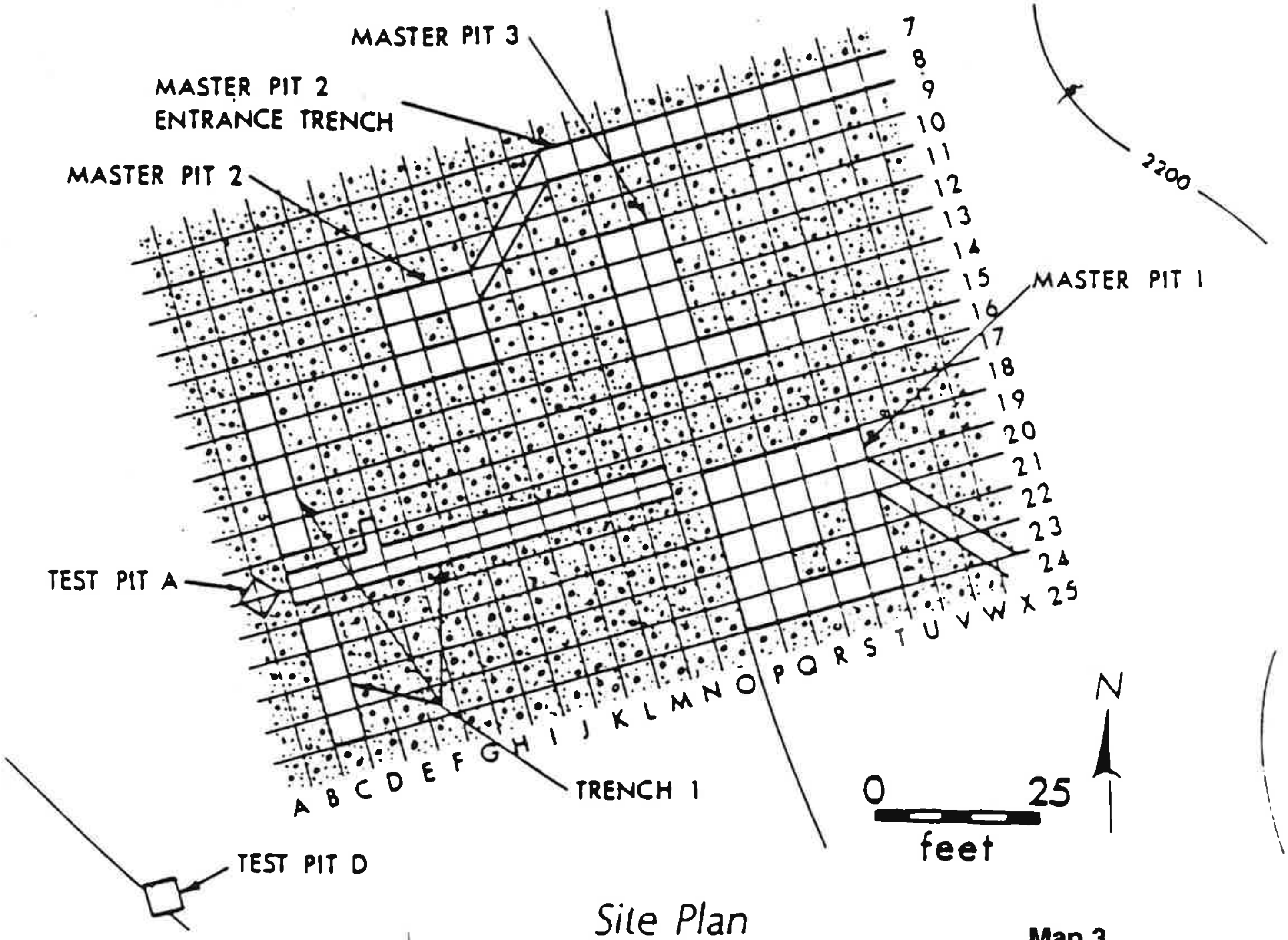
Appreciation is expressed to Roy Shlemon for his counsel in the preparation of this chapter. Similar gratitude is due Fred Budinger, George Jefferson, and Norman Meek who allowed the use of their considerable work in the Lake Manix Basin.



Map 2.

Generalized Geologic Map

F Budinger



Map 3.

Calico Early Man Site

V. Hipsley

DESERT STUDIES CONSORTIUM
CALIFORNIA STATE UNIVERSITY
(714) 773-2428

WELCOME TO THE DESERT STUDIES CENTER

The following information is designed to make your stay at the Desert Studies Center safe, interesting and enjoyable. Please read this carefully.

LOCATION

The Desert Studies Center is located in the east Mojave Desert at Soda Springs approximately 11 miles southwest of the town of Baker, California; 60 miles east of Barstow, California; and approximately 90 miles southwest of Las Vegas. It is reached from Interstate 15 by exiting at the Zzyzx Road offramp and driving south on Zzyzx Road to the road end, approximately four miles. The road is graded, although unpaved over most of its length.

WHAT TO BRING

A. ESSENTIAL
- sleeping bag or blankets & sheets
- flashlight
- boots or sturdy walking shoes
- canteen
- writing materials
- toilet articles, towel, washcloth
- sun-screen
- hat
- in winter: layered clothing, including a warm jacket, scarf, gloves

B. DESIRABLE
- bandana
- skin cream
- first aid kit
- insect repellent
- binoculars
- camera and film
- sunglasses
- cooler with beverages
- earmuffs or stocking cap - winter
- tissues (Kleenex)
- shorts
- bathing suit - summer
- thongs
- pillow
- thermal underwear - winter

Remember, the desert can be very cold and windy in the winter and early spring and very warm at other times.

DEPT. OF BIOLOGICAL SCIENCE, CALIFORNIA STATE UNIVERSITY, FULLERTON, CALIF. 92634

REGULATIONS

As a desert field station of the California State University, standards of conduct established for CSU campuses apply here. Our regulations also prohibit:

-loud or boisterous behavior after 10:00 p.m.

-pets

-firearms

-illegal drugs

-alcohol consumption, except in moderation by those at least 21 years of age

The Desert Studies Center occupies land designated by an agency of the federal government as an "Area of Critical Environmental Concern", due to the presence of an endangered species of fish, the Mohave Tui Chub, sensitive habitats and a variety of archaeological sites. Because of this, please do not collect any material, plants or animals without prior authorization and do not wade or throw anything into the ponds.

FOR YOUR SAFETY

If you leave the Center, tell someone where you are going and when you plan to return. Never hike alone. Take plenty of water along. Wear hiking boots and a hat.

Exercise care while walking or working in the field. Look before you step and avoid placing your hands where you cannot see. It is good practice to empty your shoes and shake your clothing before putting them on, since scorpions are occasionally found in the rooms. Poisonous snakes and Black Widow Spiders have been found at the Center.

The emergency message telephone number at the Center is (619) 733-4266. Other phone calls must be received or placed in Baker. In the event of an accident or injury, notify the Manager immediately.

FACILITIES

Sleeping accommodations are dormitory style with two to 12 individuals sharing each room. Furnishings include beds, mattresses, chairs, dressers, and mirrors. Cleanup procedures are posted in or near each room. Please clean your room before departure. Lockers are available for storage of valuables; however, you will need to furnish a padlock. The central washhouse has hot showers and flush toilets. A newly built and equipped kitchen provides space for group food preparation. The tap water at Soda Springs is not satisfactory for drinking because of its high salt content. Drinking water is available at the drinking fountain at the west end of Lakefront dormitory and in the kitchen. Please help us conserve drinking water.

Power is provided by propane generator throughout the facility from dusk until 10 p.m.. Study room, kitchen and washhouse lighting are provided until 11 p.m. from the alternate energy system. Sleeping room lighting is not provided after 10 p.m. Most individuals find that an ordinary flashlight is adequate for essential lighting after this time. However, if additional lighting will be needed, bring a battery or gas lantern.

ADMINISTRATION

The Center, a desert field station dedicated to teaching and research on topics related to the desert, is operated at Soda Springs by a consortium of campuses of the California State University under an agreement with the Bureau of Land Management of the U.S. Department of the Interior. Soda Springs is a unique natural environment with rich cultural resources.

The administrative office of the Center may be contacted by writing or phoning:

Desert Studies Center
Department of Biology
California State University, Fullerton
Fullerton, CA 92634
phone: (714) 773-2428

The staff of the Desert Studies Center hope that you have an enjoyable visit and will plan to return soon.

April, 1989

WELCOME:

The Desert Studies Center, a field station of the California State University (CSU), provides opportunity for individuals and groups to conduct research, receive instruction and experience the desert environment. Established in 1976 under a management agreement with the Bureau of Land Management, the Center is operated for the CSU by the California Desert Studies Consortium, an organization of seven southern California CSU campuses: Dominguez Hills, Fullerton, Long Beach, Los Angeles, Northridge, Pomona and San Bernardino.

The Center is situated at Soda Springs on the shore of Soda Dry Lake and at the western edge of the East Mojave National Scenic Area. As such it serves as a convenient departure site for groups visiting the Death Valley National Monument, the Kelso Dunes, the Afton Canyon riparian areas, the Cinder Cones, the Cima Dome, the historic Mojave Road, the Early Man Site at Calico, the Providence, the New York, the Granite and the Clark mountains, and many other interesting features of the Mojave Desert.

Soda Springs itself is of great interest to historians, archaeologists and biologists. Evidence of prehistoric and historic activity are readily seen, including prehistoric quarry sites and artifacts of ancient man, such as projectile points and rock art; a Native American burial site; the historic Mojave Road (During 1860 the site served as a US Army outpost, and was called Hancock's Redoubt.); remnants of a wagon road stop; several locations of evaporative salt mining; mill sites; the Tonapah and Tidewater Railroad berm; and many relics remaining from the Zzyzx Mineral Springs and Health Spa era.

Biologists find Soda Springs of unusual interest because of the Mohave Tui Chub, *Gila bicolor mohavensis*, an endangered species in the minnow family, which inhabits local ponds with another Mojave Desert native, the Saratoga Springs Pupfish *Cyprinodon nevadensis nevadensis*. In addition, a variety of desert reptiles and mammals have been seen at Soda Springs. Mammals include pocket mice, kangaroo rats, antelope ground squirrels, bobcat, ringtailed cat, kit fox, gray fox, coyote, and several species of bats. Reptiles include Chuckwalla, Collared, Whiptail and Zebratail Lizards, Shovelnose Snake, Mojave Green, Sidewinder and Speckled Rattlesnakes, Gopher Snake, Red Racer and Desert Tortoise. Further, over 170 kinds of birds have been seen.

This rich variety of wildlife results from the diverse habitats and plant communities located near the Center. These include halophytic vegetation, marsh communities, ponds and springs with pondweed, cattail and sedges, extensive creosote bush-scrub and saltbush-scrub stands, sand dunes with sand-adapted vegetation and plants of rocky slopes.

The existence of these biological and cultural resources has made possible a number of field and laboratory investigations.

Recent studies conducted at the Center have included: temperature regulation and behavior in the Chuckwalla; physiological ecology and temperature regulation in dragonflies; climate of Baker and the East Mojave Desert; reproductive ecology, energetics and ecological tolerances in the Mohave Tui Chub; hydrology of the Soda Lake area; and a technological analysis of a prehistoric quarry workshop in the Mojave Sink.

FACILITIES

Sleeping accommodations are dormitory style, with single, double and bunk beds with mattresses in two to ten person rooms. There are also restrooms with hot showers, a self-service kitchen, and indoor and outdoor eating areas. Recreation vehicles can be accommodated, providing they do not require hookups. There are no camping facilities at the Center, however camping is permitted in the Rasor Open Area approximately 4 miles south of the facility, accessible from the Rasor Road exit of I-15.

In addition to living accommodations, there is a laboratory for both individual and group use, a modest library and two classrooms, the largest of which can accommodate 70 persons.

All facilities at the Center are wheelchair accessible.

Kitchen facilities include stoves, refrigerators, pots, pans and other related cookware. Although most individuals and groups prepare their own meals, the Center can arrange for meal service for groups of 10 or larger, given adequate notice.

Recreation facilities include a campfire circle, a volleyball court, a basketball hoop, horseshoe pits and a soaking pool.

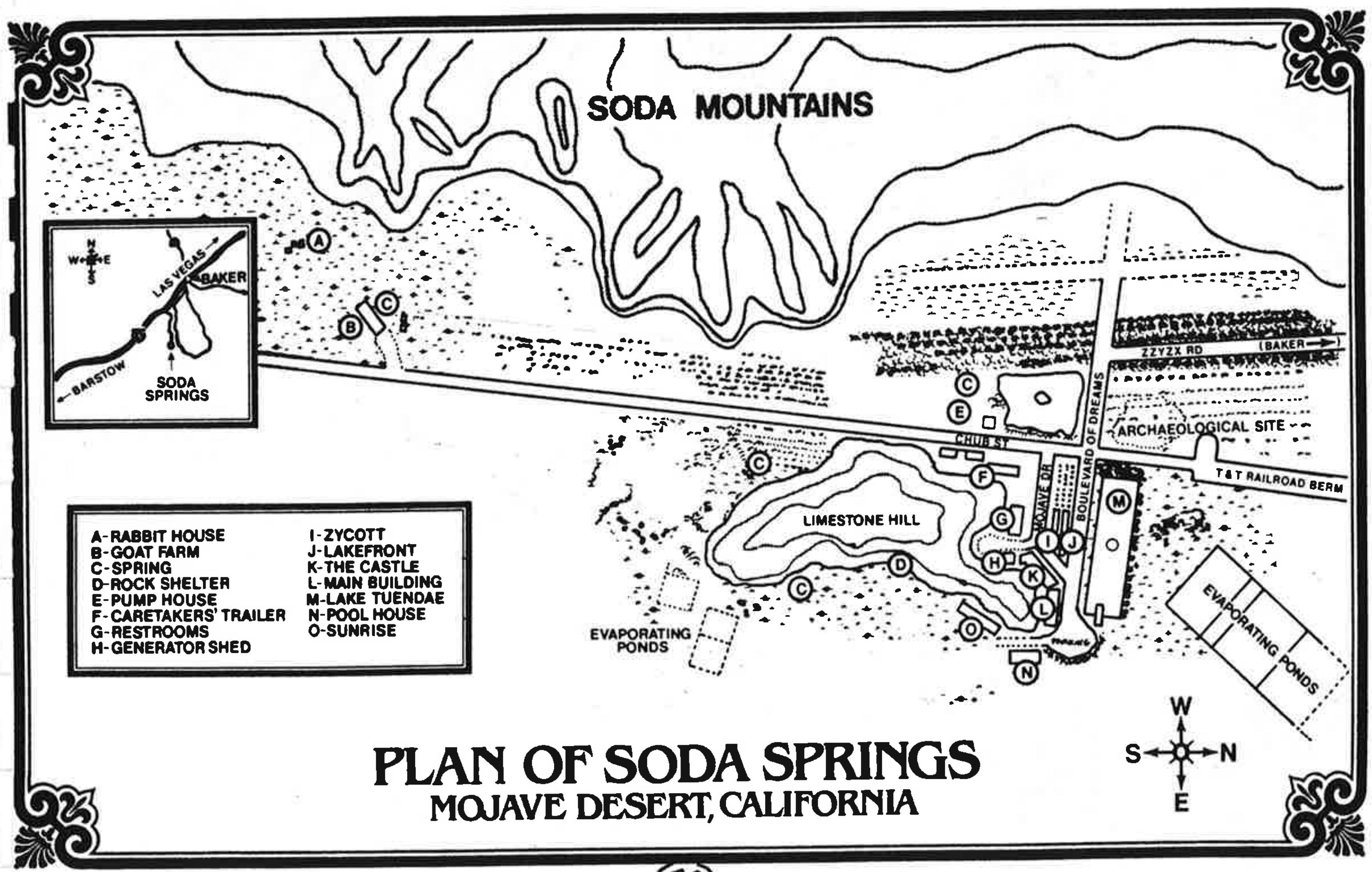
CLIMATE

The Eastern Mojave Desert is characterized by wide day-night temperature fluctuations, strong winds and bright clear skies. Winter temperatures extend below freezing and summer temperatures can exceed 118 degrees. Desert nights can be quite cold. Rainfall averages less than 8 cm. per year, usually confined to the winter months. However, summer thundershowers and flash floods are not unknown.

