Trough to trough

The Colorado River and the Salton Sea

Robert E. Reynolds, editor

THE SALTON SEA, 1906

Trough to trough—the field trip guide

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Proceedings of the 2008 Desert Symposium

Robert E. Reynolds, *compiler*

California State University, Desert Studies Consortium and LSA Associates, Inc.

April 2008

Front cover: Cibola Wash. R.E. Reynolds photograph.

Back cover: the Bouse Guys on the hunt for ancient lakes. From left: Keith Howard, USGS emeritus; Robert Reynolds, LSA Associates; Phil Pearthree, Arizona Geological Survey; and Daniel Malmon, USGS. Photo courtesy Keith Howard.

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The 2008 Desert Symposium field trip

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Day 1

What we will see: Our 180 mile route will contrast floras of the eastern Mojave Desert, with those in lower elevations of the Colorado Desert. At Granite Pass, we enter Bristol–Danby trough which drains to the Colorado River near Vidal. At Amboy, outcrops of Bouse sediments containing the early Pliocene Lawlor Tuff (4.83 Ma) indicating that the Bristol–Danby trough was filled to approximately 950 feet elevation, allowing it to connect with the Blythe Basin to the southeast. Southeast in the Bristol–Danby trough, sediments containing Pleistocene vertebrate fossils suggest a complex biotic community. Special thanks to Keith Howard, Phil Pearthree, Jon Spencer, and Paul Stone for discussions, suggestions, and reviews of Day 1 of this trip.

Convene at Zzyzx with a full tank of gas for the 180 mile trip. Wear sturdy shoes and dress for the occasion; bring water, hat, and sunscreen. On the night before the trip, fill your vehicle with gas and check fluids and tire pressure.

Proceed north to I-15 and the Zzyzx Road overpass. Enter the freeway and proceed east on I-15 toward Baker. Exit at Kelbaker Road. **TURN RIGHT** (south) toward Kelso and proceed about 50 feet to the first cattle guard where we will zero-out our odometers.

We will be passing Pliocene to late Quaternary cinder cones and lava flows and crossing topography and terrain that are a result of Miocene extensional tectonics and the development of the right-lateral Southern Death Valley–Avawatz–Soda–Bristol fault zone. We are in the Soda Lake drainage basin and will travel past Kelso to Granite Pass where we enter the Bristol–Danby trough, which drains east through Rice Valley and along Vidal Wash to the Colorado River.

0.0 (0.0) Cross the first cattle guard**. Set odometer to 0.0.** Continue easterly on Kelbaker Road.

0.2 (0.2) The "Mojave National Preserve" sign on the right is located at the high stand of pluvial Lake Mojave, elevation 935 ft.

1.6 (1.4) 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 and dunes that may be covered by flowers in the spring (Gardner, this volume). Climbing dunes bury the flanks of Little Cowhole Mountain at 3:00. The road crosses recent fan deposits that have transported well-varnished basaltic boulders twelve miles from the Cima volcanic field.

5.0 (3.4) The outcrop ahead is Teutonia Quartz Monzonite (TQM). Beyond at 10:30 and at 2:00 are granitic domes (Reynolds et al, 1996) below elevated late Miocene through Pleistocene basalt flows. To the right are young basalt flows coincident with the modern topography; erosion of the surrounding surface has left the flows slightly elevated.

6.6 (1.6) The road bends to the right and ascends the southern Cima volcanic field. The next nine miles pass prominent pediment domes. These granitic domes were tilted east by listric-normal faults, and now sit with the retreating scarp facing west and the original surface tilted east.

11.1 (4.5) 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 is regularly plowed from the next two miles of road.

14.2 (3.1) Continue past 17-Mile Point. The Old Government Road crosses here, at a point midway between the 35-mile stretch between Marl Spring to the east and Fort Soda at Soda Spring (Zzyzx) 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 notch cut across flows where basalt ponded against the flank of Old Dad Mountain.

16.6 (2.4) On the left is the Black Tank flow, the youngest in the Cima field, tentatively dated at less than 0.02 Ma (Renault and Wells, 1990). On the right skyline at 12:00 to 6:00 are the Kelso Mountains, Radar Ridge, and Old Dad Mountain. East-tilted 10–12 Ma fanglomerates are faulted against Tertiary through Precambrian rocks (Barca, 1966). Neogene faults are predominantly northwest-trending, right-lateral strike-slip shear zones (Skirvin and Wells, 1990).

