The Changing Face of the East Mojave Desert

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and

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Table of Contents

The Changing Face of the East Mojave Desert: Field Trip Guide 3
Robert E. Reynolds

Vertebrate Ichnostratigraphy of the Glen Canyon Group (Jurassic) in Zion National Park, Utah 15
Joshua A. Smith and Vincent L. Santucci

Bird Footprints from the Miocene of California 21
William A.S. Sarjeant and Robert E. Reynolds

Neogene Erosional Surfaces in the Northeastern Mojave Desert, California 41
Robert E. Reynolds and James Calzia

Kelso Depot 44
Valerie Prehoda

A Field Investigation of the Clark Mountain Fault Complex, San Bernardino County, California 46
David R. Jessey, Don W. Tarman, Miho Waki, and Suzanne M. Baltzer

"Borax" Smith and the Tonopah & Tidewater Railroad 50
Stephen P. Mulqueen

Climate Variation since 1900 in the Mojave Desert Region 54
Richard Hereford and Robert H. Webb

Mojave Desert Invasive Species Awareness 56
Valerie Prehoda

Wolves of Shoshone, Southern Death Valley 58
Robert E. Reynolds

The Franklin Wells Hectorite Deposit, Inyo County, California 61
Greg Wilkerson, Larry Vredenburgh, Thomas J. Serenko, and Ted H. Eyde

The Hanging Gardens of Amargosa Canyon 65
Maria Lum, Robert E. Reynolds and Andrew Sanders

Abstracts from the 2001 Desert Symposium 69

Front cover: View north of Salt Spring. The saddle contains the Salt Spring gold mine. Strata and surfaces dip to the east. Quartz monzonite is overlain by Miocene basaltic andesite which in turn is overlain by Proterozoic rocks.

Back cover: Eastern Star Mine. Landslide sheets of Paleozoic carbonate rocks interfingering with Miocene siltstone in Shadow Valley Basin have been tilted eastward by listric faulting. Kingston Peak (distant) consists of the 12.4 Ma Kingston pluton, unroofed about 10 Ma.

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The Changing Face of the East Mojave Desert: Field Trip Guide

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Introduction

On this trip we will look at changes to the surface of the Mojave Desert from the distant past, the prehistoric and historic past, and the very recent past. We will see tracks of extinct animals, the paths of ancient avalanches, soil profiles and fault scarps that have shaped today's topography, wagon tracks from pioneers and argonauts, and the bed of railroads that opened access to mines and tourist resorts. Natural or man-made, all of these events left traces on the fragile crust of the Mojave Desert. This guide is the result of contributions and discussion from many individuals. Special acknowledgment is made to David Miller and David Bedford, U.S. Geological Survey. We suggest you allocate three days to enjoy the entire trip.

You can help protect natural and cultural resources for future generations on federal, state, and private land. Don't drive off approved roads. View an archaeological or historic site from a distance to reduce impacts to the site. Do not collect cultural resources: potsherds, flakes and other prehistoric artifacts or historic remains, including can dumps and glass. Fossils are also part of our national heritage and may not be collected. Do not disturb wildlife or plant life; do not pick wildflowers or plants or gather firewood. Take only pictures! If you travel to remote areas, be certain that your vehicle has been serviced and carry adequate emergency supplies, including plenty of water. Tell someone where you are going and when you expect to return. Archaeological, historical, and natural resources are protected by law. Severe civil and criminal penalties can be brought against individuals who damage or destroy resources. You can join and enjoy a volunteer program that helps protect resources: ask the Bureau of Land Management, National Park Service, and Desert Discovery Center for details.

Field Trip Guide

The trip starts at Kelbaker Road, south of Baker, California on Interstate 15.

0.0 (0.0) EXIT freeway at Kelbaker offramp, cross first cattle guard, and go easterly on Kelbaker Road. Notice the "Mojave National Preserve" sign on the right; it is located approximately at the elevation (935') of the high stand of pluvial Lake Mojave.

1.7 (1.7) Cross a second cattle guard. On the right skyline, Old Dad Mountain at 1:30 and the Cowhole Mountains at 2:30 flank the northern edge of Devils Playground. Climbing dunes bury the north flank of Little Cowhole Mountain at 3:00. The Little Cowhole Mountains contain Goodsprings Dolomite above a contact with quartz monzonite.

For the next several miles the road crosses Holocene and modern distal fan deposits from the Cima volcanic field, approximately 15 miles east. Well-varnished basaltic boulders and cobbles are scattered across this arkosic surface. These clasts have been transported six miles across slopes of 1.5° and another six miles across slopes of 2° to 4.°

4.0 (3.3) The outcrop ahead is Teutonia Quartz Monzonite. Beyond at 10:00–10:30 and at 2:00 are granitic domes below elevated late Miocene basalt flows. To the right are young basalt flows roughly coincident with the modern drainage and topography, just slightly elevated by erosion. On the skyline at 2:00 are older Pliocene basalt flows which have been severely undercut by erosion.

Kelbaker Road is surrounded by granitic alluvial fan products. These granites provide favorable conditions for biologic soil crusts (Hereford and Webb, this volume). Basalt cobbles armor the surface, slowing the rate of erosion on pediment surfaces.

5.6 (1.6) The road bends to the right and ascends toward the southern part of the Cima volcanic field. The next nine miles provide views of the pediment domes that form prominent elements in this part of the eastern Mojave Desert landscape.

10.2 (4.6) Slow for an abrupt 90° curve to the right (south). Large inselbergs of granitic gneiss block the view on the left. The road crosses an active piedmont northwest of the Cima volcanic field. Alluvial debris from floods are regularly plowed from the next two miles of road. Several cones of the Cima volcanic field are visible on the left. On the right, Old Dad Mountain is at 12:00 to 2:00 and Soda Lake is at 2:00.

13.0 (2.8) **STOP 1**. 17-Mile Point (named because it was midway along the 35-mile stretch between Marl Spring on the east and Fort Soda on the west). Petroglyphs in the vicinity may have been left by Native Americans traveling on the Mojave Trail. The Old Government Road crosses here at a point between Marl Spring and Fort Rock Spring to the

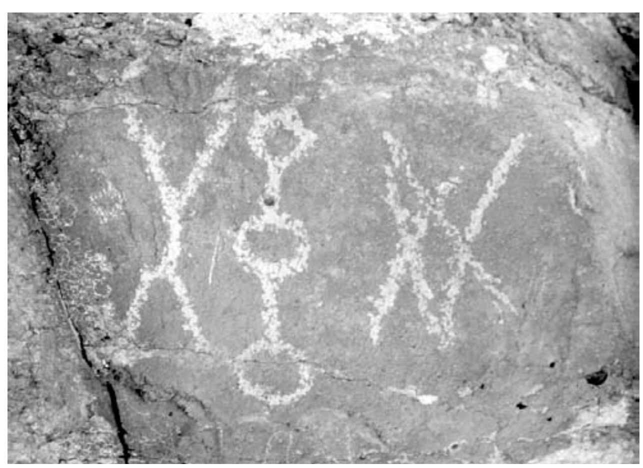

Figure 1. Petroglyph near 17 Mile Point on the Mojave Trail/Old Government Road.

Figure 2a (above). View north across Cima volcanic field toward Kingston Peak.
Figure 2b (below). View north toward Cima Dome. Clark Mountain (left); Kessler Peak (right).

east and Fort Soda at Soda Spring to the west (Casebier, 1975).

Kelbaker Road crosses a 0.17 ± 0.06 Ma basalt flow (at road level) over reddened sediments and passes the western end of higher flows that range in age from 0.17 to 0.58 Ma. Sources of these flows are vents located 2 miles east (Wells and Reynolds, 1990). The 0.58 Ma flow buries early to middle Pleistocene fan systems and younger flows have partly buried the 0.58 Ma flow. The basalt flow temporarily dammed all drainage from the southern part of the Cima volcanic field. The road passes through a shallow notch cut across the distal end of these flows where basalt ponded against the east flank of Old Dad Mountain, driving the wash farther west where it eventually cut down through the Proterozoic carbonate rocks to "avoid" the basalt. Late Pleistocene fans along the east flank have been truncated by the canyon down-cutting.

Climb up the basalt to witness spectacular pavement and Av horizons. This is the birthplace of modern thought on AV horizons and other studies on hydrology of paved surfaces in various microtopographic settings (Renault and Wells 1990, Birkeland 1984, McFadden, Wells and Dohrenwend, 1986).

Return to vehicles and proceed south on Kelbaker Road.

15.3 (2.3) On the left is the Black Tank flow, the youngest in the Cima field, tentatively dated at less than 0.02 Ma by a variety of experimental techniques (Renault and Wells 1990). On the right skyline at 12:00 to 6:00 are the Kelso Mountains, Radar Ridge, and Old Dad Mountain. This region is underlain by 10–12 Ma eastward-tilted fanglomerates faulted by the eastern California shear zone (ECSZ) against Tertiary through Precambrian rocks (Barca 1966). Neogene faults are predominantly northwest-trending, right-lateral strike-slip shear zones (Skirvin and Wells 1990, Dokka 1989).

16.5 (1.2) Pass through a dip. On the right is a ridge of Miocene granitic boulders shed from the Teutonia Quartz Monzonite (TQM) terrane to the east.

19.0 (2.5) Pass the junction on the left with the Aiken Cinder Mine Road, marked by a dirt pile with a sign. Note your mileage for the next turn that leads to the microwave station access road on the right in 0.4 mi.

19.4 (0.4) TURN RIGHT and proceed south toward the transmission towers and microwave complex on the ridge.

21.3 (1.9) Join the powerline road at a complex intersection and proceed south-southwest toward three transmission towers. Continue south along "Radar Ridge" to the microwave station.

23.0 (1.7) **STOP 2**. PARK near the cut at the south side of the microwave station. The fine-grained sediments in the cut dip approximately 20°E. The rocks exposed in the cut are primarily TQM, a black gneiss, and large clasts of zircon-bearing tuff with a sanidine-rich lithophayse. Look down to the ridge to the west to a thick sequence of granitic cobbles. Sediments dipping 20°E suggest that this fault block is in the modestly-tilted Cima terrane. The Cima terrane north of the Nipton fault zone (Miller 1995) and south of the Halloran Fault (Jennings 1961) has been modestly extended westward. The area north of the Halloran Fault to the Halloran power line road has been severely extended, and sediments and surfaces dip 45°E.

The hills between Kelso Peak and Old Dad Mountain consist of coarse gravel fanglomerates, landslide breccias, and other deposits such as fine-grained siltstones and freshwater limestone. Moderately well-developed bedding, cut-and-fill structures, and several clast compositions can be observed in exposed outcrops. Stratigraphy (Skirvin and Wells 1991) west of Radar Ridge is summarized as follows:

- Unit 6b: conglomerate of monomictic plutonic rocks
- Unit 6a: conglomerate of mixed lithologies
- Unit 5: volcanic flows, breccias and volcaniclastic sediments: purple, tan, green and black
- Unit 4: Planar sandstone and gravel with clasts from overlying volcanics
- Unit 3: interbedded sandstone and conglomerate including clasts of Peach Springs Tuff (PST)
- Unit 2: Peach Springs Tuff: pink, purple, tan
- Unit 1: Mixed lithology conglomerate with red clay matrix

This section west of Radar Ridge is similar to deposits described in the Halloran Hills (Reynolds 1991), Shadow Valley (Friedmann 1999), and the Kingston Range (McMackin and Prave 1991), and may imply similar tectonostratigraphic origins.

In the vicinity of the radio towers the dominant clasts are granitic rocks found in the Kelso Mountains 3 km east. Gravels to the southeast of the radio towers along the flank of the Kelso Mountains are predominantly composed of Proterozoic gneiss clasts that can be followed to their bedrock source 1–2 km to the east. Northeast of the radio towers, where the powerline crosses Kelbaker Road, the gravels consist of equal parts of Teutonia granitics and Proterozoic gneiss.

Gravels along the southwest Kelso Mountains have their sources in bedrock in the Kelso Mountains, but dip southeast towards their source, indicating post-depositional structural reconfiguration. Clasts around the radio towers include boulders identified as the 18.5 Ma Peach Springs Tuff and the Kessler Springs Adamellite. Peach Springs Tuff crops out along the east side of Old Dad Mountain near the base of the basin sediments (Skirvin and Wells 1990), to the north near Indian Springs (Wilshire 1992), and southwest of Cima (Reynolds and others 1995). The only known outcrops of the Kessler Springs Adamellite are some 32 km to the northeast on the east side of Cima Dome (Beckerman and others 1982). Wilshire (1992) reports non-local clasts of altered granite and Proterozoic syenite that may originate in the northern Mescal Range. Along Kelbaker Road, the gravels contain clasts of granites found in the Kelso Mountains and clasts of Proterozoic gneiss from the south side of the Kelso Mountains and northeast in the Marl Mountains.

One scenario that accounts for lithologic sources is that a large Miocene basin developed west of outcrop sources in the Kelso Mountains, Cima Dome area, and the Mescal Range. The basin, now east of fault-bounded Old Dad Mountain, was initially filled with fine-grained sediments, freshwater limestone, and volcanics, followed by megabreccia landslides and cobble conglomerate. The Kelso Mountains had to have been a local highland to shed sediments westward, while Cima Dome could not have been elevated in order to shed Kessler Springs Adamellite and Mountain Pass syenite to the location of the radio towers. Basin fill by coarse debris probably culminated with upper plate detachment and listric normal faulting that created Cima Dome and other domes between 10 and 9 Ma.

The nature of faulting that has occurred since the basin filling is not yet well understood. Dip-slip faulting with little or no strike-slip component is documented along the western Kelso Mountains. Faults along the east side of Old Dad Mountain may include a significant right-lateral strike-slip component (Skirvin and Wells 1990). Mapping in the Kelso Quadrangle (Bedford, in review) and observations by other authors in the vicinity of the radio towers suggest a large, Pliocene-Pleistocene (?) fault system that traverses the basin between the Kelso Mountains and Old Dad Mountain where dip-slip movement can be documented (Curry and Reseigh 1983). There also may be considerable right-lateral strike-slip offset that totals from 2 km to 6 km. The timing and amount of strike-slip offset along the local Radar Ridge Fault is considered preliminary and tenuous based on horizontal offsets of Cretaceous plutonic rocks and Proterozoic gneiss. This fault system may also be related to the fault system described by Skirvin and Wells (1990) along the eastern side of Old Dad Mountain. Old Dad Mountain marks the ECSZ (Skirven and Wells 1990).

At Stop 4 we will look at the relationship of chaotically-deposited Proterozoic/Paleozoic carbonate rocks on weathered granitic rocks. We will see a similar relationship in Railroad Valley of the Silurian Hills.

The panoramic view shows the Granite Mountains (south), the Bristol Mountains and Kelso Dunes (south-southwest), the Cady Mountains (southwest), Soda Lake and the Mojave River drainage (west), Soda Mountains (west-northwest), Avawatz Mountains (northwest), Kingston Peak and Halloran Hills (north), Charleston Peak and Clark Mountain (north-northeast), and the Mid Hills and Providence Mountains (east and southeast). The Cima volcanic field to the north contains Pliocene flows between 7 Ma and 5 Ma (north of I-15). The older flows help define past surfaces that were above and less steep than the surfaces under Pleistocene flows in the foreground.

Figure 3. Prospect Wash, view south-southwest. Fault-bounded Proterozoic/Paleozoic carbonates sit chaotically on Jurassic? granitic rocks.

RETRACE to the junction of the microwave access road with the transmission line access road.

24.5 (1.5) Three forks; take the left fork.

24.8 (0.3) TURN LEFT (southwest) on main transmission line access road. Along this road a number of stub roads lead to towers on the left and right; avoid them and continue along the main access road.

25.6 (0.8) Approach crest of ridge with caution.

25.7 (0.1) **STOP 3**. STOP at the crest of the ridge. The west side is much steeper than east. Look downhill to the west where coarse granitic conglomerate gives way to fine-grained Miocene silty arkosic sandstones at the base of the ridge. To the west-northwest are sheets of Paleozoic landslide breccia associated with granitic gravels on top of fine-grained sediments that contain dark-colored pyroxene andesite and the much lower PST. Proceed down this steep road with caution, allowing enough room for the vehicle in front of you to negotiate turns.

25.9 (0.2) Use caution around switchbacks. If you cut it too tight you may have to make a Y turn. Keep your eyes on the road but occasionally look at the large size of the granitic boulders in the road cut walls. Imbrication reaffirms flows from the east.

26.2 (0.3) Take the left turn, avoiding the stub road to the right.

26.3 (0.1) Fine-grained Miocene sediments in canyons to the left and the right dip about 10 degrees to the northeast. In the canyon on the left is an angular unconformity; the contact is west-dipping as are the inset Pleistocene? gravels that lie above the unconformity.

27.0 (0.7) BEAR LEFT through a 3-way intersection. The road that trends to the right (north) will be our exit route to avoid the powerline switchbacks.

27.6 (0.6) Road divides; take either branch.

28.5 (0.9) Bear left at fork.

28.7 (0.2) The canyon narrows. Note the black and pink outcrops of gneissic rock. The pistachio green color is from associated epidote.

29.3 (0.6) The canyon widens at valleys of the Old Dad Mountain Fault (Barca 1966, Jennings 1961, Scirven and Wells 1990), one of the NNW-trending faults in the ECSZ.

Figure 4. Old Dad Mountain, view north, consists of a chaotic jumble of Proterozoic/Paleozoic carbonates resting on a deeply-eroded surface developed on Jurassic? granitic rocks.

The ridge ahead consists of reddish-brown granites of undetermined affiliation. On the slope facing us are steep-dipping, gray marble slabs that have been prospected for copper.

29.8 (0.5) **STOP 4**. TURN RIGHT and PARK just past the railroad tie fence. On the south face of Old Dad Mountain (north), the metamorphosed Monte Cristo Limestone sits on reddish granitic rocks. When we walk up the wash we'll see that these granitic rocks have leisingang weathering rings between joint sets, indicating that they were deeply weathered below an erosional surface. The contact between the granitics and the carbonates was originally mapped by Barca (1966) as a thrust fault. It is possible that this was a carbonate gravity slide block from the Soda or the Avawatz Mountains area that was emplaced on a mid-Tertiary erosional surface developed on granitic rocks. Right lateral movement on the ECSZ would allow for the present position of this relationship. Return to vehicles.

31.0 (1.2) Pass epidote-colored outcrops of gneiss in the wash.

32.0 (1.0) **STOP 5**. PARK beneath powerlines. To the north are light-colored Tertiary Miocene sediments at the base of the hill. This section is reported to contain PST; dark pyroxene andesite is upsection. Above this Miocene sedimentary and volcaniclastic section is a resistant Paleozoic carbonate sheet with the characteristic cavernous weathering of a brecciated avalanche deposit. Proceed.

32.9 (0.9) Three-way intersection. Proceed north on the left branch. Do not go right, up the switchbacks.

34.4 (1.5) At 9:00, note well-developed pavement on the dip slope ridge.

34.6 (0.2) Road bends easterly.

34.9 (0.3) Continue past a left turn and proceed easterly.

36.1 (1.2) Pass the previously-taken right turn on the powerline road to Old Dad Mountain.

36.4 (0.3) TURN LEFT at a complex junction and proceed north to Kelbaker Road.

38.4 (2.0) Stop at Kelbaker Road, watch for traffic, and TURN RIGHT.

40.5 (2.1) Slow for sharp right turn.

41.2 (0.7) Cross the cattle guard and pole line road at the powerlines.

41.8 (0.6) The basalt flow at 10:00 is slightly elevated but generally conforms to existing topography. To the right at 2:00 are the Providence Mountains.

42.2 (0.4) Pass left turn (pole line) to Marl Spring, a stop on the Old Government Road between 17 Mile Point and Rock Springs (Casebier 1975).

44.5 (2.3) Look west along the utility road to Cedar Canyon cutting through the Mid Hills. At 10:00, Pinto Mountain contains flat-lying 18.5 Ma PST near its base and the 17.8 Ma tuff of Wild Horse Mesa (McCurry et al. 1995) near its top. The flat-lying Early Miocene tuffs (Miller 1995) on the erosional surface developed on Teutonia Quartz Monzonite in the unextended Mid Hills block are an example of what the Cima/Halloran terrane might have looked like before extension. We are on the extended Cima terrane (Reynolds and Calzia, this volume) which includes the mylonitized shear zone at Teutonia Peak. This has been offset 17 km west/left-laterally from the Pinto Mountain shear zone in the New York Mountains (Miller and others, 1996). This is similar to the amount of offset described on the Nipton fault zone (Miller 1995) between the Mescal Range and the eastern New York Mountains.

50.3 (4.8) Cross a cattle guard. Well-developed pavement is to the east at the base of the Paleozoic limestone Kelso Hills. Look south-southwest to the Granite Mountains and Kelso Dunes (Lancaster 1995).

52.4 (2.1) Stop, TURN LEFT on Cima Road, passing the north side of Kelso Depot (Prehoda, this volume). The station was named for a railroad official when it was established on the San Pedro, Los Angeles and Salt Lake railroad (later, Union Pacific) in 1906 (Gudde, 1969). Proceed north

Kelso Depot under restoration. National Park Service photo, 1998.

Figure 5. View east of Kessler Peak in the Ivanpah Mountains. The Kingston Range-Halloran Hills detachment zone has dropped the pre-Miocene erosional surface in the foreground from a similar surface on the range top to the east.

on Cima Road. We are crossing the trace of the Cedar Canyon Fault as extrapolated by Jennings (1961), although no outcrop evidence exists for its location here. This relatively young fault may play an important role in the topographic evolution of western Lanfair Valley and the New York Mountains.

53.6 (1.2) **STOP 6** at single pole transmission line. WALK EAST across tracks to discuss decreasing eolian sand in the alluvial system. As we walk eastward up the Providence fans, the age and maturity of the soil dictates available soil moisture for plants. The reduction in eolian sand and increase in imbricated pavement reduces available rodent habitat.

56.1 (2.5) Hayden Siding.

56.2 (0.1) Continue past Globe Mine Road.

58.9 (2.7) Dawes siding. Culverts under the railroad here were built in 1926. Continue past Macedonia Canyon Road.

59.6 (0.7) The view northwest at 10:00 is toward offset outcrops delineating the Ivanpah Valley Fault mapped by Jennings (1961) that strikes southwest along Cima Dome. Outcrops of the PST next to this fault raise the possibility that it offset the tuff. Three exposures of the PST can be found along this part of Cima Dome, and in one location the tuff lies on highly fractured and slightly mineralized Teutonia Adamellite (Beckerman and others, 1982). However, the fractures in the granite strike perpendicular to the fault shown by Jennings. Undissected PST overlies fractured granite, indicating that fracturing is older than ~8.5 Ma (Reynolds and others 1995). Several nearly east-striking lineaments cut granite and dikes upslope from the PST outcrops. No offsets have been observed in this area that can be demonstrated to be Miocene or younger.

Figure 6. View SSE of Cima Dome (right) and detachment zone west of Kessler Peak (left).

63.3 (3.7) Continue past Cedar Canyon Road, proceeding north on Cima Road.

66.6 (3.3) Cima Store is on the left.

66.7 (0.1) Cross the first set of tracks and TURN LEFT before the second set of tracks. Proceed northwest up Cima Dome.

68.1 (1.4) Cross under the powerline.

71.9 (3.8) Pass the south entrance to Kessler Spring Ranch.

72.3 (0.4) Kessler Spring and ranch are on the right (east) side of road.

73.0 (0.7) Cross a wash. Notice rounded boulders on the granitic surface on both sides of the road.

73.3 (0.3) Pavement bends northwest. Pull to the right and PARK at a north-trending dirt road.

STOP 7. We are standing on the exhumed, boulder-covered, pre-Miocene erosional surface. The hillside to our east is a scarp representing the mid-Miocene breakaway zone of local extensional tectonics. One-half mile east and 500 feet above, the pre-Miocene surface reappears on top of Kessler Peak and the Ivanpah Range. To the north the view shows Clark Mountain and the west end of Copper World ridge. Displacement can be measured from granitic outcrops on the west end of Copper World Ridge to granitic outcrops in Shadow Valley (Reynolds and others, 1996). Sediments deposited on this pre-Miocene surface dip 12°–20° eastward, suggesting that the Cima block between the Nipton fault zone and the Halloran fault zone was only modestly extended.

RETRACE to the pavement of Cima Road.

73.5 (0.2) Watch for oncoming traffic and TURN RIGHT on Cima Road. Continue on the pavement.

73.7 (0.2) Slow for curves.

74.0 (0.3) Pass the rail head to the migmatite ridge at Teutonia Peak (Reynolds and others1996).

75.2 (1.2) Continue past the road to Valley View Ranch.

77.5 (2.3) View north of imbricated Early Cretaceous thrusts in Striped Mountain and the Mescal Range. Two repeated red beds of Wood Canyon and Zabriskie Quartzite, among the oldest rocks in the Mescal Range, are at the west end of the range, thrust over the gray carbonates in the center of the range. These gray carbonates are in turn thrust over the black rhyolite complex of the Cretaceous Delfonte Volcanics at the east end of the range (Fleck and Reynolds 1996).

78.0 (0.5) Pass a corral on the right.

83.0 (5.0) The hill due west is composed of monolithologic granitic breccia. Mohawk Ridge is to the northeast (Wise 1996, 1990).

84.2 (1.2) Pass the left turn to Aiken Wash and Cinder Mine Road.

Figure 7. Erosion exposes the thick, dense, mid-Pleistocene pedogenic carbonate at the Valley Wells copper smelter. When the smelter was receiving ore from the Copper World mine, dug out cabins were excavated under the solid carbonates.

84.9 (0.7) Proceed over I-15.

85.3 (0.4) TURN RIGHT on dirt road.

85.4 (0.1) **STOP 8**. We are at lacustrine sediments that contain Late Pliocene rodents dating to approximately 2.4 Ma. High in the section is the transition from the Irvingtonian Land Mammal Age (LMA) (150 ka) to the Rancholabrean LMA. Below the Irvingtonian/Rancho-labrean transition are pedogenic carbonates that may have developed before 0.3 Ma. East of the north-south fault immediately west of where we are standing, the carbonates are found below a pavemented surface with "transverse pavement pans." These pans are oriented transverse to the shallow slope of the valley, and each is stepped down toward the axial drainage of the valley. These "transverse pans" seem to be useful indicators of an underlying soil profile with thick pedogenic carbonates.

As we retrace to Cima Road, we will drive down a scarp with twenty feet of down-to-the-west displacement. The offset is complicated, and deposition suggests that the basin depocenter moved from east to west through time (Reynolds and others 1991). The view northwest shows basalt flows surrounding Paleozoic limestone. RETRACE to Excelsior Mine Road (Cima Road North).

85.6 (0.2) Stop at Excelsior Mine road. TURN RIGHT.

85.9 (0.3) Pass under transmission line.

86.1 (0.2) Slow for bend.

86.6 (0.5) Pass right turn to Valley Wells Copper Smelter (Vredenburgh 1996). Look for a pile of gravel on the left (west) .

87.0 (0.4) TURN LEFT on water line road just past the gravel pile.

87.6 (0.6) **STOP 9**. Stop at crossroads and terraced desert pavement with "transverse pans." This example of "transverse pans" overlying well-developed pedogenic carbonate is typical of what can be seen throughout the Halloran Hills and may indicate a marker horizon developed prior to 0.3 Ma. RETRACE to Excelsior Mine Road.

88.3 (0.7) Excelsior Mine Road. TURN SOUTH and proceed back to gas line.

89.7 (1.4) Gas line. TURN RIGHT and proceed westerly.

Figure 8. View east across imbricated pebble pavement referred to herein as "transverse pavement pans."

90.8 (1.1) Stop, open gate, proceed through, and close gate.

92.5 (1.7) **STOP 10.** The low relief granitic dome on the north is flanked on the east by east-dipping Miocene lacustrine sediments covered with Miocene basin-filling breccias and debris flows. The eastern end of this TQM outcrop is 10 km west of the closest outcrop of TQM on the breakaway zone at Clark Mountain. The granitic domes in the Halloran terrane are of low relief compared to those in the Cima terrane, perhaps because extension was more severe in the Halloran terrane. Continue west.

94.1 (1.6) Pass through second gate.

94.9 (0.8) Pass an outcrop of glassy ash overlain by pedogenic carbonate. The glassy ash was deposited after 9 Ma (M. Perkins, pers. comm. 2000) and is the youngest datable deposit to be east-tilted by listric normal faulting during detachment of the Halloran upper plate. This relationship suggests that Miocene sediments and late Pleistocene pedogenic carbonates were uplifted on the east side of a north-trending fault. Basalt flows to the right (northwest) are about 4.5 Ma (Turrin and others 1985) and flowed on an elevated, 1.1° shallow east-dipping surface.

96.5 (1.6) TURN LEFT (south) toward Halloran Summit overpass.

96.8 (0.3) PARK prior to the freeway fence. **STOP 11**: an overview of domes in the Cima terrane, extensional tectonics, surfaces, and basalts.

In freeway road cuts, Miocene siltstone and volcaniclastic sediments dip 30° to the east. On the south side of the freeway, a large outcrop of the pyroxene andesite is located on the east-dipping pre-Miocene granitic surface. As we proceed westward, we will pass debris and slide blocks of pyroxene andesite that were shed north across the Halloran transfer fault into the extending Halloran terrane. At Hal-

Figure 9. View west of bleached marble slide block surrounded by 4.5 Ma basalt flows.

Figure 10. Road cut at Halloran Summit exposes lacustrine siltstones that dip 30° eastward.

Figure 11. West of Halloran Summit, 5 Ma basalts flowed on a 1° west-dipping surface developed after 9 Ma on east-tilting gravels.

loran Springs, sediments and surfaces dip 45° east. In Mesquite Wash, west of Halloran Springs, pyroxene andesite on the weathered granitic surface indicates approximately 7 mi left-lateral offset from the comparable outcrop south of the Halloran transfer fault on the Cima terrane. The Halloran terrane was moved 5.8 mi west from the HH-KR detachment zone on the west slope of Clark Mountain and was extended by listric faulting a distance of 7 mi, suggesting that the outcrops at Mesquite Wash are almost 13 mi west of their original position. TURN ONTO WESTBOUND FREEWAY.

97.0 (0.2) Sediments in the road cut dip 30°E.

100.4 (3.4) East-dipping sediments beneath the basalt flow on the north side of I-15 suggest that this outcrop is north of the Halloran Fault. What appears to be a baked contact may actually be a rubified soil profile.

102.4 (2.0) EXIT at Halloran Springs Road.

102.7 (0.3) Stop, TURN RIGHT on Halloran Springs Road.

103.1 (0.4) Pass Halloran Springs and prepare to stop.

103.2 (0.1) **STOP 12.** We are north of the Halloran Fault. The gray hill of metamorphic rock to the west is a shutter ridge between branches of the fault. Walk east to arkosic sediments dipping 45°E. Clasts in the sediments consist primarily of imbricated TQM suggesting their source was from the west or southwest. The hill to the east contains a slab of distinctive granitic rock and debris of pyroxene andesite that were shed into this basin from sources in the Cima terrane to the southeast, across the left-lateral Halloran transfer fault. Return to vehicles, proceed 0.2 mi west.

103.4 (0.2) Leaving the pavement, TURN LEFT on the dirt road.

103.8 (0.4) Pass pyroxene andesite on granitic rocks. The east-west orientation of this contact is due to drag folding along the Halloran Fault.

104.1 (0.3) TURN LEFT (south) into Bull Spring Wash. Proceed 100 feet to the road to Heyten's Well and TURN RIGHT.

105.9 (1.8) STOP at Mesquite Wash. **STOP 13**. The 12.3 Ma pyroxene andesite sits on the pre-Miocene, iron-stained, granitic surface and dips steeply east along with overlying arkosic conglomerates. This relationship of granite, Peach Springs Tuff and/or pyroxene andesite, and coarse basin fill is repeated throughout the Cima/Halloran terranes. The degree of dip to the east reflects the severity of extension.

108.5 (2.6) Heyten's Well area. East-dipping pyroxene andesite is a repeated section here, indicating that we have crossed another west-dipping listric normal fault.

109.6 (1.1) Workings of the "Wander" Mine (actually the Wanderer mill and mine, Tucker 1931), shown on a 1902 miners' map and among the earliest gold mines in the Halloran Hills (Vredenburgh, 1996). The Telegraph mine at Halloran Summit is active when the price of gold is high.

109.7 (0.1) Big dip. Take the left fork toward the Avawatz Mountains.

110.8 (1.1) Pass an outcrop of dark andesite breccia.

Figure 12. Halloran Springs. View northeast of east-dipping arkosic sediments and granitic conglomerates. The distant hill consists of distinct granitic rocks and pyroxene andesite debris shed northward across the Halloran transfer fault.

Figure 13. Mesquite Wash. Thick, dense pedogenic carbonate on a mid-Miocene erosional surface developed over TQM may be equivalent to the pedogenic carbonate exposed at Valley Wells.

Figure 14. Powerline Road. Pedogenic carbonates on mid-Miocene erosional surface developed over TQM may be equivalent to the pedogenic carbonate exposed at Mesquite Wash and at Valley Wells.

110.9 (0.1) Continue past the road to the Turquoise mines at Auto Club signposts. The turquoise mines can be seen to the east at 3:00. We are driving along the trace of the Cree Fault (Reynolds 1997). The western branch of the Willow Wash Fault has offset Turquoise Mountain (with the microwave station) approximately 2 miles from the turquoise mines (Reynolds 1997).

111.1 (0.2) Pass dark andesite overlying rounded, subaerially-weathered boulders.

112.3 (1.2) Proceed north-northwest and join the second road to the turquoise mines. The Silver Lake talc mines are to the north.

113.3 (1.0) Stop at the intersection with the power line road. TURN RIGHT.

114.9 (1.6) Slow through the S curve and dip.

118.0 (3.1) **STOP 14**. Park in cleared area. View north shows Miocene silicified limestone and pyroxene andesite overlying the pre-Miocene surface, but here the contact relationship is folded anticlinally by drag folding with an east-dipping axis. In Shadow Valley Basin to the north, Mesozoic TQM is missing (Reynolds and Calzia, this volume) . Proceed, and continue past the road from Heyten's Well.

119.4 (1.4) Continue past a road from the south. We are in a very flat valley with mature desert pavement ramping shallowly up hills to the west. This pavement surface runs northwest to Eastern Star Wash (Stop 19) in Valjean Valley. The surface may be controlled by development of subsurface pedogenic carbonate (Reynolds and Calzia, this volume) .

120.1 (0.7) **STOP 15**. Park and inspect late Pleistocene pedogenic carbonates and the weathered granitic surface. Return to vehicles and proceed through concordant summits of a dissected pediment.

122.4 (2.3) Continue past road cut to talc mines.

124.2 (1.8) Proceed past left turn to the site of Silver Lake.

125.0 (0.8) Stop at Hwy 127, check for traffic, TURN RIGHT, and proceed toward Shoshone. Shoreline Butte with wave-cut benches is at the close margin of Silver Lake to the southwest (Brown et al. 1990) .

131.5 (6.5) Continue past right turn to Riggs.

135.0 (3.5) TURN RIGHT off Hwy 127 and cross Silurian Dry Lake towards a gap in a ridge of Proterozoic/Paleozoic carbonates called "The Islands."

135.2 (0.2) West edge of the playa.

135.7 (0.5) Proceed northeast at the east edge of the playa.

138.4 (2.7) Enter "The Islands." Note the chaotic internal structure of late Proterozoic and early Paleozoic rocks (Kupfer 1954, 1960). Kupfer (1960) indicates that the west flank of Middle Island, to the north, consists of quartzite and dolomite of the Pahrump group. The middle and eastern portion of Middle Island is recrystallized carbonate rock (marble) that he refers to the Riggs Formation.

138.6 (0.2) Intersection with the Tonopah and Tidewater Railroad, constructed in 1905 (Mulqueen, this volume) . The Annex talc mine is within one mile to the east. Proceed 0.1 mile east.

138.7 (0.1) **STOP 16**. PARK and WALK 0.1 mi south to look at weathered Teutonia Quartz Monzonite with leisingang weathering rings. This is the pre-Miocene or early Miocene erosional surface that received chaotic deposition of metamorphosed carbonate gravity slide blocks (Kupfer 1954, 1960; Reynolds and Calzia, this volume). Farther east in the Silurian Hills, fensters in the chaotic Paleozoic limestone reveal west-striking Miocene sediments and pyroxene andesite that dip 45° to the northeast. RETRACE to intersection.

138.8 (0.1) TURN RIGHT and proceed north parallel to the T&T railroad grade.

139.2 (0.4) **STOP 17**. Park at the north end of the railroad cut in red sediments. These red sediments filled the extending basin between 12 million and 10 million years ago. The presence of Tapeats Sandstone in a red ground mass suggests a source from weathered sediments from the north and south side of Clark Mountain. Similar basin-filling sandstone with clasts of Tapeats Sandstone can be seen at the east end of the Silurian Hills.

139.9 (0.7) Northwest across T&T grade are red beds in fault contact with chaotic carbonate slide blocks. The red silty sandstone contains clasts of Tapeats Sandstone. The trace of an old wagon road from Kingston Spring to Silver Lake (Thompson 1929) leaves ruts in the terrace pavement, but the ruts don't cross the two youngest surfaces (an active wash and the next bench up) , indicating centennial activity.

142.5 (2.6) Site of Valjean and the intersection with Kingston Wash Road. Proceed north parallel to the east side of the T&T rail bed.

142.8 (0.3) **STOP 18**. Ponding water has deposited sediments on the east side of the T&T since its construction in 1905 (Hereford, this volume). RETRACE.

143.1 (0.3) Site of Valjean, a stop on the T&T railroad (Mulqueen, this volume). Proceed east on the road heading toward Kingston Wash and Eastern Star Mine.

144.2 (1.1) Caution: dip.

148.0 (3.8) Stay right, passing the left fork to Kingston Wash.

148.5 (0.5) Caution: dip.

149.0 (0.5) The road runs upon a late Pleistocene surface above a thick pedogenic carbonate equivalent to the Valjean

Figure 15. Fans shed from the eastern Avawatz Mountains are different ages and exhibit different stages of desert pavement development and dissection.

Valley surface (Stop 15) and possibly equivalent to the carbonate at Valley Wells. As we drive eastward on this surface, look for mature, varnished desert pavement in canyon bottoms 20 feet below this surface.

149.5 (0.5) Pass south of a drainage exposing thick Pleistocene pedogenic carbonate.

150.5 (1.0) We are driving on a terrace underlain by indurated pedogenic carbonate. In Eastern Star Wash, 20' below the pedogenic carbonates, an extremely mature, varnished desert pavement indicates a 15k+ surface (Wells and others 1990).

151.4 (0.9) The road drops into a wash.

151.5 (0.1) **STOP 19**. Park and inspect the pedogenic carbonate and underlying red Miocene sediments. Miocene sediments in the vicinity contain tracks of proboscideans, carnivores, camels and pronghorn.

152.3 (0.8) Pass mine workings.

153.2 (0.9) Eastern Star Mine. Miners explored for lead, silver, zinc veins (Wright et al. 1953) in the landslide blocks. The veins disappeared suddenly at the basal contact when prospect tunnels encountered Miocene sandstone. RETRACE.

154.0 (0.8) Pass site of Valjean.

158.7 (4.7) Stop at Highway 127. Look for traffic; TURN RIGHT and proceed north.