The night sky over Soda Springs is usually cloud and smog free and excellent for some kinds of astronomical observations. Qualified individuals and groups have access to the Center's Celestron 11-inch reflecting telescope.

A Short History of Soda Springs

By Anne Q. Duffield



PLAN OF SODA SPRINGS
MOJAVE DESERT, CALIFORNIA

Anemopsis califórnica
Yerba Mansa.

Prior to 8,000 B.C.

Pleistocene Lakes Period -- The evidence for man's presence in this earliest, least well-defined and most controversial period comes from large chopping and scraping tools found along the margins of this desert's Ice Age lakes. Like Lake Manix, near Barstow, and Lake Manly in Death Valley, Pleistocene Lake Mojave (which included Soda Lake) was formed from the run-off of San Bernardino Mountain glaciers. Examples of tools thought to date from early times are found at the Calico Early Man site, at China Lake, and possibly near Soda Springs. In 1929, Malcolm Rogers referred to these tools as belonging to the Malpais Tradition and felt they were associated with trails, cairns and cleared areas in the desert pavement known as "sleeping circles". These features are found north of Soda Springs.

8,000 B.C. to 5,000 B.C.

Lake Mojave Period -- By 8,000 B.C. a change in tools occurred which distinguishes this period from the preceding one; large projectile points appear. Several different projectile point traditions are known throughout the Great Basin area, such as the firmly dated fluted points of western and southern Nevada and southeastern California, and Malcolm Roger's San Diegito Tradition points. Also included is the Lake Mojave point, first identified by the Campbells in 1937 and found along the ancient beaches of Soda and Silver dry lakes. Among the distinctive Lake Mojave tools are leaf-shaped points, keeled ("turtleback") scrapers and "crescent" tools.

5,000 B.C. to 2,000 B.C.

Pinto Period -- Taking its name from the distinctive tools found first in the Pinto Valley near Joshua Tree, this period is marked by the introduction of milling and grinding tools, suggestive of the hunting and gathering way of life. Some experts believe fluctuations in the climate may have caused one-time big game hunters to rely more on plant foods for survival, thus creating the typical "Desert Culture" pattern. Pinto Period tools have been found in the lowest deposition levels at the Soda Springs Rock Shelter (SBr-363b).

2,000 B.C. to A.D. 500

Amargosa Period -- This period begins with another type change in projectile points; a decrease in their size and an increase in refinement of manufacturing technique. By 1,350 years ago, this trend is seen as the transition from spear, atlatl and dart to bow and arrow. Projectile points found at Soda Springs from these times are of the Elko, Humboldt and Gypsum types. There is definite evidence at the end of this period of an intrusion of the Southwest pueblo culture at the nearby Halloran Springs turquoise mines.

A.D. 500 to the 1860's

Mohave/Chemehuevi Period -- The ancestral development of the historically recorded desert groups is included in this period, for both the Yuman-speaking Mohaves along the Colorado River, and the Chemehuevi or Southern Paiutes who speak a Shoshonean language. Ceramics appear at Soda Springs during this time in at least three distinct types. This period is also characterized by a further change in projectile points; initially the Rose Springs and the Eastgate types were made. After A.D. 1200, Desert Side-Notched and Cottonwood Triangular points are common and these have been found at Soda Springs. Also during this time Mohave Indians utilized ancient trails to trade with coastal Indians, perhaps passing through and resting at Soda Springs.

March, 1776

Padre Francisco Garces was the first European known to have crossed the Mojave Desert. Wishing to reach the Mission San Gabriel, he enlisted the aid of Mohave Indian guides to show him their route between springs across the desert. He probably passed just south of Soda Springs as he traveled toward the Arroyo de los Martires and Canon Rio de las Animas, now called Afton Canyon.

December, 1819

Heading east, Lt. Gabriel Moraga probably got as far as Soda Springs before turning back to the reliable water of the Mojave River. With his expedition of about fifty men, he had planned to strike at the Mohave villages. He believed these Indians were responsible for raids on the horse and cattle ranches in the San Bernardino Valley.

1826 - 1827

Jedediah Strong Smith, the first U.S. citizen to enter California overland, was also apparently the first American to visit Soda Springs. In 1827, the Mohaves attacked while his party crossed the Colorado, and the survivors were forced to rely on Jed Smith's memory of the route to water to reach safety.

1829 - 1831

Several parties of American trappers passed through Soda Springs, including Christopher "Kit" Carson with the Ewing Young group and the Yount-Wolfskill party on their way west.

November, 1853

Lt. Robert Williamson's description of the Soda Lake area included mention of "...several fine springs, slightly brackish but not unpalatable". Thus his report on the survey of the 35th Parallel as a railroad route contains the first certain written reference to Soda Springs.

March 8, 1854

In his railroad survey report, Lt. Amiel Weeks Whipple notes "...the dry bed of the lake covered with efflorescent salts, probably sulphate of soda." and called it Soda Lake on his map. "Soda" was eventually applied to the springs as well, thus Whipple is credited with having named this site.

1857 - 1860

Edward Fitzgerald Beale established the wagon road, later known as the Mojave Road, as a freight and postal route. In 1857, he began his "Great Camel Experiment" by using camels as pack animals along this road.

1860

Between May and July, 1860, Major James H. Carleton, U.S. Army 1st Dragoons, conducted a series of successful campaigns against hostile Paiute Indians near Soda Springs. An outpost was established at the springs, officially named Hancock's Redoubt, and described as "...a series of breastworks and corrals... constructed of mud and willow brush." The outpost was abandoned soon after.

1863 - 1864

Traffic on the Mojave Road increased after gold and silver were discovered in Arizona and the Arizona Territory was formally created. Supplies were regularly freighted from Los Angeles to Fort Mojave in Arizona over this road, with a water stop at Soda Springs.

August 21, 1867 to May 23, 1868

The outpost at Soda Springs was regarrisoned from Camp Cady to supply Army escorts for Mojave Road traffic, threatened by marauding desert Indians. During this time a least one stone building and a corral were constructed, and these ruins apparently were still visible at the site in 1944.

August 30, 1871

"Jottings By the Way En Route to Ivanpah" from the San Bernardino Guardian published at this time shows the use of the Mojave Road and Soda Springs by civilians only. The military had withdrawn from the area, after selling Camp Cady to private interests in March, 1871. Letter #3 adds "The boys have built for the use of the public a nice bathing place and invited us to take a bath while they are preparing dinner".

1876 through 1900

This commercial rest stop operation at "Soda Station" was mentioned again by several writers from 1876 on. A drawing of one of the buildings in use in 1880 is on display in the Main Building at Soda Springs. George Hetzel was stationkeeper in 1882 and Col. Alonzo Smith called the site "Shenandoah Camp" in a letter dated February 23, 1885.

1900 Census

This document shows Frank and Sarah Riggs lived in the Soda Springs area; Frank listed himself as a "mining expert". In 1889 they included "Soda Lake Station" in their claim on the five-acre Hetzel Mill site, and in 1898 claimed water rights on the "upper Badger Holes, one-half mile north" of the station.

November, 1905 - March, 1906

Through these winter months work crews laid track from Ludlow to Silver Lake for the Tonopah and Tidewater Railroad. Built by Francis "Borax" Smith to carry ore and passengers across the desert, a "station" was opened at Soda Lake, for passengers only, on November 8, 1907 and closed for good on August 31, 1908.

1906 - 1940

The Tonopah and Tidewater Railroad ran one train daily through Soda Springs goods and passengers for other destinations. On June 14, 1940, all operations ceased, and the rails were torn up between July 18, 1942 and July 25, 1943.

1907 - 1912

The Pacific Salt and Soda Company made improvements at the site while trying to recover salts from Soda Lake brine by solar evaporation. The firm changed hands several times and probably built the narrow gauge on the flats to connect to the main line.

1914 - 1916

According to Edmund C. Jaeger (1958), Pastor Charles T. Russell, co-founder of Jehovah's Witnesses, attempted with his followers to establish a religious colony at Soda Springs. They planned to support themselves by processing the salts from the lake. Pastor Russell died October 30, 1916.

December 7, 1919

While researching his Routes to Desert Watering Places on the Mohave Desert, David G. Thompson visited Soda Springs, took several photographs and described the site as deserted.

September, 1936

A story entitled "Desert Madness" written by Erle Stanley Gardner appeared in this issue of Field & Stream. It described an automobile trip the author made to shoot bullfrogs with a bow and arrow in the pools at Soda Springs.

June, 1937

"The Archaeology of Pleistocene Lake Mohave", an analysis of the prehistoric tools found at Soda Springs and in the area by Elizabeth and William Campbell, was published by the Southwest Museum in Paper Number Eleven.

September, 1944

Curtis and Helen Springer first arrived from Hollywood at Soda Springs and described it as a "mosquito swamp". They immediately began to plan what would become known as Zzyzx Mineral Springs and Health Resort.

1944 to 1974

For these thirty years the Springers occupied the land and built the avenues, structures and pools of Zzyzx Health Resort. Their guests enjoyed a special blend of diet, religion, and health treatments, and the desert climate.

1974

After lengthy court proceedings, the Bureau of Land Management took possession of the facilities at Soda Springs from the Springers.

1976

The Bureau of Land Management signed a five-year agreement with the California Desert Studies Consortium, then consisting of seven campuses of the California State University system.

1976 through the Present (1986)

The California Desert Studies Consortium began restoration and management of Soda Springs for use as a desert teaching and research facility. With the extension of the agreement with the BLM in 1981, the Consortium continues to participate in the partnership for use of this unique desert facility.

LATE PROTEROZOIC AND LOWER CAMBRIAN ROCKS

John H. Stewart

Underlying Rocks

Late Proterozoic to Devonian strata deposited along and inland from the North American continental margin in the Western United States rest unconformably on structurally complex crystalline basement rocks consisting of gneiss, schist, quartzite, marble, greenstone, and granite ranging in age from about 2,500 Ma to about 1,410 Ma and on younger supracrustal sedimentary and volcanic rocks ranging in age from about 1,450 Ma to 900 or 800 Ma .

The younger supracrustal rocks, the Belt Supergroup (Middle Proterozoic) and related rocks, are composed of argillite, shale, siltstone, and quartzite, locally abundant dolostone, limestone, conglomerate, and thin mafic lavas and gabbroic or diabase sills (1,150-1,100 Ma). The Belt Supergroup and Uinta Mountain Group (Middle Proterozoic) are 20 km and 7 km thick, respectively, and define deep epicratonic troughs. The Middle and Late Proterozoic Grand Canyon Supergroup (4 km thick) and the Precambrian Crystal Spring and Beck Spring Formations may also have been deposited in troughs, whereas the Middle Proterozoic Apache Group and Troy Quartzite, judged from their thinness and wide distribution, may be shelf deposits. The deep epicratonic troughs containing the Middle Proterozoic Belt Supergroup and related rocks contrast strongly with the laterally continuous miogeocline or miogeosyncline along the continental margin in Late Proterozoic to Devonian time. Locally, between the earlier Precambrian rocks and the terrigenous detrital sequence at the base of the continuous continental-shelf sequences, significant diamictite and volcanic sequences have been found.

Diamictite and Volcanic Sequence

Late Proterozoic and Lower Cambrian rocks in the Western United States are divided into a diamictite and volcanic sequence and an overlying terrigenous detrital sequence (Stewart and Suczek, 1977). Each of these sequences is lithologically and tectonically distinct and is described separately.

The diamictite and volcanic sequence contains a variety of rock types that commonly vary abruptly in facies and thickness. The most distinctive rock is diamictite consisting of well-rounded to angular clasts, locally as large as 1 m, set in a clay, silt, and fine-sand matrix. The clasts are of both extrabasinal and intrabasinal origin. The diamictite occurs as massive beds, graded beds, or laminated siltstone with isolated clasts. At some locations, striated and faceted clasts, dropstones with "splash-up" borders, isolated sand and gravel clots, and a striated pavement, all features indicative of a glacial origin, have been noted (Blick, 1979, 1981; Ojakangas and Matsch, 1980; Crittenden and others, 1983). The diamictite is interpreted to have formed in a variety of ways including deposition as terrestrial or subaqueous lodgement till or flowtill, as debris dropped from a floating ice sheet, and as proximal turbidites in relatively deep water.

Diamictite forms a relatively small to a moderately large part of the diamictite and volcanic sequence. It occurs interstratified with phyllite or argillite, graded sandstone, quartzite, pebble to cobble conglomerate, carbonate rocks, and mafic volcanic rocks. The sedimentary rocks associated with the diamictite have been interpreted to include relatively deep as well as shallow marine deposits. The mafic volcanic rocks associated with the diamictite are altered and their original composition is difficult to determine, although they have generally been considered to be tholeiitic basalts (Stewart, 1972; Miller and Clark, 1975; Yates, 1976; Hammond, 1983; Devlin and others, 1985; Harper and Link, 1985). Pillow basalts are recognized locally.

The diamictite and volcanic sequence occurs discontinuously in western North America (Fig. 2; Plate 2-1). It is widely exposed in northeastern Washington and adjacent parts of British Columbia (Aalto, 1971, 1981; Reesor, 1973; Glover and Price, 1976; Miller, 1983) where it forms the Windermere Group (Supergroup of Canada) and includes such units as the Shedroof Conglomerate, Leola Volcanics, Monk Formation, and Three Sisters Formation in Washington; in southern Idaho (Link, 1981, 1983) and northwestern Utah (Blick, 1979, 1981; Christie-Blick, 1982, 1983; Crittenden and others, 1983) where it forms the Pocatello Formation of southern Idaho and the formation of Perry Canyon, the Mineral Fork Formation, the Sheeprock Group, and the Horse Canyon Formation of northwestern Utah; and in the Death Valley region of eastern California (Wright and others, 1974; Miller and others, 1981; Miller, 1985; Walker and others, 1986) where it forms the Kingston Peak Formation.

In some areas, the diamictite and volcanic sequence was deposited in locally deep troughs that were in part formed by syndepositional faulting. In the Death Valley area of eastern California, the Kingston Peak Formation, which varies in thickness from a few meters to more than 3 km over a horizontal distance of less than 4 km, contains abundant coarse detritus and locally intact slabs of older rock as much as 1.5 km in strike length (Troxel and others, 1977; 1987). The abrupt changes in thickness and the abundance of coarse detritus suggest deposition in a fault-bounded trough or rift valley (Wright and others, 1974; Stewart and Suczek, 1977). Wright and others (1974) ascribed emplacement of the gigantic slabs of older rocks to sedimentary processes, whereas Walker and others (1986) suggested tectonic emplacement during transtensional events associated with syndepositional strike-slip faulting. In southern Idaho, Link (1983) described abrupt local facies changes and an abundance of clasts derived from exposed and uplifted parts of the diamictite and volcanic sequence, and he suggested that syndepositional tectonism is responsible for these relations. In northeastern Washington, F.K. Miller (1983) proposed a deep basin bounded by a high-angle fault on one side to account for abrupt changes in facies and thickness in the Windermere Group. Deposition of the diamictite and volcanic sequence in fault-bounded basins has also been demonstrated in other parts of western North America (Christie-Blick and others, 1980; Eisbacher, 1981).

The age of the diamictite and volcanic sequence is poorly constrained. Miller and others (1973) indicated K-Ar isotopic ages of from 918 to 827 Ma for whole rocks and mineral separates from greenstone in the sequence in northeastern Washington. More recent work suggests that the K-Ar system may be disturbed and that these dates are too old (Devlin and others, 1985); a Sm-Nd whole-rock mineral age of about 760 Ma has been obtained for those rocks (Devlin and others, 1988). In northwest Canada, diabase dikes and sills that predate diamictite deposits presumably correlative with the diamictite deposits in the Western United States are approximately 770 Ma on the basis of Rb-Sr isochron dates (Armstrong and others, 1982). In British Columbia, Canada, gneissic granite that unconformably underlies diamictite-bearing rocks of the Windermere Supergroup is about 730 Ma on the basis of U-Pb analysis of zircons (Parrish and Armstrong, 1983; Evenchick and others, 1984). Paleontological dates based on identifications of microscopic planktonic algae (acritarchs) from interbeds within the diamictite indicate a Vendian age (650-570 Ma) in Utah and southwestern Alberta (Moorman, 1974; Knoll and others, 1981).