18.1 (1.5) Pass through a dip. On the right is a ridge of Miocene granitic boulders shed from the TQM terrane to the east.

20.6 (2.5) Continue past the junction on the left with the Aiken Cinder Mine Road, marked by a dirt pile with a sign.

21.0 (0.4) Continue past a right turn toward a microwave complex on the ridge.

24.0 (3.0) Continue past the transmission line running from Nipton (east) through the Kelso Dunes to Pisgah Crater. Prepare for sharp left bend in the road.

27.0 (3.0) Continue past the Old Government Road running east to Cedar Canyon and Fort Rock Springs.

The view southeast is of Kelso Wash and Cedar Wash that drain the New York Mountains and flow through the sand dunes of the Devils Playground to Soda Lake (Zzyzx).

35.5 (8.5) Cross Kelso Wash.

36.0 (0.5) **STOP** at the intersection with Cima Road. Kelso Depot is to the southeast, renovated by the National Park Service. The small settlement around this important railroad station and yard provided water, gasoline and food for travelers, who, if traveling by automobile, had reached the "end of the line" in 1917. No reasonably passable road went west along the LA&SLRR. The only exit from Kelso Valley was north, via Cima and Valley Wells, or east to Fenner and then south to National Trails Highway (Thompson, 1929).

Proceed south on Kelbaker Road. The Providence Mountains on the east reach 7,000 feet and contain piñon and juniper forest (Gardner, this volume).

36.6 (0.6) Cross a cattle guard. Slow to 45 MPH around curve.

39.7 (3.1) Continue past a left turn to the Vulcan Iron Mine in the Providence Mountains.

39.8 (0.1) Kelbaker Road bears west.

43.6 (3.8) Continue past a road to the Kelso Dunes.

44.1 (0.5) Proceed through a junction with a power line/gas line road.

44.6 (0.5) Kelbaker Road bears left (south).

48.3 (3.7) Continue past a right turn to Cottonwood Spring.

48.7 (0.4) Note the reddish-brown soil with carbonate root casts in a cut on the east side of the road. This is the most well-developed soil profile that we pass in the southeastern Soda Basin drainage.

50.2 (1.5) Continue past a right turn toward Snake Springs, Granite Cove, and Dorner's Camp.

50.3 (0.1) The microwave station at Granite Pass. We are entering the Bristol–Danby trough, a drainage that runs southeast to the Colorado River near Vidal.

50.4 (0.1) Slow for a 30-MPH curve.

51.6 (1.2) Continue past the intersection with Hidden Hills Road. The Van Winkle Mountains are at 10:00 (Miller and others, 1985).

54.0 (2.4) Continue past a right turn to the microwave station.

56.3 (2.3) View at 10:00 of the flat surface of the granitic pediment at the south base of the Granite Mountains. The pediment was produced by mid-Tertiary erosion (Reynolds et al, 1995).

58.0 (1.7) Proceed under I-40. We can see Miocene volcaniclastic flows and pyroclastic rocks of the Brown Buttes to the west and the northern Marble Mountains to the east. To the south, Bristol Lake is divided by structures connecting faults in the Bristol Mountain with faults in the Iron Mountains. The western half of Bristol Lake is saline, and the eastern half of the basin contains fresh water that flows along Fenner Wash from the 7,000-foot peaks of the New York Mountains. At Cadiz, we will see three lobes of the Fenner Wash delta. The northern lobe is a groundwater discharge (GWD) platform that was deposited into a topographic depression, the southern lobe was deposited by GWD over a near-bedrock source of fanglomerates, and the central lobe retains deltaic configuration at the mouth of Fenner Wash.

60.3 (2.3) South along Kelbaker Road the pediment cut on granitic rock gives way to a Late Pleistocene–Holocene soil profile. For two-tenths of a mile, pedogenic carbonates and reddish arkosic sands are exposed in a low road cut.

62.8 (2.5) Well-developed desert pavement is visible in the saddle to the west at 10:00.

64.7 (1.9) Continue past a road to Orange Blossom Wash and a microwave station.