164.6 (5.9) Lake Dumont. To the south is Avawatz Peak which rises to an elevation of 6,150 ft. Avawatz Peak alluvial fan segments are differentiated by relative age dating techniques (McFadden et al. 1989) into at least six units ranging from mid-Pleistocene to late Holocene. The late Pleistocene fan chronology is greatly influenced by local base level changes (Ritter 1989) resulting from fluctuations in Lake Dumont levels. A clastic wedge of bedded sand interbedded with coarse fan gravels is tentatively interpreted as a fan-delta associated with fluvial conditions on the Avawatz Peak fan during lake building filling phases (K. Anderson and Wells, 1997). The view to the south shows scarps of the southern Death Valley fault zone and Mule Springs Fault at the northern base of the Avawatz Mountains. The Avawatz Peak fan grading to the Dumont basin supplied water during the late Pleistocene (K. Anderson, pers. comm. 1997). Stratigraphic relationships and radiocarbon ages suggest that the earliest-known Lake Dumont phase (30,000 BP) predated earliest-known Lake Mojave phase (22,000 BP). Mojave River waters probably did not contribute to lake-building events during this time, implying that local precipitation from Kingston Wash, Salt Creek, and the Avawatz Mountains may have contributed to perennial Lake Dumont stands.

165.8 (1.2) TURN RIGHT into Salt Spring Visitor Center.

166.0 (0.2) **STOP 20**. PARK at turn-around. Salt Spring lies 0.5 mi to the north. The spring was used by New Mexican traders in the 1830s, and it became a stop along the Old Spanish Trail. The waters are an almost-saturated solution of glauber and epsom salts. Active gold mining started at Salt Spring in 1851 (Harder 1997, Lyman and Walker 1997). Transportation difficulties and Indian attacks culminating in the massacre of seven miners in the 1860s closed the mines. Mining activity resumed in the 1880s and 1890s (Lingenfelter 1986). The Amargosa Mine is privately-owned (Harder 1997). We are within less than 0.25 mi of the Mojave River canyon cut by Salt Creek which drained out of Lake Dumont. The BLM is eradicating tamarisk here (Prehoda, this volume).

The peak west of Salt Spring is quartz monzonite. In the saddle to the northeast, metamorphosed Carrara Formation is exposed. The section above the Carrara has been removed by erosion. A Miocene basaltic andesite breccia (12.8 Ma, Calzia, pers. comm. 1997) was deposited on this erosional unconformity. Later, the sequence of Paleozoic carbonate rocks was emplaced by gravity-driven transport on the Miocene volcanic rock. The dark carbonate rock is the Bonanza King Formation, the well-layered, variegated grey and brown is Bird Springs Formation, and in the saddle to the north is east-dipping Bonanza King Formation. All are breccia sheets and glide blocks deposited in Tertiary times.

Look south to the southernmost tip of the southern Salt Spring Hills which consist of the Pahrump Group overlain by the Noonday, Johnnie, Stirling, Wood Canyon, Zabriskie, and Carrara formations. Paleozoic carbonates are absent in the southern Salt Spring Hills. RETRACE to Highway 127.

166.1 (0.1) TURN RIGHT (north) on pavement, watching for cars.

167.0 (0.9) Pass the Wade Exit Monument. Harry Wade was a member of the "Sand Walking Company" that reached Salt Lake City in 1849 too late in the season to cross the Sierra Nevada into California. The company decided to break

Figure 16. Pre- to early Miocene erosional surface with leisingang weathering rings. The Proterozoic and Paleozoic rocks of the Silurian Hills have been emplaced on this surface.

Figure 17. T&T railroad grade north of Valjean. Silts have been deposited east of the grade, providing a centennial record of storm events for the area.

away from the Old Spanish Trail and other travelers led by Jefferson Hunt to take a supposed short cut through Death Valley. Wade abandoned the short cut and led his family and wagon out of Death Valley along the Amargosa River, rejoining the Old Spanish Trail at this point (Lingenfelter 1986).

169.2 (2.2) Cross the Amargosa River. We are driving up the broad, fan-shaped braid plain of Pleistocene gravels overlain by Holocene fluvial and aeolian sediments. The Amargosa River has not caused much incision into this shallowly-convex landform. To the northwest are the Saddle Peak Hills containing a northwest-trending dike swarm. The intrusion of the Kingston pluton in the Kingston Range halted southwest extension at approximately 12.4 Ma. However, the pluton itself has been tilted 30° to the east and is cut by younger extensional faults (J. Calzia pers. comm. 1997, Jachens, pers. comm. 2001). North-northwest in the Saddle Peak Hills, red Proterozoic rocks of the upper Kingston Peak Fm are overlain by tan late Proterozoic Noonday Dolomite.

171.1 (1.9) Continue past the dirt road to the Dumont Dunes and head toward the Sperry Hills. The fan that extends south from the Sperry Hills is only a few meters thick at most. Bedrock of Precambrian gneiss is exposed in gullies to the east.

175.1 (4.0) Prior to the left bend in the road, look to the right at 2:00 to a light gray limestone megabreccia sheet and dark volcanic rocks interbedded with the China Ranch beds (Wright, 1974). The China Ranch beds are a western extension of the late Miocene basin formed by extensional tectonics.

176.9 (1.8) Pass a road to a microwave station.

177.3 (0.4) The Sperry Hills are light-colored because they contain abundant granite boulders from the Kingston Peak pluton.

178.4 (1.1) Ibex Pass; enter Inyo County. We pass from bedrock granite to a granite boulder conglomerate dipping north 25° on the north slope of the Sperry Hills. A few miles east, the boulder conglomerate is unconformably overlain by an 8.4 Ma tuff.

181.9 (4.5) Lake Tecopa sediments dip gently eastward. In 0.2 mi we will see the Lava Creek B Ash, dated at 0.62 Ma (Hillhouse 1987).

183.1 (1.2) Continue past Spanish Trail Mesa, on the right.

183.6 (0.5) TURN RIGHT on the Old Spanish Trail and pass through Lake Tecopa sediments. Dated tuffs, the youngest of which can be seen to our north, include (from oldest), the Huckleberry Ridge Tuff (2.02 ± 0.08 Ma), the Bishop Tuff (0.759 Ma), and the Lava Creek B Ash (0.62 Ma) (Hillhouse 1987, Sheppard and Gude 1968). These dated tuffs allow development of a magnetostratigraphic section showing that lake sediments were deposited between approximately 2.5 Ma and 0.5 Ma. Fossil vertebrates in the lake indicate Blancan and Irvingtonian land mammal ages (LMA) (Woodburne and Whistler 1991, James 1985). Fractures in the lacustrine sediments contain a Rancholabrean LMA fauna, less than 0.15 Ma (Reynolds 1991). The presence of a tephra layer found in the upper portion of the lake suggests < 160 ka for the draining of Lake Tecopa (Morrison 1991). Using experimental 3He cosmogenic surface exposure dating of a high stand wavecut bench, Anderson and others (1994) found ages close to the 160 ka date.

From this point, the Spanish Trail from Emigrant Pass and Resting Spring in Chicago Valley ran southerly to Salt Spring, to Renoville, and then south of the Avawatz Mountains to Bitter Springs. A later, steeper route ran through the Avawatz Mountains to Cave Spring and Garlic Spring (Reynolds 1999, Mendenhall 1909, Lyman and Walker 1997).

186.1 (2.5) Slow for dip into Amargosa River bed.

187.5 (1.4) TURN RIGHT (south) onto a dirt road just past the Tecopa Post Office.

187.9 (0.4) Continue along the dirt road past a right fork.

188.0 (0.1) Pass the mill site.

188.1 (0.1) **STOP 21**. PARK at Amargosa Natural Area. Do not block the road. WALK SOUTH on the T&T RR grade into the upper part of Amargosa Canyon. We are now at the head of Amargosa Canyon. The T-5 terrace surface here is incised several meters, and it converges with the modern floodplain a short distance to the south. Sediments under this surface date to between 415 B.C. and A.D. 1663 (D. Anderson et al. 1997).

WALK along trail to viewpoints (see Lum and others, this volume).

• First 1/3 mile: The colorful Amargosa Gorge. At the top of the gorge, tan Pleistocene gravels are on top of purple

Figure 18. Pedogenic carbonate is exposed on red Miocene gravels. This carbonate may be the same as that which occurs along the powerline road, the south flank of the Halloran Hills, and at Valley Wells.

Proterozoic sediments deposited 600 million years earlier. The blue-gray silts in the canyon bottom are sediments from Lake Tecopa that have been washed into the gorge.

• Rolling Stones: first railroad cut. Pleistocene conglomerate capping the gorge contains a mixture of boulders from distant mountain ranges: Tapeats Sandstone from Clark Mountain (25 miles southeast); mylonite and granitic porphyry from Kingston Peak (10 miles east); Wood Canyon Quartzite from the Dublin Hills (10 miles north); and Zabriskie Quartzite from the Resting Spring Range (10 miles north).

• Cross stream cut: The stream cut shows layers of recent sediments with channel cutting and filling. Rust-colored stains are from oxidizing iron-rich sands of hematite and magnetite. The black color is a stain from manganese oxide.

• Two-thirds mile: Mushroom Rock. Water from Chicago Valley pours out high above the canyon bottom where calcite-cemented conglomerate (top) meets the Sterling Quartzite. Erosion has sculpted a mushroom-shaped rock from the conglomerate.

• Three hundred feet: Zabriskie Quartzite. 600 million year-old purple Zabriskie Quartzite is exposed between the trail and the Tonopah and Tidewater railroad cut.

• Six hundred feet: "Hanging gardens" (Lum et al., this volume) formed when waterfalls flowed from the contact at the base of the conglomerate. These ancient cascades with mineral-rich "hard water" left travertine onyx drapes that contain imprints of fossil vegetation.

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Vertebrate Ichnostratigraphy of the Glen Canyon Group (Jurassic) in Zion National Park, Utah

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Abstract

A paleontological survey of Zion National Park was initiated in 1997 by staff from the National Park Service's Geologic Resource Division. During the Zion Paleontological Survey more than two dozen new vertebrate ichnofossil localities were documented in the park. The majority of the fossil tracksites occur in the Early Jurassic Glen Canyon Group, including the Moenave, Kayenta, and Navajo formations. The Mesozoic track assemblages from Zion National Park are typical of the Glen Canyon Group occurring elsewhere on the Colorado Plateau. The dominant ichnogenera identified in Zion include *Grallator* and *Eubrontes* which are attributed to small and medium sized theropod dinosaurs, respectively. Twelve localities contain one or both of these ichnogenera. In addition, very small tridactyl impressions discovered in the Whitmore Point Member of the Moenave Formation and an unusual ornithopod-like tridactyl track from the Springdale Sandstone Member of the Moenave may represent new track morphotypes.

Introduction

Zion National Park is located in southwestern Utah (Figure 1) within the Colorado Plateau geographic province . The park is situated on the Kolob Terrace, a middle "step" between the lower Uinkaret and higher Markagunt Plateaus. This "step" between the plateaus is a mile vertical interval of impressive canyons, cliffs, and broad terraces often creating spectacular scenery (Gregory, 1939).

Considerable attention has been directed towards understanding the geology of Zion National Park. Fossils have been identified in rocks ranging from Permian through Cretaceous in age (Hesse, 1935; Hamilton, 1984) in the park, although there has been little attention directed towards the paleontological resources until recently. The first comprehensive paleontological resource inventory at Zion National Park was initiated in 1997. Twenty-two vertebrate tracksites were discovered in Zion between 1997 and 1999. One locality in the Springdale Sandstone Member of the Moenave Formation preserves a trackway with at least 18 individual footprints of a possible new tridactyl track-type. Very small bird-like tracks have been discovered from more than one locality in the Whitmore Point Member of the Moenave. Study of these ichnofossils in the park enables a comparison with time-equivalent vertebrate traces occurring in areas outside of Zion.

The first report of trace fossils from Zion National Park appears in 1935 in the "Zion-Bryce Nature Notes". This internal park report documents the discovery of dinosaur tracks along the highway at the base of the Mountain of the Sun. Due to rerouting of the highway in late 1935, the tracks have not been relocated. Stokes and Bruhn (1960) published on tridactyl dinosaur tracks from the Kayenta Formation in the park. Additional vertebrate tracksites have been reported from the Moenave, Kayenta, and Navajo formations and from Quaternary / Holocene lacustrine deposits within the park (Santucci et a(Peterson and Pipiringos, 1979)l., 1998; Smith and Santucci, 1999; F. Peterson, personal communication, 2000).

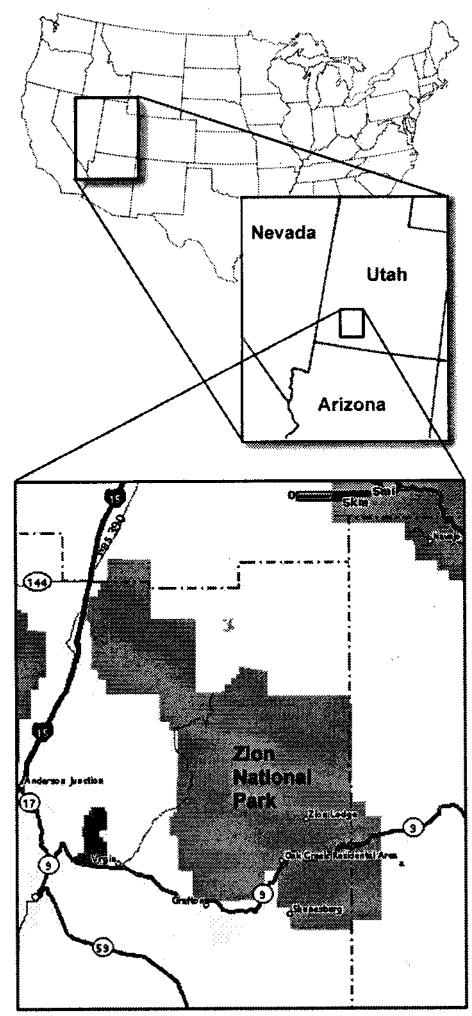

Figure 1: Location map of Zion National Park.

Zion Stratigraphy / Paleontology

The rocks exposed in Zion National Park range from Permian through Cretaceous in age (Figure 2). During this interval, the Zion area was repeatedly covered by marine transgressions from seaways that lay largely to the west, north, or east. The oldest unit exposed in Zion National Park is the early Permian Toroweap Formation. The Kaibab Formation of late early Permian age is a marine limestone unit, overlying the Toroweap. The Kaibab is exposed in two small areas in the northwest corner of the park along the escarpment produced by the Hurricane fault. Brachiopods, bryozoans, corals, crinoids and sea urchins have been recovered in the Zion area (McKee, 1952) although fossil preservation is generally poor.

The Moenkopi Formation (Early to Middle Triassic) represents both shallow marine and nearshore terrestrial environments in and near the Zion region. Fossilized marine bivalves, snails, and ammonites (*Meekoceras* sp.) are known from the formation. A few pieces of fossilized wood and bone have also been found in this unit. The Virgin Limestone Member contains fossil asteroid starfish and abundant internal molds of mollusks

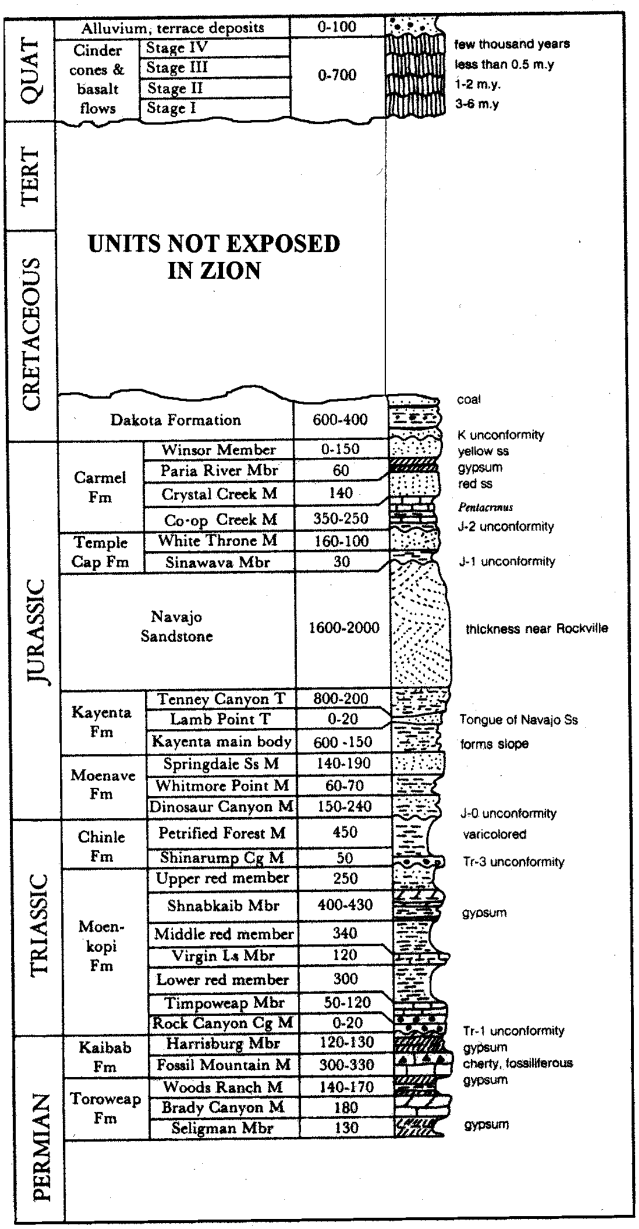

Figure 2: Stratigraphic column of Zion National Park and area (after Hintze, 1988).

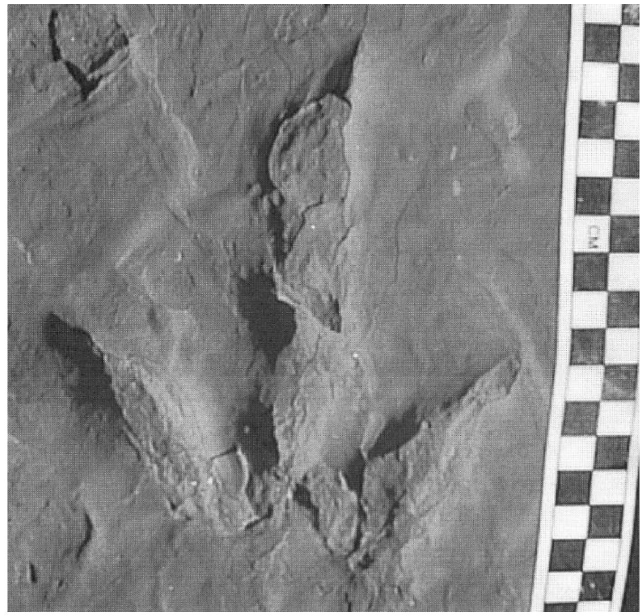

Figure 3: Grallator *sp. impression from the Whitmore Point Member of the Moenave Formation in Zion National Park.*

The Chinle Formation (Late Triassic) includes petrified wood that was originally transported by streams from the east and southeast. The logs are found in the basal Shinarump Conglomerate Member and have been identified as *Araucarioxylon* sp. and *Woodworthia* sp. Fossilized bones from the labyrinthodont amphibian *Metoposaurus* sp. have been collected from freshwater mudstone beds near Cougar Mountain.

The Glen Canyon Group (Early Jurassic) consists from oldest to youngest, the Moenave, Kayenta, and Navajo formations. Pond and stream deposits from the Moenave For-

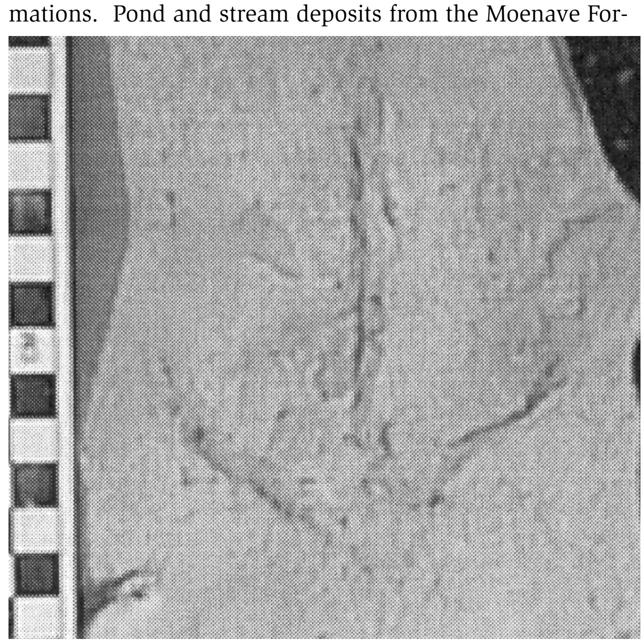

Figure 4: Widely splayed tridactyl track from the Whitmore Point Member of the Moenave Formation in Zion National Park.

Figure 5: Bird-like tridactyl track with apparent hallux impression from the Whitmore Point Member of the Moenave Formation in Zion National Park.

mation contain the remains of the fish *Semionotus kanabensis* (Hesse, 1935; Day, 1967). Fossil vertebrate tracks have been found in both the Whitmore Point and Springdale Members of the Moenave in the park (Smith and Santucci, 1999). The Kayenta Formation consists primarily of fluvial siltstone and sandstone deposited in sabkhas. Several thin limestone beds in the Kayenta preserve fossil trails of aquatic snails or worms. A number of fossil vertebrate tracksites are documented from this formation. The Navajo Formation consists of large-scale, cross-bedded, eolian sand deposits. The Navajo appears to be largely devoid of body fossils in Zion National Park, although a few tridactyl dinosaur footprints are known from this unit in the park.

The Middle Jurassic Carmel Formation includes several light tan to gray limestone beds that contain marine fossils, including crinoids, pectens, oysters, and other bivalves (Gregory and Williams, 1947). The crinoids are identified as *Isocrinus* sp. An oolitic limestone bed containing algal balls, bivalves, and gastropods is present along Wildcat Canyon Trail.

A small exposure of the Cretaceous Dakota Sandstone is exposed in the northwest corner of the park on top of Horse Ranch Mountain. The formation contains a basal conglomerate overlain by a series of sandstone and mudstone beds, some of which contain freshwater bivalves and plant impressions.

Quaternary and Holocene alluvial and lacustrine deposits occur in Zion Canyon and in other areas of the park. The remains of a bison (*Bison antiquus*) were collected in the park many years ago (Wayne Hamilton, personal communication, 1998). Artiodactyl and bird tracks have been collected from lake sediments in the Coalpits Wash area (Santucci et al., 1998). Hevly (1979) analyzed pollen and spore samples taken from Quaternary lacustrine sediments in Zion National Park.

The Glen Canyon Group

The Glen Canyon Group is separated below from the fluvio-lacustrine sediments of the Late Triassic Chinle Formation by a regional, systemic unconformity called the J-0 unconformity. It is also separated from the overlying Temple Cap Sandstone and the Carmel Formation by the J-1 unconformity (Pipiringos and O'Sullivan, 1978).

The Wingate Sandstone Formation is not present in the Zion National Park area, but is the lateral equivalent of the Moenave Formation. The lower beds of the Moenave intertongue with the upper beds of the Wingate in the Painted Cliffs of Arizona (Harshbarger et al., 1957), showing the Wingate to be the oldest unit in the Glen Canyon Group.

The Early Jurassic Moenave Formation includes, from oldest to youngest, the Dinosaur Canyon, Whitmore Point and Springdale Sandstone members. The Dinosaur Canyon Member consists of red mudstone, siltstone, and some sandstone deposited in mudflat, channel, and overbank environments. The Whitmore Point is a gray mudstone and shale unit deposited primarily in lacustrine environments. The Springdale Sandstone Member forms a red cliff composed of many sandstone, shale, and limestone conglomerate lenses deposited by high energy streams (Gregory, 1939). The fined-grained, well-sorted sediments of the Moenave Formation represent a fluvial/lacustrine system (Miller et al., 1989) that originated in a highland source region in the ancestral Rockies of western Colorado. The Moenave sediments accumulated along the southwest margin of the Wingate erg as it drained highlands from the south in Arizona (DeCourten, 1998). The three members of

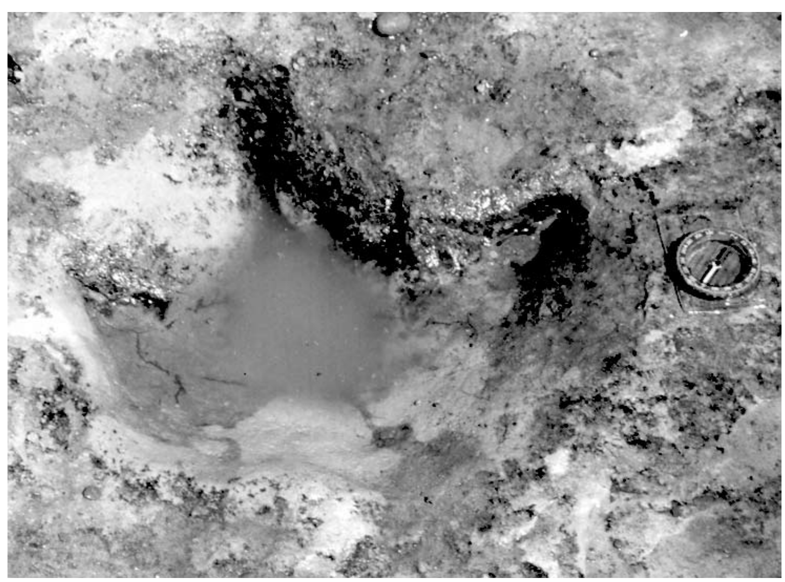

Figure 6: Ornithopod-like tridactyl track from the Springdale Sandstone Member of the Moenave Formation of Zion National Park.

Figure 7: Small, "fleshy" tridactyl track from the Kayenta Formation in Zion National Park.

the Moenave Formation lie conformably atop one another and range from the older late Sinemurian to the younger early Pleinsbachian in age (Peterson and Pipiringos, 1979).

The Kayenta Formation consists of a series of alternating mudstones and sandstones forming a slope with many small resistant ledges. The Kayenta sediments were deposited by an extensive braided river system during the interval between the older Wingate and younger Navajo Deserts (DeCourten, 1998). The Kayenta has two recognized facies, designated "typical" and "sandy", which are differentiated based on their proportion of sandstones to siltstones (Harshbarger et al., 1957). The Kayenta Formation is Pliensbachian and early Toarcian in age (Peterson and Pipiringos, 1979).

The Navajo Sandstone Formation is a laterally extensive eolian deposit forming cliffs up to 1,500 feet high in Zion National Park. The erg represented by the Navajo Sandstone covered much of the North American southwest and was much larger than the Wingate erg of earlier times, which covered only eastern Utah. The Navajo Desert existed during the late Pliensbachian and Toarcian Stages (Peterson and Pipiringos, 1979).

Excluding the Rock Point Member of the lower Wingate Sandstone which is below the J-O unconformity, the Glen Canyon Group is considered entirely Early Jurassic in age (Peterson and Pipiringos, 1979).

Vertebrate Ichnostratigraphy

The extensive exposures of the Glen Canyon Group in the southwestern United States presents the opportunity for paleontologists to examine the fossil record from the period immediately after the Late Triassic extinctions. While skeletal material has been found in the Glen Canyon Group, it is relatively rare considering the extent of these formations. The ichnological record of vertebrates in the Glen Canyon Group strata provides a more complete picture of the fauna above the Triassic-Jurassic boundary.

Zawiski (1986) summarized the debate concerning the ecological success of dinosaurs over other archosaurian groups during the Late Triassic. This success may be attributed to either the opening of ecological niches created by the Late Triassic extinctions or the "superior" adaptations and adaptability of the dinosaurs. Nonetheless, the dinosaurs experienced an explosive adaptive radiation during the beginning of the Jurassic. The track record in Zion National Park provides evidence of the post-extinction faunal turnover.

The ichnogenera *Grallator* and *Eubrontes* are abundant in the Moenave and Kayenta formations within Zion National Park. These two ichnogenera are similar to each other in their tridactyl morphologies, but the tracks are considered taxonomically distinct based upon size. *Grallator* (Figure 3) is associated with a small theropod and *Eubrontes* is associated with a larger theropod (Lockley, 1991).

Fossil footprints are not know from the Dinosaur Canyon Member of the Moenave Formation within Zion National Park. In the overlying Whitmore Point Member of the Moenave there are many localities documented with *Grallator* and *Eubrontes* tracks. At least four of the Whitmore Point tracksites contain small (< 10 cm) tridactyl tracks with very narrow digits (Figures 4 and 5). The thin width of the phalangeal impressions may be due to underprinting or some other preservational phenomena, but a more detailed study is needed.

In the Springdale Sandstone Member of the Moenave Formation is a trackway of unusual "ornithopod-like" tridactyl tracks. These three-toed tracks have a broadly widened heel that appears to be more like those of an ornithopod than a theropod dinosaur (Figure 6). The trackway includes at least eighteen individual footprints. The tracks are deeply impressed (~ 5 cm) into the rock indicating a soft, wet substrate for the trackmaker, and other localities in the Springdale preserve underprints of *Eubrontes*-like tracks. These "ornithopod-like" tridactyl tracks may represent a new track morphotype.

One locality in the Kayenta Formation at Zion National Park preserves a rounded impression with either four or five digits. This rounded ichnite is similar to *Brasilichnium* which is often attributed to a mammal-like reptile (Lockley, 1991). Associated with this impression are two different sized examples of *Grallator,* and unidentified oval-shaped tracks (< 10cm) in a trackway of nine individual footprints. At another Kayenta locality in the park, numerous small (< 6 cm), "fleshy" tridactyl tracks were discovered (Figure 7).

A single vertebrate tracksite with several tridactyl footprints is reported from Navajo Sandstone in the park (F. Peterson, personal communication, 2000). Dinosaur tracks commonly occur in the interdunal "oases" deposits within the Navajo Formation. Several Navajo fossil localities are documented in the nearby Grand Staircase-Escalante National Monument preserve *Eubrontes*, *Brasilichnium*, and possibly *Grallator* and *Anomoepus* tracks (Foster et al., 1999). *Grallator, Anchisauripus,* an unidentified tridactyl track type, and tracks of unidentified quadrupeds are found in the Aztec Sandstone Formation of California (Reynolds, 1989). The Aztec Sandstone is the lateral equivalent of the Navajo Formation. Further prospecting in the expansive exposures of Navajo Sandstone within Zion National Park is likely to yield additional vertebrate tracks.

Conclusions

Zion National Park contains a classic western exposure of the Glen Canyon Group of the Colorado Plateau, which sits unconformably above the Late Triassic Chinle Formation (Clark and Fastovsky, 1986). The Triassic-Jurassic faunal transition after the Late Triassic extinction can be examined through the vertebrate ichnology of the Glen Canyon Group, especially within the fluvial and lacustrine deposits of Zion National Park. Like other Glen Canyon strata, the Zion section shows a marked reduction, and absence in some cases, of non-dinosaurian ichnites of dominant Late Traissic forms. Similarly there is an increase in dinosaurian ichnites, most representing theropods. The recent National Park Service sponsored paleontological survey of Zion National Park has revealed new vertebrate ichnofossils that, along with data from other ichnofossil localities in the region, will be helpful in understanding the nature of the Triassic-Jurassic faunal transition. Additionally, the survey demonstrates the scientific value of the park's paleontological resources.

Acknowledgements

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Bird Footprints from the Miocene of California

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INTRODUCTION

The collections of the Raymond M. Alf Museum of Paleontology (Claremont, California) and of the San Bernardino County Museum (Redlands, California) contain a variety of specimens of bird footprints including numbers of species not previously described. We believe that clear descriptions and illustrations of the morphology of fossil footprints are required (Sarjeant and Reynolds, 1999) so that the footprints, insofar as their preservation permits, may be placed into ichnotaxa — into genera and species characterized by the morphology of the imprints themselves. The names of these taxa should reflect their morphology. If a name reflects the presumed affinity of the trackmaker, it should relate to a larger taxonomic group rather than to an osteologically-based taxon.

Avian footprints have been described quite widely from Cenozoic strata, but relatively few taxa have been accurately characterized. Moreover, as Sarjeant and Langston (1994, p. 7) noted:

> Bird footprints present particular problems to the paleoichnologist in that they can be used only to a limited extent to identify particular systematic categories. This is because, to an even greater degree than in other animal groups, the morphology of the foot represents behaviour rather than affinity. Consequently, though the makers of some bird tracks can be named with reasonable confidence, much more often their identification is difficult or impossible.

The classification and the descriptive approaches we adopt are discussed on later pages.

HISTORY OF STUDY

Early Reports

Edward Hitchcock reported what he believed to be avian footprints from the red sandstones of the Connecticut Valley as early as 1836. He styled them "ornithichnites" and called their study "ornithichnology". Later work revealed that the footprints were of bipedal reptiles (thecodonts and coelurosaurs): the sandstones were of Late Triassic to Early Jurassic age, amply predating the first appearance of birds (see Sarjeant, 1987, 1995). However, bird tracks have subsequently been reported from the later Mesozoic, their character and occurrence being usefully summarized by Lockley *et al.* (1992).

Cenozoic bird footprints were recorded by Jules Desnoyers (1859) as part of a footprint assemblage from the gypsum deposits of the Paris region, and by A. Portis (1879) from the Eocene strata of the Piedmont region of northern Italy. However, though Portis illustrated his specimen and even named it as *Ornithichnites argenterae*, his identification is unconvincing — it appears to be a sedimentary structure of non-biological origin.

Following the pioneer reports by Desnoyers and Portis from the early Cenozoic, the next records of fossil bird tracks came from the latest Cenozoic of New Zealand. Footprints of the extinct moa were reported from Holocene beach deposits by T.B. Gillies (1872). Moa footprints were reported by Williams (1872) and again by Hill (1895); Hutton (1898) recorded fossil footprints of a kiwi-like bird. Subsequent reports of fossil bird tracks from the Quaternary have been few; the only extended account is of ratite tracks from Argentina (Aramayo and Bianco, 1987).

Eocene

In 1906 a convincing illustration of bird tracks from French Eocene gypsum was published by Stanislas Meunier. These are now named *Fuscinapeda meunieri* and are considered to be footprints of wading birds (Sarjeant and Langston, 1994, p. 15).

More than a half-century elapsed before the next report of Eocene avian footprints was published, when H. Donald Curry (1957) illustrated two types from the Uinta Basin of Utah. Next, Plaziat (1965) illustrated Eocene footprints from the French Pyrenees. Web-footed imprints were reported by Erickson (1967) from the Green River Beds of Utah; his work was followed up by Moussa (1968). The tracks, thought to be those of *Presbyornis*, were formally named *Presbyorniformipes feduccii* in a general review by Lockley and Hunt (1995). Sarjeant and Langston (1994) described, illustrated and named six new taxa of bird footprints from late Eocene (Chadronian) strata of western Texas.

Oligocene

The first description of Oligocene bird tracks was from Spain, by Hernandez-Pacheco (1929). Mangin (1962) reported Spanish bird tracks more vaguely dated as Paleogene, and Raaf *et al.* (1965) described avian footprints from Lower Oligocene strata in Spain. De Clercq and Holst (1971) have reported Oligocene bird tracks from Switzerland, and Demathieu *et al.* (1984) from southeastern France. Paleogene avian imprints from King George's Land, Antarctica, have been recorded by Covacevich and Lamperein (1969, 1970, 1972) and Covacevich and Rich (1977). The footprints described by Trusheim (1929) from Germany, characterized as five-toed prints with three digits foward and two laterally, are so extraordinary that they must be questioned.

Miocene

The earliest record of Miocene bird footprints is an illustration by H.G. Grozescu (1914) depicting footprints of a wading bird from the Early Miocene (Burdigalian) of Romania. H. Donald Curry (1939, 1941) noted bird tracks from Miocene and Pleistocene strata of Death Valley, but 45 years elapsed before these were first described and illustrated by Scrivner and Bottjer (1986) and subsequently by Santucci and Nyborg (1999) and Nyborg and Santucci (2000). M. Paucy (1942) reported tracks of gulls from the Middle Miocene (Helvetian) of Romania. Later records from the Romanian Miocene were by Vialov and Flerov (1952), Vialov (1960), Panin and Avram (1962), Panin (1965) and Kordos and Prakfalvi (1990). Swiss Miocene tracks have been reported by Speck (1945) and Weidmann and Reichel (1979). Tasnádi Kubacska (1974) reported, and Kordos (1983, 1987) described and illustrated in detail, Early Miocene avian footprints from northwest Hungary. Wetmore (1956) reported Miocene bird footprints from Louisiana.

Pliocene

Pliocene avian footprints were first reported by Alden H. Miller and James F. Ashley (1934), who recorded and described what they believed to be goose footprints from the Moraga Valley of California. Johnston (1937) illustrated bird tracks from the Pliocene of west Texas. Elsewhere in the world, Pliocene avian footprints have been recorded from Iran by Lambrecht (1938), from Argentina by Bonaparte (1965), from Japan by Yoshida (1967) Ono (1984), and from the Anza-Borrego desert in California by Buccheim and others (1999) and Remeika (1999).

Temporal distribution of ichnotaxa discussed in this paper is shown in Table I.

CLASSIFICATION

The first general classification of avian footprints was formulated by Panin and Avram (1962), who defined several new avian ichnogenera and assembled them into families. Vialov (1960) had earlier proposed that all bird ichnites be placed into his Order Avipedia. Later, apparently unaware of Panin and Avram's work, Vialov (1966) proposed that all fossil bird footprints be placed into a single ichnogenus, *Avipeda* Vialov. The latter proposal was adopted by Scrivner and Bottjer (1986) but rejected by Sarjeant and Langston (1994, p. 7-8), who preferred to modify and extend the classification formulated by Panin and Avram (1962). The work of Lockley *et al.* (1992) on Mesozoic bird footprints accords with Sarjeant and Langston's approach, which is followed below.

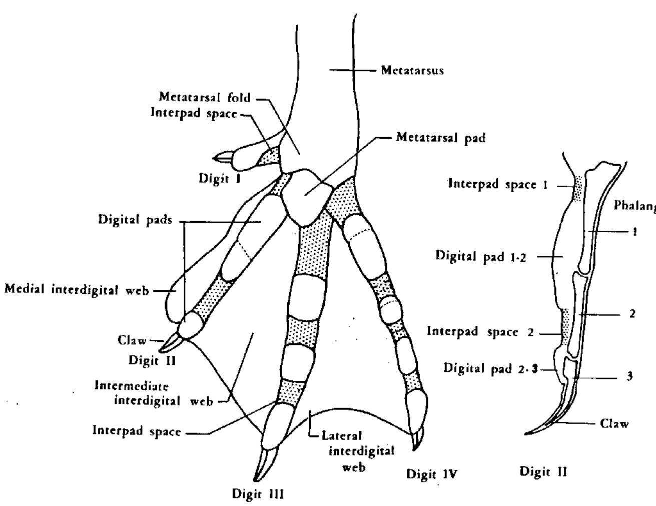


Figure 1. The terminology of the avian foot. Left: seen from beneath. Right: in lateral view. The foot is that of a White Pekin Duck. (Drawing by J. Fay, reproduced from Lucas and Stettenheim, 1972).

SYSTEMATICS
Preamble

The terminology for the parts of the avian foot, adopted herein, essentially coincides with that set forth by Lucas and Stettenheim (1992: see Fig. 1). Measurements are given as fully as the specimens permitted. It should be stressed, however, that bird track patterns (other than those of running birds) are closely controlled by the behavior of the moment, such as food procurement (some birds, such as egrets, wiggle their toes while standing to attract prey, for example), taking flight, or landing. Although measurements of step and stride provide some constraints, they have less meaning than in the tracks of reptiles or mammals. Interdigital angles are determined not only by behavior and the shape of the digit, but also by the character of the substrate, the digits spreading more widely on soft sediment surfaces than on hard. Consequently, though such measurements are helpful in describing a track, they should be used only with caution in characterizing a footprint morphotype. In addition, digit I is only rarely impressed; though not indicated on a footprint, it may very well have been present on the foot of the trackmaker.