Terrigenous Detrital Sequence

The terrigenous detrital sequence (Late Proterozoic and Lower Cambrian) at the base of the Paleozoic miogeosynclinal assemblage consists dominantly of quartzite and interstratified argillite or phyllite. The quartzite characteristically occurs as thick cliff-forming units that dominate the local landscape. In some regions the sequence rests unconformably on the diamictite and volcanic sequence, in other regions it appears to be gradational with this sequence, and in still other areas it rests on sedimentary, igneous, or metamorphic rocks older than the diamictite and volcanic sequence. In much of the Western United States, the terrigenous detrital sequence is conformably overlain by interstratified Cambrian shale, siltstone, phyllite, and limestone that grade upward into thick units of limestone and dolostone.

The terrigenous detrital sequence is widely distributed in the Western United States (Fig. 2; Plate 2-2). It occurs in northeastern Washington (Miller and Clark, 1975; F. K. Miller, 1983), central and southern Idaho (Hobbs and others, 1968; Crittenden and others, 1971; Oriel and Armstrong, 1971; Ruppel and others, 1975; Lindsey, 1982), western Utah (Crittenden and others, 1971; Blick, 1979; Christie-Blick, 1982), Nevada (Stewart, 1970, 1974), eastern California (Stewart, 1970), and southern California (Cameron, 1982). The sequence probably was originally continuous along the western margin of North America (Fig. 4), although rocks of the sequence have not been recognized in southern Washington and northern Idaho, perhaps because they were removed by rifting sometime in the Phanerozoic.

FIGURE 4 NEAR HERE

The quartzite in the terrigenous detrital sequence consists for the most part of light-gray, pinkish-gray, or pale-red, fine- to medium-grained, quartz-rich rock that is either cross stratified, irregularly or wavy laminated, or evenly parallel laminated. Granule to pebble conglomerate with clasts of quartz and quartzite, and locally jasper, occurs locally. Very fine to fine grained, parallel laminated quartzite is also common. The quartzite occurs interstratified with reddish-brown or greenish-gray, laminated siltstone, argillite, or phyllite. The siltstone, argillite, or phyllite occurs either as thin laminae or irregular wavy laminae or lenses interstratified with the quartzite or as thick units, some several hundreds of meters thick, between major quartzite units. The terrigenous detrital sequence also contains varied amounts of limestone and dolostone. In places such rocks are sparse, whereas in other places carbonate rock, particularly dolostone, occurs in units as thick as about 600 m.

Rocks of the terrigenous detrital sequence are interpreted to have been deposited in shallow-marine environments, probably mainly on a tidal-dominated shelf (Stewart, 1970; Barnes and Klein, 1975; Klein, 1975; Benmore, 1978; Diehl, 1979) and in braided fluvial systems (Diehl, 1979; Mount, 1982; Christie-Blick, 1984; Schneck and McCollum, 1985). Shallow-marine tidal-dominated shelf deposits are indicated by current directions that locally show a bimodal and bipolar character, suggesting the ebb and flow of tidal currents (Fig. 4). Some units may be subtidal sand bodies developed during major storms (Mount, 1982). Peritidal oolite lime sands occur locally (Moore, 1976). Braided-stream deposits are indicated by the presence of shallow channels containing conglomerate, by features that suggest transverse and longitudinal sand bars and overbank fine-grained deposits, and by the widespread distribution of coarse-grained sandstone and conglomeratic sandstone.

Stratigraphic units in the terrigenous detrital sequence are generally lithologically similar and persistent along sedimentary strike, generally in a north-south direction, and they change facies and thickness across sedimentary strike, generally in an east-west direction. The persistence of some of the units is truly remarkable. For example, the Zabriskie Quartzite (Lower Cambrian) is recognized throughout the southern Great Basin region of Nevada and California, in the Victorville-San Bernardino Mountains region of southern California, and in the Caborca region of Sonora, Mexico, where it is called the Proveedora Quartzite (Stewart and others, 1984). Across sedimentary strike, units commonly become more silty and carbonate rich to the west. This relation is particularly evident in the southern Great Basin where units such as the Zabriskie Quartzite change facies from quartzite in the east to interstratified quartzite and siltstone and finally almost entirely siltstone (Harkless Formation) in the west. Shallow-marine carbonate units, such as the Reed Dolostone of eastern California and western Nevada, are thickest to the west and lens out eastward within largely terrigenous units.

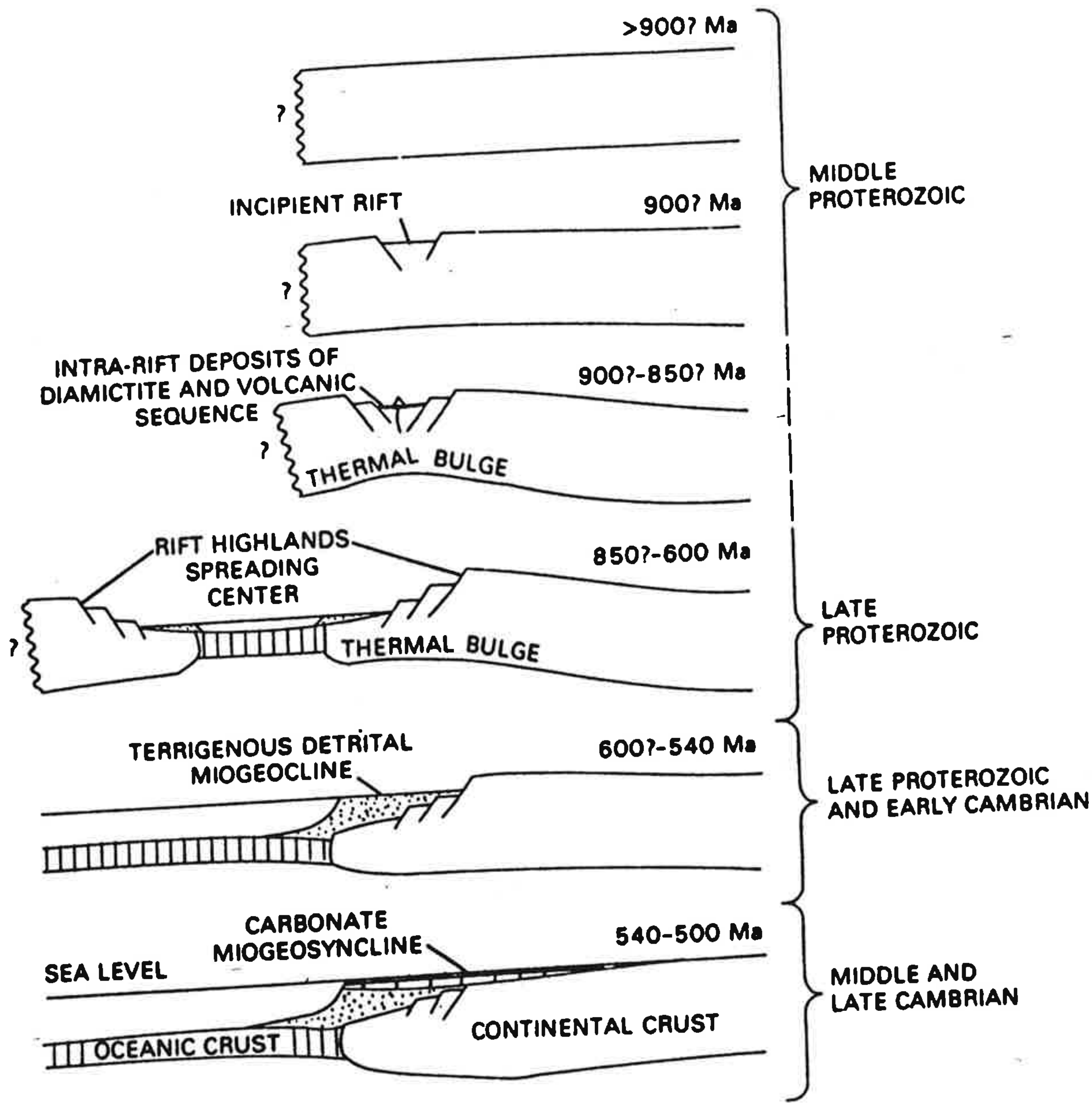
The terrigenous detrital sequence ranges in thickness from a zero edge in eastern areas to more than 6,000 m locally in western areas (Plate 2-2).

The upper part of the terrigenous detrital sequence contains sparse, but locally abundant, Early Cambrian biotas consisting of trilobites, brachiopods, mollusks and small shelly fossils, sponges, archeocyathids, stromatolites, algae, algal-like microorganisms, and trace fossils (Cloud and Nelson, 1966; Stewart and others, 1984).

Tectonic Models

The terrigenous detrital sequence in the Western United States forms a well-defined westward-thickening miogeoclinal sedimentary wedge (Fig. 2; Plate 2-2). The extent and shape of this sedimentary wedge differs significantly from the depositional patterns of both earlier Precambrian rocks, such as the Belt Supergroup and Uinta Mountain Group, that accumulated in deep epicratonic troughs, and the diamictite and volcanic sequence that appears to have accumulated in fault-bounded basins. This change in depositional patterns is thought to represent a major change in the tectonic setting of western North America related to rifting that created a new, or at least reshaped, continental margin along western North America.

The diamictite and volcanic sequence may represent deposits that accumulated in rift-valley basins that formed prior to the main stage of rifting (Fig. X). Such an interpretation is supported by the discontinuous geographic extent of the diamictite and volcanic sequence in western North America, by the abundance of presumably rift-related volcanic rocks (tholeiitic? basalt) in the sequence, and by the indication of significant faulting during deposition of the sequence. In British Columbia, the term East Kootenay orogeny has been used to describe tectonic events prior to deposition of the diamictite and volcanic sequence (Windermere Supergroup) in Canada. Recent work, however, indicates that the term East Kootenay orogeny is better restricted to a 1,350- to 1,300-Ma event that apparently terminated deposition of the Belt and correlative Purcell Supergroups and involved folding, regional metamorphism, and granitic intrusion (McMechan and Price, 1982). The term Goat River orogeny was used by McMechan and Price (1982) in British Columbia and Hayhook orogeny (Young and others, 1979) in the northern Canadian Cordillera for the event that occurred during deposition of the



>900? Ma
?
INCIPIENT RIFT
900? Ma
?
INTRA-RIFT DEPOSITS OF
DIAMICTITE AND VOLCANIC
SEQUENCE
900?-850? Ma
?
THERMAL BULGE
RIFT HIGHLANDS
SPREADING
CENTER
850?-600 Ma
?
THERMAL BULGE
TERRIGENOUS DETRITAL
MIOGEOCLINE
600?-540 Ma
CARBONATE
MIOGEOSYNCLINE
540-500 Ma
SEA LEVEL
OCEANIC CRUST
CONTINENTAL CRUST
MIDDLE
PROTEROZOIC
LATE
PROTEROZOIC
LATE PROTEROZOIC
AND EARLY CAMBRIAN
MIDDLE AND
LATE CAMBRIAN

Figure 'x'.

diamictite and volcanic sequence and involved uplift, block faulting, and low-grade regional metamorphism. The Goat River orogeny is considered to be related to the rift-valley stage of the Late Proterozoic rifting. In the Western United States, faulting synchronous with deposition of the diamictite and volcanic sequence has been described in northeastern Washington (Miller, 1983), southern Idaho (Link, 1983), and eastern California (Wright and others, 1974; Troxel and others, 1977; Walker and others, 1986). In eastern California, Walker and others (1986) have proposed tectonic events including folding, development of cleavage, and later low-angle normal faults during the time when the diamictite and volcanic sequence was being deposited. Although their proposals have been challenged by Troxel and others (1987), Walker and others (1986) related these events to transtensional deformation associated with strike-slip faulting.

Timing of this initial stage of rifting is poorly constrained, but, on the basis of dates mentioned earlier, the diamictite and volcanic sequence and the rift-valley stage of rifting are probably younger than 730 Ma.

The main stage of Late Proterozoic rifting is interpreted to have started shortly before deposition of the terrigenous detrital sequence, which is considered to be the initial part of the miogeoclinal-miogeosynclinal succession related to a newly formed continental margin (Fig. X). Analysis of subsidence rates (Stewart and Suczek, 1977; Armin and Mayer, 1983; Bond and others, 1983; Christie-Blick, 1984; Bond and Kominz, 1984; Bond and others, 1985), after removal of isostatic effects of sediment and water, suggests that subsidence was related to initial stretching of the crust and to thermal contraction. Subsidence curves suggest that the main stage of rifting started at about 600 Ma. This age is compatible with the 600-Ma age (J.B. Saleeby, Calif. Inst. Tech., 1987, written commun.) of a plagiogranite in ophiolitic rocks in the northern Sierra Nevada of California and with the 565-570 Ma age (Wallin and others, 1988) of tonalite from the Trinity ultramafic sheet in the Klamath Mountains of northern California. The ophiolitic rocks may have formed at an oceanic spreading ridge related to the main stage of rifting, although the original position of these rocks relative to Cordilleran miogeoclinal rocks is uncertain.

The apparent long span of time between presumed initial rifting and the main stage may be due to a prolonged episode of tectonic activity (Fig. X). Rifting may have taken place in two distinct breakup events (Bond and Kominz, 1984), one during deposition of the diamictite and volcanic sequence and one in the Early Cambrian during deposition of the terrigenous detrital sequence, or the breakup events may have been protracted and episodic (Devlin and Bond, 1988). The initial rifting event, as proposed by Walker and others (1986), could be related to transtensional tectonics associated with strike-slip faulting and thus may not be strictly part of the rifting events that formed the Cordilleran continental margin.

The source terrane of the terrigenous detrital sequence may have been the initial rift bulge (uplifted area) that was created by thermal expansion during continental rifting (Fig. X). Such uplift is well known along the Afro-Arabian rift system (Baker and others, 1972; Kinsman, 1975; Lowell and others, 1975). Cessation of deposition of terrigenous detritus in the miogeocline may be related to the destruction of the bulge by thermal contraction due to cooling and by erosion. After the bulge had been lowered to a critical level, the Early Cambrian ocean transgressed eastward into cratonic areas. As a consequence, coarse detrital material was trapped in more easterly coastal areas on the craton, and the Middle Cambrian miogeosynclinal-shelf area was an area of carbonate deposition relatively free of terrigenous detritus.