65.3 (0.6) Cross Orange Blossom Wash near Windy Point. Jurassic granitoids in the nearby Bristol Mountains form dark outcrops; white stripes and blobs are in some places albitized granitoids and in others are giant xenoliths of marble. Orange Blossom Wash drains the Bristol Mountains and the western Granite Mountains.

65.7 (0.4) The Hope/New Method mine is located to the west (Jenkins, 1995) about one mile north along Kelbaker Road. Collectors have recovered a variety of uranium minerals, including rare fluoborite, at this prospect.

67.6 (1.9) At the bend in road, the Blackjack iron mine and Snowcap limestone mine are two miles west (Wright and others, 1953; Brown, 2003).

69.3 (1.7) **STOP** at Route 66 (National Old Trails Highway). Bristol Lake to the south is divided by a groundwater barrier. The western half of the lake is saline and the eastern half of the basin contains fresh water that flows along Fenner Wash from the 7,000 foot peaks of the New York Mountains. The saline portion of the lake produces commercial salt (NaCl) and calcium chloride (CaCl) as well as the minerals celestine (SrSO4) and temperature-sensitive antarcticite (CaCl2.6H2O). The fresh water portion supports commercial citrus and grapes. The GW barrier might be an unmapped portion of the Bristol–Granite fault zone (Brady, 1992) that trends southeast toward the northwest-trending faults in the Iron Mountains (Bishop, 1963). The trend of such a fault trace would project to near Bolo Hill.

At the turn of the last century (Mendenhall, 1909), water in the Bristol Basin was unavailable along the Santa Fe Railway except as dispensed from water tenders at Amboy, a stage stop on the route to the Dale Mining District to the south. East of Cadiz, along Fenner Wash at the north end of the Ship Mountains, water of excellent quality and abundance was available for travelers from railroad pumping stations at Siam and Danby. By 1921 (Thompson, 1929), Amboy was important enough to claim "water, gasoline, general supplies, and a hotel and garage accommodations." An oiled road crossed east over the southern Marble Mountains to Danby (gasoline and food) and Fenner (meals, gasoline, and groceries). Travelers could take the southern route—"Parker cutoff"—through Cadiz Valley, or take a better road south from Danby to the Parker Cutoff. Water was available at section houses along the AT&SFRR. Many travelers still preferred the longer but quicker and smoother route east to Needles, then south to Parker. Although Cadiz was the major junction of the two routes, it never boasted having supplies or accommodations other than emergency water (Thompson, 1929). The route south of Amboy was very sandy on the south side of Bristol Lake and at Dale Lake, and automobiles had to "... cross it on deflated tires." The mines at Dale closed in 1918, and the road fell into disuse.

TURN RIGHT (west) toward Amboy on Route 66. View of Amboy Crater (Hazlett, 1992). The Amboy cone, 246 feet tall and 1508 feet around at its base, has had at least six eruptive phases. It is believed to be about 6000 years old. The Amboy lava field covers 43.5 square miles (Parker, 1963).

74.2 (4.9) Slow entering Amboy. Prepare to turn right just past Roy's Café.

TURN RIGHT (north) at break in phone pole barrier and proceed north between buildings.

74.6 (0.4). Follow the dirt berm as it bears northwesterly.

74.9 (0.3) **TURN RIGHT** (northeast) over the berm and proceed to the gas line road at the fenced booster station.

75.3 (0.4) **TURN LEFT** (west) on the gas line road.

75.7 (0.4) The berm on the right (north) ends.

75.8 (0.1) TURN RIGHT (north) on the dirt road.

76.0 (0.2) STAY LEFT as the road forks. Cross the wash and BEAR RIGHT to regain the road. Proceed north.

76.4 (0.4) Proceed through dip.

76.6 (0.2) **Park. STOP 1-1. Lawlor tuff at Amboy**. Walk east to an outcrop with Lawlor Tuff (4.83 Ma) in lacustrine Bouse sediments at approximately 951 ft elevation (Reynolds and others, this volume; Fig. 1-1). Note the southeast dip, indicating probable deformation of the sequence. Tuffs dated to 3.6 Ma have been identified from cores in Bristol Lake to the south, but the Lawlor Tuff (4.83 Ma) has not yet been recognized there (Rosen, 1992). Return to vehicles and RETRACE south to the gas line road.