Many specimens described herein are not the original footprints — not molds, formed when the foot was implanted into the sediment surface, but casts formed by sediment that filled the footprint, the cast being preserved on the underside of the overlying bed. Consequently there has been a reversal of image, the right side becoming the left. The captions of our photographs of casts reflect this, wherever possible identifying the foot correctly: however, the figures correspond with the photographs and, in such instances, exhibit a left-to-right reversal, in comparison with the symmetry of the original footprint. Nomenclature is illustrated in Figure 1. The authors have included angles of divarication showing the span between adjacent digits.

CLASS AVES
SUBCLASS NEORNITHES
Morphofamily Avipedidae Sarjeant and Langston, 1994

Diagnosis. "Avian footprints showing three digits, all directed forward. Digits united or separate proximally. Webbing lacking or limited to the most proximal part of the interdigital angles." (Sarjeant and Langston, 1994, p. 12).

Ichnogenus *Avipeda* Vialov, 1965, emend. Sarjeant and Langston, 1994.

Diagnosis. "Avian footprints of small to large size, showing three short, thick digits, with distinct claws. Length of central digit (III) less than 25% greater than that of the lateral digits. Total interdigital span 95° or less. Digits closely convergent or united proximally; webbing lacking or limited to the most proximal part of the interdigital angles" (Sarjeant and Langston 1994, p. 12).
Type Species. Avipeda phoenix Vialov, 1965. Miocene (Burdigalian), Ukraine.

Avipeda thrinax Sarjeant and Reynolds, ichnosp. nov.

Plate 1; Figs. 2-3

Diagnosis. Avian footprints of small size, having three almost rectilinear digits (II to IV). Digits of moderate thick-

Table I. Age distribution of Avian Ichnotaxa.

Taxa referenced, this paper	PALEOCENE	EOCENE	OLIGOCENE	MIOCENE					PLIOCENE	PLEISTOCENE
				Arikarrean	Hemingfordian	Barstovian	Clarendonian	Hemphillian		
Ornithichnites argenterae		X								
Fuscinapeda meunieri		X								
Presbyorniformipes feducci		X								
Avipeda thrinax					X					
Avipeda gryponyx							X			
Aviadactyla media					X	X				
Aviadactyla panini						X				
Aviadactyla vialovi						X	X			
Aviadactyla scrivneri								X		
Ornithotarnocia lambrechti					X					
Alaripeda lofgreni								X		
Gruipeda becassi						X				
Culcitapeda ascia					X					
Culcitapeda tridens					X					
Culcitapeda eccentrica					X					
Charadriipeda recurvirostrioidea							X			
Anatipeda californica							X			
Anatipeda alfi							X			
?Anatipeda							X			
"Goose"									X	

ness, with conspicuous claws bent inward at an angle of around 25° to the digital axes. Claws separated from pads by a distinct interpad space. Digits united proximally by a metatarsal pad. Total interdigital span less than 80°, the interdigital angle between II and III being less than that between III and IV. Digit III somewhat longer than digit IV and markedly longer than digit II. Webbing lacking. Trackway narrow; stride long.

Holotype. Slab exhibiting three impressions, two of the left foot and one of the right; unnumbered specimen (Pl. 1, Fig. 2), lodged in the collections of the San Bernardino County Museum, Redlands, California.

Derivation of Name. Greek *thrinax*, trident, three-pronged fork.

Horizon and Locality. Miocene (Hemingfordian). Little Piute Mountains, San Bernardino County, California.

Dimensions. Holotype: Stride 107 mm; pace 114 mm: breadth of trackway 30 mm. Length of pes 23 mm, breadth 20.5 mm. Length of digits: II, 12.5 mm; III, 17 mm; IV, 15.5 mm. Breadth of digits: 3 mm. Estimated range of dimensions (based on ca. 60 footprints): Length of pes 20–28m, breadth 17–25 mm. Length of digits: II, 10–15 mm: III, 15–20 mm: IV, 13–18 mm.

Divarication of Digits. See Fig. 2.

Discussion. Avipeda thrinax differs from *A. adunca* Sarjeant and Langston, 1994, from the Late Eocene of Texas, in exhibiting a narrower interdigital span, a distal interpad space and proximal linkage by a conspicuous metatarsal pad. It differs from *A. phoenix* Vialov (and from *A.* aff. *phoenix* of Sarjeant and Langston, 1994) in having more slender digits and a markedly narrower interdigital span. The nature of the trackmaker cannot be determined since, as Sarjeant and Langston noted (1994, p. 2), the *Avipeda* style of footprint is too simple to be characteristic of any particular avian order. These Little Piute tracks were referred to sandpipers or plovers (Reynolds and Knoll, 1992).

Avipeda gryponyx Sarjeant and Reynolds, nov.

Plates 2, 3, 4; Figures 4, 5

? 1979. "Pistes de petit bécasseau." Weidmann and Reichel, fig. 5.

Diagnosis. Avian footprints of small size, having three slender digits, the outer ones (II and IV) curving forward, the central digit (III) curving in toward the track axis. Digits acuminate, but claws not distinct; interpad spaces not evident. Digits united proximally, but lacking webbing or an intertarsal pad. Interdigital span (at base) around 95°. Length of digits almost uniform; interdigital angle between II and III less than that between III and IV. Trackway narrow: stride short.

Type Material. Holotype: series of seven footprints, with partial impressions of others, on slab V94021/110 (P. 4, Fig. 4). Raymond M. Alf Museum of Paleontology, Claremont, California.

Derivation of Name. Gr., *grypos*, curved: *onyx*, talon, claw.

Horizon and Locality. Avawatz Formation, Miocene (Clarendonian), Avawatz Mountains, San Bernardino County, California.

Dimensions. Holotype: Stride 42 mm; pace 61 mm; breadth of trackway 40 mm. Length of pes ca. 19 mm, breadth ca. 27 mm. Length of digits: II, ~14.5 mm; III, ~16 mm; IV, ~14 mm (the curvature of the digits makes these measurements inexact). Breadth of digits: max. 2 mm.

Plate 1 (left). Avipeda thrinax *Sarjeant and Reynolds, nov. The holotype slab, showing three successive footprints.*

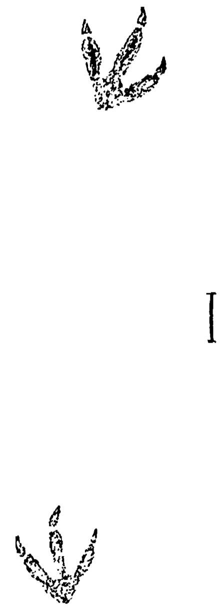


Figure 2 (below). Avipeda thrinax *Sarjeant and Reynolds,* ichnosp. nov. *Interpretative drawing of the holotype track. [Scale bar = 1 cm].*

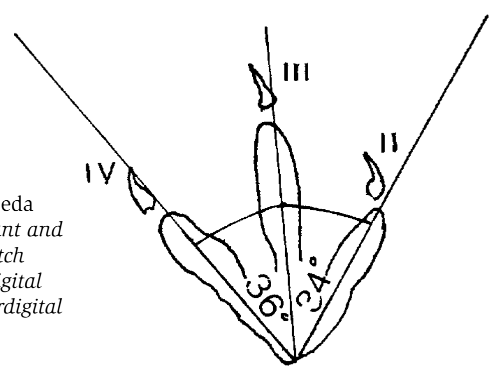


Figure 3. Avipeda thrinax *Sarjeant and Reynolds. Sketch to illustrate digital axes and interdigital angles.*

Divarication of Digits. See Fig. 5.

Discussion. The curvature of the digits, their thinness and their proximal union combine to differentiate *A. gryponyx* from all other ichnospecies of *Avipeda*. The digits of *A. adunca* Sarjeant and Langston, 1994 are broader and have distinct claws; those of *A. thrinax* exhibit a metatarsal pad and a narrower interdigital span.

The footprints illustrated from the Early Miocene (Burdigalian) of Switzerland by Weidmann and Reichel (1979) are comparable to *A. gryponyx*, but digit III appears proportionately shorter. Their suggestion — that the footprints are those of a sandpiper comparable to the little stint (*Calidris minuta*) — accords with our own view that these are footprints of small wading birds.

Ichnogenus *Aviadactyla* Kordos, 1985, emend. nov.

1983 *Aviadactyla* Kordos, 1983, p. 276, 364.
1990 *Carpathipeda* Kordos *in* Kordos and Prakfalvi, p. 211, nomen nudum

Original Diagnosis. "Bird footprint of small to medium size consisting of three toes. The prints of all three toes are thin, stick-like, shallowly imprinted. Longest is the middle toe, to be followed by the gradually shorter inner and outer toes. The distal end of the inner toe print is, in normal case, farther away from the basic line (the line normal to the middle toe) than the end of the middle toe print. Consequently, it is slightly asymmetric." (Kordos, 1985, p. 364).

Emended Diagnosis. Avian footprints of small to moderate size, composed of three digital impressions. Digits of slender to moderate width, tapering distally and sometimes exhibiting distinct, slender claws but typically without, or with only feeble, indication of digital pads or interpad spaces. Length of central digit (III) less than 25% greater than that of the lateral digits. Total interdigital span exceeds 95°. Digits convergent proximally but usually isolated (though digit II may have a minimal contact with digit III). No indication of a metatarsal pad or of webbing between digits.

Type Species. *Aviadactyla media* Kordos, 1985, p. 276-277; pl. 3, figs. 1-5, text-fig. 6: tab. 1.

Discussion. The genus was originally defined by a combined generico-specific diagnosis. Since this was not wide enough to permit the inclusion of related morphotypes, it is here emended. The diagnosis of *Carpathipeda* differs in such small measure from that of *Aviadactyla* that we consider it preferable to synonymise them. Moreover, the validity of *Carpathipeda* is questionable. It was defined by a combined generico-specific diagnosis which, normally, should have been acceptable under Article 13(c.) of the *International Code of Zoological Nomenclature* (Rideet al., 1985). But a second species of different morphology, *C. vialovi*, was simultaneously described, invalidating this procedure.

The emendation clarifies the essential features of the genus, permitting the unambiguous inclusion of other footprint ichnospecies with three widely spreading digits of similar size. The digits of *Avipeda* have a narrower spread (see above), while *Fuscinapeda* Sarjeant and Langston, (1994, p. 13) is distinguished by having a proportionately much larger central digit (III) and *Culcitapeda* nov. gen. (see below) by lacking conspicuous claws. *Antarctipeda*

Plate 2. Avipeda gryponyx *Sarjeant and Reynolds, nov. Close-up of part of holotype slab V94021/110, showing five footprints. (The whole slab is illustrated on Plate 4).*

Plate 3. Avipeda gryponyx *Sarjeant and Reynolds, nov. Part of large slab, showing many footprints.*

Plate 4. Avipeda gryponyx *Sarjeant and Reynolds, nov. The holotype slab V94021/110, showing seven clear footprints and a number of others that are incomplete or less clear.*

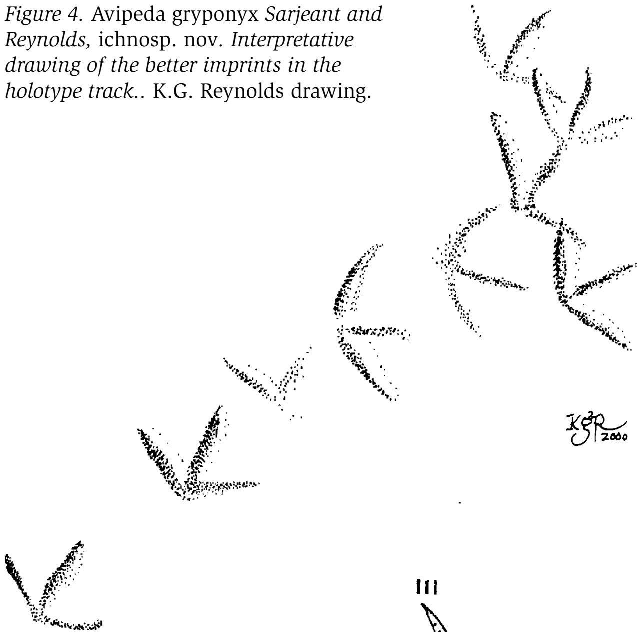


Figure 4. Avipeda gryponyx *Sarjeant and Reynolds,* ichnosp. nov. *Interpretative drawing of the better imprints in the holotype track..* K.G. Reynolds drawing.

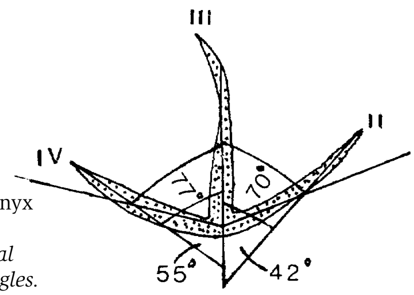


Figure 5. Avipeda gryponyx *Sarjeant and Reynolds. Sketch to illustrate digital axes and interdigital angles.*

Plate 5. Aviadactyla vialovi *(Kordos* in *Kordos and Prakfalvi) Sarjeant and Reynolds, comb., nov., emend. Slab V94021/272 showing at least eight footprints.*

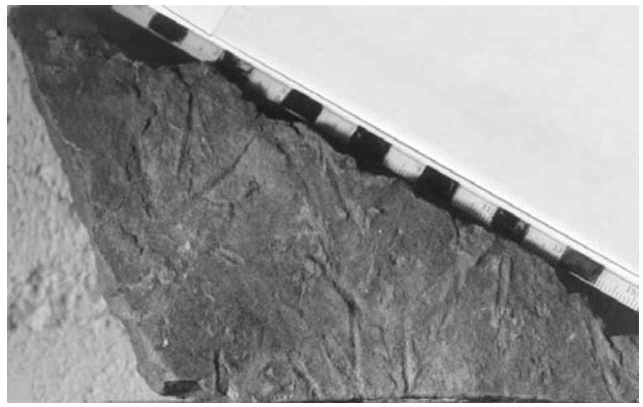


Plate 6. Aviadactyla vialovi *(Kordos* in *Kordos and Prakfalvi) Sarjeant and Reynolds, comb., nov., emend. Surface V94021/278 showing several overlapping footprints.*

Covacevich and Lamperein (1972, p. 73-74) has digits of similar form, but also a conspicuous fourth digit (I), backwardly directed. *Aquatilavipes* Currie, 1981 emend. Lockley et al., 1992 differs in showing proximal fusion of the digits.

Aviadactyla panini (Kordos *in* Kordos and Prakfalvi, 1990) comb. nov.

1990 *Carpathipeda panini* Kordos *in* Kordos and Prakfalvi, p. 203-205, figs. 1-3; tab. 1.
Discussion. This transfer is made because the species was placed originally into an invalid genus and as consequence of our treatment of that genus as a subjective synonym of *Aviadactyla*.

Aviadactyla vialovi (Kordos *in* Kordos and Prakfalvi, 1990) comb. nov., emend.

Plates 5, 6; Figs. 6, 7.

1957 Unnamed bird tracks. Curry, fig. II.
1962 Pattes d'oiseaux. Mangin, fig. 2.
1964 Pattes d'oiseaux. Plaziat, text-pl. 2, text-fig. 2
1971 Bird footprints. de Clerq and Holst, fig. 4.
1979 "Piste d'un limicole de la taille du chevalier guignette." Weidmann and Reichel, Fig. 3.
1990 *Carpathipeda vialovi* Kordos *in* Kordos and Prakfalvi, p. 206-207, 211-212: text-fig. 3; tab. 1.
*Original Diagnosi*s. "The three-toed mold of a medium-size bird. Of the mold of the three slightly asymmetrically-arranged toes the middle one is the longest, whereas the two extreme ones have nearly the same length. There is no web observed. The linking of the sole with the toe-ends towards the sole, as well as the wide spreading of the extreme toes, with respect to the middle one, carries morphological connection with the *Carpathipeda panini* species" (Kordos *in* Kordos and Prakfalvi, 1990, p. 211-212).
Emended Diagnosis. Avian footprints of small to moderate size, having slender and flexible digits (II to IV) with slender claws whose inclination is only slightly divergent from the digit axis. The digits lack interpad spaces. Interdigital span variable according to pace and substrate, ranging from about 80° to over 155°. The interdigital angle between digits II and III is slightly less than between digits III and IV. Proximally the digits converge, with digit II sometimes in slight contact with digit III; but digit IV is always separate and neither webbing nor a metatarsal pad are present. The digits are of comparable length, with digit III slightly the longest. Trackway of moderate width; stride of moderate length.

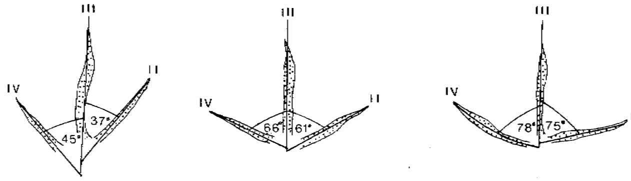


Figure 7. Aviadactyla vialovi *(Kordos* in *Kordos and Prakfalvi). Sketch to illustrate digital axes and interdigital angles, showing variation in position of the lateral digits.*

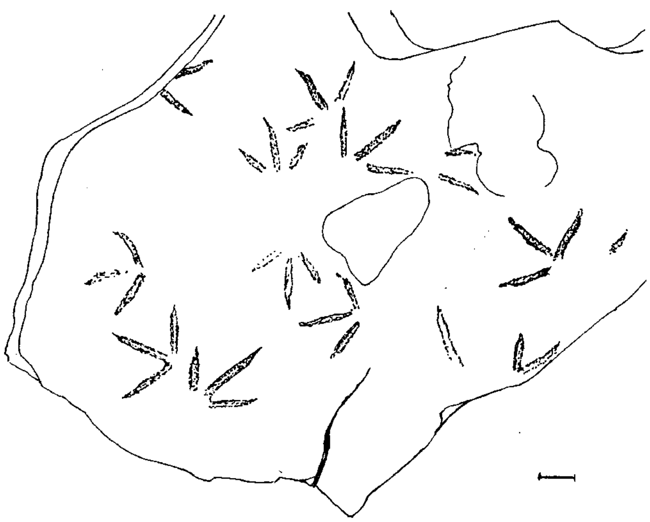


Figure 6. Aviadactyla vialovi *(Kordos* in *Kordos and Prakfalvi) Reynolds and Sarjeant,* comb. nov., emend. *Interpretative drawing of the Californian slab. [Scale bar = 1 cm].*

Holotype. Specimen V.15276 (Vt 142), collections of the Hungarian National Geological Institute, Budapest.
Locality and Horizon. Miocene (Helvetian), Prisaca, Putna, Rîpa Porcului, Romania.
Dimensions. Holotype: see Kordos and Prakfalvi, 1990, tab. 1.
Figured Specimens. (a.) Specimen V94021/272 (Pl. 5, Fig. 6); (b.) Specimen V94021/278 (Pl. 6). Lodged in the Raymond M. Alf Museum of Paleontology, Claremont, California.
Locality and Horizon. Avawatz Formation, Miocene (Clarendonian), Avawatz Mountains, San Bernardino County, California.
Dimensions of Figured Specimens. See scales on plates.
Interdigital Angles. See Fig. 7.
Discussion. The specimens collected by Raymond M. Alf and his students from the Webb Schools include a plethora of avian imprints, most of which accord with *Carpathipeda vialovi*. The flexibility of the digits and the variations of substrate hardness combine to cause a considerable variation in the interdigital span and interdigital angles (see Fig. 7), but the relative uniformity in digit length, the slenderness of the claws and the fact that they are almost aligned with the digit axes are consistent features. No examples have been reported of all three digits being in proximal contact, but digits II and III sometimes just touch.

Avian footprints of this type have been illustrated from the Eocene of Utah (Curry, 1957) and of south-western France (Plaziat 1964); the Tertiary of Navarre, Spain (Mangin, 1962); the Oligocene (Chattian) of Switzerland (de Clerq and Holst, 1971); and the early Miocene (Helvetian) of Romania (Kordos and Prakvalfi, 1990).

These footprints are, as Weidmann and Reichel (1979) pointed out, certainly those of wading birds. They indicated the Common Sandpiper (*Tringa hypoleucos*) as possible trackmaker: the illustration of the tracks of the Dunlin or Red-backed Sandpiper (*Erolia alpina*) by Jaeger (1948, p. 142) also accord closely with the morphology of *A. vialovi*. It is most likely that the tracks were made by birds comparable in foot structure and habits, and quite probably related, to the living sandpipers.

Ichnogenus *Ornithotarnocia* Kordos, 1985, emend.

1985 *Ornithotarnocia* Kordos, pp. 269, 362-363.
Original Diagnosis. "Bird print of medium size consisting of three toes. Biggest is the print of the middle toe, widening gradually towards the proximal third and having a pointed end. The following is the print of the outer toe, its morphology is similar to the middle one. The inner toe is variable, funnel-shaped. The three toe-prints are approximately symmetrical." (Kordos, 1985, p. 363).
Emended Diagnosis. Avian footprint of moderate to large size, composed of three digital impressions. Digital impressions broad, tapering, without distinct digital pads or interpad spaces and without distinct claws. Central digit (III) longest, characteristically more than 25% longer than the lateral digits (II and IV). Total digital span-exceeds 95°. Digits united proximally, but without a distinct metatarsal pad.
Type Species. *Ornithotarnocia lambrechti* Kordos, 1985. Early Miocene, Hungary.
Discussion. A combined generico-specific diagnosis was originally presented; it is emended to facilitate comparison with those of other avian ichnogenera. *Ornithotarnocia* differs from *Fuscinapeda* Sarjeant and Langston, 1994 in having thicker digits, without indication of claws (though these are not always clear in *Fuscinapeda*) and without a "heel" formed by the metatarsal pad. It differs from most other avian footprint ichnogenera in the wide spread of the digits, their greater thickness and their lack of claws.

Ornithotarnocia lambrechti Kordos, 1985

Plate 7; Figures 8, 9.
1985 *Ornithotarnocia lambrechti* Kordos, p. 269-276, 363-364: figs. 1-4, pls. I-II: tabs. 4-6.
1987 *O. lambrechti* Kordos: Kordos, p. 456, text-fig. 2 nos.

Plate 7. Ornithotarnocia lambrechti *Kordos. Slab A500-8159 (SBCM 1.137.1) showing one complete and one incomplete footprint cast.*

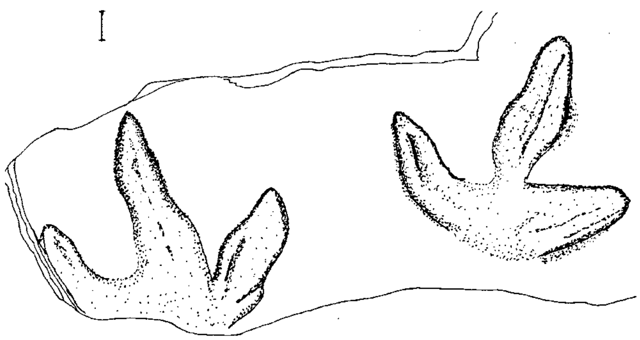


Figure 8 Ornithotarnocia lambrechti *Kordos. Interpretative drawing of the Californian specimen. [Scale bar = 1 cm].*

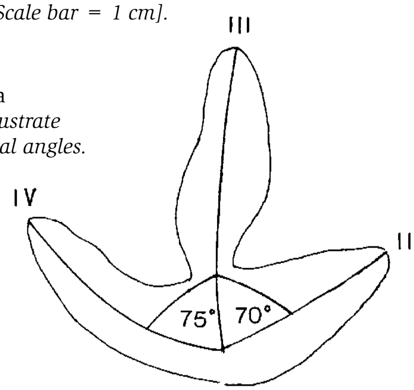


Figure 9 Ornithotarnocia lambrechti. *Sketch to illustrate digit axes and interdigital angles.*

106, 260-264.
Diagnosis. As original diagnosis of ichnogenus.
Holotype. Footprints 9 and 12 on slab V.12721, Palaeovertebrate Collection, Hungarian Geological Institute, Budapest.
Horizon and Locality. Ipolytarno Beds, Early Miocene (Helvetian), Ipolytarnóc, Nógrád County, northwest Hungary.
Dimensions. Type material: see Kordos 1985, tab. 5.
Figured Specimen. A500-8159, San Bernardino County Museum, Redlands, California (Pl. 7, Fig. 8).
Horizon and Locality. Boron Open Pit Mine, San Bernardino County, California, SBCM 1-137-1.
Dimension. Figured specimen: Length of pes 84 mm, breadth overall 87 mm. Length of digits: II, 44 mm; III, 60 mm; IV 33 mm. Maximum thickness of digits: II, 15 mm; III, 21 mm; IV, 25 mm (based on the specimen at right on Fig. 8).
Interdigital Angles. See Fig. 9.
Remarks. Kordos (1985) presented a very detailed analysis of the morphology of *O. lambrechti*, demonstrating a high degree of morphological variation in the imprints. The California specimen falls within the range of morphologies that Kordos illustrates on his text-fig. 1. He did not suggest a potential trackmaker. The combination of lobed toes and the possibility of proximal webbing suggests the Grebe family (Podicipedidae).

Morphofamily Gruipedidae Sarjeant and Langston, 1994, emend. 1994

Gruipedidae Sarjeant and Langston, p. 8.
Original Diagnosis. "Avian footprints showing four digits, three of which (II to IV) are directed forward and the fourth (I) directed posteriorly, its axis either coinciding with, or at an angle to, that of digit III. Digits united or separated proximally. Webbing absent or limited to the most proximal part of the interdigital angle."
Emended Diagnosis. Avian footprints showing four digits, three of which (II to IV) are directed forward and the fourth (I) directed posteriorly, its axis either coinciding with, or at an angle to, that of digit III. Claws may be distinguishable, but the digits give no indication of digital pads or interpad spaces: the metatarsal pad is most often not impressed. Digits united or separated proximally. Webbing absent or limited to the most proximal part of the interdigital angle.
Type ichnogenus. *Gruipeda* Panin and Avram 1962, emend. Sarjeant and Langston 1994.
Remarks. The ichnogeneric diagnosis is emended to clarify the feature serving as distinction between this family and the Family Ignotornidae Lockley *et al.*, 1992 — the indication of pads and interpad spaces in the footprints of the latter family.

Ichnogenus *Gruipeda* Panin and Avram, 1962, emend. Sarjeant and Langston, 1994

Emended Diagnosis. "Avian footprints showing four digits, three of which are large and directed forward, the fourth, spur-like and short, directed backward. The interdigital angles between digits II and III and between digits III and IV are less than 70°. The axis of digit I does not correspond with that of digit III, the interdigital angle between digits I and II being greater than that between digits I and IV. Webbing absent." (Sarjeant and Langston, 1994, p. 8).
Type Species. *Gruipeda maxima* Panin and Avram, 1962, emend. Sarjeant and Langston, 1994. Miocene, Romania.
Discussion. The genus *Pluchraviipes* Demathieu *et al.* (1984) differs from *Gruipeda* in that its interdigital angles (II-III and III-IV) both approach 90 degrees, imparting a "t" shape to the three digits, from the center of which the halux is directed obliquely.
Included Species. Gruipeda diabloensis Remeika, 1999, Pliocene, Anza-Borrego Desert State Park, California.

Gruipeda becassi (Panin and Avram, 1962) Sarjeant and Langston, 1994, emend.

Plate 8; Figures 10, 11
1962 *Charadriipeda becassi* Panin and Avran, p. 467, pl. 9 fig. 30.
1964 *Gruipeda becassi* (Panin and Avram) Sarjeant and Langston, p. 8
1992 *Koreanornis* Lockley *et al.*, 1972
Original Diagnosis. "Footprints comparable to those of the [living] snipe" (new transl.)
Emended Diagnosis. Avian footprints showing four digits, three (II-IV) directed forward and large, the fourth (I) large, directed backward and of moderate length. The digits are robust and rather blunt-tipped, with indication of pads but without distinct claws. Digit III is longest, digit IV almost as long and digit II somewhat shorter than III; the available portion of the impression of digit I is almost one-third the length of digit III and oriented 180° to it. Interdigital angles: II-III, 70°: III-IV, 50°. The digits were flexible, sometimes curving (digit IV especially so); they might be proximally united by a metatarsal pad, when digit I is at an angle of almost 90° to digit II, or might not be united, in which case the axis of digit I may be in line with digit III. Webbing is lacking.
Holotype. The specimen illustrated by Panin and Avram, p. 1.9 fig. 30; lodgement not indicated.
Horizon and Locality. Miocene (Helvetian), Prisaca-Putna,

Plate 8. Gruipeda becassi *(Panin and Avram) . V94272/200, a single footprint.*

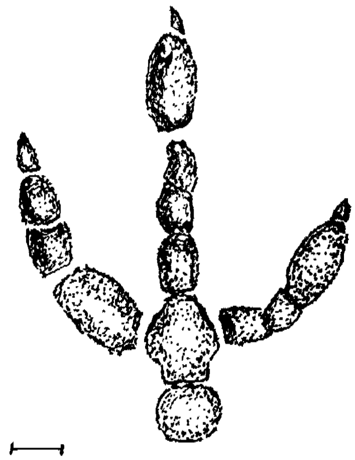


Figure 10 Gruipeda becassi *Sarjeant and Reynolds, emend. Interpretative drawing of a track associated with* Amphicyon *tracks at the Raymond Alf Museum. [Scale bar = 1 cm].*

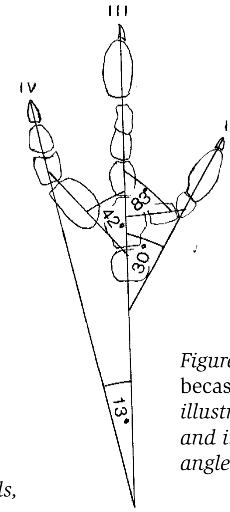


Figure 11. Gruipeda becassi. *Sketch to illustrate digit axes and interdigital angles.*

Rîpa Porcului, Romania.
Dimensions. Holotype: length of digit I, sic 38-30 mm: II, 30 mm; III, 40 mm: IV, 31–33 mm. [NOTE: Panin and Avram quote the length of digit I as 38–30 mm but, since their illustrations show it to be only half the length of digit II, this must be an error. Digit I of the specimen figured herein measures 18 mm].
Interdigital Angles. See emended diagnosis.
Figured Specimens. Bird footprints on large slab with amphicyonid tracks (specimen V94272/200; Pl. 8), Raymond M. Alf Museum of Paleontology, Claremont, California.
Horizon and Locality. Barstow Formation, Miocene (Barstovian), Mud Hills, San Bernardino County, California.
Dimensions. Figured specimens: see scale on Plate 8.
Discussion. The carnivore footprints on the large slab, on which these footprints are to be seen, were described by Alf (1966); however, no mention was made of the avian footprints. Though they were not considered sufficiently clear to be drawn in detail, they accord with *Gruipeda becassi* closely enough to be attributed confidently to that ichnospecies. Buccheim *et al.* (1999) picture tracks from the Pliocene that might be similar to *G. becassi*.

The digit curvature to be noted in some footprints (*e.g.*, that at lower left in Pl. 8) is seen also on the Romanian holotype slab (at lower center, Panin and Avram pl. 9 fig. 30). Those authors attributed it to the plasticity of the casting medium. However, since it was a fine sandstone, we consider this explanation unlikely and believe instead that it resulted from the flexibility of the digits, seen also in Panin and Avram's (1962, text-fig. 12) drawing of footprints of the snipe (*Gallinago gallinago*). In particular, the shifting position of digit I, relative to the other digits, may be noted both in that sketch and in the fossil footprints from Romania and California. The imprints are too robust for those of a snipe. They are similar to but smaller than those of an eagle (Chase, 1969; Murie, 1954) and might be attributable to an owl (Strigidae) or hawk (*Buteo* sp.).

Ichnogenus *Alaripeda* Sarjeant and Reynolds, nov.

1986 *Avipeda* sp. D. Scrivner and Bottjer, p. 295, fig. 3D.
Diagnosis. Avian footprints showing three or, often, four digits. The central digit (III) is directed forward, but may curve quite sharply; digit I is short, less than half the length of digit III, often oriented reverse of the axis of digit III but sometimes deviating up to 20°. The other digits (II and IV) are directed laterally and may also curve. Digits united or separate proximally. Length of digit III comparable to (or less than 25% greater than) that of digits II and IV. Webbing lacking; no indication of a metatarsal pad.
Derivation of Name. L., *alaris*, of wings: *peda*, foot, in reflection of the overall footprint shape.
Type Species. *Alaripeda lofgreni* Sarjeant and Reynolds, nov., Miocene, California.
Discussion. The impressions of digits II and IV are directed laterally, rather than forward or backward, distinguishing this ichnogenus from all other tridactyl ichnogenera. Although only one species is currently recognized, separating the ichnogeneric diagnosis from that of the ichnospecies will facilitate comparisons with other ichnogenera.

Alaripeda lofgreni Sarjeant and Reynolds, nov.

Plate 9; Figures 12, 13

Diagnosis. Avian footprints of small size, showing four digital impressions, the three larger curving forward; digit III directed forward and inward toward the track axis. Digit I very short, sometimes not imprinted and oriented reverse of axis of Digit III. Digits II and IV oriented laterally. All digits are slender and, though acuminate, lack distinct claws. Digital pads are not distinguishable and webbing is lacking. Digit III is shorter, and curves more strongly, than the lateral digits. Digit I is less than half the length and breadth of Digit III. The digits are united proximally, in a position slightly forward of the backward curve of the lateral digits. No metatarsal pad is present. Imprint Digit I present in 80% of the tracks. Trackway narrow; stride moderate.
Holotype. Slab with five complete and three partial footprint impressions (Pl. 9, Fig. 12): specimen no. V.94285/201, Raymond M. Alf Museum of Paleontology, Claremont, California.
Derivation of Name. Honoring Donald Lofgren (Director of

Plate 9. Alaripeda lofgreni *Sarjeant and Reynolds, nov. The holotype slab V94285/201, showing six complete and two partial footprint molds.*

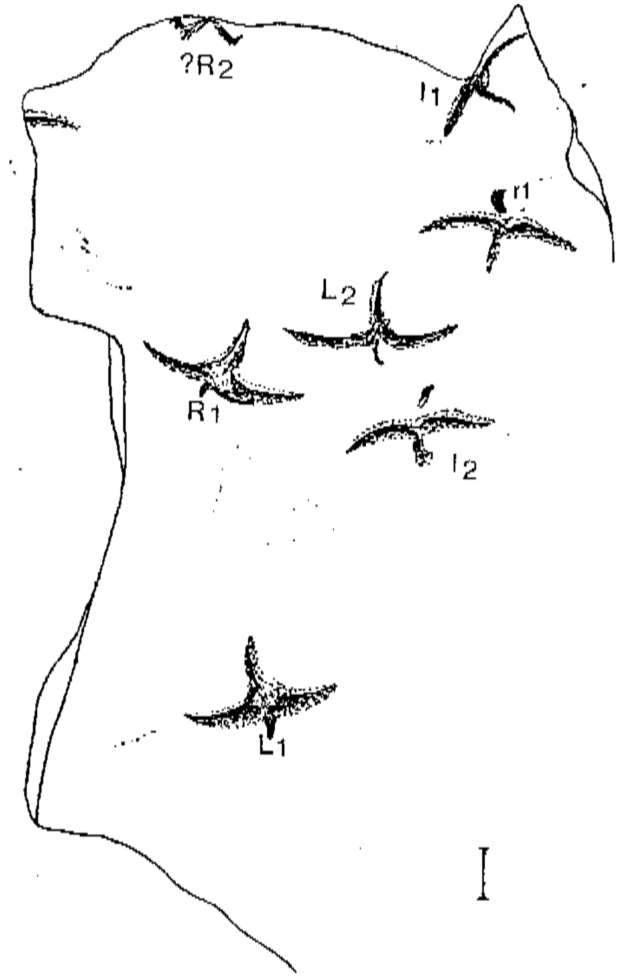
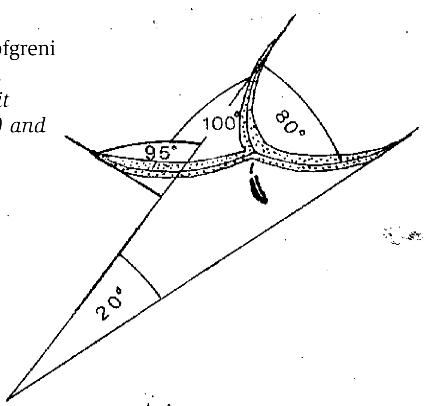


Figure 12. Alaripeda lofgreni *Sarjeant and Reynolds,* ichnogen. et sp. nov. *Interpretative drawing of the holotype slab. [Scale bar = 1 cm].*

Figure 13. Alaripeda lofgreni *Sarjeant and Reynolds. Sketch to illustrate digit axes (strongly curving) and interdigital angles.*



the Raymond M. Alf Museum of Paleontology), in gratitude for his generous assistance to our research.
Locality and Horizon. Miocene, California (not precisely located). However, similar tracks (*Avipeda* sp. D, Scrivner and Bottjer, 1986) and matrix occur at Copper Canyon in Death Valley and suggest a late Miocene (Hemphillian) age (Scrivner and Bottjer, 1986).
Dimensions. Stride up to 65 mm, pace up to 70 mm. Length of pes 18 mm, breadth 34 mm. Length of digits: II, 13.5 mm; III, 12 mm; IV, 13.5 mm (approximate averages of five impressions).

Divarication of Digits. See Fig. 13.
Discussion. Though this slab is not precisely localized, the unique character of the footprints causes us to feel them worthy of erection as a new ichnotaxon. The literature presents no illustrations of similar footprints of this small shorebird. Compare illustrations in Scrivner and Bottjer (1986) and Santucci and Nyborg (1999).

Morphofamily Anatipedidae Sarjeant and Langston, 1994

1962 Anatipedae Panin and Avram, 173, *nomen nudum*.
1994 Anatipedidae Sarjeant and Langston, 17.
1994 Charadriipedidae Sarjeant and Langston, 11.
Diagnosis. Avian footprints showing four digits, three of which (II to IV) are directed forward, the fourth (I) directed posteriorly, its axis either coinciding with, or at an angle to, that of digit III. Digits I to IV are united proximally and linked by webbing; digit I may be united to the others or separate.
Type Genus. *Anatipeda* Panin and Avram, 1962, emend. Sarjeant and Reynolds, nov.
Discussion. When erecting the Family Charadriipedidae, Sarjeant and Langston (1994) selected *Charadriipeda recurvirostrioidea* Panin and Avram as its type species, believing this to exhibit only three forwardly directed digits. Panin's later revision (1965, p. 145; fig. 1), in which he demon-

strated that this ichnospecies (illegitimately renamed *C. recurvirostra*) shows a fourth, posteriorly directed digit I, undermines the distinction between the genera *Charadriipeda* and *Anatipeda*: moreover, it makes nonsense of the differentiation of the two families. Abandonment of the family name "Charadriipedidae" is therefore proposed. Emendations of the genera *Charadriipeda* and *Anatipeda* are outlined below.

Ichnogenus *Charadriipeda* Panin and Avram, 1962, emend. nov.

1962 *Charadriipeda* Panin and Avram, p. 465-467.
1994 *Charadriipeda* Panin and Avram emend. Sarjeant and Langston, p. 11.