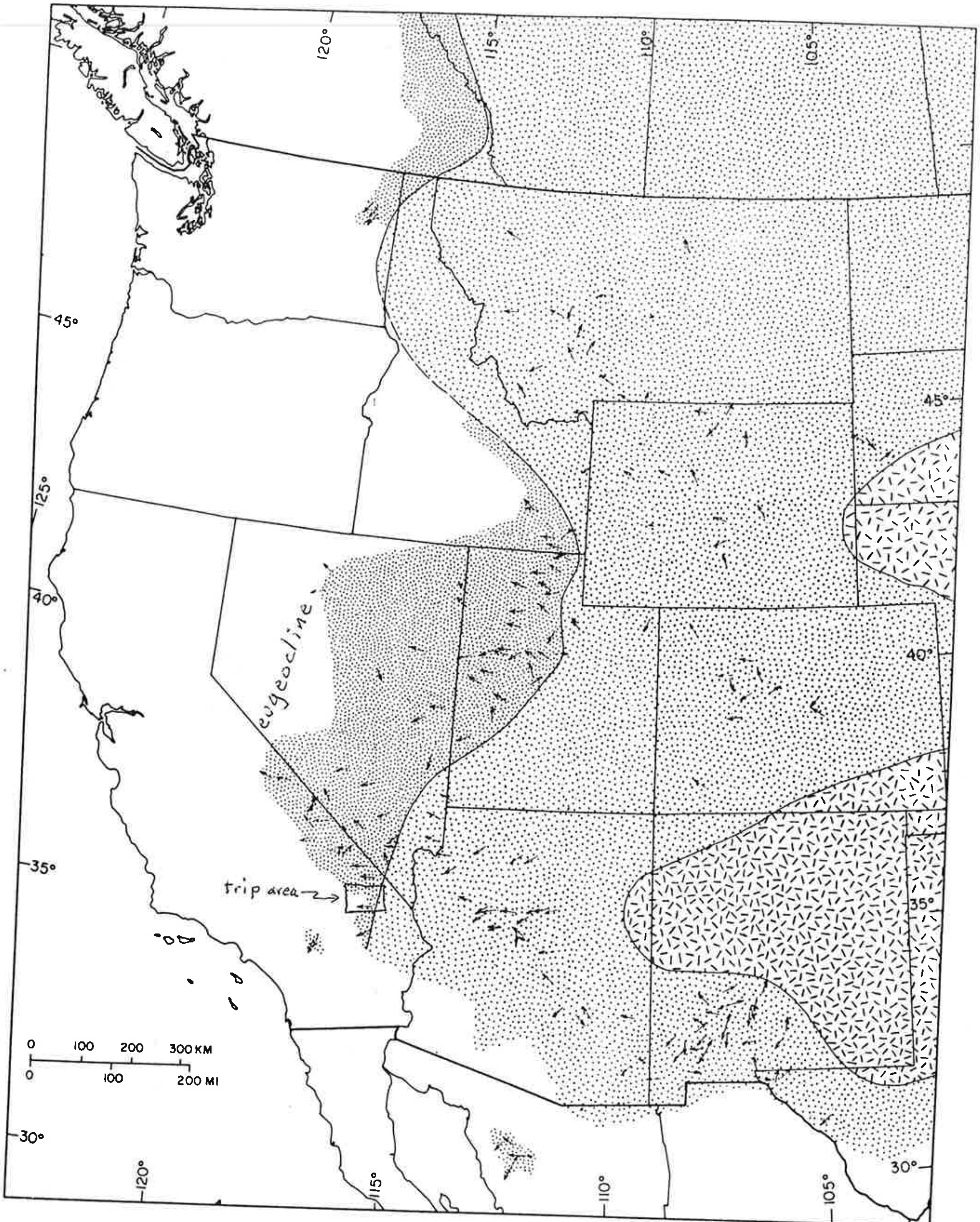
GEOLOGIC HISTORY--OVERVIEW OF CONTINENTAL MARGIN DEVELOPMENT

Forrest G. Poole

Late Proterozoic and Cambrian rocks of the Western United States are mostly shallow-water deposits that formed on a broad shelf along the western margin of the North American craton. Relatively deep-water deposits, some of which are allochthonous, crop out in a few areas near the western margin of the shelf. The Late Proterozoic and Cambrian shelf deposits consist of three main lithogenetic sequences, in ascending order: (1) a discontinuous sequence, locally as thick as 3,000 m, of diamictite, mudstone, sandstone, conglomerate, and mafic volcanic rocks of Late Proterozoic age; (2) a westward-thickening wedge, locally more than 6,000 m thick, of Late Proterozoic and Lower Cambrian terrigenous detrital rocks of shallow-subtidal and intertidal origin; and (3) a Middle and Upper Cambrian sequence of predominantly shallow-subtidal carbonate rocks generally about 2,000 m thick. The rate of accumulation of strata was greatest in late Precambrian and Early Cambrian time. Accumulation and subsidence rates may be related to thermal contraction that followed an uplift related to heating at a spreading center (Stewart and Suczek, 1977; Armin and Mayer, 1983; Bond and others, 1983; Bond and Kominz, 1984). This sequence of events may be related to fragmentation and reshaping of the western margin of the United States by rifting in the Late Proterozoic (Stewart, 1972). The diamictite and volcanic sequence may have been deposited in rift valleys that formed during the early stage of the rifting; the terrigenous detrital sequence may be related to erosion of a thermally expanded area near the rift; and the carbonate sequence may be related to widespread shallow-water shelf sedimentation that occurred after destruction of the thermally uplifted area by cooling and thermal contraction and by erosion.

The Cordilleran continental margin apparently began development following the Late Proterozoic rifting (Stewart, 1972), and by Middle Cambrian time the basic tectonic framework of the Western United States that controlled Middle Cambrian to Devonian deposition included, from east to west, a cratonic platform, a continental shelf, a continental slope, a continental rise, a marginal ocean basin or inner-arc basin, and possibly an island arc. Because of their tectonic instability, the marginal ocean basin and continental rise contain only fragmentary records of Late Proterozoic to Devonian deposits. Preserved ocean-basin and continental-rise deposits are characteristically thin-bedded chert, mudstone, siltstone, limestone, volcanic rocks, and some sandstone and conglomerate, all indicative of neritic, bathyal, and abyssal environments. The continental shelf contains a nearly complete record of as much as 6,000 m of Middle Cambrian to Upper Devonian deposits that are characterized by thick units of limestone and dolostone and some units of sandstone and siltstone. Terrigenous clastic sediments were derived mainly from the cratonic platform. Several regionally persistent quartz-sand-bearing carbonate units and quartzose sandstone units are recognized. The continental-shelf sediments were deposited in shallow-subtidal, intertidal, and some supratidal environments. Depositional trends varied considerably on the continental shelf owing to sea-level changes, provenance of sediment, and paleotectonic features. Persistent arches that extended westward across the shelf from the Transcontinental-basement arch influenced lithofacies and thickness trends from the Middle Cambrian to the Upper Devonian (Plates 2, 3). A transitional zone, perhaps 100 km wide, separated the continental-shelf and continental-rise facies. This zone, which is characterized by as much as 4,000 m of thin-bedded limestone, mudstone, siltstone, and sandstone including many sediment gravity-flow deposits, apparently represents a gently but irregularly inclined continental slope at moderate water depths. The cratonic platform contains a fragmentary record of Middle Cambrian to Middle Devonian deposits because of widespread vertical tectonic fluctuation and erosion. The Upper Devonian contains mostly intertidal and supratidal rocks, generally less than 300 m thick, characterized by limestone and dolostone and local beds of sandstone and siltstone.

Widespread crustal movements that probably were related to interactions between oceanic and continental plates along the northeast Pacific margin produced several regional unconformities within the Middle Cambrian to Upper Devonian interval. Accelerated seafloor spreading west of the North American continental margin in Middle to Late Devonian time apparently initiated the Antler orogeny and resultant Mississippian flysch and molasse deposition in the foreland basin east of the orogenic highland. Marginal ocean basin or inner-arc basin, continental-rise, and continental-slope rocks of Cambrian to Devonian age were strongly deformed and thrust eastward over autochthonous continental-slope and -shelf rocks in Late Devonian and Early Mississippian time. These rocks of the Antler orogen are represented in the Roberts Mountains allochthon in Nevada and adjacent States. Overprinting of Devonian and Mississippian deformation by Permian to early Tertiary deformation accounts for the present distribution of eugeosynclinal rocks of the Roberts Mountains allochthon. Many lithotectonic accreted terranes in the Western United States contain Devonian and older rocks that are not paleogeographically compatible with coeval rocks of the North American continental margin. Most of these terranes were emplaced and sutured to western North America in Mesozoic and Cenozoic time.



EXPLANATION

Current direction

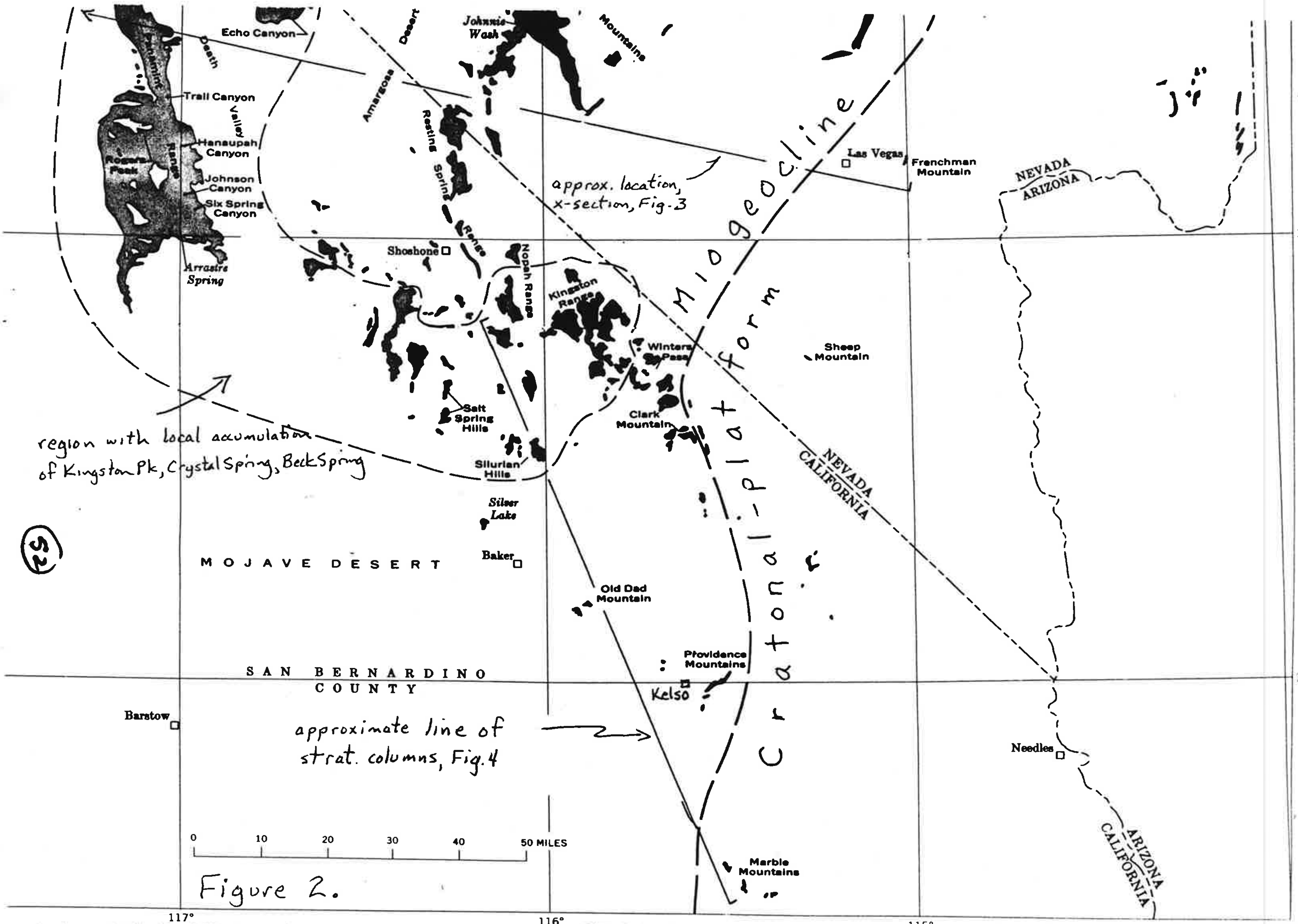
Bimodal-bipolar current directions

Late Proterozoic and Cambrian rocks absent

Cambrian cratonal rocks, partly restored. Late Proterozoic rocks probably not present

Miogeoclinal Late Proterozoic and Cambrian rocks

Figure 1.



Echo Canyon
Death
Panamint
Trail Canyon
Valley
Range
Hanaupah Canyon
Rogers Peak
Johnson Canyon
Six Spring Canyon
Arrastre Spring
Amargosa
Desert
Johnnie Wash
Mountains
Resting Spring Range
Shoshone
Nopah Range
Kingston Range
Winters Pass
Clark Mountain
Salt Spring Hills
Silurian Hills
Silver Lake
Baker
MOJAVE DESERT
Old Dad Mountain
Providence Mountains
Kelso
SAN BERNARDINO COUNTY
Barstow
Marble Mountains
Las Vegas
Frenchman Mountain
Sheep Mountain
NEVADA
ARIZONA
NEVADA
CALIFORNIA
ARIZONA
CALIFORNIA
Needles
0
10
20
30
40
50 MILES
117°
116°
115°
approx. location, x-section, Fig. 3
Miogeocline
Cratonal-platform
region with local accumulation of Kingston Pk, Crystal Spring, Beck Spring
approximate line of strat. columns, Fig. 4

Figure 2.

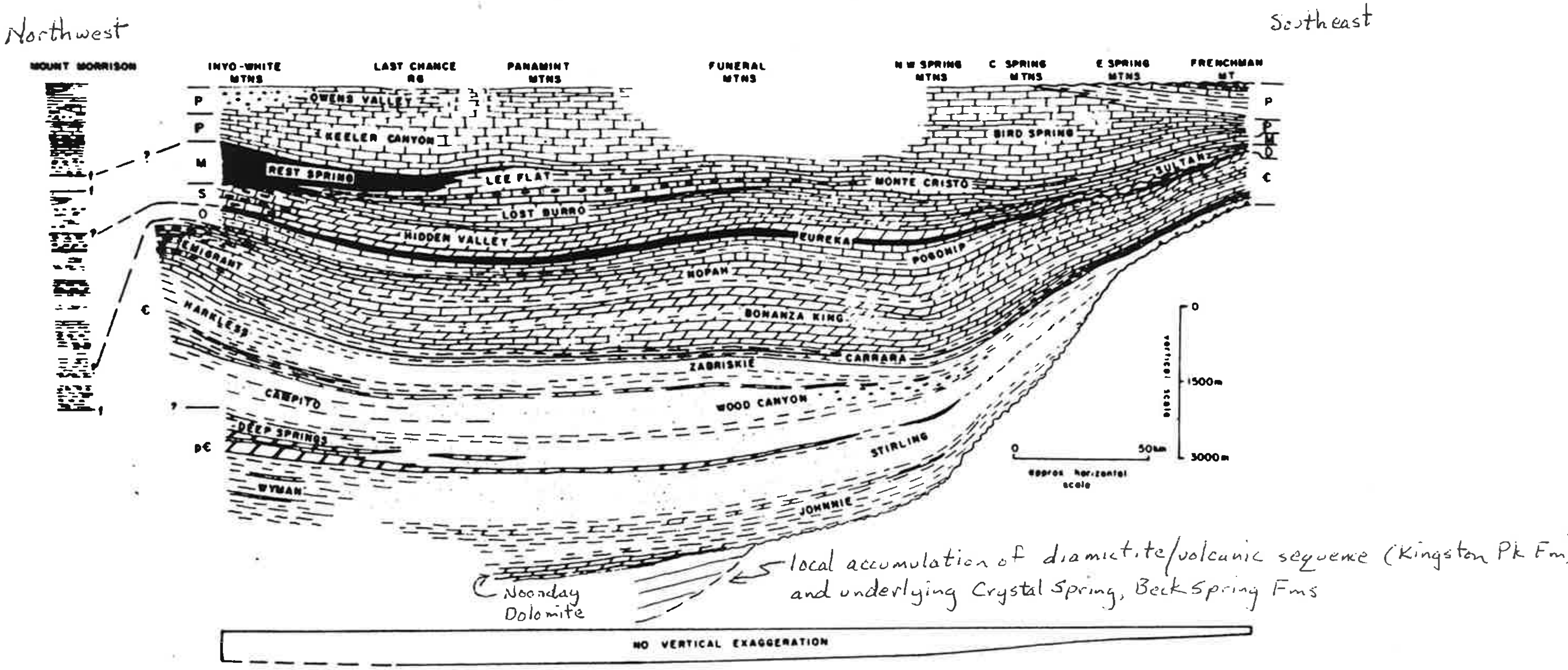


Fig. 3. Generalized stratigraphic framework of late Precambrian and Paleozoic rocks on a transect from near Las Vegas, Nevada (Frenchman Mountain), to near Mono Lake, California (Mount Morrison). No Pennsylvanian and Permian rocks crop out in the vicinity of the Funeral Mountains and are thus not shown in this section. Structural relations between the Mount Morrison rocks and thus of the Inyo-White Mountains are unknown,