77.6 (1.0) TURN LEFT (east) at the junction of the Lawlor Tuff road with the gas line road.

78.0 (0.4) TURN RIGHT (south) at the compression station.

78.4 (0.4) Cross the apex of the landing strip berm.

78.7 (0.3) **STOP** at Route 66 on the west side of Roy's Gas Station. Watch for traffic and TURN LEFT (east) on Route 66. Proceed to Chambliss.

78.8 (0.1) Pass Amboy cemetery to the south.

83.6 (4.8) Continue past Kelbaker Road on the left (north) and Bolo Hill, one-half mile southeast (Lerch, 1992). Bolo Hill contains Jurassic granitoids and Jurassic eolian sandstone. Continue east on Route 66 to Chambliss.

88.8 (5.2) Continue past a left turn to the Iron Hat Mine in the southern Marble Mountains. The Iron Hat mine was

Figure 1-1. The Lawlor Tuff at Amboy, view east.

active in the 1940s; the iron ore (hematite and magnetite) occurred in small, shallow lenses in Cambrian? limestone (Bridenbecker, this volume; Wright and others, 1953).

89.1 (0.3) **TURN RIGHT** at Chambliss (now called Cadiz) onto Cadiz Road.

92.3 (3.2) **Slow**. The road bears left (east) as we pass historic railroad station of Cadiz. This is the north GWD platform of Fenner Wash. White GWD sediments on the east side of Cadiz Road have been dated by optically stimulated luminescence and radiocarbon methods at about 10 ka (Reynolds and others, 2003).

93.1 (0.8) Continue past a left turn to the Cambrian Latham Shale trilobite localities (Mount, 1980) in the Marble Mountains to the north.

Figure 1-2. Archer cemetery.

93.4 (0.3) The road bears right (south) and crosses the Burlington Northern/Santa Fe tracks.

93.6 (0.2) Pass south through an intersection on the south side of the tracks.

95.7 (2.1) Cross the railroad tracks and **BEAR LEFT** (southeast). To the west and north is the Fenner Wash delta. Fenner Wash drains more than 1,200 square miles. Distinctive detrital spherolitic opal indicates that the source of sediment is from Lanfair Valley via Hackberry Wash to Fenner Wash. We are in the central lobe of the three-lobed outwash. The northern lobe is between Orange Blossom Wash and central Fenner Wash delta (elevation 740') and may receive subsurface and surface overflow from both. The central lobe (elevation 820') was deposited as a deltaic marshland during the late middle Pleistocene (Illinoian interglacial). The southern lobe at Archer (Stop 1-2, elevation 750') receives both subsurface and surface overflow from Fenner Wash and discharge (including evaporation) is at the groundwater barrier of the southern Ship Mountains.

Delta sediments have produced a mid- Pleistocene fauna consisting of xeric small mammals, birds, lizards, and snakes. Horses and proboscideans are absent, but camel and pronghorn are present. The two antelope, along with the giant tortoise, *Geochelone,* suggest the mid-Pleistocene Irvingtonian age of the fauna, perhaps older than 300,000 years (Reynolds and Reynolds, 1992). Also present are a toad; the clam *Pisidium casertanum*; land snails *Physa* sp., ?*Succinea*, and ?*Planorbula*; and aquatic snails *Fossaria* sp., *Gyraulus* sp., and a pupillid (?*Vertigo* sp.) (Pedone, p. c. 2003).

96.0 (0.3) Cross the All American gas transmission line east of the two heat station tanks. We will be crossing braided channels of Fenner Wash for the next several miles.

99.7 (3.7) **STOP 1-2. Archer sediments**. The white Archer sediments are in the southern lobe of three fluvial and groundwater discharge lobes created by Fenner Wash. Fenner Wash drains the New York and Providence Mountains, as well as part of the Old Woman Mountains, and therefore has a water source similar to Kelso Wash. These deposits at elevation 750' lie on granitic fanglomerate from the southern Ship Mountains. Features indicate this deposit is the result of marsh/spring and evaporative groundwater discharge. These sediments have produced a Pleistocene fauna consisting of xeric small mammals, birds, lizards, and snakes including a boa, and one species of gastropod, the land snail *Succinea* (Reynolds and Reynolds, 1992). Return to vehicles at the gas line. **PROCEED SOUTHEAST** to Milligan.