Emended Diagnosis. Avian footprints showing four digits, three of which (II to IV) are large and directed forward, the fourth (I) directed backwards, short and spur-like; it is not always imprinted. The central digit III is much longer (typically more than 25%) than the lateral digits (II and IV); the interdigital angles separating it from them are around 70° (allowing for curvature). Digits II-IV are united proximally and linked by webbing almost to their tips: digit I may be united to the others or separate. Digits acuminate or bearing claws.

Type species. *Charadriipeda recurvirostrioide*a Panin and Avram, 1962, emend. Sarjeant and Langston, nov. Miocene, Romania.

Discussion. The diagnosis is emended to stress the length of the central digit (III), the feature serving to distinguish this genus from *Anatipeda*.

Charadriipeda recurvirostrioidea Panin and Avram, 1962, emend. nov.

Plate 10

?1957 Track of a web-footed bird. Curry, fig. 5.
1962 *Charadriipeda recurvirostroidea* Panin and Avram, p. 465-466, pl. 7 fig. 26, pl. 8, fig. 27.
1965 *Charadriipeda recurvirostra* Panin, p. 145, pl. 4 figs. 9-10; text-fig. 1, *nomen nudum*.
1994 *Charadriipeda recurvirostrioidea* Panin and Avram, emend. Sarjeant and Langston, p. 11-12.

Emended Diagnosis. Avian footprints of small size, having three digits (II-IV) directed forwards and a fourth (I) directed backward, connected to the other digits proximally. The central digit (III) is more than 25% longer than the lateral digits (II and IV); these diverge from it at angles less than 70° (allowing for curvature), the angle between III and IV being greater than that between II and III. Webbing links digits II-IV. The axis of the short digit I diverges at a sharp angle (approaching 90°) from that of digit II and is almost in line with the axis of digit IV. Trackway narrow; stride long.

Holotype. The specimen figured by Panin and Avram (1962, pl. 7 fig. 26). Lodgement not stated.

Horizon and Locality. Miocene (Helvetian), Prusaca-Putna, Ripa Porcului, Romania.

Dimensions. Holotype: overall length 18 mm. Length of digits: II, 13 mm; III, 27 mm; IV, 20 mm.

Divarication of Digits. Not stated by Panin and Avram (1962). Sarjeant and Langston (1994, p. 12) considered II-III as 45°, III-IV as 55° on the holotype. In the specimen figured by Panin (1965, text-fig 1), I-II is ca 90°, IV-I almost 180°.

Figured Specimen. V94021/270 (Pl. 10), Raymond M. Alf Museum of Paleontology, Claremont, California.

Horizon and Locality. Avawatz Formation, Miocene (Clarendonian), Avawatz Mountains, San Bernardino County, California.

Dimensions. Figured specimen: overall length ca. 90 mm, breadth ca. 60 mm. Length of digits: II, 44 mm; III, 76 mm; IV, c. 49 mm. Digit I not clearly discernible.

Discussion. The single Californian specimen consists of one relatively good impression (at lower left in Pl. 10) and one incomplete specimen (upper center on Pl. 10). Unfortunately, even the better specimen is marred by other sedimentary structures and can not be accurately figured. Both specimens are larger than the holotype but, in other respects, closely comparable. Panin and Avram (1962, p. 465-466, compare the footprints with those of extant avocets (*Recurvirostridae*).

Genus *Anatipeda* Panin and Avram, 1962, emend. nov.

1962 *Anatipeda* Panin and Avram, 1962, p. 467
1994 *Anatipeda* Panin and Avram, emend. Sarjeant and Langston, p. 17-18.
1995 *Presbyorniformipes* Lockley and Hunt, fig. 6.9 (in caption), nomen nudum

Emended Diagnosis. Avian footprints showing four digits, three of which (II to IV) are large and directed forward, the fourth (I) directed backwards, short and spurlike; it is not always imprinted. The three principal digits (II-IV) are of fairly uniform size; the interdigital angles separating them are around 70° (allowing for curvature). Digits II–IV are united proximally and linked by webbing, almost to their tips; digit I may be united to the others or separate. Digits acuminate or bearing claws.

Type Species. *Anatipeda anas* Panin and Avram, 1962, emend. Sarjeant and Langston, 1994, p. 17-18. Miocene (Helvetian), Romania.

Discussion. The ichnogeneric diagnosis is emended to clarify the distinction from the emended *Charadriipeda, i.e.*, the more uniform size of digits II-IV. The name *Presbyorniformipes* Lockley and Hunt was published with neither a description nor the citation of any previously published description, in contravention of Act. 13(a) of the *International Code of Zoological Nomenclature* (Ride *et al.*, 1985), and is thus invalid; moreover, its morphology (as illustrated

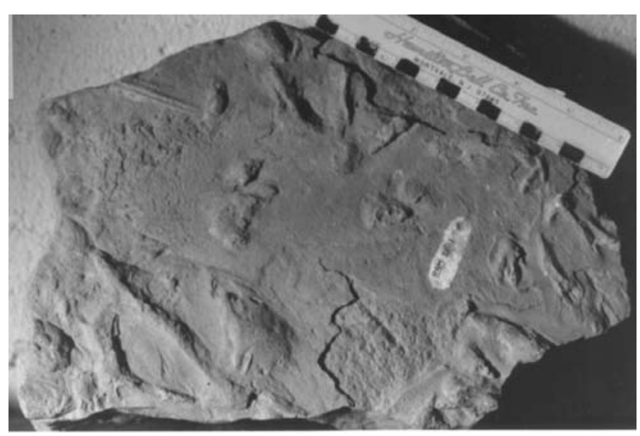


Plate 10. Charadriipeda recurvirostrioidea *Panin and Avram, emend. nov. A relatively complete cast is seen at lower left, parts of other casts at lower right and top centre. The slab, V94021/270, also shows prod-marks and imperfect footprints of other kinds.*

Plate 11. Anatipeda californica *Sarjeant and Reynolds, nov. The holotype, V94021/115, a cast of a left pes.*

by Erickson, 1967 Pl. 1 and Fig. 1; and by Lockley and Hunt 1995, fig. 6.9) presents no clear differences from *Anatipeda*.

Anatipeda californica Sarjeant and Reynolds, nov.

Plate 11, 12; Figures 14, 15

Diagnosis. Avian footprints of small to moderate size, having three digits (II-IV) directed forwards and a fourth (I) directed backwards, without proximal connection to the other digits. The three principal digits (II to IV) are of comparable length; the interdigital angle separating II from III is smaller than that between III and IV. Webbing links these digits, its anterior edge forming two catenary curves between the bases of the claws on those digits. These claws, though slightly curving, are essentially in line with the digit. The digits themselves are of moderate thickness; a metatarsal pad links their bases and each digital impression is interrupted three or more times at the positions of spaces between digital pads. The axis of the short digit I diverges strongly (at around 95°) from that of digit II and is almost in line with the axis of digit IV. Trackway moderately broad; stride short.

Plate 12. Anatipeda californica *Sarjeant and Reynolds, nov. The paratype, V94021/269, a cast of a right pes.*

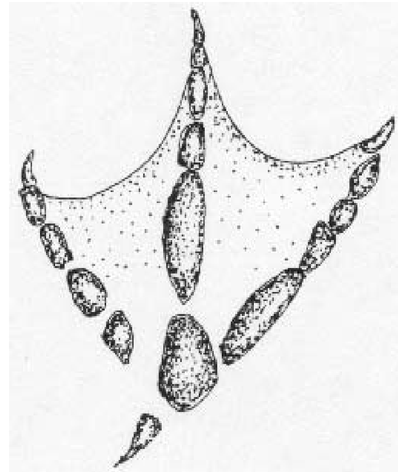


Figure 14. Anatipeda californica *Sarjeant and Reynolds,* ichnosp. nov. *Interpretive drawing of the holotype.*

Derivation of Name. L. *californicum*, of California.

Type Species. Holotype: Cast of left pes: V.94021/115, (Pl. 11, Fig. 14). Paratype: cast of right pes: V94021/269 (Pl. 12). Raymond M. Alf Museum of Paleontology, Claremont, California.

Horizon and Locality. Avawatz Formation, Miocene (Clarendonian), Avawatz Mountains, San Bernardino County, California.

Dimensions. Holotype: length (from tip of digit III to tip of digit I) 84 mm, maximum breadth 70 mm. Length of digits: I, ca. 11 mm; II, 46 mm; III, 55 mm; IV, 54 mm. Maximum breadth of digits: I, 4 mm; II, 7 mm; III, 7 mm; IV, 6.5 mm. Paratype: length 63 mm (digit I not indicated), maximum breadth 73 mm. Length of digits: II, 44 mm; III, 50 mm; IV, 48 mm. Breadth of digits: II, 6 mm; III, 6.5 mm; IV, 5.5 mm.

Divarication of Digits. See Fig. 15 and diagnosis.

Discussion. The paratype was chosen as an example of a footprint in which digit I is not indicated: in all other respects, it accords with the holotype. *Anatipeda californica* differs from *A. anas* Panin and Avram in the greater thickness and lesser length of its digits and in having webbing with a cateniform anterior margin. As Sarjeant and Langston noted (1994, p. 17): "Footprints of this nature may be made by members of the Pelecaniformes (pelicans and allies),

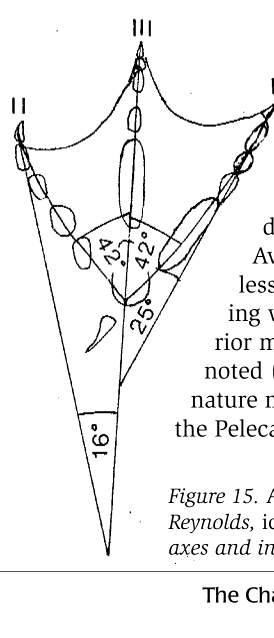


Figure 15. Anatipeda californica *Sarjeant and Reynolds,* ichnosp. nov. *Sketch to illustrate digit axes and interdigital angles.*

Plate 13. Anatipeda alfi *Sarjeant and Reynolds, nov. The holotype slab, V94021/111, showing four footprint casts: those at left are the holotype specimens.*

Phoenicopteriformes (flamingos) and Anseriformes (ducks, geese and swans)."

Anatipeda alfi Sarjeant and Reynolds, nov.

Plates 13, 14, 15; Figures 16, 17

Diagnosis. Avian footprints of small to moderate size, having three digits (II-IV) directed forwards and a fourth (I) directed backwards, without proximal connection to the other digits. The three principal digits (II-IV) are of comparable length: the interdigital angle separating II from III is smaller than that between III and IV. Webbing links these digits, its anterior edge forming only a slight curve between the bases of the claws on those digits. Claws straight, those of digits II and IV in line with the digit axis, that of digit III directed outward. The digits themselves are quite thick: a metatarsal pad links their bases, but this (along with digit I) is not always impressed. The digits show interruptions at the positions of interpad spaces: in digits II and III, there may be only one such division; in digit IV, at least two. The axis of the short spur-like digit I diverges strongly (at around 90°) from that of digit II and is almost in line with the axis of digit IV. Trackway moderately broad; stride short.

Plate 14. Anatipeda alfi *Sarjeant and Reynolds, nov. Cast of single footprint, V94021/113, a left pes.*

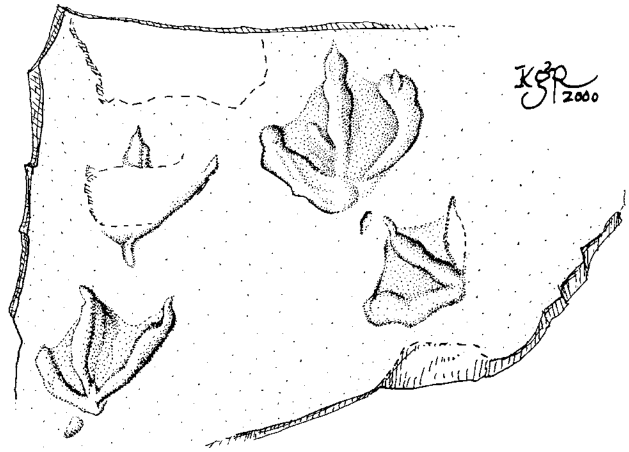


Figure 16. Anatipeda alfi *Sarjeant and Reynolds,* ichnosp. nov. *Interpretative drawing of the holotype slab.* K.G. Reynolds drawing.

Derivation of Name. After Raymond M. Alf, who either collected or sponsored the acquisition of the fine palaeoichnological collection now housed in the Museum that bears his name.

Type Material. Holotype (casts of right and left pedes): V94021/111 (Pl. 13, at left; Fig. 16), *Figured Specimens*: V94021/113 (cast of left pes: Pl.14): V94021/112 (adjacent casts of left and right pedes: Pl. 15) Raymond M. Alf Museum of Paleontology, Claremont, California.

Horizon and Locality. Avawatz Formation, Miocene (Clarendonian), Avawatz Mountains, San Bernardino County, California.

Dimensions. Holotype: length of left pes (from tip of digit I to tip of digit III), 76 mm; maximum breadth 66 mm. Length of digits: I, 12 mm; II, 40 mm; III, 48 mm; IV, 48 mm. Maximum breadth of digits: I, 3.5 mm; II, 8.5 mm; III, 9 mm; IV, 9 mm. (Right pes similar). Range of dimensions (based on figured specimens and four others measured): length of pes (from base of metapodium to tip of digit III) 58–70 mm, maximum breadth 66-83 mm; length of digit II,

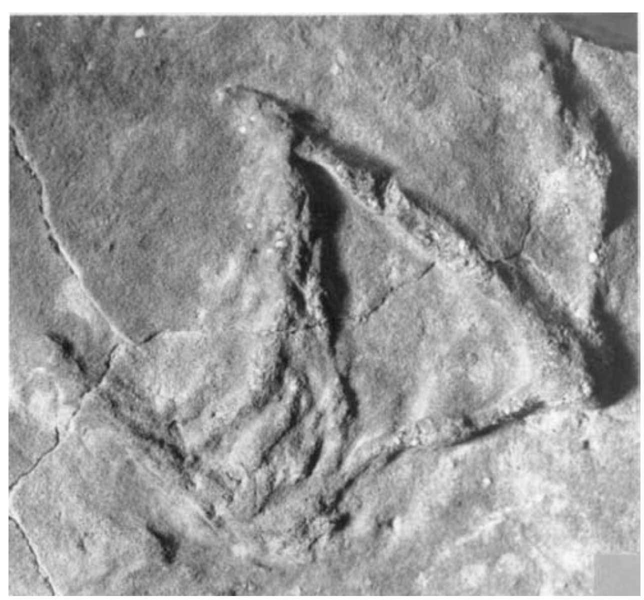


Plate 15. Anatipeda alfi *Sarjeant and Reynolds, nov. Adjacent casts, V94021/112, of left and right pedes.*

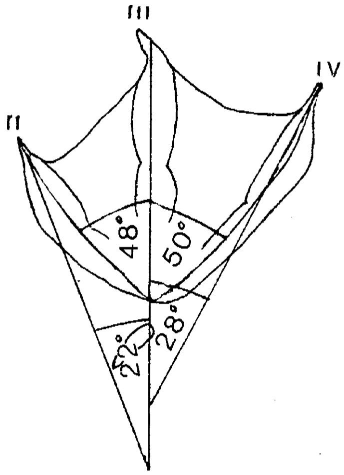


Figure 17. Anatipeda alfi *Sarjeant and Reynolds. Sketch to illustrate digital axes and interdigital angles.*

40–46 mm: III, 48-50 mm: IV, 47–50 mm, breadth of digit II, 4–8.5 mm: III, 6-9 mm: IV, 5–9 mm.

Divarication of Digits. See Fig. 17 and diagnosis.

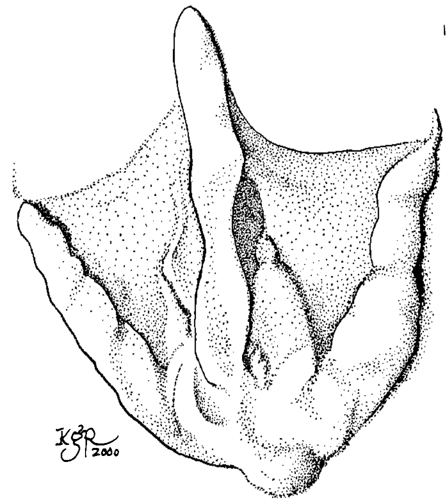
Discussion. These footprints resemble in general features those illustrated from the Green River Formation (Eocene) of Utah by Erickson (1967), and reillustrated by Lockley and Hunt (1995, figs. 6.8, 6.9) under the invalidly published name *Presbyorniformipes feducci*. However, they differ in the lesser separation of digit I from the main footprint (the impression of digits II–IV), the less arcuate posterior margin of the main footprint (with a more distinct metapodium) and a lesser proportionate breadth. They differ from *A. californica* in having thicker digits and a different anterior web outline. (For discussion of affinities, see under *A. californica*).

?*Anatipeda* sp.

Plate 16; Figures 18, 19

?1956 Goose footprint. Wetmore, Fig. 1.

Plate 16. ?Anatipeda *sp. Cast of left pes, V94021/274, incomplete.*



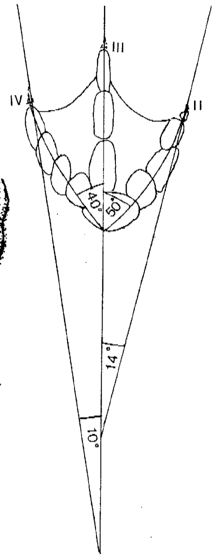


Figure 18 (above). ?Anatipeda *sp. Interpretative drawing: the broken lines indicate the presumed positions of claws.* K.G. Reynolds drawing.

Figure 19 (above right). ?Anatipeda *sp. Sketch to illustrate digital axes and interdigital angles.*

Description. Avian footprint of large size, apparently tridactyl (II-IV), with thick digits linked proximally to a metapodium. All digits appear clawed. The central digit (III) is somewhat longer than the lateral digits, by a factor of less than 20%. Webbing unites the digits up to about the middle of the most anterior digital pad, the webbing's anterior margin forming two catenary curves. Digit II is markedly closer to digit III than is digit IV: the interdigital angles do not exceed 50 . All digits exhibit interpad spaces. Posterior margin of imprint a hemiellipsoid.

Figured Specimen. Cast of left pes, V94021/274 (Pl. 16, Fig. 18), Raymond M. Alf Museum of Paleontology, Claremont, California.

Horizon and Locality. Avawatz Formation, Miocene (Clarendonian), Avawatz Mountains, San Bernardino County, California.

Dimensions. Figured specimen (Pl. 16, Fig. 18): length 113 mm (exclusive of claw), maximum breadth 103 mm. Length of digits: II (without claw), 73 mm; III (without claw), 88 mm; IV with claw 72 mm, without claw 57 mm. Maximum breadth of digits: II, 18 mm; III, 18 mm:; IV, 18 mm.

Discussion. This single large avian footprint, the largest in the assemblage from the Avawatz Formation, is on a slab which, frustratingly, has been broken at both front and rear. Consequently, a claw is seen only on the impression of digit IV and it cannot be confirmed whether digit I was impressed. The generic placement is thus provisional and conceivably this specimen could be in the Avipedidae.

There is strong resemblance to the "goose footprint" figured from the Pliocene of Louisiana by Wetmore (1956). However, the digits of the latter do not exhibit interpad spaces.

Ichnofamily Culcitapedidae Sarjeant and Reynolds, nov.

Diagnosis. Avian footprints whose tridactyl character is evident only by forward prolongations (sometimes inconspicu-

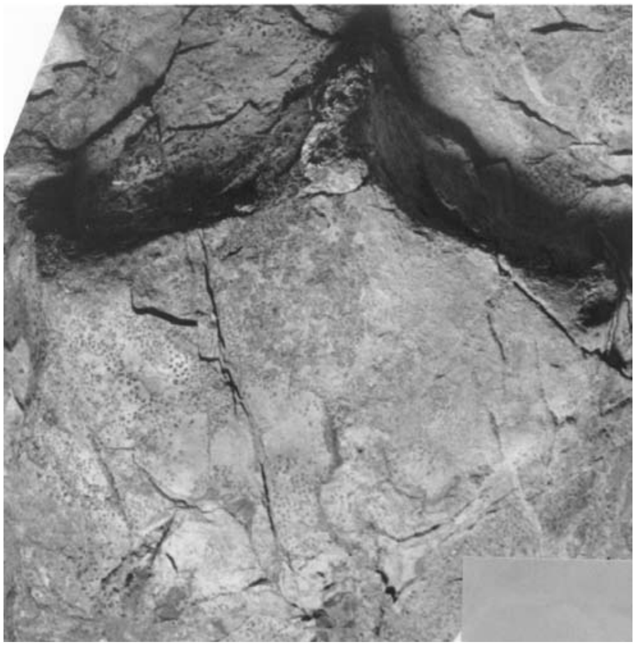


Plate 17. Culcitapeda ascia *Sarjeant and Reynolds, nov. Holotype (cast of right pes), A500-8177 (SBCM 1.36.7).*

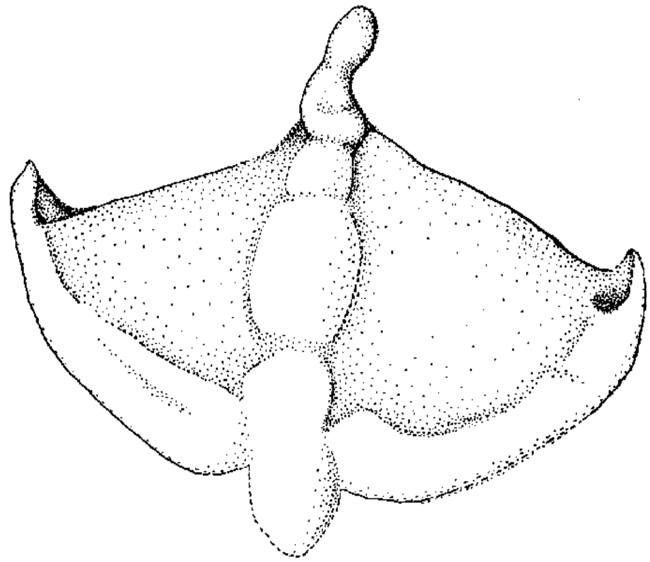


Figure 20. Culcitapeda ascia *Sarjeant and Reynolds, ichnogen. et sp. nov. Interpretative drawing of the holotype.* K.G. Reynolds drawing.

ous) of a foot-pad or web. The footprint may show slight deepening beneath the presumed positions of the bones of the digits, but no other features of the digits are discernible.
Type Genus. *Culcitapeda* Sarjeant and Reynolds, nov. Miocene, California.
Discussion. The paucity of features indicative of pedal osteology distinguishes the members of this family from all other avian ichnotaxa.

Ichnogenus *Culcitapeda* Sarjeant and Reynolds, nov.

Diagnosis. Avian footprints whose tridactyl character is made evident only by forward prolongations (sometimes inconspicuous) from a foot-pad or web. The print showed slight deepening beneath the positions of the bones of the digits, but these are not otherwise indicated. Posterior outline of footprint semicircular or nearly so; prolongation of central digit (III) more pronounced anteriorly and posteriorly than those of the lateral digits (II and IV).
Derivation of Name. L., *culcita,* cushion; *peda*, foot.
Type Species. Culcitapeda ascia Sarjeant and Reynolds, nov. Miocene, California.
Other Species. Culcitapeda tridens Sarjeant and Reynolds, nov. Miocene, California. *Culcitapeda eccentrica* Sarjeant and Reynolds, nov. Miocene, California.
Discussion. These remarkable footprints are undoubtedly those of birds with strongly webbed feet. Flamingos have been suggested as possible trackmakers but, as Jaeger (1948, pl. 130) shows, their footprints usually are clawed, with digits more distinct and with digit I imprinted behind the main foot impression. The footprints of swans and geese do not exhibit large claws, but the digits are distinct in the footprint and digit I is also impressed (*idem*). Since these casts represent the infillings of quite deep footprints, with a strong forward slant, it is possible that digit I was lifted too high to be impressed: but the other features should have been evident.

This genus differs from *Phoenicopterichnum* Aramayo and Bianco 1987 in its lesser length, lesser degree of digital definition, and absence of a metatarsal pad. Those footprints (from the Quaternary of Argentina) were considered to be made by flamingos. The California footprints were made by a large aquatic bird; flamingo, with a fossil record in California of approximately 20 million years (Reynolds, 1998; Reynolds *et al.*, 1995), is still a consideration.

***Culcitapeda ascia* Sarjeant and Reynolds, nov.**

Plates 17, 18, 19; Figures 20, 21, 22

Diagnosis. Avian footprints of quite large size, tridactyl and very strongly webbed. Digits indicated by a strong forward prolongation, having the outline of an equilateral triangle (III), and forwardly-curving prominences arising from the

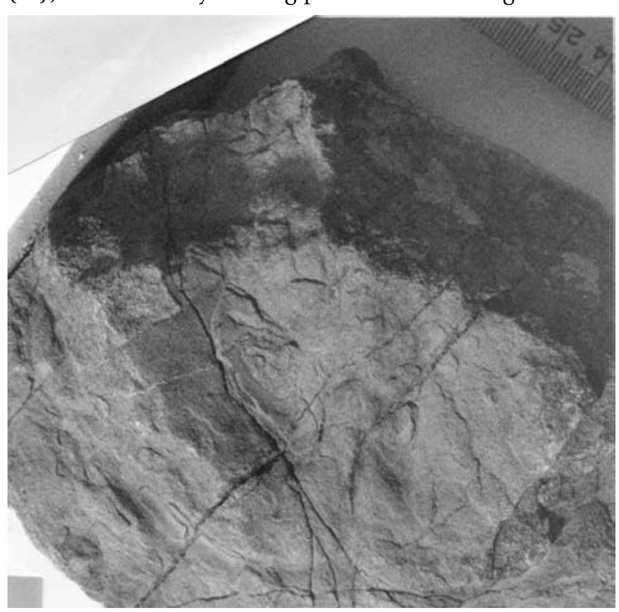


Plate 18. Culcitapeda ascia *Sarjeant and Reynolds, nov. Paratype (cast of left pes), A500-8178 (SBCM 1.36.7).*

Plate 19. Culcitapeda ascia *Sarjeant and Reynolds, nov. Cast A500-8176 (SBCM 1.36.7), damaged at side and front, showing interdigital indentations.*

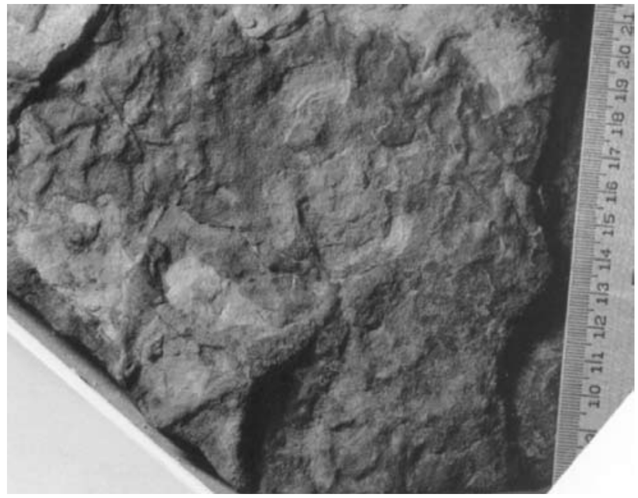


Plate 20. Culcitapeda tridens *Sarjeant and Reynolds, nov. Cast of left pes, A500-8179 (SBCM 1.36.7).*

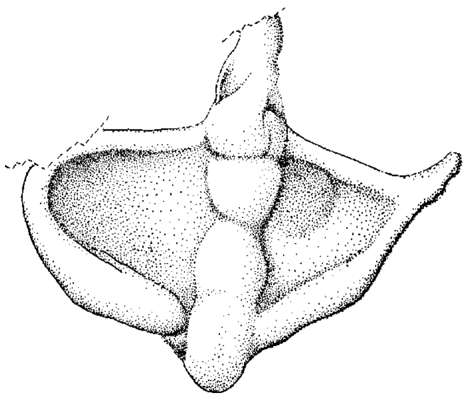


Figure 21. Culcitapeda ascia *Sarjeant and Reynolds, ichnogen. et sp. nov. Interpretative drawing of footprint on broken slab showing interdigital indentations.* K.G. Reynolds drawing.

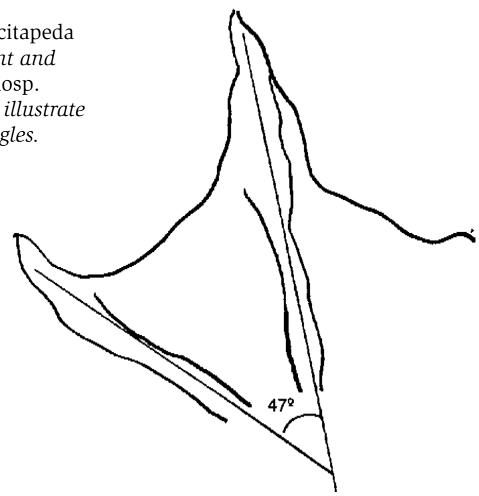


Figure 24. Culcitapeda tridens *Sarjeant and Reynolds,* ichnosp. nov. *Sketch to illustrate interdigital angles.*

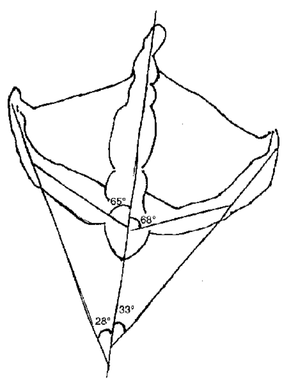


Figure 22. Culcitapeda ascia *Sarjeant and Reynolds, ichnogen. et sp. nov. Sketch to illustrate digital axes and interdigital angles.*

footprint's widest point (II and IV). The digits display minor asymmetry, one (II) being placed slightly closer to digit III than the other (IV). Posterior profile of footprint almost semicircular.
Derivation of Name. L. *ascia*, carpenter's adze; with relation to the overall shape.
Type Material. Holotype; cast of right pes (Pl. 17, Fig. 20), specimen no. A500-8177. Paratype; cast of left pes (Pl. 18): specimen no A500-8178. Cast of right pes; figured specimen (Pl. 17: specimen no. A500-8176. Lodged in the San Bernardino County Museum, Redlands, California.
Horizon and Locality. Holotype and Paratype: early Miocene, SBCM 1-36-7, Turks Mine East, Whipple Mountains, San Bernardino County, California. Figured Specimen: Miocene, SBCM 1-36-7, Turks Mine East, Whipple Mountains, San Bernardino County, California.
Dimensions. Holotype (right pes, Pl. 17): length 105 mm, breadth 115 mm. Paratype (left pes, Pl. 18): length 103 mm, breadth 113 mm. Figured Specimen (damaged; Pl. 19):

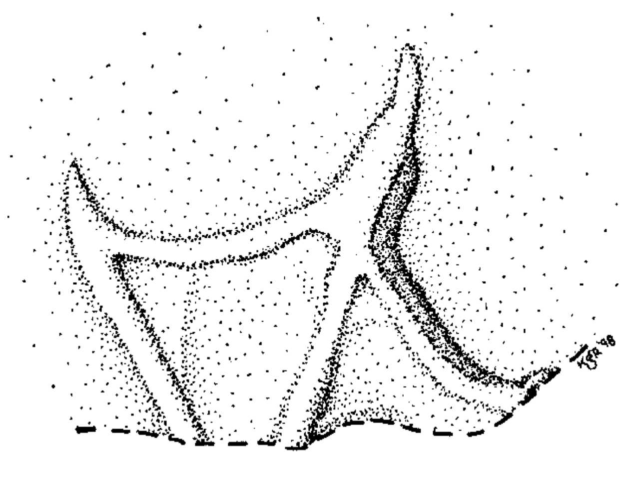
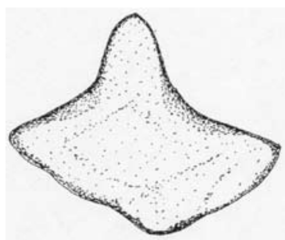


Figure 23. Culcitapeda tridens *Sarjeant and Reynolds,* ichnosp. nov. *Interpretative drawing of the holotype. [Scale bar = 1 cm].* K.G. Reynolds drawing.

Plate 21. Culcitapeda eccentrica *Sarjeant and Reynolds, nov. The holotype, A500-8163 (SBCM 1.137.1),a cast of a left pes.*

Figure 25. Culcitapeda eccentrica *Sarjeant and Reynolds, nov. Interpretative drawing of the holotype. [Scale bar = 1 cm].*



length 96 mm, breadth ~ 110 mm. Range (five specimens): length 96-110 mm, breadth 110-125 mm.
Discussion. Hollowing between digits is feeble on the type specimens, but more marked on the figured specimen. This suggests that the digits are peripheral in position, but it does not permit reliable determination of interdigital angles. (For discussion of affinity, see under ichnogenus, above).

Culcitapeda tridens Sarjeant and Reynolds, nov.

Diagnosis. Avian footprints of moderate size, very strongly webbed and tridactyl with a high degree of definition in the terminal digits. Digits indicated by a distinct, strong forward prolongation. This imparts to the footprint the outline of a slender equilateral triangle (III) with slender, forwardly-

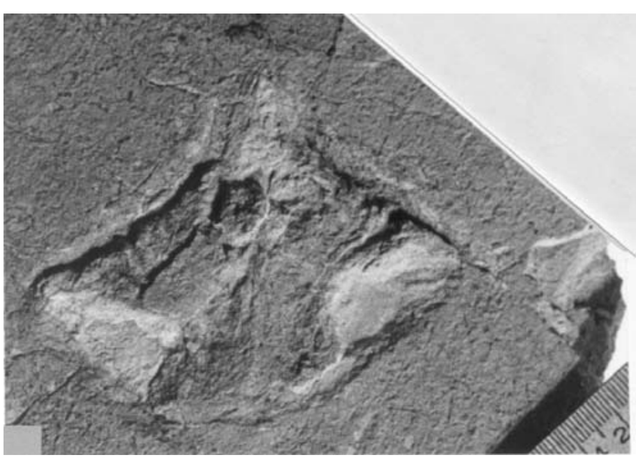


Plate 22. Culcitapeda eccentrica *Sarjeant and Reynolds, nov. The paratype, A500-8168 (SBCM 1.137.1), a cast of a right pes.*

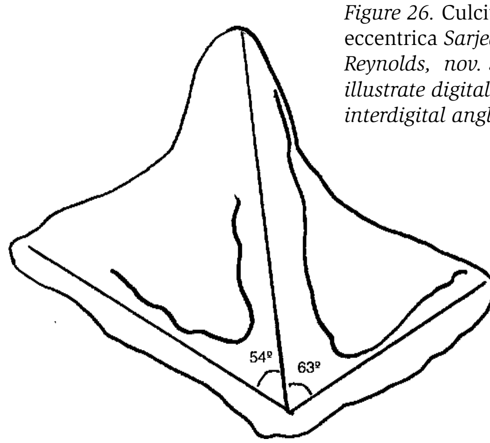


Figure 26. Culcitapeda eccentrica *Sarjeant and Reynolds, nov. Sketch to illustrate digital axes and interdigital angles.*

curving prominences arising from the footprint's widest point (II or IV). The digits display minor asymmetry, one (II) being placed slightly closer to digit III than the other (IV). Posterior profile of the footprint was not imprinted.
Derivation of Name. L., *tridens*, a fork with three tines.
Type Material. Holotype: cast of right pes (Pl. 20), specimen no. A500-8179. Lodged in the San Bernardino County Museum, Redlands, California.
Horizon and Locality. Holotype and figured specimen: early Miocene, SBCM 1-36-7, Turks Mine East, Whipple Mountains, San Bernardino County, California.
Dimensions. Holotype and figured specimen (right pes): length 61 mm, incomplete; breadth 82 mm, incomplete.
Discussion. The imprint of *C. tridens* is 30% smaller than that of *C. ascia*. Hollowing between digits is strong. The anterior margin of web is not at 90º to digit III, but runs posteriorly from digit III to the lateral digits. Digit III extends noticeably anterior to the lateral digits a distance of approximately 40% of the length of the foot. The impression of the terminal phalanges is strong and slender and much longer than those in *C. eccentrica*. *C. eccentrica* is similar in size to *C. tridens* but does not exhibit impressions of terminal digits; moreover, it is strongly asymmetrical. The trackway may have been made by a flamingo or one of its allies.

Culcitapeda eccentrica Sarjeant and Reynolds, nov.

Plates 21, 22; Figures 25, 26

Description. Avian footprints of moderate to large size, tridactyl and very strongly webbed. Digits indicated by a forward prolongation in the shape of an isosceles triangle, with longest axis corresponding to the digit axis (III), and by the two extreme lateral extensions of the footprint (II and IV). The digits display strong asymmetry, with digit II much closer to III than digit IV. Posterior profile of footprint asymmetrically rounded-triangular, the outbulge oblique to the forward prolongation of digit III.
Derivation of Name. L., *eccentricus*, not having the same center, eccentric; with reference to the footprint's strong asymmetry.
Type Material. Holotype: cast of a left pes, specimen A500-8163 (Pl. 21, Fig. 25). Paratype: specimen A500-8168 (Pl. 22). Lodged in the San Bernardino County Museum, Redlands, California.
Horizon and Locality. early Miocene, 1-137-1, Boron Open Pit Mine, San Bernardino County, California.
Dimensions. Holotype (left pes): maximum length 72 mm

(obliquely from tip of forward prolongation to tip of backward prolongation), breadth 87 mm. Paratype: length 72 mm, breadth 88 mm. Third specimen not measurable. *Discussion*. The strong asymmetry and more pronounced forward prolongation distinguish this ichnospecies from *Culcitapeda ascia* and *C. tridens*. Hollowing between digits is so feeble that the exact position of the lateral digits was not measurable. Consequently, interdigital angles could not be determined. (For discussion of affinities, see under ichnogenus, above).

SUMMARY

Avian footprints are abundant at certain time periods in the Miocene of California, but have hitherto received little attention. Thirteen footprint types are recognized, four of which have been reported earlier from the Miocene (Helvetian) of eastern Europe (*Aviadactyla vialovi, Gruipeda becassi, Ornithotarnocia lambrechti* and *Charadriipeda recurvirostrioidea*). Eight others represent footprint morphotypes undescribed hitherto, four being assigned to existing ichnogenera (*Avipeda thrinax, Avipeda gryponyx, Anatipeda californica* and *Anatipeda alfi*) and four to new ichnogenera (*Alaripeda lofgreni, Culcitapeda ascia* and *Culcitapeda eccentrica*). One other morphology, represented by a single specimen, is given only provisional taxonomic assignment.

In order to clarify the definition of the avian ichnotaxa, the diagnosis of the existing morphofamily Gruipedidae is emended and the new morphofamily Culcitapedidae erected, while emended diagnoses are presented for the ichnogenera *Aviadactyla*, *Ornithotarnocia* and *Charadriipeda*. The new combination *Aviadactyla panini* is proposed.

This avian assemblage consists of the footprints of water birds (with the exceptions of *Gruipeda becass*i and *Aviapeda thrinax*). Consequently, the representation of avian systematics is somewhat biased. However, the trackway record indicates that certain water-feeding morphologic adaptations were distinct from the Eocene or Miocene to present. Remarkably, only two of the five avian footprint morphotypes described (as *Avipeda* A–E) by Scrivner and Bottjer (1986) from the Neogene Copper Canyon Formation of Death Valley, California, are represented.

It is hoped that this study will serve as basis for future researches on the Tertiary avian ichnofaunas of North America.

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The first author is indebted to Dr. Peter Flood (Veterinary Anatomy, University of Saskatchewan) for help concerning the terminology of birds' feet. All photographs were taken by the first author; we thank Kathryn G. Reynolds for drawing certain trackway figures. We accept joint responsibility for the opinions expressed.