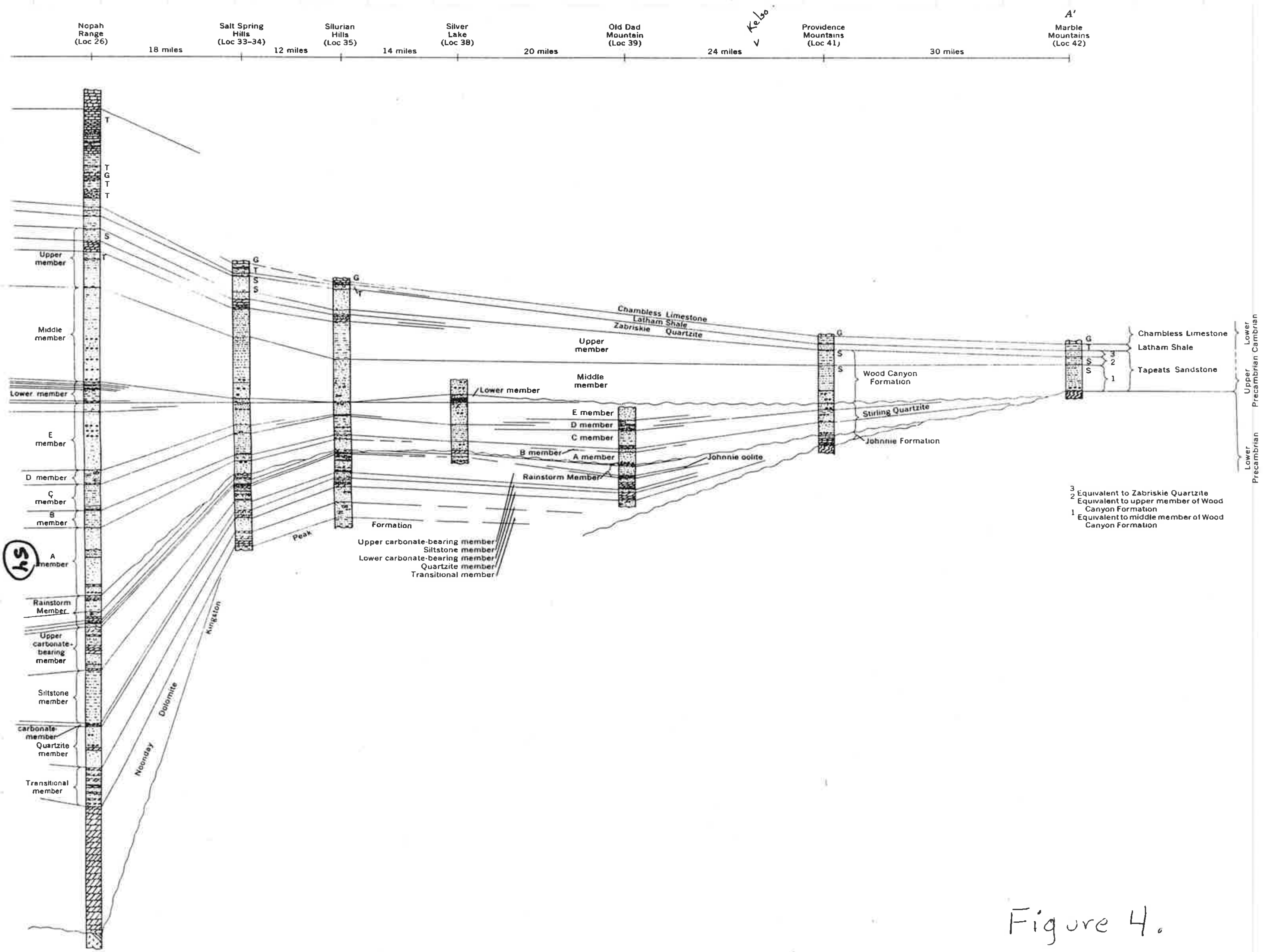
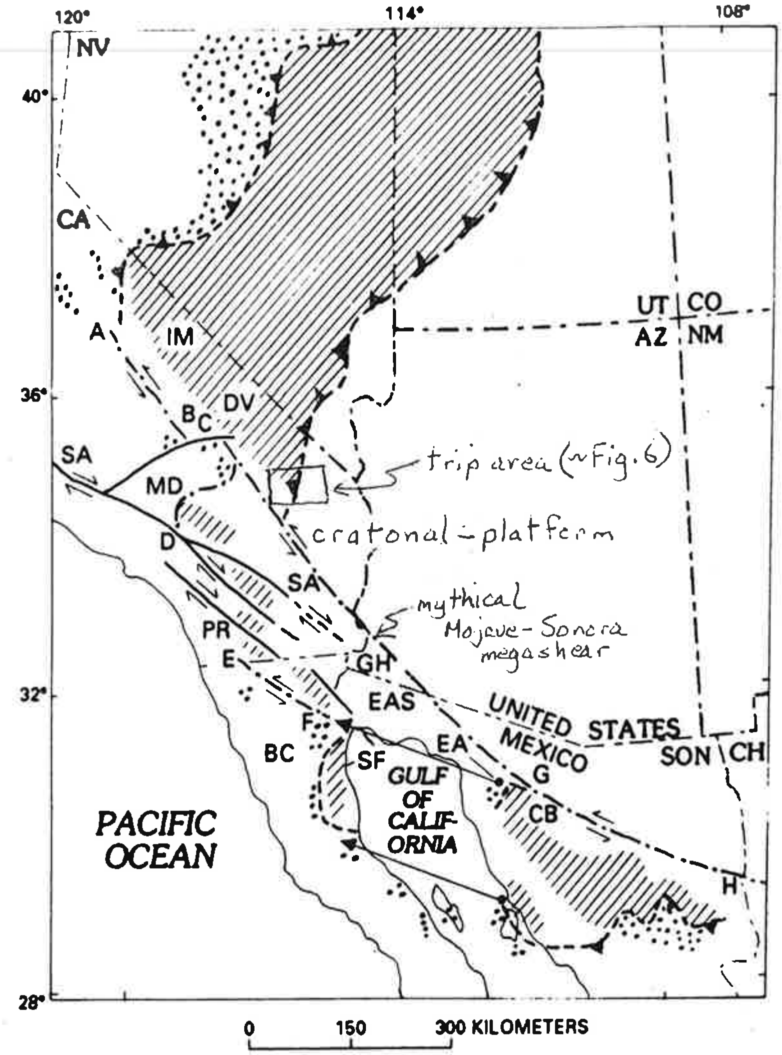

A'
Nopah Range (Loc 26)
Salt Spring Hills (Loc 33–34)
Silurian Hills (Loc 35)
Silver Lake (Loc 38)
Old Dad Mountain (Loc 39)
Providence Mountains (Loc 41)
Marble Mountains (Loc 42)
18 miles
12 miles
14 miles
20 miles
24 miles
30 miles
Kelso
54
Upper member
Middle member
Lower member
E member
D member
C member
B member
A member
Rainstorm Member
Upper carbonate-bearing member
Siltstone member
carbonate-member
Quartzite member
Transitional member
Chambless Limestone
Latham Shale
Zabriskie Quartzite
Upper member
Middle member
Lower member
E member
D member
C member
B member
A member
Johnnie oolite
Rainstorm Member
Formation
Peak
Upper carbonate-bearing member
Siltstone member
Lower carbonate-bearing member
Quartzite member
Transitional member
Kingston
Noonday
Dolomite
Wood Canyon Formation
Stirling Quartzite
Johnnie Formation
Chambless Limestone
Latham Shale
Tapeats Sandstone
Lower Cambrian
Upper Precambrian
Lower Precambrian
3 Equivalent to Zabriskie Quartzite
2 Equivalent to upper member of Wood Canyon Formation
1 Equivalent to middle member of Wood Canyon Formation

Figure 4.



EXPLANATION

Eugeoclinal and moderately deep to deep-water offshelf strata—Includes anomalous Permian rocks at El Antimonio

Miogeoclinal strata

Cratonal-platform strata

Facies or thrust boundary—Inferred Paleozoic continental margin is approximate boundary, before Paleozoic or Mesozoic thrusting, between eugeoclinal and miogeoclinal strata

Late Cenozoic strike-slip fault—Dashed where inferred; arrows show direction of relative movement

Hypothetical late Paleozoic or Mesozoic strike-slip fault—Arrows show direction of relative movement

Inferred late Cenozoic displacements on San Andreas fault system and on rift and fault systems in Gulf of California—Ball indicates original position; arrowhead indicates position after displacement

Figure 5. Map of the Western United States and northern Mexico showing distribution of facies of uppermost Proterozoic and Paleozoic rocks, possible Permian or Mesozoic left-lateral strike-slip faults, and late Cenozoic right-lateral faults. Symbols: A, B, C, D, E, F, G, and H, points on hypothetical faults mentioned in text; AZ, Arizona; BC, Baja California; CA, California; CB, Caborca; CO, Colorado; CH, Chihuahua; DV, Death Valley; EA, El Antimonio; EAS, Ejido Aquiles Serdan; GH, Gila Mountains; IM, Inyo Mountains; MD, Mojave Desert; NM, New Mexico; NV, Nevada; PR, Peninsular Ranges; SA, San Andreas fault; SF, San Felipe; SON, Sonora; UT, Utah. Distribution of facies in Baja California and the Peninsular Ranges largely after Gastil and Miller (1984). Original position of rocks in Baja California and Peninsular Ranges of California relative to those in Sonora uncertain (see discussion in text).

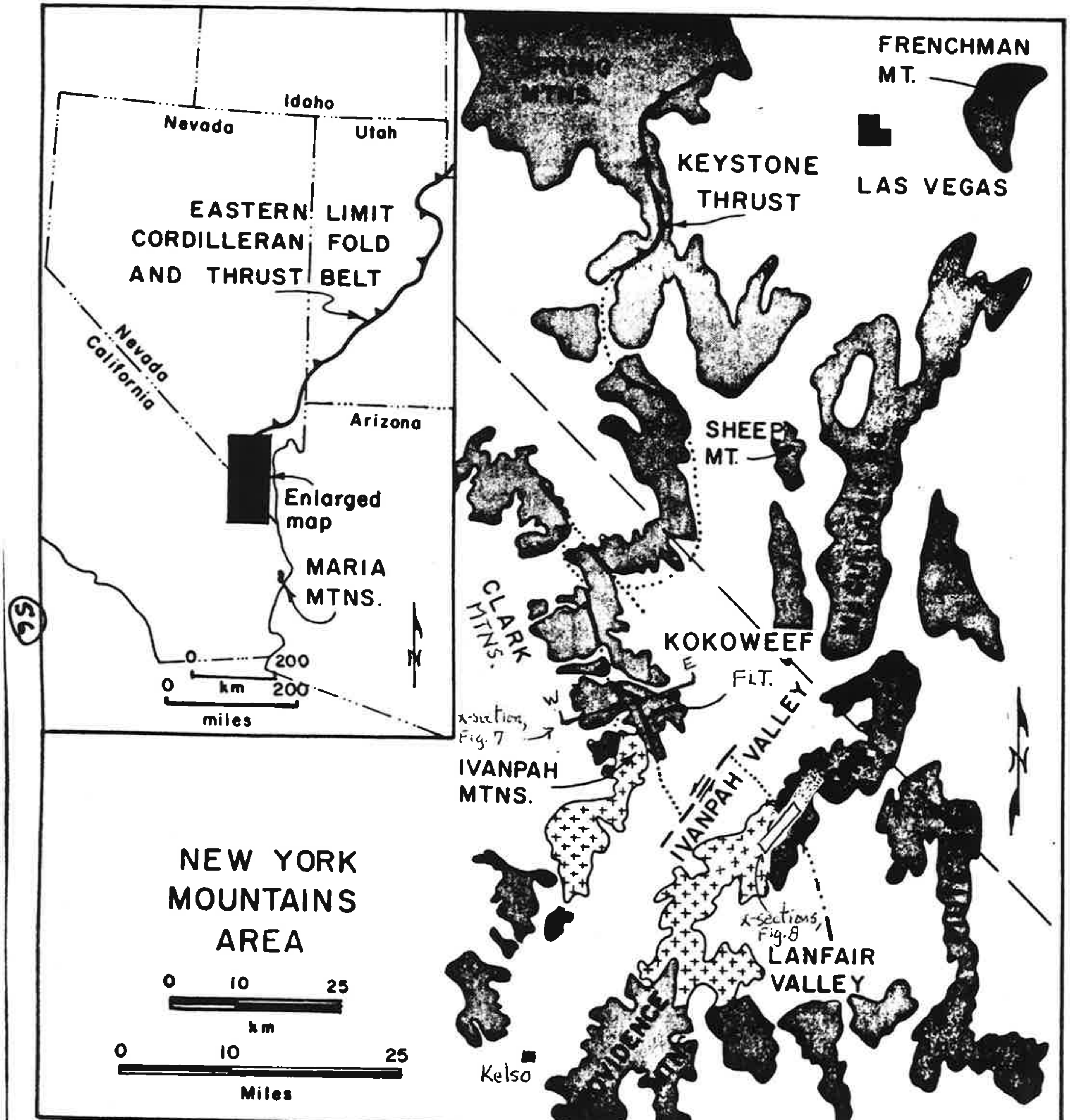


Figure 6. Index map of the location of the Sagamore Canyon–Slaughterhouse Spring area, New York Mountains, California, and its relation to geology of adjacent areas (plus-sign patterns = plutons; shaded areas are ranges exposing pre-Cenozoic rocks).

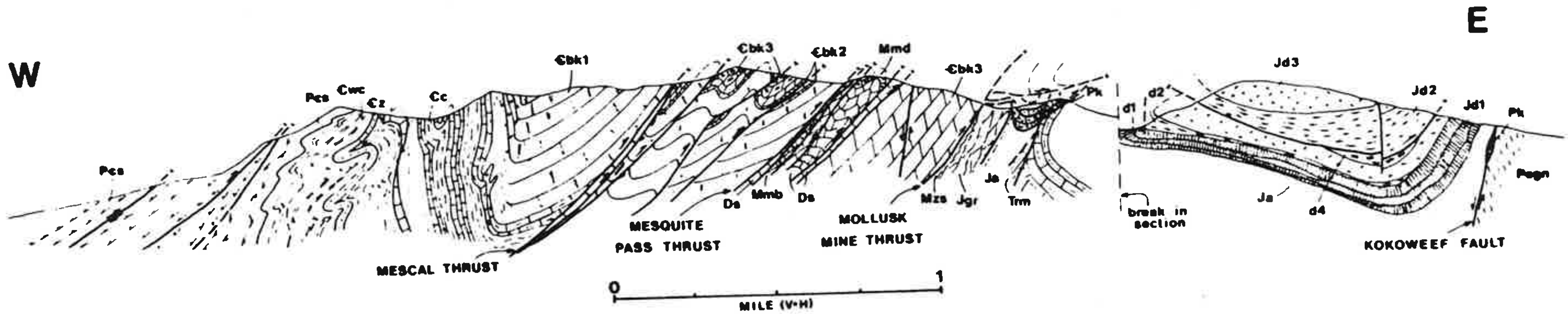


Figure 7. Cross-section through the southern Mescal Range (south of Piute fault, Fig. 9) of the Clark Mountain thrust complex. Various parts of this section will be seen at stops 2-3, 4, 5, and 6. Rock units from west to east: Stirling Quartzite (P€s); Wood Canyon Formation (€wc); Zabriskie Quartzite (€z); Carrara Formation (€c); Bonanza King Formation (€bk) with subunits 1-3; Bullion and Dawn Anchor Members of the Monte Cristo Formation (Mmb and Mmd); Sultan Formation (Ds); Jurassic pluton (Jgr); Mesozoic clastic sediments (Ms); Kaibab Limestone (Pk); Moenkopi Formation (Trm); Aztec Sandstone (Ja); Delfonte Volcanics (Jd) with subunits 1-4; Precambrian gneissic basement (P€gn).