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Neogene Erosional Surfaces in the Northeastern Mojave Desert, California

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ABSTRACT

Five erosional surfaces that pre- and post-date Tertiary crustal extension are present in the northeastern Mojave Desert. A pre-Miocene surface suggests that the Halloran Hills were uplifted and eroded to exhume granitic rocks of the Teutonia Batholith before 18.5 Ma. An early Miocene surface with irregular topography containing lacustrine basins was developed before 13 Ma and was faulted concurrent with extension in the Shadow Valley Basin between 13–9 Ma. Listric normal faults dissected this terrain and tilted recognizable erosional surfaces and sedimentary sections eastward. An early late Miocene erosional surface planed the earlier surfaces prior to emplacement of gravity glide blocks of metamorphosed carbonate rocks from the Avawatz Mountains. This surface developed prior to 7.5 Ma basalt flows in the eastern Halloran Hills. Subsequent erosion on the Soda–Avawatz fault zone caused steepening of slopes into Soda Basin and topographic isolation of the late Miocene basalt flows. Several million years of tectonic stability culminated in a late Pleistocene erosional surface characterized by dense, resistant pedogenic carbonate rocks. These pedogenic carbonate rocks are offset by faults in Shadow Valley. Base level changes in Soda Basin, as well as continued faulting on the Soda–Avawatz fault zone, have left the pedogenic carbonate rocks elevated on the north and south slopes of the Halloran Hills.

INTRODUCTION

Tertiary deposits within the northeastern Mojave Desert include several erosional surfaces reflecting changes in base level during Neogene tectonic events. These consist of pre-Miocene, early Miocene, early late Miocene, late Miocene, and mid-Pleistocene erosional surfaces. This paper describes the characteristics of these five erosional surfaces separated by tectonic periods. The focus of this paper is on the area north of the unextended Mid Hills block (Miller, 1995a), west of the Mescal Range, Clark Mountain, and Mesquite Hills, and south of the Kingston Range (Figure 1). Structurally, the area lies north of the projection of the Ivanpah Valley fault (Jennings, 1961) and the Nipton fault zone (Miller, 1995b), west of the Kingston Range–Halloran Hills detachment zone (KR-HHDZ; Burchfiel and Davis, 1988), and south of the Kingston Range (Calzia and others, 2000). This area can be divided into (from south to north) the Cima Terrain (CT), Halloran Terrain (HT), and Shadow Valley Basin (SBV).

PRE-MIOCENE EROSIONAL SURFACE

The pre-Miocene erosional surface is characterized by rounded leisingang-stained granite boulders formed by subaerial weathering (Figure 2). This type of weathering was described from the Pioneertown locality (Oberlander, 1972) where the granitic erosional surface is preserved under arkosic sediments and basaltic flows. Surface water penetrates the granitic bedrock along systems of fractures and joints. Not only does chemical weathering loosen individual quartz and feldspar crystals, but percolating ground water penetrates the granite and precipitates metallic oxides in zones parallel to the joints. These zones become concentric toward the interior of the boulder (leisingang rings). When exhumed by erosion, the once-buried bedrock appears as a granitic surface with isolated or stacked subrounded boulders stained red by goethite.

In the HT and CT, a similar erosional surface is developed on granitic rocks of the Cretaceous Teutonia Batholith (TB) beneath the middle Miocene Peach Springs Tuff and early Miocene sediments. Near Francis Tank and Willow Wash (Figure 1), the iron-stained boulders are covered by resistant gravels of the Cambrian Wood Canyon Formation and Zabriskie Quartzite. The presence of the 18.5 Ma (Nielson and others, 1990) Peach Springs Tuff (PST) suggests that this surface was exhumed before the inception of middle Miocene extension (Calzia, 1990). PST on weathered granite is locally exposed east of Indian Spring (Wilshire, 1992) and west of Kelso Peak (Skirvin and Wells, 1990). A similar tuff is reported in wells on the east side of Cima Dome (Sharp, 1957) and is described west of Cima (Reynolds and others, 1995). It is often coincident with the middle Miocene erosional surface described below.

EARLY MIOCENE EROSIONAL SURFACE

Three local basins developed in the CT and HT after deposition of the PST. One basin is west of Kelso Peak at the east margin of Old Dad Mountain. Another basin is present at Halloran Summit, and the third is in the vicinity of Squaw Mountain (Figure 1). These basins contain lacustrine siltstones and limestones and are separated by a topographic high of the TB granitic rocks covered by arkosic sediments. The outcrop pattern of the basins does not correspond to the outcrop pattern of the PST suggesting that tectonic events formed the basins after 18.5 Ma. The basins and intervening area are capped by a 12.8 Ma (John Nakata, written commun.; Wilshire, 1991) pyroxene andesite.

SVB began to fill with fine-grained sandstones, lacustrine siltstone, limestone, and volcanic rocks between 13.4–13.1 Ma (Friedmann, 1995). These rocks are similar to but con-

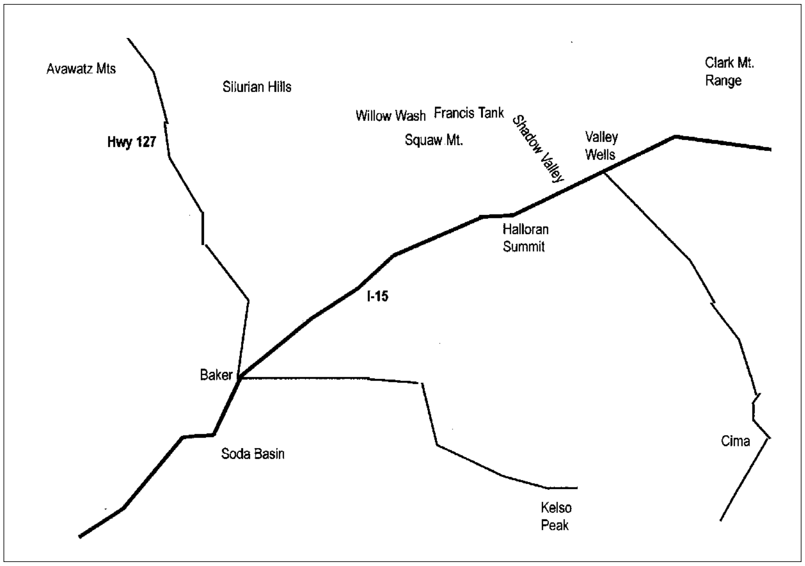

Figure 1. Vicinity Map.

siderably thicker than the lacustrine sediments deposited on the early Miocene erosional surface. SVB as well as the HT and CT were differentially covered by greater or lesser amounts of coarse debris from the KRR-HHDZ after the 12.8 Ma pyroxene andesite was emplaced.

MIDDLE MIOCENE EXTENSION

Middle Miocene extension in SVB included uplift of the footwall scarp of the KR-HHDZ and east tilting of upper place rocks by listric normal faults (Fowler and Calzia, 1999). Blocks of sediment-covered granitic rocks of the TB in the HT and CT also were tilted eastward during extension in SVB.

Friedmann (1999) reported that east tilting of sediments in SVB occurred after 10 Ma. A 9 Ma (Perkins, pers. commun. to Reynolds, 2001) glassy ash near Halloran Summit was involved in eastward tilting of sediment-covered granitic rocks in the HT. These data suggest that listric normal faulting and extension continued until 10–9 Ma. Extension caused fault blocks to tilt eastward, repeating the erosional surface of granite–sediments–andesite–megabreccia at least five times from Kelso Peak and Halloran Summit to the Silurian Hills (Figure 1). Subsequent erosion caused the exposed fault scarps to retreat to the pre-Miocene surface, reducing the angle between these two erosional surfaces.

The Mid Hills block south of the Nipton Fault (Miller, 1995a) was apparently unaffected by extension. In the CT, north of the Nipton Fault and south of the Halloran Fault (a transfer fault parallel to Interstate Highway 15), listric fault blocks of granitic rocks are tilted eastward as the area was modestly extended westward. In the HT, north of the Halloran Fault and south of SVB, severe extension tilted fault blocks, erosional surfaces, and overlying sediments as much as 45° east.

EARLY LATE MIOCENE EROSIONAL SURFACE

The early late Miocene erosional surface developed of the east-tilted fault blocks. Erosion caused the fault scarps on the west side of individual fault blocks to retreat rapidly, probably faster than older scarps that had been armored by the precipitation of metallic oxides, silica, and clays. The degraded scarps are distinct from the older scarps because the younger scarps have little or no oxide staining and do not have abundant rounded granitic boulders produced by subaerial weathering.

The early late Miocene surface was subsequently smoothed by erosion into a relatively planar feature. Glide and slide blocks as well as chaotic assemblages of metamorphosed Proterozoic and Paleozoic carbonate rocks were deposited on this surface. These carbonate rocks did not come from the vicinity of the Kingston Range or Clark Mountain since the carbonate rocks that remain at those locations are not metamorphosed (Calzia, 1990; Burchfiel and Davis, 1971). The metamorphosed carbonate rocks probably come from the Avawatz Mountains (Spencer, 1990; Calzia and Ramo, 2000). If emplacement of the metamorphosed carbonate rocks was gravity driven, then a shallow topographic gradient must have existed from the Avawatz Mountains to Squaw Mountain, a distance of 39 km. The existence of this gradient suggests that the Avawatz Mountains were uplifte4d during formation of the early late Miocene erosional surface. This surface is capped by undeformed 7.5 Ma (Turrin and others, 1985) basalt flows in the HT. These data suggest that the early late Miocene erosional surface and gravity glide blocks developed rapidly between 9 and 7.5 Ma.

LATE MIOCENE EROSIONAL SURFACE

Undeformed 4–4.5 Ma (Turrin and others, 1985) basalt flows define the topography of the late Miocene erosional surface in CT and HT. These magmatic rocks flowed eastward into Shadow Valley and westward into the then-forming Soda Basin (Figure 1). The paleoslope from HT to the east was 1°, comparable to the present-day slope. The 5 Ma slope was 0.5° west, much less than the current 2.8° slope into Soda Basin. The inception of the eastern California shear zone (Brady and Dokka, 1989) may have enhanced erosion on slopes facing Soda Basin. Erosion was probably slow between 7.5 and 5 Ma (producing a relatively low gradient) and increased during the last five million years.

Fig. 2. Leisingang weatering rings (metallic oxides) in the surface between marble flocks.

LATE PLEISTOCENE EROSIONAL SURFACE

A cross section of a late, but not latest, Pleistocene erosional surface is present in Shadow Valley at Valley Wells (Figure 1). Lacustrine sediments at this location contain 2.0–0.5 Ma mammal fossils. These sediments are overlain by thick pedogenic carbonate deposits and are capped by an alluvial pavement. The pedogenic carbonate rocks are overlain by lacustrine silts that contain Rancholabrean LMA horse west of a north-trending fault near the middle of the valley (Reynolds and Jefferson, 1991; Scott, 1996). These data suggest that the pedogenic carbonate rocks at Valley Wells may be older than 0.5 Ma.

The imbricated alluvial pavement above the pedogenic carbonate rocks consists of pebble-size gravel deposits that are locally interrupted by linear rows of bushes, pebbles, and silt. These linear features are oriented across the slope of the valley and are apparently formed by sheet flooding on very shallow slopes. The alluvial pavement also steps downward toward the center of the valley. The pedogenic carbonate rocks and the alluvial pavement can be recognized over a 300 square mile area from the summit of the HT to Highway 127 (Figure 1). Near Highway 127 where the pedogenic carbonate rock is stripped from the underlying erosional surface, the exhumed erosional surface includes pocketed, cavernous, and etched boulders of granitic rock that are reminiscent of granitic boulders beneath the pre-Miocene erosional surface.

SUMMARY

Five Neogene erosional surfaces are present in the northeastern Mojave Desert. Each surface reflects changes in base level associated with regional tectonic events. Careful examination of the rocks and relief of each surface contributes to the geologic history of this complex and fascinating region.

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Kelso Depot

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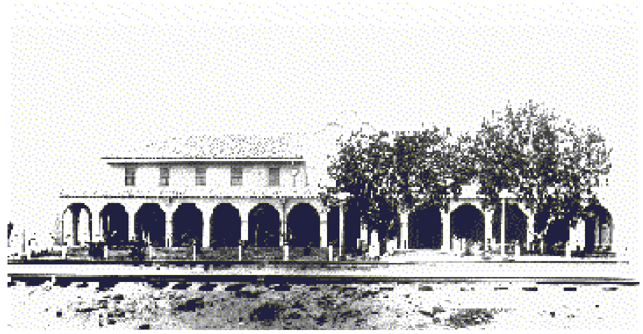
As we drive along in our oft-times air-conditioned 4-wheel drive vehicles, regarding the spare desert terrain through our dusty windshields, it's easy to romanticize about the glory days of the Wild West—brave new railroad lines glinting in the sun, wizened prospectors tugging recalcitrant burros through rocky passes… Such are the thoughts that may pass through our minds as we chance upon incongruous bits of human presence in the desert.

The sight of Kelso Depot, shining white and looming large in the distance as we crest the side of Cima Dome towards the beckoning sand dunes and grand adventures within the Providence Mountains, is a case in point. Questions immediately rise, and imaginations boil. What is this place and what is it doing here? What stories can it tell?

Happily for those intrepid desert adventurers with vivid imaginations, history has been kind, even as time has not. In 1998, the National Park Service commissioned several worthy professionals to publish a structural report of the Kelso Depot, the primary source of information for this article. Entitled the "Kelso Depot Historic Structure Report," it contains a wealth of fact and memory, and was provided to the author by Mr. Sean McGuinness, Chief Ranger for the Mojave National Preserve. Phil Varney's excellent "Southern California Ghost Towns" also served as a reference.

Kelso Depot is a story of railway and water. By April 1904, the San Pedro, Los Angeles & Salt Lake Railroad, brainchild of Senator William Clark, had reached Siding No. 16, which consisted of a tent camp for the railroad construction crew and three warehouses. As the story goes, two warehousemen decided to give it a real name. They placed their names on little pieces of paper, throwing one in a hat for the third warehouseman who had recently moved on. His name was John H. Kelso, and, as luck would have it, his name was pulled. Thus Kelso Depot was born, when the Union Pacific officially opened up its line from Salt Lake City to Los Angeles for business on May 1, 1905. The 2.2 percent grade from Kelso up to the Cima summit required the use of a "helper" locomotive, and lots of water to power the steam locomotives of the day. Though Kelso was not at the bottom of the grade (roughly 29 miles west at Cork siding), it had water, pulled from deep wells supplied by springs flowing underground from the Providence Mountains to the southeast. The original depot, built in 1905, was a humble, utilitarian structure. After the Union Pacific acquired full ownership of the line in 1921, it began a modernization effort. That year, curiously enough, several depots along the line burned down. First to go was Yermo, in June. In September, the Caliente NV depot and part of the Kelso depot went up in flames. A year later, the lunchroom at Kelso also burned down.



Kelso Depot, 1924, photos by Union Pacific Railroad.

So it was that on March 2 of 1924, a new lunch room station and club house at Kelso was opened. President Gray of the Union Pacific Railway reported this to his superiors back in New York.

> We have just completed a modern Mission Type depot, restaurant and club house at this point, and it is now proposed to build some parking in front and each end of the building, in which will be planted grass, trees and shrubbery. This parking will be outlined by fence built of wooden posts with pipe hand railing made from discarded boiler tubes. Kelso is in the desert, where there is very little green vegetation to be seen, and it is particularly desirable to beautify and make

Kelso Depot, photo courtesy of Mojave River Valley Museum.

> attractive our station grounds so that they will be particularly inviting to passenger en route to and from California.

Throughout the war years, Kelso thrived, in large part due to the Vulcan Mine, just nine miles away, opened by the Kaiser Steel Mill to meet military demands for iron. At the height of its operation, train cars hauling more than 2500 tons of ore a day rumbled past the elegant Kelso Depot on their way to the mill in Fontana. Inevitably, however, progress took its toll of Kelso. The iron mine closed in 1949 due to high sulphur content and reduced product demand. Diesel replaced steam, and by 1959, the trains no longer needed to stop before tackling the steep grade. The Depot hung on through the 1970s as a popular place to eat, 1950s style. The railroad crews' rooms and the telegraph office were rented out to tourists for $7 a night. As the years drifted by, the large waiting room, the basement dancehall and community center rooms saw less and less activity as the town quietly died.

Flash forward 20 years to March 14, 1984, when Mark Hemphill recorded this observation of Kelso for a book he was writing on the diesel locomotive era of the Union Pacific Salt Lake Route.

> At day's end the wind dies out. The cottonwood trees around the Kelso depot come alive with the noisy chatter of hundreds of birds. After dark the platform lamps come on, little pools of yellow light on the brick platform. Bats swoop and dip through the trees, homing in on insects that dizzily circle the lampposts. The swing-shift counterman props the lunchroom door open in hopes of some cooling breeze. His transistor radio broadcasts Hank Williams through the screen door into the calm desert night, and Jeannie Pruitt sings about her satin sheets for the ten-thousandth time. A few men from a maintenance gang enjoy a smoke on the steps of their bunk cars, then retire to bed. The pay phone on the depot wall offers a scratchy connection with the rest of the world. After a few rings an operator in Los Angeles answers, then pauses as you tell her your location, dumbfounded that big Pacific Bell has a pay phone identified only as Kelso #1…

By 1984, it was readily apparent to the 'bean counters' of Union Pacific that Kelso had outlived its economic value as a meal stop for its employees, and so it was at midnight of June 30, 1985, "after 61 years, 3 months and 17 days, the last official functions of the Kelso Depot, employees hotel and restaurant came to an end, when the Lunch Room closed permanently".

But for a few brave BLM and Union Pacific employees, local citizens and perceptive legislators, we would be denied the delightful sight of Kelso Depot's whitewashed walls and red tile roof shining in the sun. After much acrimonious debate and last minute wranglings, Union Pacific officials met with BLM and local activists on December 17, 1985 to officially lease the depot for preservation purposes. On August 19, 1992, they donated it to BLM, and serious restoration efforts commenced. Then came the Desert Protection Act of 1994, wherein Congress established the Mojave National Preserve, transferring almost 1,600,000 acres of BLM lands to the National Park Service (NPS). Included in that transaction was the Kelso Depot. NPS, recognizing the amount of federal resources already committed and the labor of love expended by a concerned public, has decided to open the depot to the public as the main visitor center for the Mojave National Preserve. Chief Ranger Sean McGuinness reports that construction is scheduled for early fall of 2001, due to the outstanding architectural plans drawn up by the design firm, Architectural Resources Group from San Francisco. It was quite a challenge to adapt the historic building to meet current codes and disability access requirements. Modern requirements, such as the elevator and fire sprinkler system, earthquake retrofit and state-of-the-art, environmentally friendly heating and cooling system, have been designed into the resurrection of its pre-WWII period appearance, to include historic landscaping. Input from the local Mojave National Preserve Advisory Group has been valuable in the planning process. Because of their recommendations, local citizens like Rob Blair, Irene Ausmus and Willie Heron will soon be able to sit around the counter of the "Beanery" once more, sipping coffee and ice tea, and regaling other visitors with their stories of life in the Mojave. Rooms on all three floors will display natural and cultural history exhibits, highlighting the many wonders of the Mojave Desert. A theater will run short movies to inspire and teach, and the old basement reading room will once more echo with the voices of folks sharing information at community meetings and environmental educational programs. Parking has already been added to the east of the building, along with a 24-hour comfort station. NPS is still gathering material for the exhibits and historical refurbishment of the conductor's room, ticket office, and two upstairs bedrooms. The grand opening is scheduled for early 2003.

But for now, in 2001, it is difficult to envision the beehive of activity that was Kelso. Tumbleweeds scatter as we whiz through the ruins of a town that, through the war years of WWII, over 2000 people called home—home to Kaiser Steel's Vulcan Mine workers and their families, home to other prospector/miners, cattlemen, and homesteaders, home to Union Pacific railway employees. Gone too, are the lovely shading trees of the Kelso Depot, over 52 of them—Chinese Elms, cottonwoods, sycamores, date palms and Washingtonia fan palms, along with the Joshua trees, agaves, and ocotillos planted to maintain a desert presence amongst the grass lawns. By 1993, only 5 fan palms managed to survive the cessation of regular watering, and the oasis that once was Kelso ceased to be. Due to the those vigorous efforts of concerned citizens and government officials, such as Representative Jerry Lewis, Kelso Depot the building will remain.

Mark Hemphill poignantly concluded his observations of Kelso Depot with, "The Kelso Club will survive in body. But without rooms for seven bucks a night, ice tea served up in frosty UP glasses, and trains stopping for sack lunches, Kelso's soul is gone." I think he may be wrong. There is, after all, the ghost of Kelso, Juan Antonio, who will never leave the depot, because that is where he last saw his love. Trains still come to a slow rumble alongside. Sounds of glasses clinking and people laughing will soon waft once more from the windows of the Beanery. And as long as there are those of us who will stop to linger awhile under the arching portals of the grand old edifice, conjuring up images of days gone by, her collective soul will stay.

A Field Investigation of the Clark Mountain Fault Complex, San Bernardino County, California

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ABSTRACT

The Clark Mountain fault (CM) was first described by Hewett (1956). Despite decades of study, the geometry, kinematics and even the existence of some components of the CM fault remain the subject of debate. Our research indicates that the complex is comprised of two parallel to subparallel faults striking roughly north-south along the eastern flank of Clark Mountain and Mohawk Ridge. The westernmost of the two faults juxtaposes hanging wall Cambrian Bonanza King and footwall rocks of variable lithology and stratigraphic position (lower Cambrian to Proterozoic). The fault plane dips gently to the west (10-30°) and is characterized by a lack of brecciation in both footwall and hanging wall rocks adjacent to the fault. Northeast verging, shallowly northwest plunging, small-scale folds with amplitudes of cm's to a meter or two are common in the footwall rocks. The general character of rocks associated with this fault is markedly similar to that of the Keystone thrust in the Spring Mountains. This fault is unquestionably the Keaney-Mollusk Mine fault identified by Burchfiel and Davis (1971). The second major fault lies at a variable distance (up to a few hundred meters) to the east in the footwall of the thrust. The fault is poorly exposed, but where observed generally dips steeply (50-80°) to the west. The footwall is comprised of Precambrian metamorphic basement while the hanging wall consists of brecciated lower Cambrian Zabriskie and Carrara Formations. Slickenfiber analysis of footwall basement rocks by Rodman (1989) indicates northeast-southwest extension. Our investigations are consistent with the interpretation of normal movement along this fault. Detailed mapping shows the high angle fault to be locally over-ridden by the thrust. We are led to the conclusion that extension predates compression. Our data best fits a model of pre-thrust extension (the Clark Mountain fault and Ivanpah faults), perhaps associated with back-arc development. This was followed by northeast-directed thrusting.

Introduction

The field study area lies immediately west of the Molycorp Mountain Pass Rare Earth Mine, San Bernardino County California. It extends from the east end of Mohawk Ridge (Microwave Tower Hill) north for a distance of 10 miles to the Mesquite Mountains. Much of the study area lies within the East Mojave Scenic Preserve. Access is by a series of drill roads and 4-WD drive tracks. Topography varies from low hills (Chaos Hill) to rugged mountains (Clark Mountain). Burchfiel and Davis (1971) were the first to suggest that the faults within the study area were a part of the much larger Mesozoic Sevier Fold and Thrust Belt, a north-south belt of crustal shortening extending from southern California to, at least, Alberta.

Previous Work

Dixon Hewett was the first geologist to study the east Mojave in detail. Much of his work centered on 1500 square miles of southern California and western Nevada termed the Ivanpah Mining District. Hewett's work, although not published until 1956, was largely completed before World War II. To his credit, Hewett recognized many of the structural and stratigraphic relationships that make the study area so unique. Our research investigates an area that has remained controversial since Hewett's first map was published. Hewett mapped a fault on the east side of Clark Mountain as a normal fault (Clark Mountain Fault) based on the structural relationship. His map depicts Cambrian Goodsprings Dolomite (now subdivided into several units including the Bonanza King Formation) overlying basement gneiss. In the 1970s, Burchfiel and Davis proposed that this fault should be remapped as a decollement thrust fault, naming it the Keaney-Mollusk Mine thrust. In a 1988 field guide they offered several lines of evidence to support their hypothesis, the most compelling based upon mapping in the Mescal Range south of Mountain Pass. In the Mescal Range, Hewett's Clark Mountain normal fault can be seen to place Bonanza King Formation (Cambrian) over Cretaceous volcanics and Jurassic Aztec Sandstone. In 1989, Elizabeth Rodman studied a small portion of the Clark Mountain fault complex. She recognized the presence of not one, but two north-south striking faults lying nearly side-by-side. She interpreted the eastern-most fault as a thrust and the western fault as a normal fault. We have reexamined the area mapped by Rodman and extended our mapping both north and south of her study area.

Stratigraphy

Rocks exposed in the study area range in age from Proterozoic through Devonian. The basement is comprised of hornblende-biotite gneiss with lenses of quartzite. Age of the basement rocks is uncertain, but may be similar to the 1.7 Ga Fenner Gneiss to the southwest of the field area. Pegmatite dikes and a younger alkali granite have cut the gneiss. Both predate intrusion of a 990 Ma carbonitite complex at Mountain Pass (Beckerman, et. al., 1982). Proterozoic rocks were not differentiated during our mapping.

Proterozoic rocks are in fault contact with Lower Cambrian units throughout the field area. Cambrian Wood Canyon Formation crops out locally. It is comprised

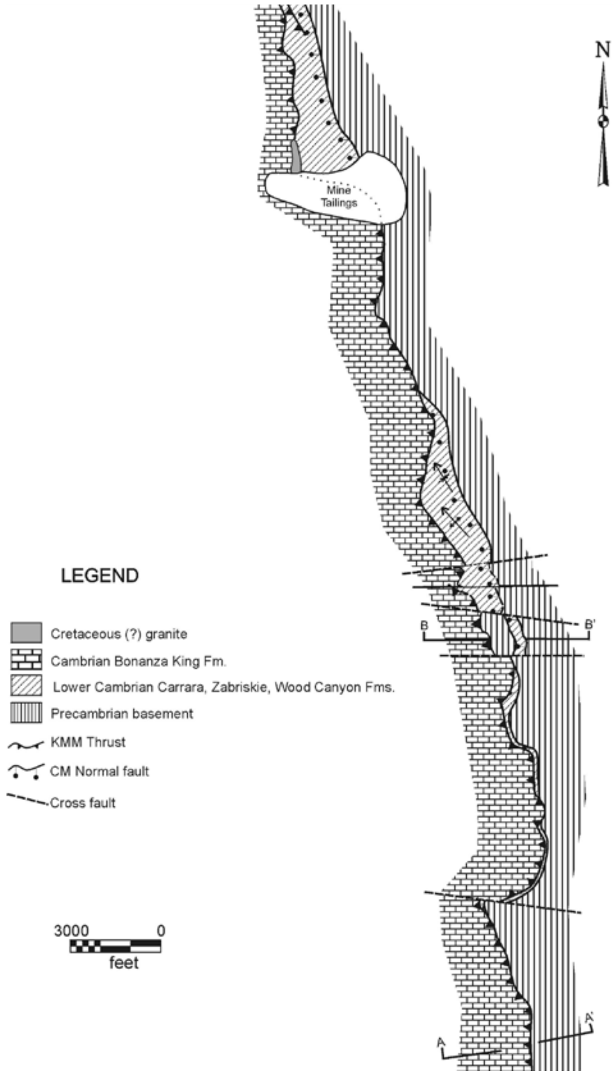

Figure 1. Geologic map of the Clark Mountain fault complex

of interbedded coarse, arkosic sandstones and polymict pebble conglomerates. It is differentiated from the overlying Zabriskie Quartzite by poor sorting, lack of cross-bedding, and the rusty, red-brown color on outcrop. Maximum outcrop thickness of the Wood Canyon rarely exceeds thirty meters. Zabriskie Quartzite conformably overlies the Wood Canyon. The Zabriskie provides an excellent marker horizon, forming prominent ridges. It is well sorted, often cross-stratified and more highly indurated than the underlying Wood Canyon. Maximum thickness of the Zabriskie locally exceeds 150 meters, but is generally 50 meters or less.

Middle Cambrian Carrara Formation overlies the Zabriskie. The lithology and thickness of the Carrara is highly variable within the field area. The variable thickness is a consequence of the fault contact with the overlying Bonanza King Formation. Nowhere in the map area is the contact conformable, the variation in thickness due to faulting out of the upper Carrara. Lithology varies both up section and along strike. To the south, shale and siltstone predominate with lesser silty carbonate. Further north, the Carrara is comprised largely of silty limestone. Locally the Carrara has been weakly metamorphosed to slate/hornfels and schist.

The contact between the Carrara and middle Cambrian Bonanza King is marked by a gently west-dipping fault. The Bonanza King forms prominent outcrops throughout the map area. It is markedly banded, comprised of alternating blue and light gray layers of limestone and dolomitic limestone. There is little or no evidence of metamorphism, even adjacent to a granitic intrusive at the Pacific Fluorite Mine. The Bonanza King is conformably overlain by Cambrian Nopah Formation and Ordovician Pogonip Group. Neither is shown on our field map as outcrops lie to the west of the mapped area along the steep slopes near the summit of Clark Mountain (both are the subject of ongoing field mapping). On Mohawk Hill Devonian Sultan lies above the Pogonip and at the summit of Clark Mountain and in the Mesquite Mountains both Mississippian Monte Cristo and Pennsylvanian Bird Springs were mapped by Hewett (1956). The western (updip) contact of the latter three formations is marked by the Mesquite Pass thrust fault.

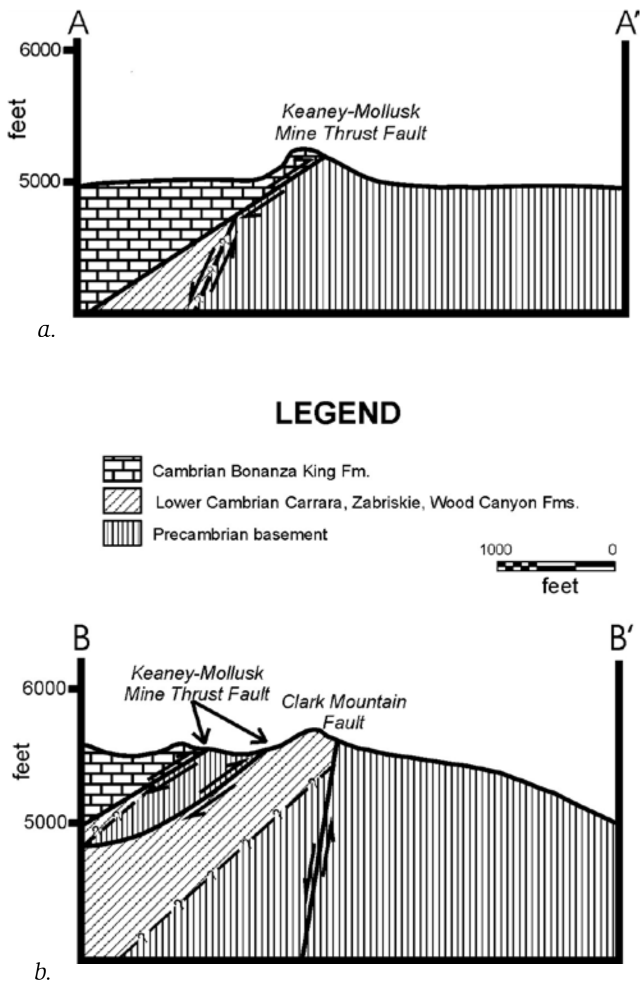

Figure 2. (a) Cross section A-A' across the east end of Microwave Tower Hill. (b) Cross section B-B' along the crest of Chaos Hill.

Figure 3. Keaney-Mollusk Mine thrust fault, Microwave Tower Hill. Upper plate rocks are Cambrian Bonanza King Formation (C_{bk}), *lower plate is Precambrian gneiss* (pC_g).

Structure

Figure 1 presents the results of our field mapping. Stratigraphic relationships are generally straightforward in the southern portion of the map area. Figure 2a is a cross section through the Microwave Tower Hill (A-A') at the west end of Mohawk Ridge. Bonanza King Formation can be seen in fault contact with the underlying Proterozoic gneiss (Figure 3). The fault plane dips west at 20-30°. Rocks along the fault plane are unbrecciated. Although the stratigraphic relationship — younger rocks (Cambrian Bonanza King) over older rocks (Proterozoic gneiss) — suggests a normal fault, we conclude this fault is a thrust fault, the Keaney-Mollusk Mine (KMM) thrust proposed by Burchfiel and Davis (1971). We base this conclusion on mapping by Burchfiel and Davis (1988) south of I-15. There, the continuation of the KMM fault southward from Microwave Tower Hill can be seen to juxtapose upper plate Bonanza King and lower plate Cretaceous Delfonte Volcanics. Furthermore, the geometry of this fault is markedly similar to that of the Keystone thrust in the southern Spring Mountains.

Father to the north (Cross Section B-B') (Figure 2b), geologic relationships become more complex. A second major fault appears to the east of the KMM thrust. This fault lies beneath the upper plate of the KMM along Mohawk ridge. Westward erosion of the upper plate block exposes the second fault east of Clark Mountain. The hanging wall of the KMM thrust remains Bonanza King, as it does throughout the study area. However, footwall rocks are comprised of lower Paleozoic clastics; the Carrara, Zabriskie and Wood Canyon Formations (Figure 4). The lower Paleozoic clastic units comprise the hanging wall of the second fault; Precambrian gneiss comprises the footwall. This fault plane is poorly exposed, but in scattered prospect pits it can be seen to dip steeply (70-80°) to the west. Footwall rocks are heavily brecciated and altered. Rodman (1989) performed slickenfiber analysis on basement rocks in the footwall of this fault. Her data suggests northeast-southwest extension. Therefore, this second fault most likely is a normal fault. Hewett (1956) first mapped a normal fault he termed the Clark Mountain fault, trending roughly north-south in this area. We have chosen to retain his terminology and term the second fault the Clark Mountain (CM) fault.

Locally, the KMM thrust bifurcates, generating a series of smaller sub-plates. This relationship is especially well developed one kilometer north of the Colosseum Mine. Here, a series of parallel fault planes repeat section and result in one of the rare instances of the classic older-over-younger relationship. Upper plate Zabriskie Quartzite has overridden lower plate Carrara Formation.

West of Chaos Hill and north of the Colosseum Mine the Carrara Formation is tightly folded (Figure 5). Stereoplots of fold data consistently show the folds to be northwest vergent. We suggest the folds developed when the upper plate of the KMM thrust moved northeastward over the ductile shales of the lower plate Carrara Formation.

Field mapping has recently commenced in the Mesquite Mountains to the north of the Clark Mountains. Preliminary reconnaissance indicates the KMM thrust can be extended into the Mesquite Range. The stratigraphic relationships are somewhat different than those in our map area. Carrara Formation appears to lie within the upper plate of the KMM thrust while the lower plate consists of lower to middle Paleozoic units. The Clark Mountain fault has not been mapped but structural relationships are complicated by Cenozoic volcanism and limited exposures. Hewett (1956) suggests that the Clark Mountain and Ivanpah faults converge in the Mesquite Mountains. We find the Ivanpah fault

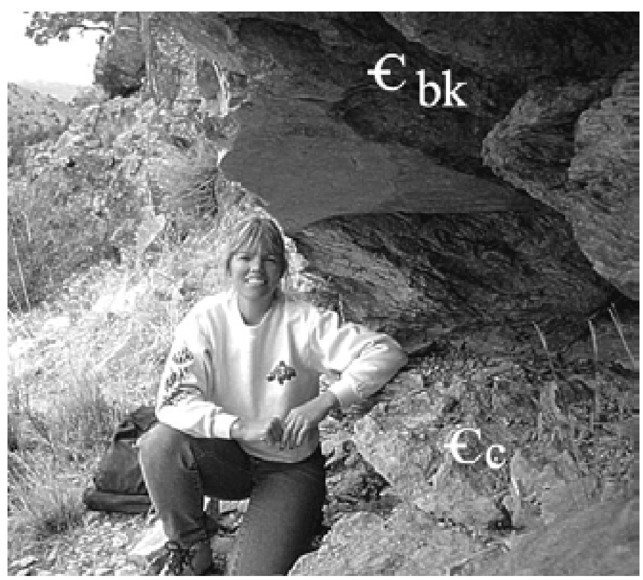

Figure 4. KMM thrust exposed north of Chaos Hill. Hanging wall is Cambrian Bonanza King Formation (Cb_k), *footwall Cambrian Carrara Formation* (C_c).

Figure 5. Small-scale folds in the Carrera Formation near Benson Mine.

to be present in the Mesquite Range, but its relationship to the CM fault remains problematic.

Conclusions

Our field investigation has shown that the Clark Mountain fault complex comprises two subparallel faults of markedly dissimilar character. The easternmost of the two faults, the Clark Mountain fault (CM fault), juxtaposes Precambrian basement and lower Paleozoic clastic sedimentary rocks. It dips steeply to the west and is characterized by extensive brecciation of hanging wall rocks. Slickenfiber data for footwall rocks suggests extension. We interpret this fault as a normal fault with the west side down. The age of this fault is difficult to constrain. South of I-15, the South fault (correlative with the CM fault) (Burchfiel and Davis, 1988) cuts Delfonte volcanics. These rocks have been dated at 100 Ma (Fleck et al, 1994), providing a maximum age for the fault. The Delfonte volcanics have an average composition approximating an andesite/dacite. Such rocks would normally be emplaced in an extensional arc or back-arc environment. Perhaps the CM fault and others such as the Ivanpah fault provided the conduit for extrusion of the volcanics. However, extension must have continued after the cessation of volcanism to yield the observed structural relationship.

The second major fault lies to the west of the CM fault, but locally overrides the CM fault. The fault plane dips gently to the west. Rocks associated with the fault lack brecciation. The hanging wall is comprised of Cambrian Bonanza King Formation while the footwall is composed of lower Cambrian/Precambrian rocks. Based on observations of faults throughout the eastern Mojave, we believe this fault to be a thrust fault. Its geometry and appearance are remarkably similar to the Keystone thrust, well exposed along Keystone Wash in the Spring Mountains. The KMM thrust has been mapped for nearly ten miles along strike and is known to continue southward in the Mescal Range (Burchfiel and Davis, 1988) and northward into the Mesquite Mountains (Tarman, Jessey, Waki, unpublished data). As such, it represents a major crustal break. Unfortunately, the low angle of the fault plane precludes any estimate of displacement along the fault, but most certainly it is on the order of kilometers. Age of the KMM thrust is more tightly constrained. Since it overrides the CM fault it most be younger than that fault and the 100 Ma Delfonte Volcanics. In the Mescal Range, the fault is cut by a granitic intrusion dated at 83 Ma (Walker, et. al., 1995). This suggests the KMM thrust was active during the mid-Cretaceous, between 83 and 100 Ma. Curiously, near the Colosseum mine a granitic intrusive is seen to cut the fault (see field map). Although this intrusive has not been dated, a nearby stock of similar granitic composition yielded an age of 100 Ma (Sharp, 1984). Does this indicate different periods of activity for segments of the fault? Sharp (1984) was also the first to suggest that the KMM thrust may have been reactivated during the Cenozoic as a normal fault. In the Clark Mountains, our mapping to date does not support this hypothesis.

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"Borax" Smith and the Tonopah & Tidewater Railroad

Stephen P. Mulqueen*

The Tonopah & Tidewater Railroad (T&T) operated between 1905 and 1938 servicing mines and communities along a route which extended north from Ludlow, California into western Nevada. What began as one man's challenge to a transportation problem at a borate mine east of Death Valley, resulted in a rail system that greatly benefitted all those who lived in the surrounding area. The history of the T&T is a story of success in overcoming great obstacles in the desert regions of California and Nevada. These obstacles included long expanses of uninhabited land devoid of trees and surface water, steep mountains, dry lakes and rivers which were subject to flooding, etc. The great geologic forces which formed high grade mineral deposits also created conditions that were formidable barriers to their economic development.

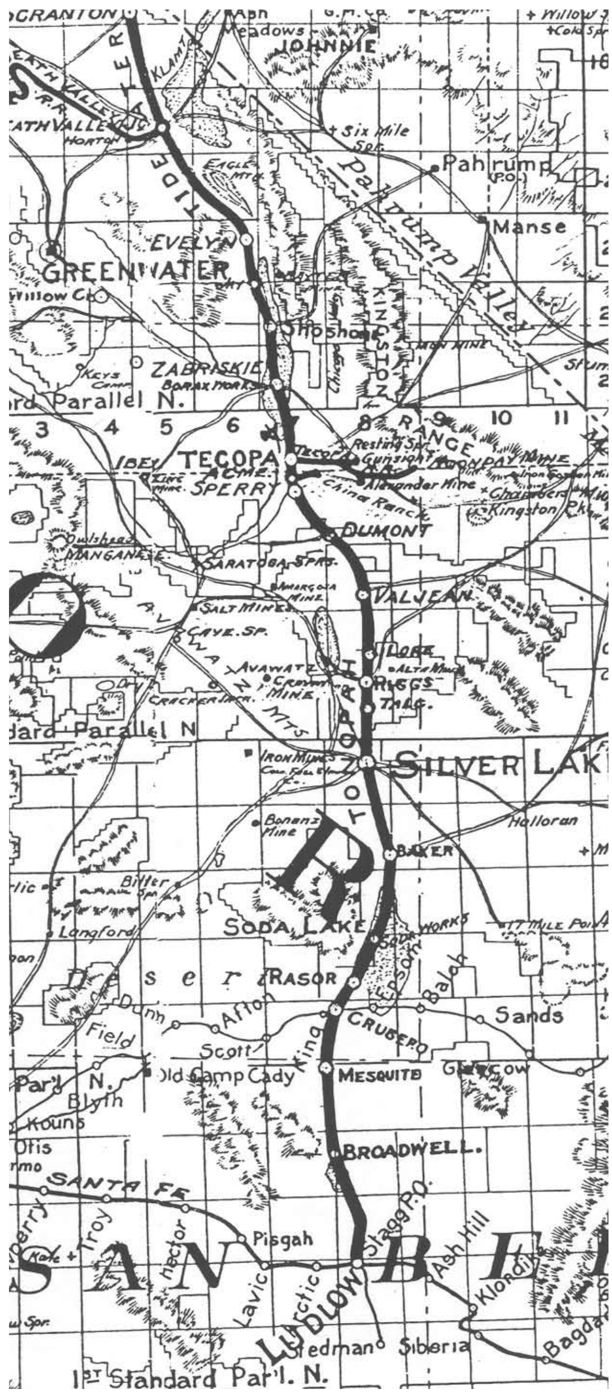
William T. Coleman

The occurrence of borate mineral deposits in the Death Valley region attracted early pioneers to that area. These minerals included borax, ulexite and colemanite which occurred naturally within lacustrine (lake) deposits at locations on the floor of Death Valley and in the hills surrounding the valley. William T. Coleman was the first to develop borate minerals from Death Valley. With the help of Chinese laborers, he successfully harvested "cottonball" ulexite from the mud flats. In 1882, Coleman built a processing plant to convert ulexite into borax, a more desirable commodity that could be marketed. He called his operations the Harmony Borax Works.

The success of similar borax operations southwest of Death Valley in what was then known as "Slate Range Playa" and later "Borax Lake" (now Searles Lake), led to the construction of the first 20 mule team wagons and rigging by John Searles in the 1870s. Coleman used this idea for shipping the Harmony borax and ordered his own wagons built to Searles' original specification. In 1882, Coleman hauled borax out of Death Valley to the Southern Pacific Railroad at Mojave using the 20 mule team and wagons.

"Borax" Smith

Coleman produced and shipped borax from Harmony for several years. By 1888, Coleman's operations met with financial losses. It was during this time that Francis Marion Smith (also known as "Borax" Smith) purchased Coleman's properties and all his holdings, including all the claims, borate deposits and mines originally held by Coleman. These properties included the borax plant at Harmony, the "cottonball" ulexite deposit within the Death Valley playa, the colemanite deposit at the Lila C. mine (southwest of the



Portion of the southern half of the Tonopah and Tidewater Company map, 1917. Map grid is standard townships (approx. 6 miles/side).

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Portion of the northern half of the Tonopah and Tidewater Company map, 1917. Map grid is standard townships (approx. 6 miles/side).

present day Death Valley Junction, at the edge of the Greenwater Range, Amargosa Valley) and the colemanite deposits at Mule Canyon near Calico. (The Lila C. was named after Coleman's daughter Lila.)

Smith was familiar with borate mining from his experience producing borax at Teel's Marsh in Nevada. In 1890, Smith combined the three properties in California and formed the Pacific Coast Borax Company (PCB). Smith's first operations after forming PCB began at Borate in Mule Canyon in the Calico Hills. From the successes at Borate, Smith formed Borax Consolidated, Limited in 1899, an international organization with headquarters in London, England. After the deposits at Borate were depleted by many years of mining, Smith began moving the mining equipment and personnel to the large deposit at the Lila C.

Hauling borax from the Lila C. proved to be Smith's greatest challenge. At that time, the closest railhead was at Ivanpah, which was more than 100 miles from the mine. He first met the challenge by placing "Old Dinah" back into operation. Old Dinah was a steam traction engine built to pull borax wagons at Borate. In April, 1904, Smith put the engine to the test. After just 14 miles, the steam boiler blew out and the machine came to a sudden, permanent stop. (Old Dinah now rests near the main entrance at Furnace Creek in Death Valley. One can still see the rupture in the side of the steam boiler.) It was the failure of Old Dinah that set the stage for the construction of the Tonopah & Tidewater Railroad.

The Tonopah & Tidewater Railroad

Smith was convinced that a railroad was the only answer to his transportation dilemma. Smith set his sights high and envisioned a railroad which would not only service his mine but also the gold and silver mines around Goldfield and Tonopah in Nevada. On July 19, 1904, the Tonopah and Tidewater Railroad Company (T&T) was incorporated by Smith in New Jersey. He immediately took title to the wagon road between Ivanpah and the Lila C. and began the task of finding investors for his great project.

Survey crews began charting a route from Ivanpah. During that time, a new Southern Pacific Line (SP) was reaching completion, known as the Los Angeles & Salt Lake Railroad (LA&SL). With the line open for traffic, survey crews also mapped a possible path for the T&T from the SP line north through the Kingston Range and on to the Lila C. Survey crews also considered a route from Las Vegas. By 1905, Smith decided to build his railroad from Las Vegas westward. On May 29, 1905, groundbreaking ceremonies dedicated the beginning of the new T&T line near Las Vegas.

Shortly after this event, Senator Clark of Nevada began having second thoughts about letting Smith build the T&T railroad through his state. Clark wanted to organize and build his own railroad from Las Vegas to the mines at Tonopah. To beat Smith at his own game, Clark organized his own railroad and formed an organization known as the Nevada Transit Company and, shortly thereafter, began construction of the Las Vegas & Tonopah Railroad (LV&T).

Clark had large investments in the mines around Goldfield and Tonopah. With a railroad to service those mines, Clark would have more control over those investments and the railroad would add to their success. At the same time, the Southern Pacific Railroad began charging the T&T the prohibitive rate of 45 cents freight for each railroad tie arriving at Las Vegas. This new freight charge would add considerably to the cost of the railroad. Shortly after being informed of this new freight charge, Smith tried to get permission to connect the T&T line to the SP line. It was flatly denied.

This action was a great setback for Smith. Over 12 miles of railroad bed had been graded. Essentially, it was a road to nowhere. He had no choice but to shift his operations from Las Vegas to Ludlow, California. By August, 1905, the transfer of equipment to the new site was completed and a tent city was constructed. The new starting point at Ludlow added 50 miles to the goal of reaching Gold Center, Nevada. (Gold Center was a railroad siding south of Beatty, Nevada).

In October, 1905, Clark purchased the 12 miles of graded railroad bed built by the T&T. This sale gave Smith and the T&T the funds to recover from the setback of the relocation. Smith wasted no time. By November, 1905, the first rail was laid at the "Big Loop", the term given to the circular rail pattern at the rail yard in Ludlow. The "Big Loop" enabled trains coming south to easily turn around for the return trip north.

From Ludlow, the railroad crossed the SP line at Crucero (Spanish word for crossing) and extended over Broadwell (dry) Lake. By March, 1906, the T&T line completed the

Principal Interior Mining Camps *of* California *and* Nevada

REACHED VIA

Santa Fe, Tonopah & Tidewater R. R., Bullfrog Goldfield R. R. and Tonopah & Goldfield R. R.

Mining Camps	Distance and Direction to Nearest R. R. Station	Telegraph Office	Express Office	Postoffice	Stage 1 Team 2 Auto 3
America Mine ... Cal.	12 miles W. of Zabriskie	Zabriskie	Zabriskie	Zabriskie	2-3
Antelope Springs ... Nev.	30 miles E. of Goldfield	Goldfield	Goldfield	Goldfield	1
Arasta Springs ... Cal.	17 miles N.W. of Silver Lake	Silver Lake	Silver Lake	Silver Lake	1-2-3
Ashford Mines ... Cal.	34 miles W. Zabriskie	Zabriskie	Zabriskie	Zabriskie	2-3
Avawatz Salt Gypsum ... Cal.	28 miles N.W. Silver Lake	Silver Lake	Silver Lake	Silver Lake	2
Baxter's Camp ... Cal.	6 miles E. of Shoshone	Tecopa	Tecopa	Shoshone	2
Baxter Springs ... Nev.	40 miles N.E. of Tonopah	Manhattan	Tonopah	Manhattan	2
Bellehellen ... Nev.	60 miles E. of Tonopah	Tonopah	Tonopah	Tonopah	2
Belmont ... Nev.	45 miles N.E. of Tonopah	Tonopah	Tonopah	Belmont	1-2
Berlin ... Nev.	90 miles N. of Tonopah	Austin	Austin	Berlin	2
Big Bell ... Cal.	25 miles S. of Rhyolite	Beatty	Beatty	Rhyolite	2
Carbonate Lead Mines ... Cal.	40 miles W. of Zabriskie, Cal.	Zabriskie	Zabriskie	Zabriskie	2
Carrara ... Nev.	3 miles N.E. of Ashton	Beatty	Beatty	Carrara	1-2
Cave Springs ... Cal.	20 miles N.W. of Silver Lake	Silver Lake	Silver Lake	Silver Lake	2
Chambers' Camp ... Cal.	20 miles S.E. of Tecopa	Tecopa	Tecopa	Tecopa	2
Chloride Cliff ... Nev.	25 miles S.W. of Rhyolite	Beatty	Beatty	Rhyolite	2
Confidence Mine ... Cal.	16 miles W. of Zabriskie	Zabriskie	Zabriskie	Zabriskie	2-3
Deming Spring ... Cal.	22 miles N.W. of Silver Lake	Silver Lake	Silver Lake	Silver Lake	2
Diamondfield ... Nev.	5 miles N.E. of Goldfield	Goldfield	Goldfield	Goldfield	2
Ellendale ... Nev.	30 miles E. of Tonopah	Tonopah	Tonopah	Tonopah	2
Golden Arrow ... Nev.	42 miles E. of Tonopah	Tonopah	Tonopah	Tonopah	2
Gold Mt. Mining District ... Nev. (Comprising Willow Springs, Old Camp, State Line, Tokop)	8 to 15 miles S.W. of Bonnie Clare	Goldfield	Goldfield	Goldfield	2
Gunsight Mine ... Cal.	7 miles E. of Tecopa	Tecopa	Tecopa	Tecopa	2
Hornsilver ... Nev.	14 miles S.W. of Cuprite	Goldfield	Goldfield	Hornsilver	2
Ibex ... Cal.	12 miles W. of Tecopa	Tecopa	Tecopa	Tecopa	2
Ibex Springs ... Cal.	14 miles W. of Zabriskie	Zabriskie	Zabriskie	Zabriskie	2-3
Iron Cap ... Cal.	10 miles N.W. of Leeland	Death Valley Jct.	Death Valley Jct.	Death Valley Jct. Cal.	2
Jamestown ... Nev.	40 miles E. of Goldfield	Goldfield	Goldfield	Goldfield	2
Johnnie ... Nev.	20 miles E. of Death Valley Junction	Death Valley Jct.	Johnnie	Johnnie	2
Keane Wonder Mine ... Cal.	24 miles S.W. of Rhyolite	Beatty	Beatty	Rhyolite	2
Lee Ranch (Resting Spg.) ... Cal.	6 miles E. of Tecopa	Tecopa	Tecopa	Tecopa	2
Liberty ... Nev.	30 miles N. of Tonopah	Tonopah	Tonopah	Tonopah	2
Lida ... Nev.	30 miles S.W. of Goldfield	Goldfield	Goldfield	Lida	1-2
Lucky Boy ... Nev.	10 miles W. of Thorne	Thorne	Thorne	Hawthorne	1-2
Manhattan ... Nev.	50 miles N.E. of Tonopah	Manhattan	Tonopah	Manhattan	1-2-3
Mayflower Mine ... Nev.	2¾ miles W. of Pioneer	Beatty	Beatty	Beatty	2
Millet ... Nev.	75 miles N.E. of Tonopah	Millet	Tonopah	Millet	1-2
Morrison's Ranch ... Cal.	5 miles S.E. of Tecopa	Tecopa	Tecopa	Tecopa	2
Montezuma ... Nev.	6 miles W. of Goldfield	Goldfield	Goldfield	Goldfield	2
Pacific Coast Borax Co. ...	Death Valley Junction, Cal.	Death Valley Jct.	Death Valley Jct.	Death Valley Jct.	Ry.
Pacific Nitre Beds ... Cal.	4½ miles S.E. of Tecopa	Tecopa	Tecopa	Tecopa	2
Pahrump Ranch ... Nev.	27½ miles E. of Shoshone	Tecopa	Tecopa	Pahrump	1-2-3
Pioneer ... Nev.	12½ miles N.W. of Beatty	Beatty	Beatty	Pioneer	1-2
Railroad Valley ... Nev.	110 miles N. E. of Tonopah	Tonopah	Tonopah	Tonopah	2
Rawhide ... Nev.	28 miles N.E. of Schurz	Rawhide	Rawhide	Rawhide	2-3
Resting Springs (Lee R.) ... Cal.	6 miles E. of Tecopa	Tecopa	Tecopa	Tecopa	2
Rhodes Springs ... Cal.	16 miles N.W. of Zabriskie	Tecopa	Tecopa	Zabriskie	2
Riggs Camp ... Cal.	1½ miles E. of Riggs	Silver Lake	Silver Lake	Silver Lake	2
Rosaiour Group ... Nev.	14 miles W. of Leeland, Nev.	Death Valley Jct., Cal.	Death Valley Jct., Cal.	Death Valley Jct., Cal.	2
Round Mountain ... Nev.	70 miles N. of Tonopah	Round Mt.	Round Mt.	Round Mt.	1-2-3
Salsbury Wash ... Nev.	30 miles E. of Tonopah	Tonopah	Tonopah	Tonopah	2
Saratoga Springs ... Cal.	10 miles W. of Dumont	Tecopa	Tecopa	Tecopa	2
Silver Bow ... Nev.	60 miles E. of Tonopah	Tonopah	Tonopah	Silver Bow	1
State Line ... Nev.	See Gold Mountain Mining District				
Telluride ... Nev.	6 miles E. of Beatty	Beatty	Beatty	Beatty	2
Transvaal ... Nev.	7 miles E. of Pioneer	Beatty	Beatty	Beatty	2
Ubehebe ... Nev.	65 miles S.W. of Bonnie Clare	Goldfield	Goldfield	Goldfield	2
Willow Creek ... Nev.	95 miles E. of Tonopah, Nev.	Tonopah	Tonopah	Tonopah	2
Willow Springs ... Nev.	See Gold Mountain Mining District				2
Wonder Mine ... Cal.	16 miles W. of Zabriskie	Zabriskie	Zabriskie	Zabriskie	2-3
Yeoman Mine ... Cal.	16 miles S.W. of Zabriskie	Zabriskie	Zabriskie	Zabriskie	2-3

Pahrump, Chicago and Stewart Valleys reached via Shoshone, Cal., on Tonopah & Tidewater R. R.
Death Valley Railroad connects with Tonopah & Tidewater R. R. at Death Valley Jct., Cal.

From the original timetable, 1917

crossing of Silver (dry) Lake north of the present day town of Baker. At that stage of the project, survey crews continued to chart out a detailed path for the railroad, in advance of the construction operations. In May of 1906, 75 miles of rail had been completed to a point just beyond Dumont, north of the Dumont dunes.

The greatest challenge that the crew faced was the 12 mile ascent over the mountains north of Dumont, through the Amargosa River Gorge and on to Tecopa on the southern edge of Amargosa Valley. These mountains were formed by left-lateral movement along the Garlock fault and extended east to west for many miles. Going around this great obstacle was not an option for Smith.

Smith met the challenge by starting at Tecopa and working downhill, from north to south. By attacking the problem in this manner, the workmen were able to used gravity to their advantage, a well-known factor commonly applied in the mining industry. This meant that the supplies and equipment would have to be offloaded at Dumont and hauled by wagon over the Ibex Pass.

By this time, the hot weather during the summer of 1906 was taking its toll on the work crew. Construction workers began quitting. By the time Smith was able to attract additional crews to the area, fall had arrived and the weather had cooled. By February 10, 1907, the line was completed from Tecopa south to Sperry, a railroad siding just south of China Ranch, where the Sperry Wash joins the Amargosa River Gorge.

Workmen constructed three trestles, excavated several long cuts, and compacted fill slopes. One of the trestles was over 500' long. In order to reduce the steep grade and at the same time avoid the bed of the Amargosa River, the railroad crossed and recrossed the canyon several times. In May, 1907, the railroad was completed through the Amargosa Gorge, connecting rails at Sperry with those at Dumont. Within days after achieving this great accomplishment, scheduled train service began operating to Tecopa.

By June, 1907, the railroad was completed to Zabriskie, a railroad siding four miles north of Tecopa. While construction continue northward, borax ore from the Lila C. was hauled by wagon to Zabriskie and transferred to the T&T line. Shortly after reaching Zabriskie, Smith formed the Tonopah & Greenwater Railroad, incorporated in 1907. He proposed a short-line off the T&T at Zabriskie to the mines of the Greenwater District in the area surrounding Greenwater Valley. The Tonopah & Greenwater Railroad was never built because of the collapse of the mining industry during the Panic of 1907.

On August 16, 1907, the railroad was completed all the way to the Lila C. mine. Ore from the mine was shipped by rail on that same day. By this time more than 700 men were working on the railroad. Camps were established at Lee's Well and at Gold Center. The railroad arrived at Gold Center on October 30, 1907. There was no celebration for this great event. By this time, the economy was feeling the full effect of the Panic of 1907. Many mines in the area continued to go bankrupt. Also, Senator Clark's Las Vegas & Tonopah Railroad reached Gold Center the year before and was completed all the way to Goldfield, Nevada.

On November 25, 1907, the T&T opened the entire line to scheduled freight service. By December 5 of the same year, the T&T boasted with the opening of passenger service. In the spring of 1908, a new rotary kiln was placed into service at the Lila C. mine. The town which grew around the Lila C. mine was named Ryan in honor of John Ryan, Smith's right-hand man. All remaining equipment, buildings and personnel were moved from Borate to Ryan.

On June 15, 1908, a holding company was formed under the name Tonopah & Tidewater Company, which assumed operations of the Bullfrog Goldfield Railroad. This gave the T & T exclusive trackage rights to Goldfield. With time, the Tonopah & Tidewater Company was absorbed by the T&T. With this action, the T&T now extended from Ludlow, California all the way to Goldfield, Nevada. In May, 1909, the Tecopa Railroad Company was incorporated in California. By 1910, a railroad spur from Tecopa was completed to the Gunsight and Noonday mines.

After ore deposits at the Lila C. were exhausted in 1914, mining operations were moved to the Biddy McCarty mine at the northeast edge of the Greenwater Range along Furnace Creek Wash. In January, 1914 the Death Valley Railroad (DVRR) was incorporated. New construction of the DVRR began at Horton, a railroad siding halfway between Death Valley Junction and the Lila C. mine. From this point, construction continued west 17 miles to the Biddy McCarty mine. On December 1, 1914, the DVRR was formally dedicated. The new town which grew up around the mine was also named "Ryan." The term (old) Ryan was later used in reference to the abandoned site at the Lila C.

The opening of scheduled rail service by the T&T brought progress to all the mines and towns along the route. The great hardship of hauling supplies and ore long distances by wagon had been superceded by the new rail service. Food, supplies, mail, mining equipment, farm equipment and even water could now be shipped with relative ease. Commodities from surrounding mines shipped on the T&T included gold and silver ores, base metal ores, borate minerals, bentonite (barium clay), and talc. The railroad brought many new industries and jobs to the area to service the mining and farming industries.

The T&T faced great challenges throughout its life. Flash floods, flooded "dry" lakes , landslides, erosion of the railroad bed, train derailments and mechanical problems were all too common on the T&T. Much of this was the result of the construction, operation and maintenance of a railroad in the harsh desert environment. Many of the conditions which resulted in damage to the T&T line were directly attributed to adverse geologic factors along the route. The railroad's greatest menace was the unpredictable Amargosa River. The river was known to turn from a dry wash into a raging torrent within minutes of a heavy downpour.

In 1927–1928, PCB began shifting its mining operations to a new deposit discovered in the Kramer Mining District, near the present day community of Boron. This was the beginning of the end for the T&T. The DVRR was officially abandoned in 1931. The T&T continued to haul supplies, equipment and ore on the line for numerous mines and town near the route. In March 1938, the T&T was severely damaged by floods from heavy rains. An application to cease operations was officially registered with the Interstate Commerce Commission in December1938 and on June 14, 1940, all operations on the T&T ceased. The War Department requisitioned the line and all its scrap iron in 1942. On July 18, 1942, contractors began removing the rails at Beatty and worked southward, using the line one last time to haul the iron. Ludlow was reached on July 25, 1943, closing a final chapter to the history of this great railroad.

Today, you can still see traces of the railroad from Ludlow to Beatty. What remains today are segments of the old railroad bed, concrete foundations around railroad sidings and bridge abutments, and culverts at most major drainage crossings. The railroad passed by the present site of Zzyzx on the west edge of Soda Dry Lake. A railroad siding at Soda was a short distance from what is now Zzyzx. When visiting Zzyzx, look for traces of the old railroad on the west edge of Soda dry lake. Highway 127 parallels and crosses the original route of the T&T as it heads north from Baker and beyond Death Valley Junction. On a calm day in the desert, some say they can still hear a train whistle along the old route!

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Climate variation since 1900 in the Mojave Desert Region Affects Geomorphic Processes and Raises Issues for Land Management

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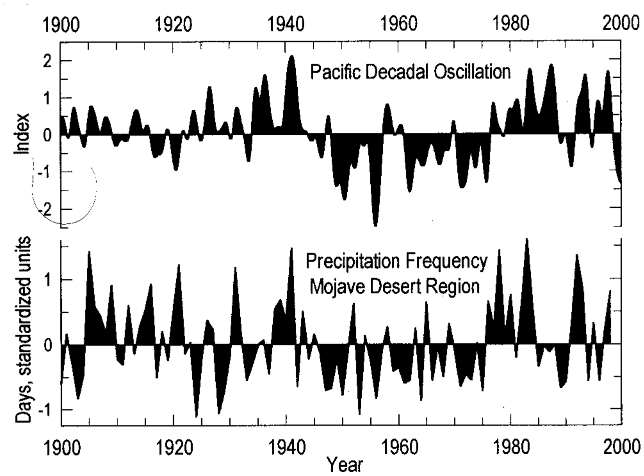
Precipitation in the Mojave Desert region varied substantially in the 20th century, causing landscape change and raising questions for land management. Precipitation patterns in this region are influenced by global-climate fluctuations of sea-surface temperature (SST) and atmospheric pressure operating on two time scales: the 4–7 year periodicity of the Southern Oscillation (SOI: El Niño and La Niña) and the decadal variations of the Pacific Decadal Oscillation (PDO), an index of the relative SST of the Northern Pacific Ocean. The average annual occurrence of daily precipitation $\geq$90th percentile, whose regional average is $\geq$55 ± 3 mm, has varied considerably, evidently in phase with the PDO. The frequency of this high-intensity precipitation, which is highly correlated with annual precipitation, was relatively large from the early 1900s to early 1940s and again from the late 1970s to 1998, whereas precipitation frequency was low in the intervening period of the early 1940s to mid-1970s. Dry years occurred during the two wet intervals but they were typically less frequent and of shorter duration than during the dry period. Likewise, wet years occurred during the dry period; these were of short duration, however, and regional precipitation was only slightly above normal.

Our results suggest these long-term changes in precipitation patterns affected overland flow and alluvial processes in the central Mojave Desert. Indeed, the physical landscape—the substrate of the desert ecosystem—was altered by the precipitation patterns of the 20th century. The Mojave River, the major drainage in the region, had large floods during nearly all Los Niños for which discharge records are available. Beginning around the mid-century, alluvial channels of large-basin streams such as the Amargosa River and Kingston, Death Valley, and Watson washes aggraded and developed floodplain-like surfaces, a likely response to few large floods which enhances sediment storage. Large, destructive floods were probably rare at this time because high-intensity precipitation was infrequent. In contrast, during the recent wet interval, several relatively large floods in the early 1980s and 1990s eroded the channels, scouring the floodplain-like surfaces.

Long-term precipitation variability alters the frequency of overland flow, which in turn affects sediment yield, surface stability, and replenishment of shallow aquifers. The frequency of overland flow and sediment yield are currently being reconstructed at 20 sites in the central Mojave Desert using artificially-ponded alluvial deposits. This alluvium



Top—*smoothed monthly indices, note sharp downward shift beginning late 1998.* Bottom—*annual frequency of daily precipitation $\geq$90th percentile averaged year-by-year at each of 52 weather stations, note increased frequency beginning 1976.*

occurs on the upslope side of several railbeds constructed around 1906 extending from Ludlow, California to north of Beatty, Nevada (Hereford and Webb, 1997; Myrick, 1992). The deposits record the number of times water and sediment entered the impoundments. Sedimentologic studies show that runoff large enough to deposit recognizable sedimentary layers occurred between 7 and 39 times across the region in the past century in basins ranging in size from 0.1 to 10 km^2. Using the presence of ^{137}Cs as a time-stratigraphic marker of the post-1952 atomic era, it appears that runoff frequency was relatively low after 1952 in at least 50 percent of the studied basins, suggesting the dry period affected runoff in small basins as well as large ones.

The response of the desert landscape to the climate variation of the past century provides a basis for predicting how the desert might respond to future climate. Current long-term climate predictions based on the PDO suggest that climate of the next 20 years may be similar to the 1940s–1970s. If so, this future climate is likely to produce several predictable responses in the desert ecosystem. Stream channels and hillslopes will likely adjust to the new precipitation regimen, as they respond to the expected decrease in the frequency of high-intensity precipitation. Alluvial channels are expected to recover or heal from the floods of the 1980s–1990s, as large floods will be relatively uncommon in the next several decades. Less-damaging floods will occur and should enhance sediment storage on developing floodplains; riparian vegetation may flourish in this flood regimen where ground-water levels do not drop substantially. Sediment yield is likely to decrease because of infrequent hillslope runoff and sediment storage in the alluvial channels of large basins. Infrequent runoff, however, could reduce recharge of shallow alluvial aquifers, although mountain-front recharge may not be significantly different from long-term rates.

Land managers should consider the potential influence of relatively dryer climate when planning restoration projects and monitoring biological components of the desert ecosystem. Restoration projects, investigations of landscape recovery, and studies of floral and faunal population dynamics undertaken in the previous 20 years were done when conditions were favorable for plant and animal growth. In the near future, persistent dry conditions will stress the flora and fauna, decrease surface runoff and replenishment of shallow aquifers, and increase recovery times from human disturbances. From the perspective of land management, the differences between the two climates are that in the dry regimen recovery times will be longer and the ecosystem will be more sensitive to disturbance.

Additional Information

Climate History Web Site: www-wmc.wr.usgs.gov/mojave/climate-history/

PDO data is from N. Mantua, http://atmos.washington.edu/pdo (accessed June 19, 2000)

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Mojave Desert Invasive Species Awareness

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February 26 – March 2, 2001, was the 2nd Annual National Invasive Weeds Awareness Week, "Pulling Together on Invasives Awareness." There is a compelling reason for this nationwide outreach program. Thousands of non-native, invasive plant and animal species are wreaking ecological havoc throughout our nation. Some federal agencies estimate over $100 billion annually in crop loss, equipment damage/replacement, native species extinction, habitat degradation, wildfire frequency/intensity/spread, and weed eradication efforts. A recent GAO report stated:

> The impact of invasive species in the United States is widespread, and their consequences for the economy and the environment profound. They affect peoples' livelihoods, placing sustainable development and industries such as agriculture, ranching, and fisheries at significant risk. Depending on the species, they have increased pest control costs, contaminated grain, reduced the grazing capacity of rangelands, lowered water tables, and displaced native plants and wildlife habitats. Invasive species are ubiquitous. Hundreds and perhaps thousands have established populations in the United States, with almost every area of the country having at least one highly damaging invasive species.

Our fragile desert ecosystem is particularly vulnerable. Invasive salt cedars have decimated precious water sources. Exotic forbs and annuals such as *Schismus* ssp., *Bromus* ssp, *Salsola* ssp, and various mustards have significantly altered the fire regime of our desert, through fuel-loading and interspacial filling between vegetative mounds. Floral species are not the only cause for concern. Faunal invasives such as ravens and feral dogs and cats are contributing to the decline of the threatened desert tortoise and other native species. Once established, invasive species are difficult, if not impossible, to eradicate because of their pervasive nature and the sheer economics involved with mitigation.

Throughout the Mojave Desert, that "one highly damaging invasive species" is *Tamarix ramossisima*, or salt cedar, also known as tamarisk or athel. Anywhere in the desert where there is (or was) a homestead, one can usually find tamarisk. They are effective windbreaks, able to flourish under austere conditions, which is why they were imported from Europe, Asia, and North Africa in the mid-1800s. The largest, *Tamarix aphylla*, while an exotic, is not generally regarded as a problem, although it is a huge water evapotranspirator. However, its almost identical (but generally smaller and bushier) relatives, *T. ramosissima*, *T. chinensis*, and *T. parviflora,* have been declared Public Enemy No. 1 of the western U.S. These aggressive salt cedars quickly escaped human cultivation to infest all the major river systems of the west (such as the Mojave, Colorado, Gila, and Rio Grande), as well as springs and seeps, those precious oases of life in the desert. Most of the river systems originally had stable ecosystems of mesquites, willows and cottonwoods, which were cut down for fuel and building (steamboats, homesteads, mines). The dam-building spree of the 1940's completely altered natural water flow (in this case, spring flooding) which is essential for cottonwood and willow germination, but detrimental to salt cedars. *Tamarix* quickly became established in these disturbed areas, forcing out native plants by decreasing the available water and increasing the salinity of the surrounding soils by exuding salt from their leaves. One mature tree can produce 500,000 seeds per year. These tiny seeds are carried by wind and water for great distances. Once established, a seedling can mature to a flowering plant in as little as 4 months.

Large game like bighorn sheep and deer will eat willow and cottonwood seedlings/saplings, but not salt cedar. Honeybees will collect pollen and nectar from salt cedar, but the end result is of inferior quality. Unlike willow and cottonwood seeds, salt cedar seeds are too small to be a food source for birds and rodents. The trees make inferior nesting sites as well. Virtually nothing will grow under and around a stand of salt cedar, because of the exuded salts, whereas cottonwood and willow stands typically form the basis of biologically rich micro-ecosystems.

Locations in Death Valley and Afton Canyon have experienced dramatic changes. At the Eagle Borax Works Spring in Death Valley, a historic one-acre pond disappeared soon after it was invaded by salt cedar. Eight weeks after the salt cedar was removed, the pond recovered. Afton Canyon, 30 miles north of Barstow on BLM land, had lost 70% of its natural vegetation since the 1960s. More than two years of dedicated eradication efforts by BLM staff, work crews, and volunteers have resulted in the return of year-round flowing

Saltcedar.

Salsola

Mustard

Tumblemustard

water and natural revegetation at its mouth. Work is continuing in the lower reaches. It is a manual labor-intensive job; the only effective way to combat salt cedar is to cut them down and treat the stumps with herbicide, usually *Garlon*.

Another common invasive throughout the Mojave is tumbleweed, that rotund fixture of cowboy country and song, which came from Russia in the flaxseed that emigrants brought with them from the Old Country. 1877 was the year, and South Dakota was the place. By 1900, it had spread westward with a vengeance and is now firmly established throughout the western states. Its scientific name is *Salsola tragus*, or Russian Thistle, although it is not actually a member of the thistle family. *Salsola paulsenii* is another aggressive subspecies. They tumble along in the wind to disperse their quarter million or so seeds per plant. They can't take hold in undisturbed areas, but establish immediately in terrain that has been graded, plowed, run-over, or otherwise degraded. If natural vegetation is allowed to regrow, the tumbleweed can't germinate, and dies out. On the other hand, if allowed to establish, it can form a huge monoculture, rendering the property virtually useless. NAS Fallon has training ranges that can no longer be used for ground operations because tumbleweed has rendered them impenetrable and because of fire hazard.

Another common invasive easy to spot in the high desert are mustards. The easiest one to find is *Brassica tournefortii*, or Sahara mustard, which came from North Africa. It is now common along roads and in cleared (disturbed) areas, and is very green, with multiple stems that can reach 3 feet in height. The flowers are tiny, dull yellow, with a basal rosette of large leaves and smaller leaves up the stems. The other is tumble mustard, or *Sisymbrium altissimum*, a native of Europe. Many sections of our state highways have been particularly infested with that invasive. It's easiest to spot after dying, because of its distinctive woody "skeleton". Both of these plants germinate, grow and flower long before any native species. Dense stands of mustards crowd out native plants, monopolizing soil moisture and causing major habitat degradation for faunal species such as the threatened desert tortoise. They also exponentially increase the risk of wildfire spread.

In Joshua Tree National Park, infestation of another invasive, red brome (*Bromus rubens*), was largely to blame for the intensity, quickness, and longevity of recent fires. Cheat grass (*Bromus tectorum*) and Mediterranean grass (*Schismus barbatus*) are also major culprits where wildfires are concerned. *Schismus* is now endemic to much of the Mojave Desert, with no eradication method known to date. Tortoises will eat *Schismus* to keep from starving, but it is too high in nitrogen and too low in other nutrients to be a good food source.

Invasive fauna such as ravens and feral dogs are also detrimental to the desert tortoise. They are voracious predators of hatchlings and juveniles, in particular, whose soft shells harbor no defense against strong beaks and canines. Adult tortoise are at risk from being flipped over by dogs and coyotes. Unable to right themselves, they soon die from exposure. Pet and feral cats create "dead zones" around human habitation sites because of their predatory skills. Birds and lizards are particularly vulnerable, as are kangaroo rats and other small mammals.

Although the seriousness of the invasive exotic species threat was recognized in the scientific community by 1958, the public did not become concerned until the 1980s, when it became a noticeable economic liability in the farming, ranching and fishing industries. A series of studies and publications led to Executive Order No. 13112, issued in 1999, which established the Invasive Species Council. In October of 2000, a draft National Invasives Species Management Plan was submitted to the American public for comment. Nine priority areas were identified: leadership and coordination, prevention, early detection and rapid response, control and management, restoration, international cooperation, research, information management, and education/public awareness. From this initiative, Weed Management Areas have been mobilized. In the Mojave, an interagency group of concerned scientists and other professionals met on 24 Jan 01 to establish the Mojave Weed Management Area. An Integrated Weed Management Plan is being developed under the auspices of the Mojave Desert Resource Conservation District.

In many cases, weed eradication is no longer a viable option in the Mojave Desert. Weed management, however, if conducted deliberately and in conjunction with sound scientific practice, can mitigate the damage already done. To meet this challenge, the dedicated efforts of all concerned are essential and critical.

For more information on invasive species or community action weed eradication opportunities, the Mojave Desert Resource Conservation District is an excellent source at (760) 242-2906, http://www.mdrcd.ca.gov, as is the California Exotic Pest Plant Council, at http://www.caleppc.org.

Wolves of Shoshone, Southern Death Valley

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ABSTRACT

Reexamination of the trackway assemblage located near Shoshone in eastern Inyo County, California, has discovered carnivore tracks attributable to wolves. Previously-described tracks at the site include those of horses, camels, and elephants. The tracks are in coarse mudflow sediments associated with Lake Tecopa, which was filled intermittently during the Blancan Land Mammal Age (LMA) and through the Irvingtonian LMA. The mid-Pleistocene (Irvingtonian LMA) Shoshone tracks are of particular interest because they are easily datable, being located immediately below 665,000 year-old Lava Creek B Tuff.

Introduction

The southern Death Valley area contains a wealth of fossil footprints (sedimentary structures called "ichnofossils"). Copper Canyon contains spectacular sequences of bird, herbivore and carnivore tracks from the early Hemphillian Land Mammal Age (LMA) (Scrivner and Bottjer, 1986; Santucci and Nyborg, 1999). Horse tracks from the Shadow Mountains are from the late Barstovian LMA (Friedman, pers. comm., 1997: Sarjeant and Reynolds, 1999). Camel and bird tracks from the southern Avawatz Mountains are early Clarendonian LMA (Evernden and others, 1964: Sarjeant and Reynolds, this volume). Camel tracks from Military Canyon in the northern Avawatz Mountains are late Clarendonian LMA (Brady, 1990). Mid-Pleistocene herbivore tracks in the Lake Tecopa sediments near Shoshone were described recently (Reynolds, 1999).

Geology

Tecopa Basin is a late Tertiary through Quaternary depocenter east of Death Valley (Louie and others, 1996). Geologic mapping (Chesterman, 1973; Hillhouse, 1987) suggests that Lake Tecopa covered approximately 250 km^2. Dated ashes such as the Huckleberry Ridge Tuff (2.02 Ma), the Bishop Tuff (758,000 ybp) and the Lava Creek B Tuff (665,000 ± 10,000 ybp) have been used as marker beds (Hillhouse, 1987). Lake Tecopa may have drained prior to the Rancholabrean LMA (~150,000 ybp) (Reynolds, 1991; Woodburne and Whistler, 1991), or within the last 100,000 years (Morrison, 1999).

Fossil Faunas

Vertebrate faunas preserved in Lake Tecopa contribute to the evidence for the presence of a freshwater lake between the late Blancan LMA (late Pliocene) and the Irvingtonian LMA (middle Pleistocene). Late Blancan LMA faunas are present low in the section (James, 1985). Large mammals and birds from the Irvingtonian LMA are associated with the Huckleberry Ridge Tuff (2.02 Ma) and the Bishop Tuff (785,000 ybp) (Sheppard and Gude, 1968; Whistler and Woodburne, 1991). They include flamingos, antelopes, llamas, large camels, giant camels, horses, mammoths, mastodons and small miolabine goat-like camels (Whistler and Webb, 2000). Fractures that post-date the drainage of Lake Tecopa contain fissure-fill deposits with Rancholabrean LMA mammals including *Equus* sp., *Camelops* sp., *Mammuthus* sp. and *Hemiauchenia* sp. (Reynolds, 1991).