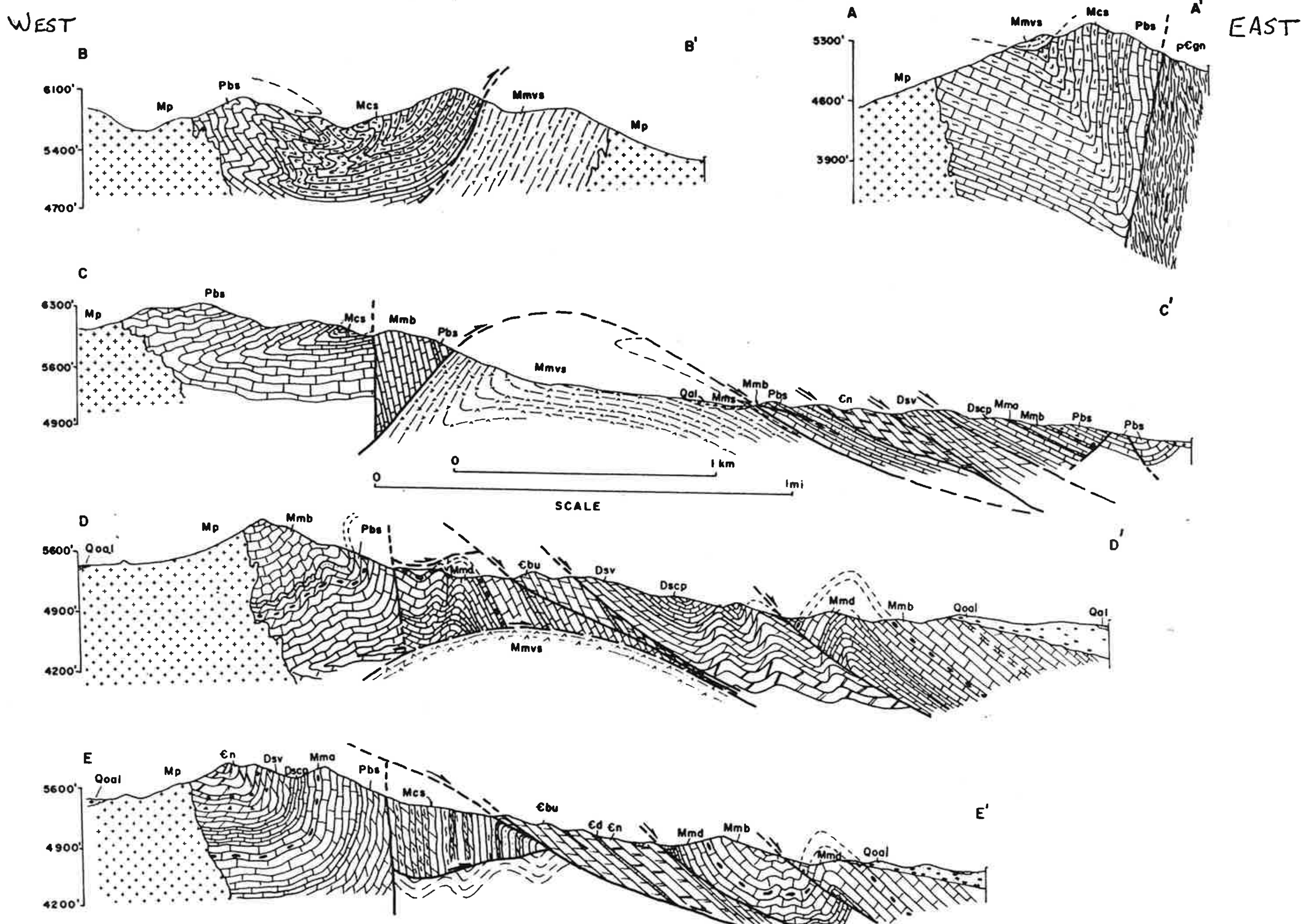


Figure 8. Geologic cross sections of the Sagamore Canyon–Slaughterhouse Spring area. Location of sections is shown in Figure 3.

STOP 8a: PEACH SPRINGS TUFF AND MIDDLE TO LATE MIOCENE STRATIGRAPHY OF THE EASTERN MOJAVE DESERT

Objectives

1. To discuss the implications of the Peach Springs Tuff for the Miocene structural evolution of the Mojave Desert.
2. To observe the Peach Springs Tuff, lacustrine rocks, and the Wild Horse Mesa Tuff.

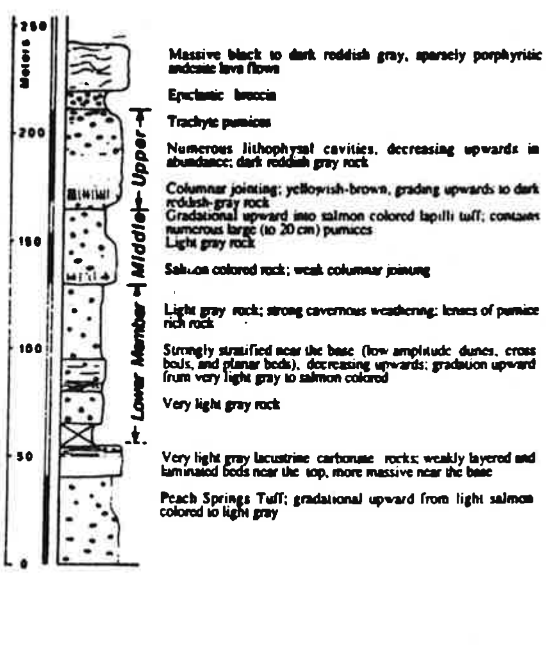
We are located on the south side of Pinto Mountain (Fig. 14). Approximately 250 m of Tertiary volcanic, lacustrine, and epiclastic rocks dip gently NE and overlie Mid Hills adamellite or Rock Spring monzondiorite (Beckerman and others, 1982). Stratigraphy of the deposits is illustrated in Figure 19. The lowermost Tertiary unit is the Peach Springs Tuff.

The Peach Springs Tuff is a particularly important volcanic unit because it may have been regionally extensive. Glazner and others (1986) have correlated the tuff from Peach Springs on the east, 320 km to the west to near Barstow. Lively debate is expected at this point! Although we are located near the middle of the tuff unit, there is no direct evidence for a source caldera in the Providence Mountains, Woods Mountains, or Hackberry Mountains area. The tuff is the subject of ongoing detailed petrological and volcanological studies by Buesch and Valentine (e.g., Buesch and Valentine, 1986).

At this locality the Peach Springs Tuff is about 40 m thick. Some of the "typical" features of the Peach Springs Tuff that are observed here are an abundance of sanidine phenocrysts, locally with a bluish chatoyance, and a distinctive salmon color.

The Peach Springs Tuff is conformably overlain by about 12 m of massive and laminated carbonate lacustrine sedimentary rocks. No fossils were observed in the sedimentary rocks here. However, fragments of petrified wood occur in similar lacustrine sedimentary rocks that overlie the Peach Springs Tuff in the northern Providence Mountains (McCurry, 1985).

Lacustrine sedimentary rocks are conformably overlain by the Wild Horse Mesa Tuff. Part of the lower member of the tuff is strongly stratified, a feature that is common for the distal facies of some ash-flow tuff sheets (Fisher and Schmincke, 1984). The upper member is conformably overlain by several meters of a breccia that consists of angular to subangular fragments of quartz monzonite, diorite, gneiss, and mylonitic granitoid rock in a fine-grained tuffaceous matrix. The largest clasts are approximately 1 m across, and the tuffaceous matrix of the deposit resembles the upper part of the underlying ash-flow unit. The breccia is probably a remnant of an alluvial fan that was derived from a source to the north. It is overlain by two andesite lava flows.



Correlation of the Peach Springs Tuff, a large-volume Miocene ignimbrite sheet in California and Arizona

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ABSTRACT

The Peach Springs Tuff is a distinctive early Miocene ignimbrite deposit that was first recognized in western Arizona. Recent field studies and phenocryst analyses indicate that adjacent outcrops of similar tuff in the central and easten Mojave Desert may be correlative. This proposed correlation implies that outcrops of the tuff are scattered over an area of at least 35 000 km^2 from the western Colorado Plateau to Barstow, California, and that the erupted volume, allowing for posteruption crustal extension, was at least several hundred cubic kilometres. Thus, the Peach Springs Tuff may be a regional stratigraphic marker, useful for determining regional paleogeography and the time and extent of Tertiary crustal extension.

INTRODUCTION

A single welded rhyolite tuff containing conspicuous chatoyant sanidine phenocrysts occurs in the Tertiary section in many mountain ranges in western Arizona and the Mojave Desert. Here we offer evidence that these scattered outcrops represent part of a single enormous early Miocene outflow sheet. Because we have been unable to find any significant petrographic, field, or chemical differences between these outcrops, the descriptions below pertain to all the outcrops in our proposed correlation.

The tuff is exposed discontinuously in a region stretching from Barstow, California, to the Colorado Plateau at Peach Springs, Arizona (Fig. 1). In most ranges it is the only welded tuff in the Tertiary section. The tuff was originally recognized over an area of about 5200 km^2 between Kingman and Peach Springs, where it was named (Young, 1966; Young and Brennan, 1974; Goff et al., 1983). Recent mapping in the Colorado River trough region extended the correlation westward into tilted Miocene sections on both sides of the Colorado River (W. J. Carr's mapping compiled by Stone and Howard, 1979; Carr et al., 1980; Dickey et al., 1980; Carr and Dickey, 1980; Suneson, 1980; Carr, 1981; Young, 1981; Howard et al., 1982; John, 1982; Pike and Hansen, 1982; Nielson-Pike, 1984).

Petrographically identical tuff occurs in most of the ranges of the central Mojave Desert. Durrell (1953) mapped chatoyant sanidine tuff near celestite deposits in the southeastern Cady Mountains. Bassett and Kupfer (1964) mapped outcrops of chatoyant sanidine tuff in the Bristol Mountains, Old Dad Mountains, Cady Mountains, and Bullion Mountains. They noted the lithologic similarities between the outcrops and suggested that they might be correlative. T. W. Dibblee, Jr. and A. M. Bassett mapped similar tuffs as unit QTr in the Bristol Mountains and Bullion Mountains, as unit Trt in the Cady Mountains, and as unit Tst in the Newberry Mountains (Kane Wash) and on Daggett Ridge (Dibblee, 1964a, 1964b, 1966, 1967a, 1967b, 1970; Dibblee and Bassett, 1966). Our recent mapping and reconnaissance in the Bristol Mountains, Cady Mountains, Marble Mountains, and Ship Mountains (Miller and Glazner, unpub. data) indicate that these units represent part of the same extensive tuff. Additional mapping in the Providence Mountains area (Goldfarb et al., 1986) and New York Mountains (Miller et al., 1986) has resulted in discoveries of similar tuff.

Correlation of the tuff would make it an exceptionally valuable stratigraphic and tectonic marker horizon because of (1) its presence in otherwise difficult-to-correlate local stratigraphic sections, (2) its deposition during a time of regional extension, and (3) its wide geographic distribution across Neogene tectonic-province boundaries.

PETROGRAPHIC AND FIELD ASPECTS OF THE TUFF OUTCROPS

The tuff is characterized by abundant large (up to 5 mm) and clear sanidine phenocrysts that commonly exhibit blue chatoyance. Sanidine makes up 70–90 vol% of the phenocryst assemblage; subequal amounts of plagioclase, biotite, hornblende, and sphene compose the remainder. Quartz is rare. Phenocrysts compose 10–20 vol% of the total rock. Lithic clasts are as large as 10 cm or more and are generally locally derived.

In outcrop, the tuff is generally strongly to moderately welded, although weakly welded facies are locally present, especially at the edges of the known distribution. Two cliffs of Peach Springs Tuff are exposed in roadcuts along U.S. Interstate 40 at Kingman. Buesch and Valentine (1986) ascribed these cliffs to variations in the degrees of welding and vapor-phase crystallization within a single cooling unit. We have not found multiple cooling units in our studies of proposed equivalent tuffs in California.

In some localities in the central Mojave Desert, the unit contains a black vitrophyre layer

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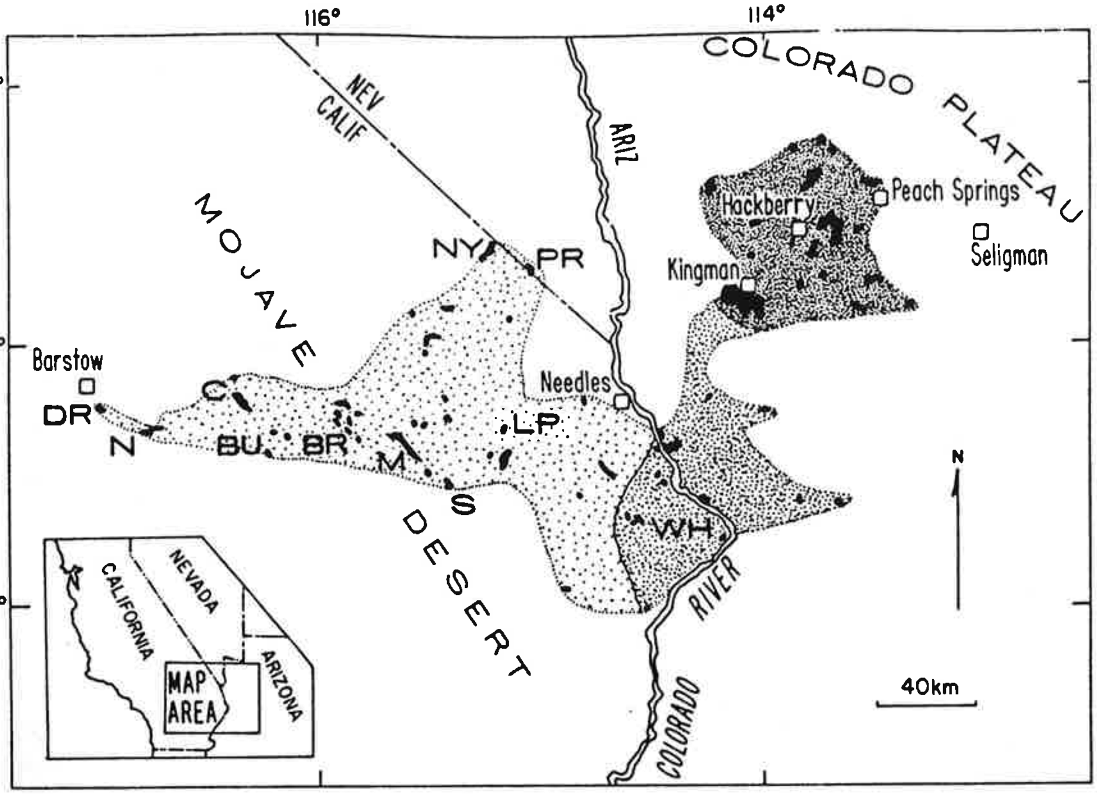

Figure 1. Outcrops (black) and known distribution (stipple) of Peach Springs Tuff and proposed equivalents. Young (1966) and Young and Brennan (1974) originally defined tuff in region between Kingman and Peach Springs (heavy stipple). W. J. Carr and coworkers and Young (1981) extended distributions to ranges bordering both sides of Colorado River (medium stipple). We propose to extend correlation from Colorado River westward to Barstow (light stipple). BR = Bristol Mountains, BU = Bullion Mountains, C = Cady Mountains, DR = Daggett Ridge, LP = Little Piute Mountains, M = Marble Mountains, N = Newberry Mountains, NY = New York Mountains, PR = Piute Range, S = Ship Mountains, WH = Whipple Mountains.

(about 1 m thick) that occurs several metres above the base and that has the same mineralogy as the main welded tuff, including chatoyant sanidine. Buesch and Valentine's (1986) studies of Peach Springs Tuff in the Kingman area have shown that vitrophyre there occurs within the densely welded zone. Buesch and Valentine (1986) also found that at Kingman, vitrophyre occurs in the "edge facies" and is absent from the "open-valley facies" of the Peach Springs Tuff. These observations indicate the extent of paleotopographic control on deposition and welding of the tuff. Color of the tuff is highly variable and includes buff, chocolate brown, salmon pink, gray, and bluish gray, depending on the degree of welding, alteration, and desert varnish. Pumice clasts are generally gray and are not glassy black in densely welded tuffs.

In the region between the Colorado Plateau and the central Mojave Desert (Fig. 1), the tuff is present locally in every range where the appropriate part of the stratigraphic column is exposed. The thickness of the tuff is highly variable, presumably because of a topographically irregular substrate (as can be seen at Kingman) and postdepositional erosion. In general, however, maximum thicknesses increase from distal exposures toward the Colorado River trough. Our observations and published measurements (Young and Brennan, 1974; Buesch and Valentine, 1986; Knoll et al., 1986) indicate that maximum thickness of the tuff increases from 10–15 m in distal exposures (Barstow; Peach Springs) to 65–85 m at Kingman and 130 m in the Little Piute Mountains.

PROPOSED CORRELATION

On the basis of stratigraphic position, lithology, petrography, and phenocryst compositions, we propose that the chatoyant sanidine tuff of the central Mojave Desert is part of the Peach Springs Tuff outflow sheet. The main lines of evidence are summarized below.

1. A single welded tuff that is petrographically indistinguishable from the Peach Springs Tuff exposed at Kingman occurs in most Tertiary stratigraphic sections between Barstow, California, and Peach Springs, Arizona. In no range have two welded tuffs with Peach Springs mineralogy been found. In most of the ranges in California, the proposed Peach Springs Tuff is the *only* welded tuff in the Tertiary section.