Shoshone Trackways

In the Tecopa Basin sediments at Shoshone, the Lava Creek B Tuff (665,000 ± 10,000 ybp, Izett and others, 1992) immediately overlies tracks of quadrupedal herbivores. The tracks (Reynolds, 1999) are located in mud flow debris, a mixture of white silt, sand, and matrix-supported gravel and cobble-sized clasts. Most of the horse tracks are distinct; the mammoth and most of the camel tracks are less well defined but fall into consistent size ranges. A distinct camel footprint provides a baseline measurement for camel tracks that are exposed. The mammals may have passed at different times when the substrate was in varying degrees of dewatering or induration. The difference in animal weight may have played a part in the clarity of track detail and impact to the substrate. Tracks are attributed to mammoths (~40 cm diameter), camels (20 cm diameter), and horses. The 24 horse tracks show variation in size attributable to a herd of individuals of different ages and sex.

Plotting the orientation of the camel and mammoth tracks show they are clustered along a bearing of S5°E to S5° W. In contrast, some of the horse tracks accord with this bearing and direction while others were traveling S65°E, and N 50° W. The tracks suggest that animals may have been traveling to Lake Tecopa, a source of water and vegetation at this time.

New Carnivore Tracks

Reexamination of the Shoshone trackway site on several instances in the year 2000 located one carnivore trackway consisting of two prints and a second area where multiple overprints were preserved. In the former trackway, the prints are relatively clear although marks left by claws are not distinct. The lack of distinct claws does not specifically identify the maker as a felid, but speaks more to poor preservation in an unfavorable substrate. Digital pads and carpal/tarsal pads are preserved as impressions.

Because the Pleistocene carnivore tracks from Shoshone are large, they were compared to tracks of wolves and mountain lion described by several authors (Chase and Chase, 1969; Murie, 1974; Rezendes, 1999). Rezendes (1999) gives characteristics of wolf tracks that distinguish them from mountain lion tracks. Both have front tracks larger than hind. Mountain lion tracks are wider than long. The digital pads are anteriorly elongate but larger to the rear, somewhat teardrop in shape. The metacarpal/metatarsal pads are trilobed, the lateral lobes smaller and set more

TABLE I: Measurements of Wolf Tracks (in inches)

	Length	Width
Manus	3-11/16	3-1/4
lateral digital pads	1-1/16	3/4
medial digital pads	1-1/8	7/16
metacarpal pad	1-7/8	2-1/16
Pes	3-7/8	2-15/16
lateral digital pads	1-1/16	3/4
medial digital pads	1-1/8	7/16
metacarpal pad	1-5/8	1-11/16

posterior than the middle lobe. The middle lobe is bi-lobed anteriorally. There is a greater definition between the lateral lobes in the metatarsal pad than in the metacarpal pad.

Wolves have tracks that are longer than wide. The digital pads are elongate ovals, equidimensional at either end, usually with thick claw marks impressed in the substrate. The middle digital pads (digits II, III) are parallel. The metacarpal pad is trilobed; lobes are configured differently than mountain lion. The metatarsal pad is a subrounded triangle, narrow anteriorly, without distinct lateral lobes.

The tracks from Shoshone (Table I) are longer than wide, and fall within the size range of wolf tracks (Rezendes, 1999; Murie, 1974). The two tracks are oriented along the same bearing, suggesting they were made by the same individual, and the larger size of the northern track suggests a manus. The manus is large with oval digital pads, the medial pads being parallel. The metacarpal pad is large and trilobed. In the presumed pes, the metatarsal pad appears to be triangular. The distance between the tracks is 22.5 inches (Figure 1), suggesting that the animal was moving at a walk or a slow trot. The trackway is along a bearing of S 10° E, similar to the bearing of herbivore tracks at this locality.

Large fossil canids known from the Irvingtonian LMA include Canis Spp and Borophagus sp. (Savage and Russell, 1983). However, the size range of canids is known to overlap, so any attempt to make an assignment to species would be inappropriate.

The second set of tracks consist of two areas, two inches apart, with multiple overprints. When running, the hind foot of an animal will often land in the print left by the forefoot. This has been observed in prints of packs of carnivores and herds of herbivores. Generally, the prints are indistinct and it is rare that individual digits can be discerned. At the second Shoshone site, four elongate digital pads and an associated carpal/tarsal pad can tentatively be identified. The size and shape of the digital pads is similar to the first trackway occurrence (Table I).

Summary

Tracks of canids from sediments of Miocene age have previously been described (Scrivner and Bottjer, 1986;Sarjeant and Reynolds, this volume). Irvingtonian LMA small canid tracks have been described from Anza-Borrego Desert (Remeika, 1999). The wolf-sized tracks from the Irvingtonian LMA mid-Pleistocene sediments of Lake Tecopa are the first Pleistocene canid tracks to be described from this deposit. In the Tecopa Basin sediments, the Lava Creek B Tuff (665,000 ± 10,000 ybp) immediately overlies the tracks.

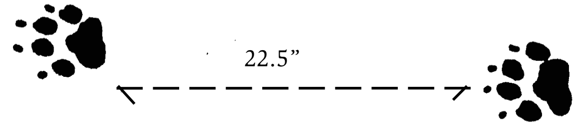

Figure 1. Wolf tracks at Shoshone, showing pace.

The mammals may have passed at different times when the substrate was in varying degrees of dewatering or induration, causing variation in track clarity.

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The Franklin Wells Hectorite Deposit, Inyo County, California

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Introduction

Hectorite, the rare lithium smectite mineral, is mined at only four locations on earth. One of these is near Franklin Wells in the western Amargosa Valley of California, on the eastern flank of the Funeral Mountains Wilderness Study Area (Figure 1). The mineral occurs in lake beds as a hydrothermal alteration product of volcanic ash along a fault zone. The deposit was originally named the Hectorite Whiting Pit. In this report it is referred to it as the Franklin Wells Hectorite Deposit.

History

Mining for carbonate on the subject claims occurred as early as the 1920s. “The deposit was first mined in the 1920’s as a source of whiting, or whitewash,” according to Jack Mayhew, former IMV (Industrial Minerals Ventures) geologist. (Hay, 1985, p.57; see also Wright and others; 1953). Mining at Hector, California (the site from which “hectorite” was named) did not commence until 1931 (Rheox, Undated; Foshag and Woodford, 1936,).

The Franklin Wells area presently mined was originally located for limestone placers on December 21, 1931, by IMV. The commodity of interest at the time of location was white lacustrine limestone for use as decorative rock and as a paint pigment.

The original mining for white limestone in the 1930s was replaced in 1974 by interest in hectorite-bearing clays positioned stratigraphically above the limestone (Hay, 1985, p.57). These clays found applications in the drilling mud and paint industries. Specialized markets for hectorite in the manufacture of rapid-speed printing inks, personal care products (e.g. shampoo), pharmaceutical and organoclay industries arose in the 1970s.

IMV corporation mined the deposit for hectorite between 1974 and 1991. The ore was beneficiated at the IMV plant in Nye County, Nevada, 1.5 miles north of the deposit. The present operator is Southern Clay Products, Inc. who develops a wide range of applications for hectorite in the organoclay industry. It is used in specialty applications such as drilling muds, polyester and fiberglass resins, and industrial coatings. An ortho-photograph of the mine area is shown in Figure 2.

Location

The Franklin Wells Deposit is in the Amargosa Valley approximately ½ mile west of Franklin Wells and nine miles northwest of Death Valley Junction in Inyo County, California. The hectorite deposit is partially within the Upper Amargosa Valley Area of Critical Environmental Concern and two miles east of the western boundary of the Funeral Mountains Wilderness Study Area.

The deposit is situated on the lower western flank of the Amargosa Valley. The relief is nearly horizontal, transected by occasional arroyos 1 to 10 feet deep.

The surface geology consists of alluvial fans and pediment surfaces. Most of the surface above the deposit is desert pavement. Vegetation is sparse, high-desert flora dominated by moderate-diversity creosote brush scrub of the northern Mojave floristic zone. In this area, the lowest portions of alluvial fans are dominated by shadscale, desert holly, and mesquite, with an understory of saltgrass (BLM,1998).

Wildlife in the mine area are reptiles (whiptail lizards, zebra-tailed lizards, sidewinder rattlesnakes), small mammals (pocket mice, Meriam’s kangaroo rats, antelope ground squirrels, desert woodrats), and birds (prairie falcons, golden eagles). No threatened and endangered species, significant archaeological sites or other sensitive resources are known to occur in the mine area (BLM, 1998).

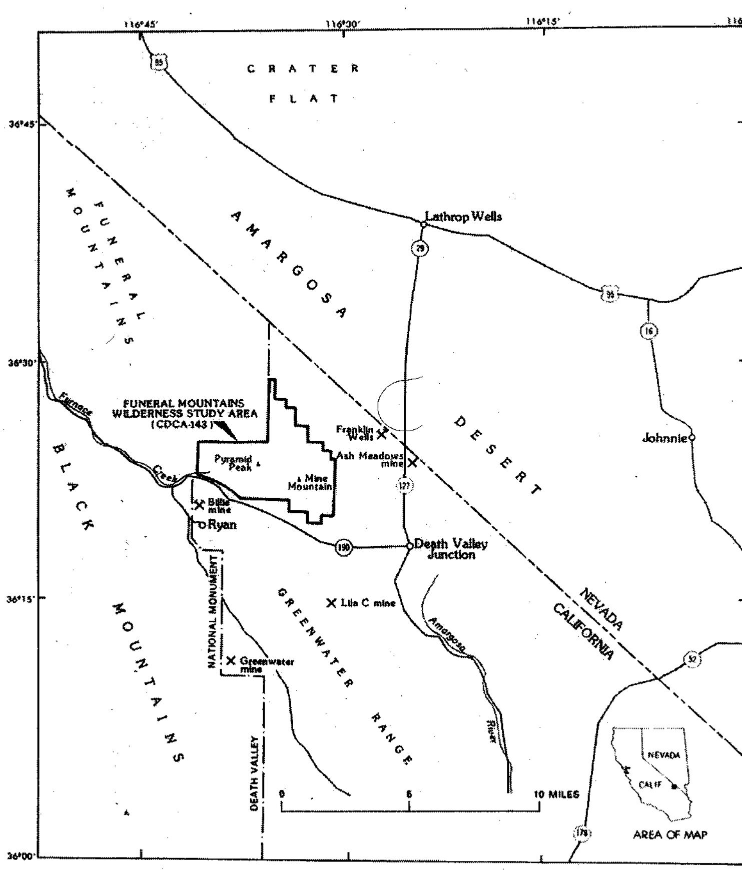

Figure 1. Location of Franklin Wells. From Armstrong and others, 1987.

Regional Geology

The Amargosa Valley is a basin-and-range structure with the Greenwater Range and Funeral Mountains to the west and the Amargosa Desert to the east. The Greenwater/Funeral mountains are fault-controlled with narrow interior valleys and are bounded by broad, coalescing alluvial fans (Armstrong et al., 1987).The Greenwater/Funeral mountains are composed of lower Paleozoic marine and metamorphic rocks (Streitz and Stinson, 1974).

Bestram (1985:9) who performed a mining claim validity examination of the Ash Meadows clay deposits 8 miles east of the Southern Clay property, summarized the regional geology for the area of the Franklin Wells Hectorite deposit:

> Rocks of lower Paleozoic and Tertiary age make up the highlands and mountains; the lowlands are mantled by various types of Quaternary deposits. Tuffs and tuffaceous sandstones make up the bulk of the Tertiary rocks found in the northern most part of the [Lathrop Wells] quadrangle. Basalt is found, commonly capping ridge tops.
>
> Structurally, the area was effected by two major periods of deformation. During the late Mesozoic-early Tertiary phase, compressional deformation predominated. Large easterly-directed thrust faults, accompanied by folding and strike-slip faulting, were the rule. About 17 million years ago, a major change occurred in the tectonic setting of the region with the onset of extensional faulting and volcanic activity (Stewart, 1980). Basin and range faulting, which began in the Miocene and continued to the Holocene, is responsible for the topography and geology seen today. It is suggested by Denny and Drews (1965) and Khoury (1978) that during the Pleistocene much of the lowlands in the Lathrop Wells and Ash Meadows quadrangles were covered intermittently by perhaps a series of pluvial lakes. Significant amounts of lacustrine sediments were deposited in the area during this period as well as the continuing influx of fluvial clastics.

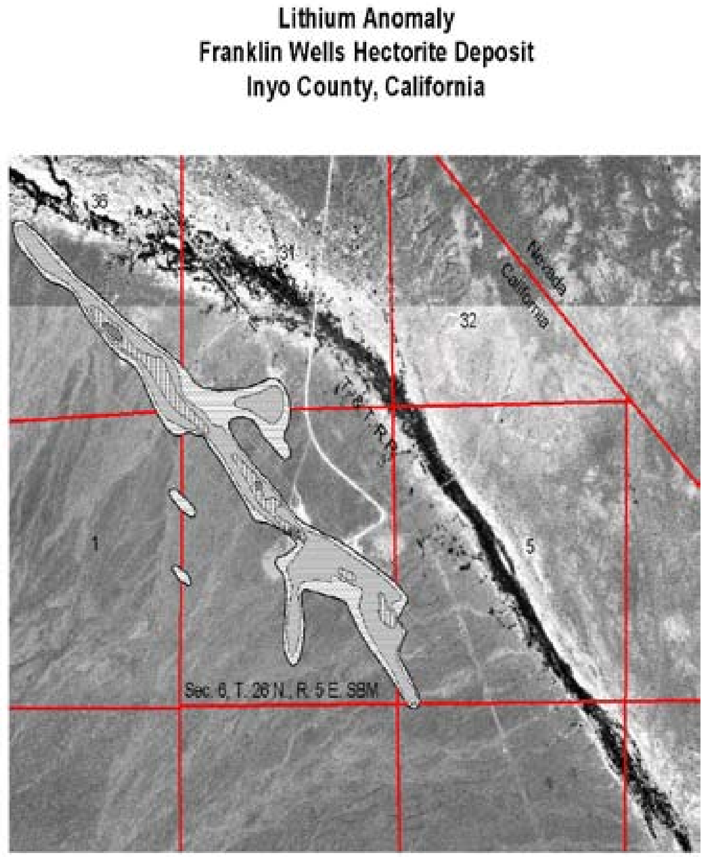

Figure 2. Orthophotograph of the Southern Clay mine at the Franklin Wells Hectorite Deposit and Lithium/Fluorine anomaly. The orthophotograph is a digital, elevation-corrected image based on U.S. Geological Survey aerial photography. The Lithium/Fluorine anomaly is from a map produced during development of the White King claim group. The Bureau of Land Management discovered the map in archives from the Floosy Doosy-White King drilling program of the 1960s during a examination of the deposit.

Regional geology is also described by Hay and others (1986:1489-1490):

> The Amargosa Desert is an intermontane basin in the western part of the Basin and Range province. It drains southward into Death Valley drainage system. Highly folded and faulted Paleozoic rocks of Cambrian to Devonian age underlie the basin and form highlands around its east, south and west sides. Miocene volcanic rocks of the Timber Mountains-Oasis Valley caldera complex border the basin on the north (Christiansen and others, 1977) and extend southward beneath the basin fill, with exposures locally in the southern part of the basin. Most of the volcanic rocks are silicic ignimbrites between 9.5 and 16 m.y. in age (Christiansen and others 1977). The volcanic rocks are overlain by a varied assemblage, including fanglomerates, siltstones, limestone and tuff. These deposits are moderately to highly deformed and have been correlated with the Furnace Creek Formation of Death Valley (Naffe, 1973) which has been dated at 5.3 to 6.5 Ma (Fleck, 1970).
>
> Relatively undeformed Pliocene and Pleistocene sediments fill the present geomorphic basin. The bulk of the basin fill is Pliocene and contains the large deposits of Mg clays. Exposed Pliocene deposits consist largely of clays and carbonate rocks that crop out widely in the eastern half of the basin and at relatively few places in the western half. The maximum exposed thickness, at Fairbanks Butte, is about 50 m, but as much as 295 m. of presumed Pliocene deposits have been penetrated by drilling in the Ash Meadows Area (Naffe, 1973) … The clay-rich Pliocene sequence probably ranges from 2 to 4 m.y. in age.

Local Geology

The geology in the Ash Meadows area is described as follows:

> The deposit mined in the Amargosa Valley region of California (in the same area as Hector) [sic, not accurate because Hector is near Newberry Springs] forms part of a thick sequence of smetcite layers. In addition to hectorite, there are extensive deposits of sepiolite and saponite—a magnesium rich smectite which matches some properties of sodium bentonite. ("IM" Oilwell Drilling Survey, 1978, p 52).
>
> Unusual and economically important clays of late Pliocene age have been found in the Amargosa Desert of southeastern Nevada. These include sepiolite, magnesium silicate , and bentonite. The sepiolite is relatively pure and contains little aluminum. The magnesium smectite is mostly stevensite with interlayered kerolite but includes

> hectoritic and probably sapionitic varieties (Eberl et al, 1982, Khoury et al, 1982). The bentonite is a volcanic ash altered to dioctahedral (sic) smectite. The clays are mined by Industrial Mineral Ventures (IMV)." (Hay and others, 1989). Stevensite and hectorite are both trioctahedral smectite minerals (Jackson, 1997, p. 293 & 623).
>
> The Amargosa Desert is now and has for at least the past 3.2 m.y. been a spring-fed hydrologic basin. Present discharge is about 58,000 m^3/day (17,000 acre ft/yr), and the Pliocene discharge was substantially greater than this. The water is of a Ca-Mg-Na-HCO_3 type and receives its solutes from recharge areas in the Paleozoic carbonate rocks and Miocene silicic volcanic rocks. The magnesium-silicate clays were precipitated by evaporation of spring water in playas, ponds, and related environments. Bentonite was formed by alteration of ash in ponds. Salinities in the ponds and playas were never high, judging from the isotopic composition of calcite and dolomite associated with the magnesium-silicate clays (Khoury and others, 1982).

Additional descriptions of the local geology are found in Cemen and others (1982), Hay and others (1986), Naffe (1973) Neumann (1984), Taylor (1986)

Deposit Geology

The Franklin Wells Hectorite Deposit has been described in the following way:

> Hectorite, a lithium-rich clay, and mineral whiting $CaCO_3$ are mined by Industrial Mineral Ventures, Inc. west of Franklin Well. Hectorite is used in the manufacture of cosmetics and ceramics. Mineral whiting is used in the paper industry. Industrial Mineral Ventures has at least 36 claims here, and has applied for patents on some of the claims. BLM estimates this deposit contains 33,000,000 tons of hectorite reserves and another 33,000,000 short tons of resources valued at $1,330,000,000. Both clinoptilolite and hectorite probably formed from alteration of volcanic sediments. Anaconda has traced the 30-500 ft. thick clinoptilolite beds in southeast dipping Tertiary or Quaternary ash flow tuff. Hectorite is in the Quaternary sediments (Marcus, 1980, p. 5).
>
> On the western flank of the Amargosa Valley of Nye County in Nevada [but in California], Industrial Mineral Ventures exploits a mixed hectorite/calcium carbonate deposit that extends a distance of about two miles and averages about 700 feet in width. Thickness of the deposit varies from the thin feathery edges of the deposit to around 40 feet at the center—an average thickness of 15 feet overall. The deposit consists of about 25% hectorite and 75% calcium carbonate although accessory quantities of silica also occur (Clarke, 1989a, p. 77).
>
> This [Hectorite Whiting Pit, Franklin Wells Deposit] mine, on the west side of the [Amargosa] basin, is in a caliche breccia about 3 km (1.9 mi) long, 0.6 km (0.4 mi) wide, and, locally at least 6 m (20 ft) thick. It formed by precipitation of calcite (whiting) and magnesium-silicate clay (hectorite) as nodules in the vadose zone within the playas (?) clays. Growth of new nodules displaced the older nodules upward, resulting in masses of brecciated nodules that disrupted the overlying clays. Sheared veins of magnesium-silicate clay are not uncommon. Samples of the clay have been identified as hectorite, but some other samples are lower in lithium and fluorine than is typical of hectorite"(Hay,1985, p. 57).

The hectorite, in zones zero to twenty feet thick, is dispersed in carbonate "breccia" overlain by zero to thirty five feet of gravel and underlain by a layer of hard limestone. Hectorite-bearing carbonate is exposed in some arroyos around the mine. The hectorite occurs in a linear band that parallels the structural axis of the Funeral Mountains to the west.

There is extensive evidence of hydrothermal activity along the surface expression of the Franklin Wells fault, including massive sinter deposits southeast of the current mine area.

At the Franklin Wells Hectorite Deposit, the valuable minerals are hectorite and some stevensite which makes up 5 to 35% (averaging 13%) of the ore. Gangue consists of other associated clay minerals, carbonate and silica. The ore body is tabular, 3 km (1.9 mi) long, 0.6 km (0.4 mi) wide, and, locally at least 6 m (20 ft) thick (Hay,1985, p. 57).

The ore body is defined by a Lithium/Fluorine geochemical anomaly, which clearly delineates the position of the Franklin Wells fault zone (Figures 2 and 3).

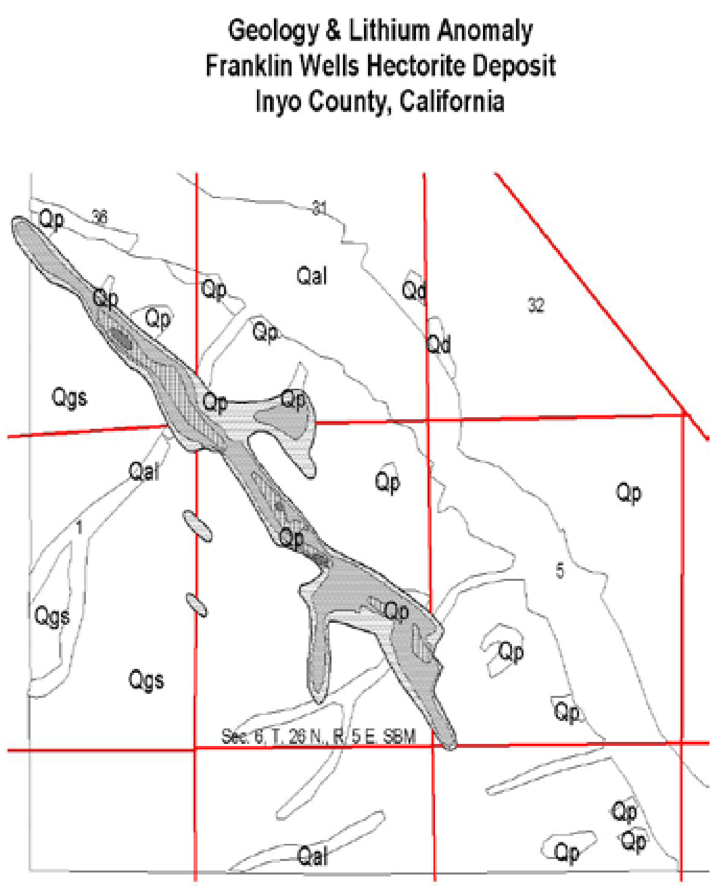

Figure 3. Geologic map of the Franklin Wells Hectorite Deposit and Li/F anomaly. Note that the anomaly is not reflected in surface geology, but is sub-parallel to a straight segment of the Amargosa River. The anomaly marks the position of the Franklin Wells fault zone. This zone is one of a series of basin-and-range faults in Amargosa Valley, which influence the position and alignment of the Amargosa River.

Mining Activity

Southern Clay Products, Inc. currently mines about 5,000 tons a year of hectoritic calcite "breccia" by open-pit methods. The material is dried on site and trucked to Las Vegas, where it is shipped by rail to the Southern Clay Products' Gonzales, Texas plant for beneficiation.

Deposit Genesis

Models for hectorite genesis are found in Asher-Bolinder (1991) where hectorite is identified as a product of hydrothermal alteration. At the Franklin Wells deposit, the hectorite is an alteration product of volcanic ash in the carbonate breccia and formed from hot spring activity along a fault More specifically, hectorite mineralization occurred as the replacement of Li for Mg in the montmorillonite crystal lattice of volcanic (dacite) ash grains during hydrothermal (spring) activity. This alteration is most pronounced along a fault zone, which we name the Franklin Wells Fault. Some hydrothermal alteration creates lens-like bodies below the overlying gravels/carbonate contact and reflects the original geometry and composition of the ash beds in the lacustrine sequence.

The three controlling factors in hectorite genesis are the presence of dacitic ash beds, a fault conduit system and lithium-rich hydrothermal activity. Such ingredients are common throughout the Basin-and-Range. The fortuitous overlapping in space and time of these conditions make hectorite a rare and valuable specialty mineral.

Acknowledgements. Kenneth Schulte, Larry Monroe and Mike McGrath contributed important insights to this paper.

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The Hanging Gardens of Amargosa Canyon

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ABSTRACT

Amargosa Canyon Natural Area is located just south of the community of Tecopa in Inyo County, California. It is notable for its colorful geology, the scenic river gorge, and unique assemblage of plants and animals. Tropical plant species, typically not able to survive through the freezing winter conditions of the region, persist because of the geothermal water flowing 30 to 100 feet down the canyon wall. *Cladium californicum* and other plants with tropical affinities may have established in Amargosa Canyon and the surrounding region by being passively imported by prehistoric cultures, Native American traders, or by livestock during the 19th century. Propagules could have been from the Gulf coast, southwestern territories, and/or the California coast. Alternatively, the plants may be relics from pluvial period that occurred in the entire southwest before the cool Quaternary effected the Mojave desert. The river ecosystem may be relict populations persisting since the semi-tropical Pliocene. The wildlife associated with the riparian wetland are either rare or have a high degree of endemism because of the isolated nature of the aquatic habitat in the desert region.

Introduction

Amargosa Canyon Natural Area, an Area of Critical Environmental Concern, is a popular natural area visited by desert enthusiasts. The canyon is located one-half mile southwest of Tecopa, California and two miles north of the San Bernardino-Inyo County Line. The canyon is the dividing line between the Sperry Hills on the west and the Alexander Hills on the east (Tecopa 7.5" USGS quad SW 1/4 section 15 T.21N. R.7E., SBBM; UTM Zone 11 570290mE, 3965850mN). Elevation is 410 m (1,345 ft) at the trailhead.

The Bureau of Land Management (BLM) affords this area special attention in order to protect important historic, cultural, and scenic values, and fish and wildlife resources while providing safe public access. Extensive removal of the invasive species, tamarisk, has been undertaken in the riparian areas. Trail improvements and an interpretive program have been initiated in Amargosa Canyon with the help of volunteers.

As soon as you hike out of the first tributary arroyo at the beginning of the Amargosa Canyon trail, grasses and forbs can be seen growing on the east canyon wall. The white, pink and purple quartzite strata in the canyon face catches your attention as you begin to walk on the old railroad bed. When you leave the stand of trees and walk up onto a small knoll of blue and purple quartzite, you are surprised by the sound of cascading water. Warm groundwater from Chicago Valley is flowing down the east canyon wall at several locations where the railroad cut was made between the knoll and the canyon wall. In contrast to the barren, steep and rocky canyon walls, the waterfalls support a dense stand of saw-grass (*Cladium californicum*). The presence of saw-grass at the springs and waterfalls is noteworthy because it is found in tropical regions of the world where winter temperatures are mild. Saw-grass is an uncommon plant found in freshwater marshes and alkali sinks in the deserts from Riverside to Inyo counties and in the cismontane regions of San Bernardino to San Luis Obispo counties (Munz 1974). It also is found in Nevada, Arizona, and Mexico. Other species of *Cladium* occur worldwide, with the greatest diversity in Australia. Because saw-grass is known to have tropical affinities, a plant survey was conducted to see if other unique plants also occur at the waterfalls.

To gather floristic data at the Amargosa Hanging Gardens, plants were collected and geologic characteristics of the sites were recorded during reconnaissance surveys in September 2000 and January 2001. A botanical literature review and herbarium record search were conducted. Plants lists have been provided to BLM for use in the Amargosa River Canyon Trail interpretive program. No records have been found to document previous floristic surveys or the occurrence of saw-grass in Amargosa Canyon.

General Site Description

The geographic region is low to medium desert (Hickman 1993). Upland vegetation is sparse. The local plant communities are desert saltbush scrub and Mojave creosote bush scrub (Holland 1986). The climate of the area is known for its wide swings in temperature from very hot summers to cold winters with the low desert areas having fewer nights below freezing. The average monthly temperature during January was 7.3°C (45°F). Typically in July, the monthly temperature averages to 31.6°C (88.7°F) (Pupfish Habitat Preservation Committee 1972). Strong winds and low precipitation are characteristic of the region.

The soils in the natural area are classified as Aridisols. These soils are too dry to support mesophytic plants. They may have clay-enriched subsoil and they may have cemented to uncemented deposits of salts or carbonates (NRCS 2001).

The waterfalls discharge at the contact of dark red-purple quartzite and an overhanging layer of calcite-cemented conglomerate. Groundwater seeps occur at various locations along the canyon wall for approximately 1,000 feet. The canyon wall aspect is toward the west and the slope is nearly vertical.

The flow of water at the seeps varies from just-saturated soil conditions down the slope to three waterfalls cascading down 30 to 40 feet. The railroad track has long since been dismantled and now the water flows along the abandoned railroad bed and discharges south of the knoll into the Amargosa River, approximately 60 feet lower than the railroad bed.

The water quality is most likely similar to that of the Tecopa Hot Springs, located 1.5 miles north. The water was warm, 80°F when measured at the base of one waterfall when the concurrent air temperature was 46°F. The water source is also high in alkali salts. Precipitates accumulate as thick crusts, and concentric calcium carbonate pearls, similar to cave pearls, have formed at the base of the falls.

Geology

Rocks of the Sperry Hills, south of Tecopa (Hillhouse 1987, Anderson et al. 1997, McMackin 1997) are described as the late Proterozoic Stirling Quartzite, the Miocene China Ranch beds and Pleistocene gravels. Major angular unconformities representing long periods of time separate each of the rock units. The Stirling Quartzite is younger than the underling portions of the Johnnie Formation (580 million years ago (Ma)) and pre-date the earliest Cambrian Wood Canyon Formation. The Miocene China Ranch beds were deposited between 12 - 8 Ma (McMackin 1997) and contain petrified wood and the tracks of camels and horses. These beds lie on top of the late Proterozoic rocks and were tilted eastward about 8 my ago. Pleistocene gravels from Kingston Peak and the Alexander Hills to the east covered the eroded surface of the previously deposited rocks. Geologic forces arched the Sperry and Alexander Hills, allowing the meandering Amargosa River to cut downward and form the spectacular gorge. The porous gravels allow water from higher elevations to flow westward above the contact with the underlying, less permeable rocks. This water crosses northwest-trending faults and the south-projected linear trace of the fault that feeds the hot springs at Tecopa. Intermixing allows warm water to feed the hanging gardens at a constant year-round temperature.

Paleontologic Framework

During the Late Cretaceous and Paleocene (100-60 Ma), the entire region of the three western deserts (Mojave, Colorado, and Sonoran) graded from a pre-humid subtropical rainforest in the north to dry tropical forest in the south (Barbour and Major 1988). The Mojave Desert in California during the Miocene and Pliocene epochs (20-1 Ma) was a rich live oak-laurel-palm woodland filled with sclerophyllous shrubs (Raven and Axelrod 1995). During that time, the plant communities of the region were similar to present-day coastal California communities.

The rapid building up of major topographic features in California occurred in the Miocene and Pliocene epochs and the Quaternary period (10-1 Ma). The Amargosa River may have been a competent, through-going drainage in the Pliocene. The rising Tecopa Hump (McMackin 1997), an anticlinal arch, caused the damming of the river that formed Lake Tecopa. The Amargosa River proceeded to cut through the arch, leaving a gorge and incised meanders. Vertebrate fossils and 2.02 Ma volcanic ashes in the lake (Hillhouse 1987) indicate that the arch dammed the river in the Pliocene, prior to 2.5 Ma (Hillhouse 1987). The Armargosa River drainage also contained Lake Ash Meadows and Lake Manly during the Pleistocene (Synder et al. 1964).

Elevation changes caused shifts in locations of plant populations and changes in genotypes. The uplift transformed the Mojave into a transitional region, intermediate in climate and altitude between the colder Great Basin to the north and the warmer Sonoran region to the south. The thorn scrub and other species, common to the Sonoran desert, were confined to the low-lying warmer basins, such as the Amargosa drainage. Due to reasons of low topography and the availability of geothermal water, members of a tropical floral assemblage may have locally survived the severe Pleistocene climate. The Pliocene was more tropical than the drier and cooler climate that followed during the Pleistocene.

In the Quaternary period (20,000 years ago), the climate of the region was cooler and wetter than today (Axelrod 1976). Precipitation was likely 15-20 inches per year. Juniper woodland could have occurred at elevations 2,000 feet lower than present-day stands of woodland on the Kingston Range. About 12,000 years before present, the climate became drier and warmer (Axelrod 1981), as is the current climate conditions.

Canyon Plant Communities

The Amargosa River is perennial in Amargosa Canyon from just north of Tecopa to Sperry. The river supports a wide riparian corridor that contains several species of willow (*Salix* sp.), catclaw acacia (*Acacia greggi*), saltbush (*Atriplex* sp.), arrow weed (*Pluchea sericea*), and dense stands of salt cedar (*Tamarix* sp.). Holland (1986) classifies this plant community as riparian scrub and Mojave riparian forest. Other plant associations found along the river are classified as bulrush series, tamarisk scrub (Holland 1986) and arrow weed scrub, mixed saltbush series (Sawyer and Keeler-Wolf 1995).

As soon as you hike out of the first arroyo at the beginning of the Amargosa Canyon trail, vegetation can be seen growing on the east canyon wall. Alkali sacaton (*Sporobolus airoides*), common reed (*Phragmites australis*), and goldenrod (*Solidago confinis*) are the dominant species on the sub-irrigated slopes. Mature screw bean mesquite (*Prosopis pubscens*) and black willow (*Salix gooddingii*) grow adjacent to the streambed.

Saw-grass Plant Community and Site Characteristics

Continuing along the trail and walking up the quartize knoll, one can easily see the waterfalls perched on the east canyon wall. In contrast to the barren, steep and rocky canyon walls, the waterfalls support a dense stand of saw-grass which is established from the top of the falls to the base and in the stream along the railroad cut. Alkali sacaton, saltgrass (*Distichlis spicata*), common reed, and big saltbush (*Atriplex lentiformis* var. *torreyi*) grow in the moist alkaline soils adjacent to the falls. The emergent aquatic plant species in the stream (bulrush-cattail series) are slender cattail (*Typha domingensis*), three-square (*Scirpus americanus*), spike rush (*Juncus* or *Eleocharis*), and saw-grass. On the banks, narrowleaf willow (*Salix exigua*) is abundant with arrow weed (*Pluchea sericia*), desert baccharis (*Baccharis sergiloides*), and southern goldenrod in the understory. No more than five trees are present in the railroad cut, either black willow or screw bean mesquite. Other plant species present in the site, but not dominant, were California loosestrife (*Lythrum californicum*), bushy bluestem (*Andropogon glomeratus*), yerba mansa (*Anemopsis californica*), water parsnip (*Berula erecta*), honey-sweet (*Tidestromia oblongifolia*), wild grape (*Vitis girdiana*), and Bermuda grass (*Cynodon dactylon*). Salt cedar (*Tamarix ramosissima*) is not present in the spring tributary, although it is abundant in the riverbed.

Bushy bluestem, another wetland species known to require mild winter conditions, is also found at the waterfall (Munz 1974). These plants have tropical affinities and in California it occurs at hot springs and in other wetlands at perennially warm, low elevations, such as the southern California coast. These species survive in Amargosa Canyon because of the perennial warm groundwater outflow and the low elevation of the site.

Approximately 188 genera seem to have radiated into the California Floristic Province from semiarid or desert areas or have come into the region from warmer, subtropical areas, such as equatorial regions in the Old and New World (Raven and Axelrod 1995). For example, *Cladium*, *Andropogon*, *Eleocharis*, *Sporobolus*, and *Scirpus* are adapted to thrive in warm and wet areas.

Cladium and other plants with tropical affinities may be established in Amargosa Canyon and the surrounding region because they are relic populations that survived from the Pliocene in this low elevation, sheltered area. Propagules of these plants could have been carried by prehistoric cultures from coastal and inland wetlands in the southwest, Gulf Coast, and Mexico and then deposited along the trade routes or could have been transported by livestock during the colonization period (19th century).

Fauna

Aquatic invertebrates in the isolated perennial waters of Amargosa River have a high degree of endemism (Williams et al. 1984). Endemism has been identified in tiger beetles (Cicindelidae), creeping water bugs (Naucoridae), giant water bugs (Belostomatidae), assimineid snails (Assimineidae), hydrobiid snails (Hydrobiidae), littoridinid snails (Littoridinidae). Vertebrates which Williams (1984) describes as relics from pluvial times or rare because their ranges have been reduced by habitat destruction are present in Amargosa Canyon. The speckled dace (*Rhinichthys osculus*), Amargosa pupfish (*Cyprinodon nevadensis*), Tecopa pupfish (*C. n. amargosae*), Armagosa toad (*Bufo nelsoni*), yellow-billed cuckoo (*Coccyzus americanus occidentalis*), least Bell's *vireo (Vireo bellii pusillis*), Amargosa pocket gopher (*Thomomys bottae amargosae*), and Armagosa vole (*Microtus californicus scirpensis*) occur in the canyon.

Human Presence

Four separate prehistoric cultural groups used the canyon in sequential order from 10,000 B.C. (Rogers 1939). These groups most likely had minimal impact on the canyon ecosystem. In the early 19th century, the canyon was used a watering and forage stop for livestock traveling the Old Spanish Trail. The trail was used to exchange goods and livestock between California and New Mexico (Lyman and Walker 1997). In the twentieth century, the Tonopah and Tidewater Railroad was constructed from Tonopah, Nevada to Ludlow, California. Extensive grading and trestle work was required to run the rail through Amargosa Canyon. In the late 1930s the railway ceased operation and during World War II, the Defense Department salvaged the rails. In 1973, Bureau of Land Management set aside its holdings in the canyon as a roadless natural area. In the future, increases in water use and development in the adjacent areas could threaten the canyon ecosystem.

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Appendix 1: Amargosa Hanging Gardens Vascular Plant Species Observed: January 2001

** indicates non-native plant species*

Angiospermae: Dicot flowering plants

Amaranthaceae (amaranth family)
Tidestromia oblongifolia (honey-sweet)
Apiaceae (carrot family)
Berula erecta (water-parsnip)
Asteraceae (sunflower family)
Baccharis sergiloides (desert baccharis)
Pluchea sericea (arrow weed)
Solidago confinis (southern goldenrod)
Stephanomeria pauciflora (wire-lettuce)
Chenopodiaceae (saltbush family)
Atriplex lentiformis torreyi (big saltbush)
Fabaceae (pea family)
Prosopis pubescens (screw bean mesquite)
Lythraceae (loosestrife family)
Lythrum californicum (California loosestrife)
Salicaceae (willow family)
Salix exigua (narrow-leaved willow)
Salix gooddingii (Goodding=s willow)
Saururaceae (lizard's tail family)
Anemopsis californica
Vitaceae (grape family)
Vitis girdiana (desert wild grape)

Angiospermae: Monocot flowering plants

Cyperaceae (sedge family)
Cladium californicum (saw-grass)
Eleocharis (spikerush)
Scirpus americanus (three-square)
Poaceae (grass family)
Andropogon glomeratus (southwestern bushy bluestem)
*Cynodon dactylon** (bermuda grass)
Distichlis spicata (saltgrass)
Phragmites australis (common reed)
Sporobolus airoides (alkali sacaton)
Typhaceae (cattail family)
Typha domingensis (slender cattail)

Appendix 2: Amargosa Canyon Vascular Plant Species Observed: September 2000

** indicates non-native plant species*

Angiospermae: Dicot Flowering Plants

Amaranthaceae (amaranth family)
Tidestromia oblongifolia (honey-sweet)
Apiaceae (carrot family)
Berula erecta (water-parsnip)
Asteraceae (sunflower family)
Ambrosia dumosa (burro-weed, white bur-sage)
Baccharis emoryi (Emory's baccharis)
Baccharis salicifolia (mule fat)
Encelia frutescens (rayless encelia)
Pluchea sericea (arrow weed)
Solidago confinis (southern goldenrod)
Boraginaceae (borage family)
Heliotropium curassavicum (wild heliotrope)
Cactaceae (cactus family)
Optunia sp. (prickly pear)
Capparaceae (caper family)
Oxystylis lutea
Chenopodiaceae (saltbush family)
Atriplex canescens (four-winged saltbush)
Atriplex hymenelytra (desert holly)
Atriplex polycarpa (allscale)
Bassia hyssopifolia
Suaeda moquinii (bush seepweed)
Cucurbitaceae (gourd family)
Cucurbita palmata (coyote melon)
Euphorbiaceae (spurge family)
Chamaesyce sp. (spurge)
Fabaceae (pea family)
Acacia greggii (catclaw)
Glycyrriza lepidota (licorice)
Prosopis pubescens (screw bean mesquite)
Lythraceae (loosestrife family)
Lythrum californicum (California loosestrife)
Polygonaceae (buckwheat family)
Eriogonum brachyanthum (spindly buckwheat)
Erigonum inflatum var. *inflatum* (desert trumpet)
Salicaceae (willow family)
Salix exigua (narrow-leaved willow)
Salix gooddingii (Goodding's willow)
Salix laevigata (red willow)
Saururaceae (lizard's tail family)
Anemopsis californica (yerba mansa)
Solanaceae (nightshade family)
Datura wrightii (jimson weed)
Tamaricaceae (tamarisk family)
Tamarix sp. * (tamarisk)
Viscaceae (mistletoe family)
Phoradendron californicum (desert mistletoe)
Vitaceae (grape family)
Vitis girdiana (desert wild grape)
Zygophyllaceae (caltrop family)
Larrea tridentata (creosote bush)

Angiospermae: Monocot Flowering Plants

Arecaceae (palm family)
Phoenix sp. (date palm)
Cyperaceae (sedge family)
Cladium californicum (saw-grass)
Scirpus americanus (three-square)
Poaceae (grass family)
Distichlis spicata (saltgrass)
Phragmites australis (common reed)
Polypogon monspeliensis * (rabbitfoot grass)
Sporobolus airoides (alkali sacaton)
Typhaceae (cattail family)
Typha domingensis (slender cattail)

Abstracts of Proceedings

The 2001 Desert Symposium, Zzyzx, California

Reproductive output in response to rainfall and forage availability in a long-lived generalist herbivore, the desert tortoise (*Gopherus agassizii*).

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The desert tortoise, *Gopherus agassizii,* is a generalist herbivore inhabiting areas of the arid southwestern United States. To maintain viable populations, tortoises inhabiting the Mojave Desert must survive and reproduce in one of the most spatially and temporally limiting and variable resource environments in the world. For several years I have studied the survivorship and reproductive output of tortoises in the Mojave National Preserve, and most recently at Fort Irwin, California. My site in the Mojave National Preserve allows comparison of tortoise survivorship and mortality along a rainfall gradient in Ivanpah Valley. Rainfall at the lower elevation end of the rainfall gradient (800 m) is usually about 1/4 to 1/3 that of rainfall at the higher elevation end of the gradient (1100-1200 m). In 1998 - 1999, mean rainfall was greater at the lower elevation areas than at the higher elevation area in Ivanpah Valley. During this interval, mean total rainfall ranged from 21.8 mm at the higher elevation, to 44.1 mm at the lower elevation. Rainfall variation was great within each area as well. Mean winter rainfall in 1999 was 7.3 mm at the lower elevation area, whereas mean rainfall at the higher elevation area was 5.8 mm Likewise, mean Spring rainfall was 12.8 mm at the lower elevation areas, whereas mean Spring rainfall was 6.0 mm at the higher elevation. Only trace amounts of spring annuals germinated at Ivanpah Valley in 1999. At the lower elevation, mean biomass of spring annuals was 0.05 g m^{-2}. At the higher elevation, mean biomass of spring annuals was 0.25 g m^{-2}. There was no production of summer annuals in 1998, which suggests that tortoises had very limited green forage plants in their diets prior to and during the 1999 nesting season. In 1999 a total of 19 female tortoises were closely monitored for determining reproductive output at Ivanpah Valley. Tortoises produced first clutches of eggs starting in early May. Oviposition of first clutches was completed by the end of June. Second clutches were produced starting in late June, and were oviposited after the first week in July. All monitored tortoises produced at least one clutch of eggs, and 11 of 19 (58%) produced two clutches of eggs. Mean size of first clutches for tortoises in the lower elevation areas was 4.0, whereas mean size of first clutches was 5.4 for tortoises at the higher elevation area. Mean clutch size for second clutches were 3.7 and 5.0, for tortoises at lower and higher elevation areas, respectively. Despite the paucity of summer and winter rainfall and negligible germination of winter annuals in 1998-1999, desert tortoises at Ivanpah Valley were capable of producing up to eleven eggs in two clutches during the 1999 nesting season. The ability of desert tortoises to produce eggs in such water- and food-limited years attests to the remarkable capacity of these animals to survive and reproduce in a spatially and temporally variable resource environment such as the Mojave Desert.

Getting started with a geographic information system

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A geographic information system (GIS), which is a combination of hardware, software, and data that permits spatial data to be analyzed digitally, can be used in many ways, including research in geography, geology, biology, and other fields. Individuals and small organizations may not be sure how to start using GIS, however. This paper briefly describes software manufactured by the Environmental Systems Research Institute, Inc. and suggests an approach toward its implementation.

Characterization of granitic alluvial fans in the Kelso Area, East Mojave Desert, California

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Characterization of surficial materials and their physical properties is an important task in order to successfully model many parameters involved in ecosystem functions such as soil moisture, groundwater recharge, and biotic activity. One physical property that appears to strongly influence ecosystem function is particle size distribution of the substrate material. Alluvial fans generated from primarily granitic sources are one of the most areally extensive surficial deposits in the Eastern Mojave Desert, yet the physical properties and the processes that occur on them are poorly understood. Geologic mapping, particle size determination, and sediment transport and soil development process studies are ongoing in the alluvial fans north of the town of Kelso in order to better understand and quantify sediment dynamics and spatial variability of granitic alluvial systems. Detailed geologic mapping of these deposits is needed because of subdued geomorphic indicators such as soil development, vertical separation between surfaces, and a general lack of desert pavement surfaces. This mapping is intended to define baseline processes occurring on these surfaces (such as overland flow vs. channelized flow transport) in order to predict and extend physical properties to other alluvial fans. Previous and ongoing particle size distribution analyses show that granitic alluvial sediments tend to be smaller in average grain size and have relatively consistent grain size distributions both horizontally across a fan surface and vertically with depth. Further research is intended to enable geoscientists to quantify physical properties for granitic alluvial sediments, understand small and large scale variability, and model physical properties for other similar areas based on process models and limited field sampling.

Preserving an historic lichen collection

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World-renowned naturalist Edmund Carroll Jaeger called the community of Riverside, California home for much of his life, from 1906 until his death in 1983. His accomplishments spanned a variety of disciplines, focussing primarily on the natural history of North American deserts. Jaeger collected thousands of specimens of vascular plants for noted herbaria, some of new taxa, but his work on lichens during the early 1930s represents a personal collecting project that was never completed or properly curated. These specimens were collected primarily from mountain ranges in several states of the American southwest.

When Jaeger served as Curator of Plants for the Riverside museum, his lichen collection was brought into what eventually came to be known as the Clark Herbarium. During 1999, museum staff were finally able to address the cataloging and long-term storage needs of the lichen collection. Locality data was retrieved and interpreted; stable and acid free packing materials were employed in a fashion that makes the collection more accessible than ever before, while at the same time affording it much greater protection. This packing effort was supplemented by a cataloging project, through which the specimens were each described and images stored on the museum's ARGUS data base software.

The Lake Manix Lithic Industry and associated technologies at the Calico site, San Bernardino County, California

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Surface sites of the Lake Manix Lithic Industry (LMLI) have been recorded in the northern half of the Manix Basin of the central Mojave Desert. They are devoid of pottery, shell objects, and projectile points. Lithic artifacts, fashioned primarily of chalcedony, chert, and jasper, include large oval bifaces, scrapers of several forms (end, straight, concave, pointed, convex, pointed, and plano-convex), cutting tools, choppers, chopping tools, large stout picks, rotational tools, gravers, cutting tools, rotational tools, and flakes, as well as cores, anvils and hammerstones. Artifacts usually exhibit rock varnish on both their buried and exposed surfaces and are often found embedded in desert pavements. Younger Paleoindian artifacts found at lower elevations along the river and in sand dune sites are not varnished, nor are they found embedded in desert pavements. Based on a dated pollen profile at site CA-SBR-2120 and the occurrence of this assemblage above the most recent shoreline elevation of Pleistocene Lake Manix (543 m), the Lake Manix Lithic Industry is inferred to be at least 18,000 years ago. The Calico Site (CA-SBR-2102), near Yermo, is a multi-component site, with assemblages of the LMLI on its surface.

The Aquatic Sonoran mud turtle (*Kinosternon sonoriense*): living with uncertainty

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Over the past 11 years (1990-2000) we have marked 1,060 individuals (155 as hatchlings and 167 as juveniles) on the El Coronado Ranch and Rock Creek Ranch in southeastern Arizona. Males and females are similar in size and general shape. Females mature in about 7 years and produce about 6.5 eggs per clutch, some females produce two or more clutches per year. Clutch size increases with body size but egg size does not. Adult Sonoran mud turtles are not long-lived compared to many other fresh-water turtles; average adult life is probably less than 20 years. Body size and probably age distributions are different among habitats categorized by permanence of water: 1) temporary water in shallow pools in spring-head canyons, 2) a semi-permanent stream, and 3) a relatively permanent stream with associated stock tanks. A first order demographic analysis suggests that nest survivorship is the most likely life history trait that compensates for low adult survival.

Northern and Eastern Colorado Desert Plan (NECO)

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The boundaries of the Northern and Eastern Colorado Desert Plan (NECO) are Interstate-40, the Colorado River, the Coachella Canal and Southern Pacific Railroad, and the eastern boundary of the West Mojave Plan. NECO, one of three BLM bioregional plans for tortoise recovery and management of other species and habitats, will have been distributed to the public as a draft plan/EIS by the time of the symposium.

Earth science exhibits at the Nevada State Museum, Las Vegas

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The earth sciences gallery at the Nevada State Museum and Historical Society is developing exhibits that reflect the geology and paleontologic history of the Silver State. Exhibits include a full-size representation of the Triassic ichthyosaur, *Shonisaurus popularis*, with some original fossil skeletal material. The Pleistocene is represented by resin cast skeletons of three megafauna: *Mammuthus columbi*, the Columbian mammoth; *Nothrotheriops shastensis*, the Shasta ground sloth; and *Equus pacificus*, the Pacific horse. Floral, faunal and climatic data from the Pleistocene are derived from two packrat nets, so the museum has developed a rat midden model with two taxidermy specimens. Rock formation and stratigraphy is important to the history of Nevada and its mining industry; a section of stratigraphy and on Nevada volcanics is included.

The first fossil *Heloderma* from the Mid-Pleistocene (Late Irvingtonian) Coyote Badlands, Anza-Borrego Desert State Park®, Southern California

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The first fossil record of the beaded lizard, *Heloderma* is reported from the Coyote Badlands of northern Anza-Borrego Desert State Park® (ABDSP), within the Colorado Desert of southern California. Chemical analysis of a 1 m thick rhyolitic ash unit verifies the presence of the Bishop Ash (~750 kyr) and places the deposits within the mid-Pleistocene (late Irvingtonian North American Land Mammal Age, NALMA). Fine screenwashing (0.5 mm) of a 1.3 m thick, greenish, silty claystone in Ash Wash, western Coyote Badlands, has produced numerous fossil vertebrates, invertebrates, and plant remains. Of particular interest is a single complete osteoderm (ABDSP 2059/V6260) from *Heloderma*. A diversity of fossil lizards have been described from ABDSP (Norell,1989), however, helodermatids have not been previously reported.

The non-imbricating osteoderms of helodermatids are characteristically thick, polygonal, and subconical in shape (Holman, 1995). The external surface is generally rugose in texture but also has been described as pitted, tuberculate, granular, vermiculate, or pustulate (Yatkola, 1976; Stevens, 1977; Pregill et al., 1986). Osteoderm texture among helodermatids is difficult to interpret, as descriptions can be subjective, morphology can vary with position on the body, and may vary ontogenetically. Another group of lizards distantly related to helodermatids are the Anguidae which also bear osteoderms. Anguid osteoderms are readily differentiated from helodermatid osteoderms by being rectangular to oval in shape, are thinner (platy), are imbricated (especially body osteoderms), and are often keeled (Mead et al., 1999).

ABDSP V6260 measures ~2mm in diameter, 1.25mm thick and is somewhat polygonal in shape in dorsal and ventral aspects. The exterior surface is conical and displays a pitted (rugose) pattern. The interior surface is smooth with a "fingerprint-like" pattern, and bears a single foramen in its center.

Found only in the New World, the Helodermatidae are known from the late Cretaceous through the Recent in North America. Fossil *Heloderma* are rare. None are known that date between Steven's (1977) report of the Miocene (Arikareean NALMA) *H. texana* from Big Bend Nation Park, Texas and Harris's (1993) report of Pleistocene (late Rancholabrean NALMA) *H. suspectum* from U-Bar Cave, southwestern New Mexico.

There are two extant species of *Heloderma*, *H. horridum* (Mexican Beaded Lizard) and *H. suspectum* (Gila Monster). *H. horridum* exists in the tropical forests of western Mexico as far north as Sonora and south into Guatemala (Pregill et al., 1986). *H. suspectum* is from the eastern Mojave, Colorado and Sonoran deserts of southeastern California, southern Nevada, Arizona, southwestern Utah, southwestern New Mexico, and Sonora, Mexico (Van Devender and Bradley, 1994). Whether ABDSP V6260 represents a modern or extinct form of *Heloderma*, or an additional member of the Helodermatidae, cannot be ascertained from this single specimen.

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A canid rotary gallop trackway in the Miocene Horse Spring Formation, Clark County, Nevada

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Canidae, the family of dogs, first appeared in the late Eocene, in North America. Having evolved from plantigrade ancestors, canids became progressively more digitigrade through the Oligocene and Miocene, presumably adopting a more cursorial locomotory behavior (Wang, 1993). Modern canids are highly cursorial, being able to run fast and maneuver with great agility on flat ground. Their fastest gait is a distinctive gallop, called a rotary gallop, in which the forefeet strike the ground immediately before the hind feet in an asymmetrical pattern that creates a "c-shaped" trackway. It is this rotary gallop that allows modern canids to be effective pursuit predators, running at high speed over long distances. The bone record does not allow us to determine when canids began to gallop, however there is anatomical evidence that they did not become pursuit predators until quite late, in the Plio-Pleistocene (Janis and Wilhelm, 1993). The trackway record is uniquely suited to providing evidence of the history of locomotor behavior, but gait-specific Tertiary carnivore trackways are very rare. Within the mid-Miocene (Barstovian) Thumb Member of the Horse Spring Formation of southern Nevada, we have discovered a well-preserved rotary gallop in the trackway of a fox-size canid. This is apparently the first documentation of a rotary gallop in Tertiary canids. The canid tracks are each about 4 cm wide, preserved on a slab of fine-grained sandstone. Numerous tracks of a plover-like bird occur on the same slab. The canid tracks are superimposed on the bird tracks, as if made by a dog chasing birds. This interval of the Horse Spring Formation consists of sandstone, siltstone, conglomerate, and breccia lithologies deposited in a shallow, perennial lake environment. The Horse Spring rotary gallop trackway, together with previous studies of canid evolution, suggests that by mid-Miocene time some canids were ambush predators who used a galloping sprint to catch birds and other small prey. The canid rotary gallop, having thus evolved for short sprints, was later adapted for longer distance pursuit predation.

A Late Pleistocene proboscidean site in the Death Valley Lake Tecopa beds near Shoshone, California.

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A proboscidean site in the southern Death Valley Lake Tecopa beds was discovered and excavated by students from Sonoma State University (SSU) in 1982-83 (James, 1983) under a permit issued by the Bureau of Land Management (BLM). The specimens currently are housed at the Shoshone Museum, Shoshone, California, designated as the official repository by the BLM. Recent examination of the bones indicate at least three proboscideans are represented. The specimens have been partially prepared, but much of the plaster and burlap jackets remain.

The specimens were recovered from a lacustrine gypsiferous silty mudstone lying above the 665 ka Lava Creek B tuff (Hillhouse, 1987; Morrison, 1999; Reynolds, this volume), and are approximately 600 ka old.

Included in the fossils recovered is specimen L200-(SSU) 106, right and left dentaries with M/1s and M/2s exposed, and L200-(SSU) 110, a right M1/. Only the M1s are in wear. The M/2s are partially erupted but not in wear. Proper measurements of the mandible cannot be taken until the jackets can be removed and the specimens cleaned and stabilized. The dental measurements (Table 1) and the observed mandibular morphology compares most closely to *Mammuthus meridionalis*.

The coronoids are low, and the ascending rami are inclined posteriorly at a very obtuse angle. The corpora of the dentaries are long (longirostral) and gracile. A prominent anterior mandibular symphyseal process extends well forward of the anterior margin of the M/1. This mandibular morphology differentiates this specimen from *Mammuthus imperator* and *M. columbi* (Maglio, 1973; McDaniel and Jefferson, 1997, 1999).

The first lamella of the right M1/ is missing, the 2nd is smooth, the 3rd to 10th are in wear, and the 11th and 12th are erupted but not in wear. The right M/1 has 10 lamellae. The first lamella of the left M/1 is missing, and 8 lamellae are in wear. The right M/2 is exposed but not in wear, The left M/2 has 12 lamellae exposed but none are in wear. The wear stage of the M/1s indicate that this is a juvenile approximately 13-14 AEY at the time of death, according to the Craig Scale (Haynes, 1991).

Other specimens of *Mammuthus meridionalis* from the southern California region include those from Anza-Borrego Desert State Park® (McDaniel and Jefferson 1997) (ABDSP 1277/V5126), the Colorado River Corridor (Agenbroad and Mead, 1992) (CRIT skull, MCM 468:67, NAU-QSP 9155, SBCM 3.3.3), and from Victorville (SBCM 01.114.279/ A2944-0021). ABDSP V5126 is approximately 1.1 Ma in age (McDaniel and Jefferson, 1997, 1999). Dates for the Colorado River materials are uncertain, but Agenbroad and Mead suggest that they may be less than 0.5 Ma. Paleomagnetic studies of the Victorville area by Cox (personal communication) places the Victorville specimen within the Brunhes Chron, 0.73 Ma to present. Scott and Springer (personal communication) have suggested that SBCM A2944-0021 is less than 0.6 Ma.

Since the Tecopa and Victorville mammoths are documented in the 0.6 Ma range, at least a 0.5 Ma range extension is confirmed for *Mammuthus meridionalis* in southern California.

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TABLE 1: Dental Measurements of the Tecopa Mammuthus meridionalis, L200-(SSU) 106 and L200-(SSU) 110.

Specimen number	TP	Side	Length mm	Width mm	Height mm	PN mm	LF	ET mm
L200-(SSU) 110	M1/	R	175.0	86.0	128.7	12	6.6	2.2
L200-(SSU) 106	M/1	R	178.2	85.3		10	5.3	2.2
	M/1	L	165.3	84.3		8(9)	5.2	2.4

Explanation: TP = tooth position; PN = number of lamellae; LF = lamellar frequency (lamellae/10 cm); ET = enamel thickness, mm; R = right; L = left.

Geologic mapping projects in the Mojave Desert area sponsored by the U.S. Geological Survey

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Several geologic mapping projects by the U.S. Geological Survey are currently underway in and near the Mojave Desert, bringing renewed vigor to understanding this still incompletely mapped area. Past projects in the Las Vegas Corridor and Needles 1° x 2° sheet have produced a large number of geologic maps. The Southern California Areal Mapping project and the Death Valley Junction project are currently preparing maps along the southern and northern parts of the desert, respectively. All of these projects, past and present, have produced detailed to intermediate-scale maps of both bedrock and surficial geology in order to systematically develop a platform for diverse research goals and applications.

A somewhat different approach has been adopted by the Mojave Desert Ecosystem Science project and the Surficial Geologic Mapping project, which focus on surficial materials with a goal of understanding surface processes and climate history, all of which can lead to more complete and understanding of the desert ecosystem and improved land management applications. For these latter projects, the focus in on surficial materials because they are generally unmapped and they receive the greatest impact from most of man's activities. Scattered detailed maps are welded into a regional 1:100,000-scsale series of maps to allow a synoptic understanding to be developed of the entire desert in the next few years.

Recent tectonic styles from the Lower Lytle Creek Divide to the Devore Graben in Cajon Pass

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The Lower Lytle Creek Divide is a prismatic structural uplift which separates the Lytle Creek and Cajon Creek Drainages. The block is bounded on the northerly side by the Glen Helen fault, but both the block and the fault are cut by E-W trending cross faults, with evidence of alternating uplift along the Glen Helen fault and displacement on the cross faults. The San Jacinto fault is sub-parallel to the Glen Helen fault, on the south side of the divide, and it appears that the cross faults terminate against the San Jacinto fault. North of the Glen Helen fault, the tectonic style is extensional, with one of the cross- faults, the Peters fault, continuing east to where it bounds the south side of the Devore graben.

The uplift of the Lower Lytle Creek Divide between the San Jacinto and Glen Helen faults was the probable cause of the diversion of Cajon Creek from draining into Lytle Creek, resulting in the formation of Cajon Creek. Cajon Canyon differs from Lytle Creek in its lack of any alluvial fan development at its mouth, in sharp contrast with the extensive fan below Lytle Creek. Lytle Creek bypassed its fan system to the east, and joins with the Cajon drainage just south-east of the end of Lower Lytle Creek Divide, both probably as a result of ongoing fault interactions.

The combination of strike-slip faulting, in both the San Andreas and San Jacinto faults, mixed with rapid uplift along the Glen Helen fault and extensional patterns along the E-W cross faults provides an insight into the dynamics of this complex area.The San Jacinto fault trends about N35W towards the San Andreas, across the San Bernardino valley. Just below the Lower Lytle Creek Divide, the San Jacinto fault bends westerly toward Lytle Creek Canyon, becomming sub-parallel to the Glen Helen and San Andreas faults, trending about N60W into the San Gabriel Mountains, a change in trend of about 25 degrees in about 6 miles. The location of this bend appears to be a significant factor in the uplift of the Lower Lytle Creek Divide.

This complex pattern of faults provides an interesting insight into the dynamics of the vertical and strike-slip tectonics of the study area. The Devore Graben, and on a larger scale, the down-dropped blocks bounded between the San Andreas and the Glen Helen faults, which form Cajon Pass. The bend in the San Jacinto fault creates a differential motion with what appears to be alternating cycles of motion between the strike-slip and the oblique tensional faults. Field evidence is clear for these alternating stages of fault motion. Much recent literature on this area attributes uplift to forces caused by "restraining bends"along faults. This uplift in a tensile setting contrasts this mechanism and may provide insight into why historic faulting on the San Andreas changes character in the Cajon Pass, as the fault moves from a trans-pressional to trans-tensional regime.

Invasive species in the Mojave Desert

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Invasive species (exotics and domestics), both flora and fauna, are wreaking eco-havoc throughout the United States. Our fragile desert ecosystems are particularly vulnerable to exotics such as *Tamarix ramossisima* and *T. chinensis* (salt cedar), which have been declared Public Enemy #1 throughout the West. My presentation will focus on the serious ramifications of salt cedar infestation, especially in riparian areas, and their removal methods/successes to date, such as has been conducted at Salt Creek, Harper Dry Lake, Afton Canyon, Camp Cady, JTNP and MCAGCC. Other invasives, such as *Salsola tragus* (tumbleweed), *Bromus rubens* (red brome), *Schismus barbatus* (mediterranean grass), and *Sisymrium altissimum* (tumble mustard), are drastically changing the fire regime of our desert through fuel-loading [biomass] and interspatial filling of vegetation mounds. In addition, they are forcing out native flora through their aggressive reproduction and exclusionary abilities. This may have serious repercussions for native fauna such as the threatened Desert Tortoise. Invasive fauna such as ravens and feral dogs, are also contributing to the decline of that threatened species. Discussion will follow on how and why these species have become such a threat, and the problems facing their removal.

Stratigraphic correlation and vertebrate paleontology of the Pleistocene Ocotillo Conglomerate and Bautista Beds in Northern Anza-Borrego Desert State Park®, California

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Late Pleistocene alluvial fan, braided stream and floodplain deposits of the Ocotillo conglomerate and Bautista beds occur in the Borrego and Coyote Badlands, respectively, in northern Anza-Borrego Desert State Park®. Radiometric, magnetostratigraphic and biostratigraphic evidence has placed these units within the Irvingtonian, and possibly earliest Rancholabrean land mammal ages. The Ocotillo conglomerate has been hypothesized to be equivalent to the Bautista beds and may occur in the same depositional basin (Remeika, 1992). Both regions are within the San Jacinto Fault zone and occur along the Coyote Creek Fault. Tectonic reconstruction of the region before strike-slip movement, indicates different depositional settings and places the two sedimentary packages on opposite sides of the detachment fault (R. Dorsey, pers. comm., 2001). A significant collection of mammalian fossils has been collected from both areas (Remeika & Jefferson, 1993). Horses and camels are among the most numerous and taxonomically diverse of all the mammalian families reported. Because of the uncertainty of the relationships of these units, a study is warranted. In addition to stratigraphic correlation, an analysis of the fossilized mammalian fauna may help to biostratigraphically correlate the units, as well as provide evidence for paleoenvrionmental interpretation.

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Local heterogeneity of plant water-related physiology in the eastern Mojave Desert

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Desert ecosystems are often characterized by extreme habitat heterogeneity over short spatial and time scales. This heterogeneity may result in highly discontinuous patterns of ecosystem function such as evapotranspiration and productivity, and vegetation properties such as species diversity and population variability. We examined a suite of physiological and morphological traits associated with water use and productivity for the dominant species of four adjacent microhabitats in the eastern Mojave Desert. Soil water availability varied nearly five-fold across sites and among species, and up to two-fold within a site. Transpiration, hydraulic conductivity and leaf mass per area were also highly variable among sites and species. Variation of water availability was only weakly correlated with stomatal conductance, transpiration and stem hydraulic conductivity, reflecting, perhaps, the shorter time scales on which these variables change. Variables which change over longer-term time scales were closely related to microsite differences. These include percent embolism, leaf mass per area and percent plant coverage. These results underscore the importance of recognizing both variability on both spatial and temporal time scales in desert ecosystems.

Eastern Mojave desert plant collections of Annie M. Alexander and Louise Kellogg, 1939–1941

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The association of Annie Montague Alexander with paleontologist John C. Merriam and zoologist Joseph Grinnell, her financing of Merriam's "Saurian expedition" to the Humboldt Range in Nevada in 1905, as well as her endowments of both the UC Museum of Paleontology and the Museum of Vertebrate Zoology are well known. Less well-known are the plant collections of Annie and her friend Louise Kellogg from 1930 until 1949. In 1939 and 1940, they collected in what is now Mojave National Preserve. Collecting at Barnwell and Clark Mountain in 1939, they returned in 1940 to collect for 2 weeks in Caruthers Canyon, Keystone Canyon and other nearby locations. In all they made more than 300 collections in Mojave National Preserve. Annie and Louise kept meticulous field journals, taking their typewriter into the field, and profusely illustrating their notes with their black and white photographs. At least one voucher of every collection is housed at UC and JEPS and as such they make an excellent well-documented historic collection from Mojave National Preserve. With the assistance of the Lawrence R. Heckard Endowment Fund of the Jepson Herbarium, the 1939 and 1940 field notes have been scanned and stored as high resolution images on the Museum of Vertebrate Zoology web server. The images have also been converted to text and a searchable text-based web site with photographs is under construction on the web server of the Jepson Herbarium. When complete the web site should provide an accessible and valuable historic and botanical resource to students, researchers, and interested laymen.

Eagle Mountain Landfill, a mixture of science, politics, and public lands policy management

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In 1936 the area of Joshua Tree National Park was set aside as a National Monument by President Roosevelt. This unique and relatively untouched land was dedicated to scientific and recreational use, and as a sustainable protected place for the natural resources and cultural landmarks of the Park.

But government can be fickle, and in 1950 mining interests succeeded in reversing part of the set-aside of this National Monument. With a stroke of a pen a large rectangular bite of land was removed from the southeast region of the monument boundaries. In a dramatic change of direction, it was reserved for commercial and exploitive uses by mining interests. Publicly owned properties within the rectangle were to be managed by the Bureau of Land Management.

Industrialist Henry Kaiser was already active in the area with patented iron ore claims. He quickly obtained government permits to mine the newly opened areas and created one of the country's most significant iron mines—a series of huge open pits which fed the hungry steel furnaces of Kaiser Steel in Fontana, California.

Business was good for Kaiser Steel until the early 1980s when modern and efficient Japanese competition drove the company into bankruptcy. Fueled by the need to fund its pension plan for retired workers, Kaiser emerged from bankruptcy with a plan to turn the abandoned open pit mine into the world's largest garbage dump.

Kaiser hired a public relations firm which quickly and effectively broadcast the message that this open pit mine, good for nothing else, could be put to use as a garbage dump for Southern California. The hole was already there—why not fill it up? They argued to the Riverside County Board of Supervisors that the project would bring 1,300 jobs and over $13 million in tax revenues to the county. In 1999, after a series of lawsuits, hearings, and official actions by many government agencies, the Eagle Mountain Landfill finally received all of its permits for operation. Two lawsuits still remain which seek to block the landfill because of its effects on neighboring Joshua Tree National Park. These suits call for the reversal of a land exchange between the Bureau of Land Management and the landfill developers. The BLM land is necessary for the operation of the dump.

Throughout the process, the Western Region of the National Park Service and local officials at Joshua Tree National Park argued that the dump would threaten the ecology and wilderness experience of the National Park. Their concerns were that this dump, the world's largest, was a gigantic biological experiment which misrepresented its scope and posed a number of risks. They pointed out the following.

The dump was not going to fill up the holes, and in fact would only fill a minor part of one of the huge open pits after fifty years of operation. Instead, the dump would be sited primarily on steep virgin hillsides and canyons surrounding the open pits.

Cultural eutrophication was a large potential problem, with no scientific testing or model to predict its results. Experts hired by the Park Service, including noted desert ecologists Dr. William Schlesinger of Duke University and Dr. James McMahon of Utah State University, indicated that the landfill would create a rich oasis of food for animals that have evolved in an environment of scarcity. The invasion of the area by animals and insects, as well as exotic plant species, would be nourished and encouraged by this oasis of food to spread throughout the region. The invasion of pests would be unpredictable in scope, probably very serious to the regional environment, and once underway it would be too late to stop.

The Park Service also expressed concerns about air quality. Joshua Tree National Park is already in a state of nonattainment under government regulations and would likely be adversely affected by ongoing railroad emissions, machinery and vehicle emissions, and particulate emissions from the onsite operation of the dump operation. Judy Rocchio of the Park Service warned that "there will be serious impacts to Joshua Tree National Park's visibility."

Additional concerns dealt with a loss of wilderness experience, light pollution, and water pollution in the surrounding aquifer. The Eagle Mountain Landfill is now cited as a classic case of planning by accident. Some people call it flypaper planning. Governmental agencies did not carefully plan and seek out the most favorable sites for landfills. Rather, they reacted to proposals from a bankrupt company, with a big hole to fill, which happened to come by and present its own campaign for approval.

Feeding behavior repertoire of the polymorphic cichlid, *Cichlasoma minkleyi* (Cichlidae)

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Previous research has described the repertoire of feeding behaviors for African cichlids. the wide range of behaviors observed within an individual cichlid has been hypothesized to contribute to the broad trophic success of cichlids, and to the rapid adaptive radiations in African lakes. It is not known if New World cichlids share this plasticity in feeding behavior. In this study we examined the feeding behavior of *Cichlasoma minckleyi* in the field. *C. minckleyi* is an endemic polymorphic cichlid found in the Cuatro Ciénegas basin of the Chihuahuan desert in north central Mexico. This species shows two distinct morphotypes. One morphotype has hypertrophied jaw musculature, robust pharyngial jaws and large, flattened, molariform teeth. The second morphotype has gracile pharyngeal jaws and associated musculature, with needle-like, papilliform teeth. It is hypothesized that the molariform morph has evolved to exploit the abundant snail resources in the Cuatro Ciénegas basin. Individuals of *C. minckleyi* were caught, anesthetized, and labeled with numbered tags. The fish were observed in the water using SCUBA equipment, and feeding behaviors were recorded on a digital video camera. Digital video was analyzed in the lab and behaviors were identified and categorized. These behaviors were compared to published descriptions of African cichlid feeding behaviors. Eight distinct feeding behaviors have been described for African cichlids. Preliminary analysis of a sub-set of our data suggests that *C. minckleyi* utilizes at least six of these behaviors. Complete analysis of our data may reveal that these fish exhibit all eight previously described behaviors and possibly some novel feeding methods. These results suggest that these behaviors are over 150 million years old and have been conserved among divergent cichlid groups. Future research will determine if there are differences in feeding behaviors between the two morphotypes, which would suggest that there is a behavioral component to intraspecific resource portioning.

The Franklin Wells hectorite deposit

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Hectorite is a rare lithium smectite clay. It is mined in only four places worldwide, three of which are in North America and two are in the Mojave Desert. The Franklin Wells deposit was discovered in the 1920's as a source of whitewash. When the mineral hectorite was discovered in the deposit in the 1970's, mining methods and beneficiation technologies changed to extracting hectorite. The deposit is confined to a fault zone which we name the Franklin Wells Fault. The fault cuts through lacustrine volcanic ash beds interbedded with alluvial gravels and sands. The known extent of the deposit contains 2 million tons of hectorite ore averaging 10% recoverable clay. This deposit formed when lithium bearing hydrothermal water encountered dacitic ash beds in the Franklin Wells Fault zone. The hectorite is a clay formed from alteration of the ash in the fault zone. The deposit is likely to be Pleistocene in age and has some generic similarities with other known hectorite deposits. This deposit is low in arsenic and mercury and so could be used in a variety of applications that are sensitive to toxic elemental content.

Motorized wreckreation on America's protected lands

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Various levels of protection from damages by motorized off-road vehicles (ORVs) are prescribed, on paper, for natural and cultural resources in America's wildlands. These range from an outright ban on motorized vehicle use in Wilderness Areas to prohibition of "impairment" of wilderness qualities for Wilderness Study Areas (WSAs). Variable levels of protection are prescribed for lands identified as Areas of Critical Environmental Concern or Special Areas. The Federal Land Policy and Management Act (FLPMA) of 1976 instructed the Bureau of Land Management (BLM) to inventory its lands for areas 5000 acres or larger having wilderness qualities. Fifteen years were given for this exercise, but earlier reports to Congress on lands previously identified as primitive were required. The inventories resulted in identification of WSAs from which the BLM selected areas for recommendation to Congress for wilderness designation. For example, in the California Desert Conservation Area (CDCA), 5.7 million acres were identified as having wilderness characteristics and 2.1 million acres were recommended for wilderness designation by the BLM. In Utah, 3.2 million acres were identified as WSAs, and a small fraction of those were recommended for wilderness status. Under Section 202 of FLPMA, revisions of land-use plans may recognize areas of wilderness characteristics not previously inventoried; these are identified as Section 202 WSAs. In Utah, a 1999 inventory identified 2.6 million acres of Section 202 WSAs in addition to the 3.2 million acres previously identified; this was still a million acres short of a comprehensive citizens' inventory.

Both the identification of WSAs and those chosen by the agencies for wilderness designation were (and are) highly controversial. As a consequence, wilderness designation is incomplete in many states. Public dissatisfaction with the BLM's recommendations in the CDCA ultimately resulted in designation of 3.7 million acres as wilderness in the 1994 Desert Protection Act, and an additional 338,000 acres were retained under protective umbrellas. All lands identified as WSAs must be managed so that their wilderness qualities are not impaired until Congress makes a final determination of their status. The Interim Management Policy for Lands Under Wilderness Review comprises 53 turgid pages of jargon, from which the following points relevant to ORV use may be wrested:

- Vehicle use in WSAs is permitted to continue, but only on "ways" documented to have existed at the time of enactment of FLPMA (October 1976).
- Cross-country ORV use in WSAs is surface-disturbing and therefore impairing and "must be denied;" this includes widening and braiding of existing ways.
- Some activities, presumably including ORV usage, of WSAs were allowed to continue "if their impacts could be reclaimed by the time the Interior Secretary's recommendations were forwarded to the President. This "opportunity" expired in September, 1992 for all WSAs recommended under the initial inventories (mandated by section 603 of FLPMA).
- The BLM says it is not required to manage Section 202 WSAs under the Interim Management Policy, but has the authority to do so.
- It is the BLM's goal for WSAs to "immediately reclaim the impacts caused by any unauthorized action to a level as close as possible to the original condition, or at least to a condition that is substantially unnoticeable."
- Sand dunes and snow areas may be designated for ORV use in WSAs, and also other areas that had been designated open before October 21, 1976.

So, what is happening out there in the wilderness? Illegal ORV incursions have been documented in 30 wilderness areas in California, and likely are much more widespread. Such incursions are frequent and on-going in some wilderness areas such as the Jacumba Mtns. Wilderness Area. Unauthorized ORV use also occurs in at least five WSAs, five ACECs, and five areas under other forms of protection. ACECs that are posted for use only of designated routes, with camping allowed only within 25 feet of the designated route center lines, have become de facto open areas in which vehicles operate as they please and camping is uncontrolled. Limited Use areas of the CDCA are similarly widely abused. Routes of heavy use proliferate in WSAs and ACECs, only to be rewarded by the BLM by designation of the user-created routes. So much for "immediate reclamation." The BLM's continued use of an "existing route" designation boils down simply to the first ORV through is illegal, everyone following is legal. It is not surprising, then, that lawsuits are beginning to proliferate in attempts to force the BLM to implement its regulations. Significant closures in the Algodones Dunes to ORV use, and closure of BLM lands at Windy Point north of Palm Springs were recently ordered by a court settlement over the BLM's failure to secure plans for protection of threatened and endangered species. Under threat of a lawsuit in Utah, closures of 8 WSAs to ORVs (except on ways that existed at the time of WSA designation) and restriction of use in a ninth WSA were ordered by the BLM, which also has undertaken extensive signing and barricade construction in many WSAs and Section 202 lands in southern Utah.