2. Major-element compositions of sanidine, plagioclase, biotite, and hornblende phenocrysts in tuff from the central Mojave Desert are identical to those from the Peach Springs Tuff at Kingman. These data are summarized in Table 1. Compositional differences between localities are smaller than the relatively small scatter of compositions found within a single thin section. Whole-rock, major- and trace-element compositions overlap but show far more scatter than the phenocryst data, presumably because of alteration of the volcanic glass and the presence of exotic lithic components.

3. Although the stratigraphic setting of the tuff varies, it consistently overlies pre-Miocene or lower Miocene rocks and underlies middle Miocene and younger rocks. At and south of the latitude of Barstow and Needles, the main pulse of volcanic rocks was erupted at about 20 Ma (Glazner and Supplee, 1982), and the tuff consistently lies at or near the top of the Tertiary section. North of this latitude (for example, Piute Range, Fig. 1), the main pulse of volcanism occurred at 12–15 Ma, and the tuff lies near the base of the Tertiary section.

4. The mean magnetic direction measured in nine widely scattered outcrops of relatively flat-lying tuff from the central Mojave Desert is indistinguishable from that measured in the Peach Springs Tuff in the Kingman area (Wells and Hillhouse, 1986). This direction has an unusually low inclination and a large declination ($I = 42.8°$, $D = 32.3°$, $\alpha_{95} = 4.4°$ at Kingman; Young and Brennan, 1974) and is therefore distinctive.

5. A mineralogic study by Sharon Gusa

TABLE 1. COMPARISON OF PHENOCRYST COMPOSITIONS: PEACH SPRINGS TUFF AND PROPOSED EQUIVALENT TUFF FROM COLORADO RIVER TROUGH AND CENTRAL MOJAVE DESERT

	sanidine			plagioclase			biotite			hornblende		
	CM	CR	PS	CM	CR	PS	CM	CR	PS	CM	CR	PS
SiO_2	65.7, 3	65.4, 4	65.4, 3	64.2, 6	64.1, 4	63.4, 9	38, 2	38.6, 1	39.1, -	47.4, 7	46.7, 4	47.4, 5
Al_2O_3	18.8, 3	18.9, 1	18.5, 1	21.7, 5	21.9, 1	21.8, 6	12.6, 8	12.7, 1	12.8, -	6.5, 4	7.0, 2	6.9, 2
FeO							14, 1	14.9, 8	14.3, -	12.7, 2	13.0, 3	13.1, 2
MnO							0.6, 1	0.6, 1	0.6, -	1.1, 1	1.0, 1	1.1, 1
MgO							16, 1	16.2, 1	16.7, -	14.9, 4	14.7, 3	15.0, 3
CaO	0.4, 2	0.5, 1	0.4, 1	3.1, 4	3.2, 3	3.5, 5	0	0	0	10.9, 6	10.8, 4	11.3, 2
Na_2O	5.3, 4	5.3, 3	5.1, 1	8.8, 3	8.6, 2	8.8, 2	0.6, 1	0.6, 0	0.6, -	2.2, 1	2.2, 0	2.2, 1
K_2O	9.2, 6	9.0, 5	9.4, 2	1.6, 2	1.7, 3	1.3, 3	9.2, 6	9.7, 2	9.6, -	0.9, 1	1.0, 0	1.0, 1
n	19	11	4	14	6	4	9	2	1	3	3	2

Note: numbers after commas give standard deviations of point analyses (in terms of units of last digit; i.e., 12.6, 8 indicates a mean of 12.6 with a standard deviation of 0.8); n = number of point analyses. CM = central Mojave (4 samples, from Bullion Mountains, Marble Mountains, southeastern Cady Mountains, and northern Cady Mountains); CR = Colorado River trough area (2 samples, from Mohave and Chemehuevi Mountains); PS = Peach Springs Tuff from Kingman area (1 sample). Samples of CM, CR, and PS were alternated during analysis. Core and rim analyzed on most grains. All analyses by A. F. Glazner on the UCLA Cameca microprobe, January 1985.

of the U.S. Geological Survey (1986, written commun.) showed that heavy mineral suites of the Peach Springs Tuff and proposed equivalents are dominated by sphene and contrast sharply with suites from several more local Miocene ash-flow tuffs in the region, including the Hole in the Wall Tuff (McCurry, 1986), the Cook Canyon Tuff of Buesch and Valentine (1986), and a tuff in the Turtle Mountains reported by Howard et al. (1982, Table 3, no. 11). Gusa's study found no evidence of significant vertical mineralogic zonation in the Peach Springs Tuff.

TABLE 2. K-AR DATES ON PEACH SPRINGS TUFF AND PROPOSED EQUIVALENT TUFF IN MOJAVE DESERT

age (Ma)	Mineral	Locality	Reference
18.8 ±0.6*	san	Milkweed Canyon	P. E. Damon, in Young
17.3 ±0.4*	san	Kingman	and Brennan (1974)
18.2 ±0.4, 18.8 ±0.5	san, bio	Whipple Mountains	Dickey et al. (1980)
20.0 ±1.0	san	Cady Mountains	Glazner (1981)
18.1 ±0.6	san	Chemehuevi Mountains	Howard et al. (1982)
18.3 ±0.6	san	Little Piute Mountains	"
20.0 ±0.5, 18.8 ±0.5	san, bio	Woods Mountains	Goldfarb et al. (1986)
19.2 ±0.6, 20.1 ±0.5	san, bio	Bristol Mountains	Unpublished
16.5 ±0.4	san	"	"
18.0 ±0.5	san	"	"
20.5 ±0.5	san	Pinto Mountain	"
16.2 ±0.4	san	Marble Mountains	"
16.7 ±0.3, 17.8 ±0.4	san, san	Mohave Mountains	"
17.4 ±0.2	san	"	"
18.0 ±0.5	san	"	"
18.6 ±0.6	san	Piute Mountains	"
17.5 ±0.4	san	Ship Mountains	"
18.3 ±1.2†			

Note: san=sanidine, bio=biotite; ± refers to stated analytical precision. Unpublished dates determined by M. A. Pernokas, J. K. Nakata, and R. F. Marvin in U.S. Geological Survey laboratories on samples collected by the authors.
*Corrected to new decay constants (Dalrymple, 1979).
†Mean and standard deviation.

AGE OF THE TUFF

The Peach Springs Tuff and its proposed Mojave Desert equivalent are characterized by discrepant K-Ar dates. Available data are summarized in Table 2. Ages determined on sanidine, the mineral most often used for dating, range from 16.2 to 20.0 Ma; the mean is 18.2 Ma. The source of the variation is unknown, but it probably is not a result of dating different units because the variation occurs within single ranges as well as between ranges.

Three samples, from the Whipple Mountains, Bristol Mountains, and Providence Mountains, have yielded concordant sanidine-biotite ages that average 18.5, 19.6, and 19.4 Ma, respectively.

SOURCE OF THE TUFF

The tuff in our proposed correlation lacks a known source. Young and Brennan (1974, p. 84) stated, "The trend of outcrop thicknesses indicates that the source of the [Peach Springs Tuff] deposits was somewhere west of the Cerbat Mountains, most likely in or near the Black Mountains" (Fig. 1). Our thickness data corroborate the assumption that the source was somewhere in the Colorado River trough area, near the southern tip of Nevada.

SUMMARY

Similarities in stratigraphic position, field appearance, petrography, isotopic ages, paleomagnetic directions, and phenocryst compositions indicate that outcrops of chatoyant sanidine ash-flow tuff in the central Mojave Desert may be equivalent to the Peach Springs Tuff. If this correlation is confirmed, then outcrops of the Peach Springs Tuff are currently scattered over an area of at least 35 000 km^2. Even allowing for northeast-southwest crustal extension of as much as 100% across the region, this implies that the tuff had a volume of several hundred cubic kilometres—the first ash-flow tuff of such magnitude recognized in southern California.

Because it may be so widely distributed, the tuff offers a method for correlating isolated Tertiary stratigraphic sections in the Mojave Desert and western Arizona (Nielson-Pike, 1984). In addition, the tuff is generally flat-lying on the Colorado Plateau, moderately tilted in the Colorado River trough, and gently tilted in the central Mojave Desert; in many areas Tertiary strata beneath the tuff are tilted more steeply (Nielson and Glazner, 1986). These relations make the tuff an excellent marker bed for studying the timing and progress of extension across the region. On the basis of its apparent presence in most lower Miocene sections in the region, the tuff was deposited on a surface of relatively low relief, with few obvious large topographic irregularities such as block-faulted ranges.

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STOP 8b. -- HOLE-IN-THE-WALL CAMPGROUND

Objectives

1. To discuss the stratigraphy of the Wild Horse Mesa Tuff.
2. To observe the lower member of the Wild Horse Mesa Tuff.

The Wild Horse Mesa Tuff is a comagmatic sequence of dominantly rhyolitic ash-flow tuffs that form a large group of mesas over an area of 600 km^2. Stratigraphic characteristics of the tuff are illustrated in Figure 17. Exposures of the horizontal to gently SE - dipping deposits vary from 20 to 320 m thick, and they have a distinctive layer-cake appearance that results from welding and devitrification zonation. The tuff is divided into lower, middle and upper members on the basis of stratigraphically coincident discontinuities in devitrification and welding zonations, phenocryst assemblage and abundance, and whole-rock chemical composition (McCurry, 1985; McCurry, in prep.). Each member is a cooling unit that consists of multiple flow units (cf., Fisher and Schmincke, 1985), many of which are well characterized by depositional bedforms of the "standard ignimbrite unit" (cf., Sparks and others, 1973). Contacts between units are primarily distinguished by moderately sorted tuff at the base a few centimeters thick (layer 2a), that grades upward into a nonsorted zone from a few centimeters to a few meters thick that is enriched by about a factor of ten or more in lithic fragments (L - zones). Ash cloud deposits (layer 3) occur at the tops, and ground surge deposits (layer 1) occur at the base of some of the flow units. However, layers of air-fall tephra are absent except between the members. Each member is interpreted to have been emplaced in what was essentially a single major eruption.

Exposures at Hole-in-the-Wall Campground are of the lower member of the Wild Horse Mesa Tuff (Fig. 17). The deposits dip approximately 3° to the southeast. Anastomosing zones of buff colored vapor phase alteration and devitrification cut across the weakly welded to nonwelded, glassy, medium gray ash-flow tuff. Near horizontal lensoid lithic fragment segregations occur in some parts of the tuff. Weak, laterally discontinuous zones of stratification can also be found in some areas. The spectacular cliffs, and cavernous weathering patterns at this locality are apparently a result of differential weathering of altered and nonaltered parts of the tuff, and weathering along joints, and around lithic fragments.

Take a break during lunch and wander down the Hole-in-the-Wall. Follow the campground road north to a large parking lot. You will find a concrete observation overlook; a little further to the north you can climb down a steep split in the rocks along a series of metal rings. Numerous depositional and vapor-phase alteration features of the lower member of the Wild Horse Canyon Tuff are beautifully exposed.

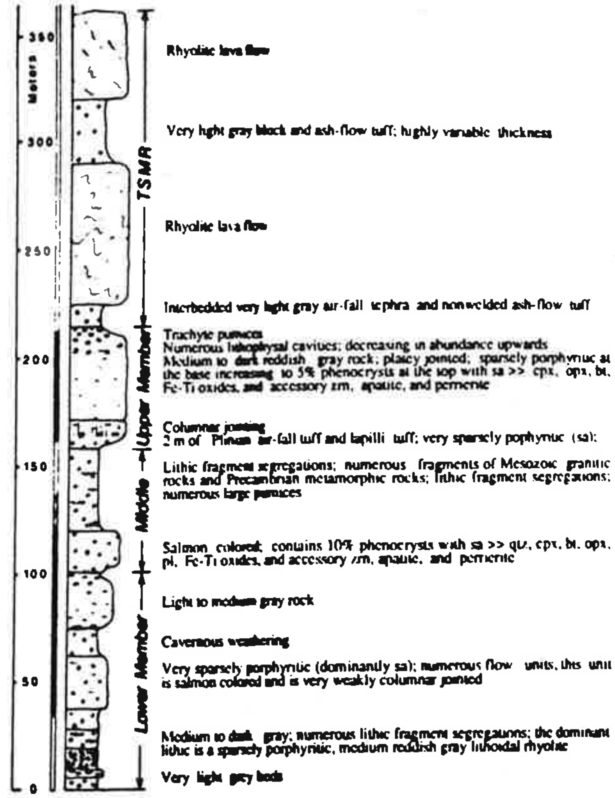

Figure 17. Simplified stratigraphic section of the Wild Horse Mesa Tuff based on a measured stratigraphic section in the northwestern corner of the Woods Mountains (after McCurry, 1985). Bar to the left of the column indicates intense devitrification - solid, partial devitrification - diagonal lines; glassy - no pattern; pattern on the column indicates dense welding - dash; moderate welding - ellipses; no welding - circles.

STOP 9. -- GEOLOGIC OVERVIEW OF THE PROVIDENCE - WOODS MOUNTAINS AREA

Objectives

1. To discuss the geologic setting of the Providence Mountains-Woods Mountains area, and to compare and contrast the Tertiary volcanic and tectonic evolution of this area with the Mojave Desert block.
2. To observe a deeply eroded early Miocene paleotopography that was buried by the Peach Springs and Wild Horse Mesa ash-flow tuffs.

The principal theme today is to illustrate features of a part of the Eastern Mojave Desert that is characterized by weak Miocene upper crustal extension, and by a style of volcanism that is unique in the Mojave Desert but that occurs in some other weakly extended continental terrains. We are located roughly equidistant between the Mojave Rift and the extended terranes of the Colorado River (cf., Anderson, 1971; Davis and others, 1980; Spencer, 1985). Exposures in this area are dominantly of early Proterozoic gneiss and granitic rocks, Paleozoic sedimentary rocks, Jurassic and Cretaceous granitic rocks, and middle Miocene volcanic rocks (Hewett, 1956; Hazzard, 1954; Goldfarb and others, in press). Pre-Tertiary rocks are exposed in deeply incised, north to northwest-trending ranges that are separated by wide alluviated valleys. These rocks were deeply eroded, and formed a topographically rugged terrain over which the Miocene volcanic rocks were deposited. Beginning at about 16.4 Ma and continuing until 15.8 Ma, volcanism was dominated by the extrusion of trachyte and mildly peralkaline rhyolite from a volcanic center located in the Woods Mountains area (McCurry, 1985; McCurry, in prep.). Erosional remnants of a rhyolite ash-flow tuff that was derived from this center extend from the Blind Hills on the south, to the New York Mountains on the north, and from the northern Providence Mountains on the west to Hackberry Mountain on the east. These rocks are overlain in some areas by small amounts of middle Miocene andesite, basalt, and alkali basalt flows. Middle Miocene rocks are weakly faulted in a pattern suggesting minor NW-SE extension.

We are standing on early Proterozoic rocks on the east flank of the northern Providence Mountains (Fig. 14). The northern Providence Mountains are an east tilted fault block of Paleozoic and early Mesozoic clastic and carbonate continental shelf sedimentary rocks (Hazzard, 1954; Goldfarb and others, in press). Four sets of normal faults are recognized (Goldfarb and others, in press; Hazzard, 1954). The absolute ages of these faults are poorly constrained. Following Goldfarb and others (in press), the oldest normal faults strike north-northwest, and dip steeply east. East striking faults drop strata down to the north. A more continuous set of N-NE striking faults vary from steeply east to vertical to steeply west dipping, and cuts the east-striking faults. Low angle, west-dipping faults are the last phase of normal faults in the Providence Mountains. Prominent reddish rocks that make up the high peaks to the east of Mitchell Caverns State Park are part of a large biotite rhyolite plug. The plug, named the Fountain Peak Rhyolite by Hazzard (1954) was intruded during or after the first three sets of faults. Although it may be Tertiary, Goldfarb and others (in press) note similarities between dikes extending from the intrusion, and Jurassic dikes in the southern Providence Mountains, and suggest that it is Jurassic. The eastern structural border of the northern Providence Mountains is bounded by the north-striking East Providence Fault. This major, east dipping reverse fault juxtaposes Paleozoic rocks against early Proterozoic rocks, and has 2.3 km of displacement (Hazzard, 1954). The fault bifurcates to the north. The easternmost segment is near vertical, cuts middle Miocene volcanic rocks, downfaulting rocks to the east by 100 to 150 m. Similar volcanic rocks form scattered exposures just north of Mitchell Caverns State Park suggesting that part of the East Providence Fault was reactivated in the opposite sense of the earlier reverse faulting, during the Miocene.

Prominent mesas to the northeast of the Mitchell Caverns State Park are of nearly flat-lying Wild Horse Mesa Tuff, a metaluminous to peralkaline ash-flow tuff that was derived from vents located in the western Woods Mountains. The 15.8 Ma tuff fills prominent paleovalleys that were eroded into Jurassic and early Proterozoic rocks. The paleovalleys have a relief of at least 160 m (McCurry, 1985) and can be seen from here, where the Colten Hills merge to the north into Wild Horse Mesa.

GEOLOGY OF THE CIMA VOLCANIC FIELD
SAN BERNARDINO COUNTY, CALIFORNIA

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GEOLOGIC SETTING

The Cima volcanic field (Fig. 1), located at the crest of the Ivanpah upland (Hewett, 1956), comprises more than 50 vents and associated flows of small volume in an area of about 300 km^2. Eruption of alkaline basaltic magmas occurred over a period of at least 7.5 Ma with a hiatus between 3 and 1 m.y. ago (Turrin and others, 1985; Wilshire and Noller, 1986). Xenoliths in the basalt contain an exceptional record of upper mantle and lower crustal processes.

The basaltic volcanic rocks overlie Proterozoic metamorphic rocks, lower Paleozoic sedimentary rocks, Cretaceous granitic rocks of the Teutonia batholith (Teutonia Quartz Monzonite) (Beckerman and others, 1982; DeWitt and others, 1984), and weakly consolidated Tertiary continental sedimentary rocks that are locally intercalated with tuff tentatively correlated with the Miocene Peach Springs Tuff of Young and Brennan (1974).

Proterozoic rocks consist predominantly of granitic and mafic gneiss and smaller amounts of schist, amphibolite, and marble. Lower Paleozoic limestone and sandstone crop out only locally within the volcanic field, but more extensive exposures of Paleozoic rocks are found in the adjacent Old Dad Mountains (Barca, 1966; Dunne, 1977). The Proterozoic and Paleozoic rocks are intruded by Cretaceous granitic rocks of the Teutonia batholith. Probably at least three separate Cretaceous plutons occur within the volcanic field: coarse-grained porphyritic granite with abundant phenocrysts of K-feldspar, medium-grained, nonporphyritic granite, and medium-grained granite crowded with mafic inclusions. Moderately abundant apophyses of granite, aplite, and pegmatite intrude older rocks adjacent to the plutons. The Cretaceous granitic rocks are intruded by a northwest-trending swarm of Tertiary andesitic to dacitic dikes (Fig. 2).

Overlying all of the above-described rocks are weakly consolidated, locally derived continental deposits with thicknesses ranging to about 300 m. These deposits are composed predominantly of coarse to very coarse boulder beds, but also include a gravity glide block of brecciated dolomite and, near the base of the section, a rhyolite tuff interbedded with fine-grained sandstone and siltstone. The tuff is tentatively identified as Peach Springs Tuff on the basis of its paleomagnetic orientation (J. Hillhouse, oral communication, 1987). If the correlation is correct, the overlying continental deposits are 18 Ma or younger, the mean age of the Peach Springs Tuff (Glazner and others, 1986). The boulder beds are dominated by granite clasts of the Teutonia that reach dimensions of 13 m. In the thickest known section of Tertiary rocks in the Cima volcanic field (immediately south of highway I-15 beneath capping basalt flows), the gravels are composed almost exclusively of Teutonia clasts with less than 5 percent of clasts representing the dike swarm rock types. However, in the southern and northern parts of the volcanic field, Proterozoic and Paleozoic rocks contributed substantially to the clast populations of the gravel beds. The large, slab-like mass of dolomite breccia is clearly interbedded with the boulder beds in the Cima volcanic field; it may have been derived from the Old Dad Mountains, to the southwest, where similar glide blocks of dolomite breccia, reaching lengths of nearly 2 km, are common (Barca, 1966; Dunne, 1977).

CENOZOIC ALKALINE BASALT VOLCANISM

Basaltic volcanism began at least 7.5 m.y. ago (Turrin and others, 1985). Like other Cenozoic Basin and Range basalt fields, the Cima basalts range from moderately ne-normative to hy-normative compositions (Wilshire and Noller, 1986). Where the basalt magma rose through the continental detrital deposits, phreatic eruptions generally occurred so that initial ejecta consist of maar beds with abundant boulders and cobbles of Teutonia granites mixed with basaltic tephra. Maar beds are associated with vents with ages as disparate as 6 Ma and 0.35 Ma indicating availabil-

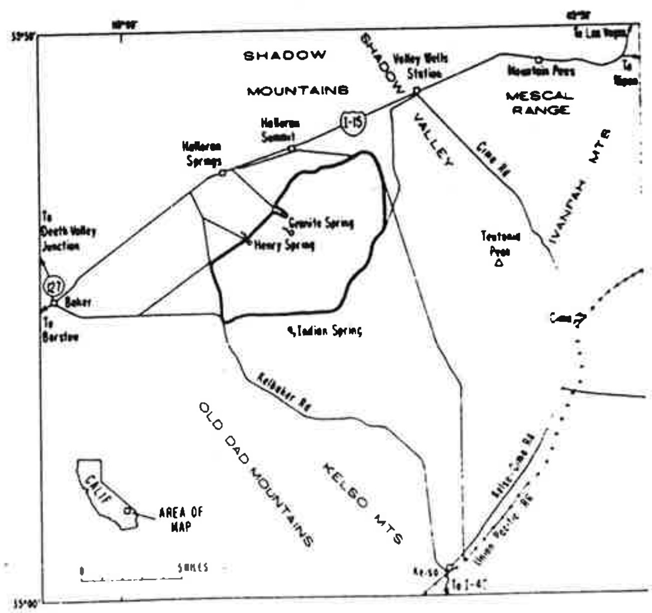

Figure 1. The Cima volcanic field (dark outlines), south of I-15 and east of Kelbaker Road, San Bernardino County, California.

ity of ground water in the Tertiary sediments over a substantial period of time. Other distinctive features of the volcanism are the very long period of time (comparable to the time of development of any one sector of the Hawaiian Ridge [Shaw, 1973]) over which quite small volumes of magma were erupted; the hiatus between 3 and 1 m.y. ago, which was followed by vigorous eruptive activtiy that has not necessarily ceased; and the exceptional record of what was happening in the lower lithosphere before and during this period of magmatism as revealed by xenoliths in the basalts.

RELATION OF STRUCTURE TO TERTIARY MAGMATISM

Widespread coarse-grained terrigenous sediments intercalated with large gravity glide blocks of Precambrian(?) and Paleozoic(?) rocks (Suneson and Lucchitta, 1983) are associated with Miocene extension in the Basin and Range Province (Eberly and Stanley, 1978). Miocene age (equal to or younger than 18 Ma) of these deposits in the Cima volcanic field is tentatively based on identification of Peach Springs Tuff within the sedimentary sequence. A minimum age of Pliocene (older than 4 m.y.) is based on the age of basalts that overlie the sediments with angular unconformity. The Tertiary dike swarm (Fig. 2) in the Teutonia granitic rocks may map the local stress field during extension. When the ages of the dikes are known (they are presently being determined), they will give a minimum age of the onset of extension.

Angular discordance between the Tertiary sedimentary rocks and the alkalic basalts indicates that deformation and substantial erosion occurred between the time of sedimentation and alkaline volcanism. The lag time between the extension recorded by the continental sediments and the eruption of alkaline basalts (about 10 m.y.) is about equal to the duration of the basaltic volcanism (more than 7.5 m.y.).

The xenoliths contained in the basaltic rocks (Katz, 1981; Breslin, 1982; Wilshire and Noller, 1986) consist of mantle peridotite representing the spinel facies (stable at pressures of about 9 to 20 kb); spinel peridotites partly reequilibrated to plagioclase peridotite (stable at pressures below about 10 kb); mantle spinel websterite (Cr-diopside group) and the equivalent rocks partly reequilibrated to plagioclase and olivine assemblages; olivine-free 2-pyroxene pryoxenite, gabbro, and microgabbro; 1-pyroxene clinopyroxenite, gabbro, and olivine microgabbro; and sparse inclusions of the granite country rock.

Composite xenoliths of spinel peridotite (and spinel-plagioclase peridotite) and all mafic rock types indicate that the mafic rocks form dikes in the peridotite. Crosscutting relations and mineral assemblages of the mafic rocks indicate a sequence of emplacement of dikes from spinel websterite to olivine microgabbro, a sequence which also represents decreasing pressure of dike crystallization.

Partial melting phenomena are found in all medium- to coarse-grained mafic and ultramafic xenolith rock types found at Cima, and some microgabbros did not complete crystallization before entrainment in

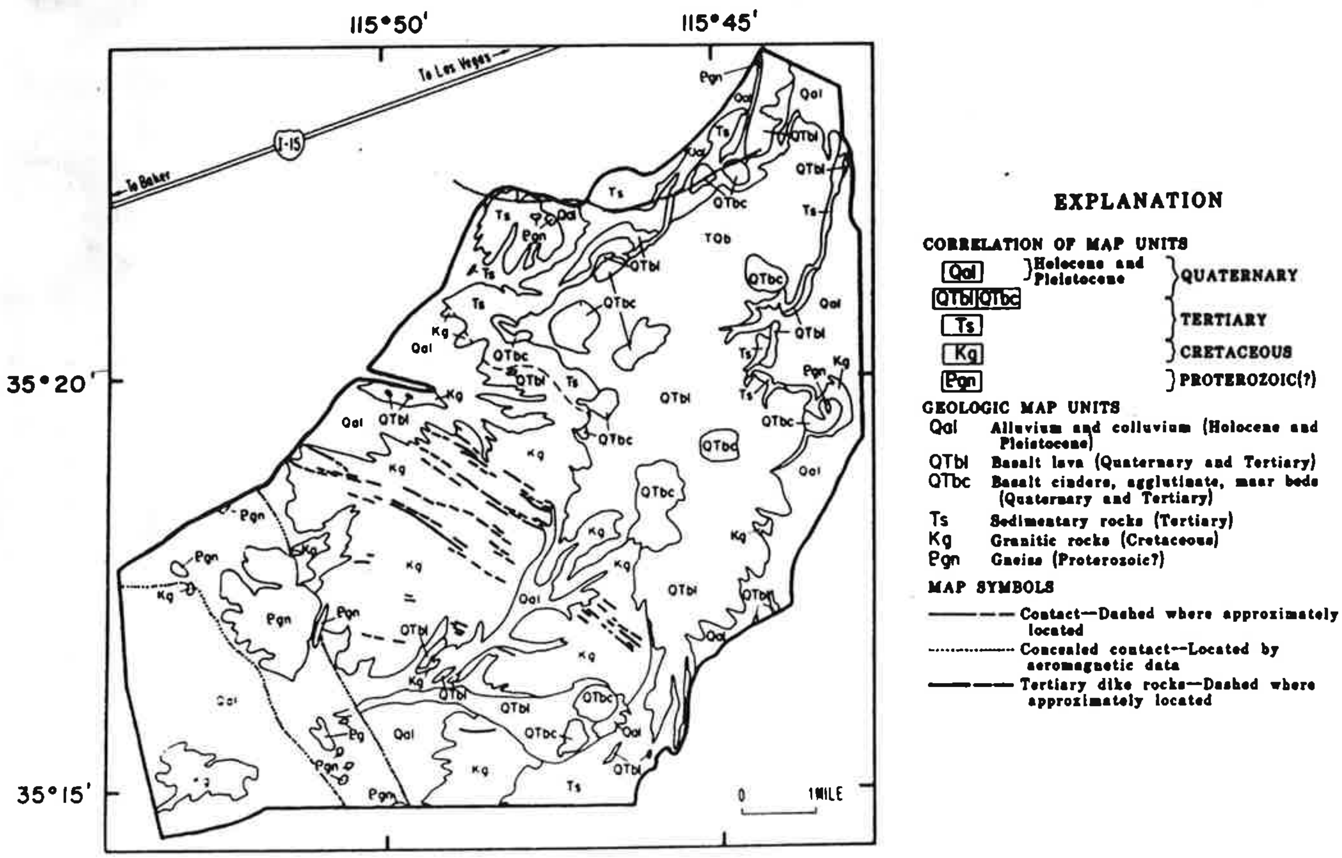

Figure 2. Geologic map of the Cima volcanic field.

Figure 3. Large slab of dolomite breccia (hill in middle ground, dolomite breccia dips gently to right), interbedded with coarse Tertiary sediments. View north in southwestern Cima volcanic field.

Figure 4. 4 m.y. old basalt flow overlying an angular unconformity. Tertiary sediments are composed largely of clasts of Teutonia granite. View in northwest corner of area mapped in Figure 2.

the host basalt. The partial reequilibration of spinel facies peridotite and Cr-diopside websterite to plagioclase facies rocks was accomplished by melting and crystallization of the melts before entrainment in the host basalt. The same phenomena are seen in the 2-pyroxene and 1-pyroxene pyroxenite-gabbro suites, in which partial melts (affecting up to 73 percent of the volume of individual xenoliths) crystallized in varying degrees before entrainment in the host basalt. The mineral assemblages in crystallized partial melts of mafic xenoliths represent either the same or lower pressures as those of their parent rocks.

These relations indicate a long history of melting, crystallization of melts trapped in the mantle, and remelting in a situation in which the upper mantle was progressively depressurized. A possible explanation of these phenomena is that the Cima xenolith population reflects the extensional thinning of the crust. Early melting, perhaps of lower crustal rocks, resulted in emplacement of the dike swarm of andesitic and dacitic rocks in fractures directly reflecting the local direction of extension (NE-SW). This was followed by a period of continental sedimentation associated with upper crustal extensional faulting, and finally by a protracted period of time in which the upper mantle responded to the extensional thinning of the crust by melting and probably by upwelling. The magmas generated by this process were mostly trapped in the lower lithosphere, creating new crust (Lachenbruch and Sass, 1978) and, by fractionation, creating the materials necessary for generation of the alkaline basalts of the Cima field (Wilshire, 1987). According to this model, the Cima volcanic field represents the ongoing responses of the upper mantle to extensional thinning that began early in the Miocene.

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SUBDUCTED OCEAN-FLOOR BASALT BENEATH THE CIMA VOLCANIC FIELD, CALIFORNIA.

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Gabbros and kindred crustal rocks, together with spinel lherzolites and other mantle-derived rocks, are common as xenoliths in the young (<1 Ma) basanitic cones and associated flows in the Cima volcanic field, Mojave Desert, California. Previously, Semken, DePaolo, and Montana (in prep) determined Nd and Sr isotopic ratios for three basanitic lavas from different cones and an olivine-gabbro xenolith in tephra from another nearby cone at Cima. εNd for the lavas ranges from +9.0 to 10.1; for the xenolith, it is +9.4. $^{87}Sr/^{86}Sr$ for the lavas = 0.70294-0.70303, but for the gabbro, it is 0.70370. We have analyzed six additional crustal xenoliths from an adjacent cone in the Cima field, ranging from tholeiitic gabbros to plagioclase wherlites, in which εNd ranges from +8.3 to 10.1, with $^{87}Sr/^{86}Sr$ ranging from 0.70266 to 0.70385. The textures range from igneous to metamorphic. These are the highest εNd values reported for continental volcanic rocks.

All six of the xenoliths are similar to type-I MORBs in their major-element compositions, $^{87}Sr/^{86}Sr$ ratios, Sr/Rb ratios (>70), εNd values, and low (<0.1 wt %) K_2O contents. The two xenoliths with $^{87}Sr/^{86}Sr \geq$ 0.70370 can be interpreted as MORB contaminated with ocean water.

Other varieties of crustal rocks, such as granulite and amphibolite, are exceptionally scarce as xenoliths at Cima. The MORB-like signature of the observed xenoliths suggests that much of the deep crust here consists of subducted ocean-floor basalt.