100.8 (1.1) Continue past a road to the right.

101.7 (0.9) Slow for dip.

102.3 (0.6) Archer Cemetery (Fig. 1-2) is on the left.

106.5 (4.2) Continue past a road south to the Kilbeck Hills.

108.3 (1.8) Continue past a road north to Skeleton Pass, Danby, and Route 66.

109.0 (0.7) The road bends at the Chubbuck Mill site. Limestone mines to the south, operated by the Chubbuck Lime Company from 1925 to 1948, explored bodies of metamorphosed limestone in the Kilbeck Hills (Wright and others, 1953).

112.0 (3.0) Slow for dip.

112.5 (0.5) Fishel Siding.

119.1 (6.6) Pass by the Old Woman Mountains and enter Danby basin. Danby and Bristol basins are at similar elevations, ~610' ft. Cadiz basin, due south, is ~70 ft lower. Ward Valley is to the north, the Turtle Mountains are at 11:00, and the Iron Mountains are at 3:00.

120.7 (1.6) Site of Milligan and its cemetery (Fig. 1-3). Continue past a paved crossroad south that leads to the Standard Salt Company.

121.7 (1.0) The Standard Salt processing plant (Calzia,

Figure 1-3. Milligan cemetery.

1992; Gundry, 1992).

121.9 (0.2) Crossroads at Milligan sign. The road has three branches: proceed on the middle branch.

124.7 (2.8) Cross a private road at the north/south power line in central Ward Valley.

128.3 (3.6) The Salt Marsh railroad siding is marked by salt cedar trees. No Bouse sediments have been observed at surface outcrops in Danby Basin. However fossil faunas reached by drill cores at depth indicate the presence of marine sediments, probably Bouse (Bassett and Kupfer, 1964; Smith, 1970; Brown and Rosen, 1992).

129.5 (1.2) Mile Post 248 on the gas line road. We will stop in 0.1 mile.

129.6 (0.1) **STOP 1-3. Salt Marsh.** The Salt Marsh site, at elevation 630', is within 20' of the current playa surface of Danby Lake. Stabilized dunes have been deposited within dissected pedogenic carbonate horizons developed on silts which contain late Pleistocene mammal fossils (Reynolds and others, 1992).

133.1 (3.5) Sablon Siding.

136.0 (2.9). **CAUTION—DIP!** The road bears south, away from the railroad tracks.

138.5 (2.5) **Stop** at Highway 62. Note the stabilized Pleistocene dunes that surround the mountains. The Arica Mountains, due south, have yielded gold ore since the late 1800s (Baltz, 1982); the Lum Grey and the Old Priest mines are visible south. Patton's Camp is to the west. Carbonate-cemented red soils on the south side of the highway have surfaces dipping into Danby basin and are covered by stabilized dunes. We are at the 850' elevation divide between Danby basin to the northwest and Rice Valley, which drains southeast into the Colorado River.

Watch for traffic and **TURN LEFT** (east) onto Highway 62.

143.3 (4.8) Cross railroad tracks and prepare to turn right.

143.4 (0.1) The site of Rice. **TURN RIGHT** (south) toward Blythe on Rice–Midland Road. Rice Army Air Field and Camp Rice Desert Training Center were established in 1942. Other camps were Young, Coxcomb, Granite, Iron Mountain, Ibis, Clipper, Pilot Knob, Laguna, Horn, Hyder, and Bouse. Operations involved thirteen infantry divisions and seven armored divisions. Training ended in the spring of 1944. The 5th Armored Division, the first unit trained at Camp Rice, spearheaded victories during World War II.

144.5 (1.1) Cross the railroad tracks.

145.8 (1.3) Dunes cross the road.

149.6 (3.8) The road bends southeast. The washes contain smoke tree, palo verde and mesquite (Gardner, this volume).

159.8 (9.3) The road ascends a ridge. Pass through the saddle between the Little Maria Mountains (west) and the Big Maria Mountains (east).

159.2 (0.3) **Stop** at the railroad crossing at Styx. Proceed southeast on Midland Road.

160.2 (1.0) The Midland mill site is at 2:00.

160.8 (0.6) **Stop** at the pavement and watch for traffic. The pavement runs west to the Midland mill site; we **PROCEED SOUTHEAST**.

162.6 (1.8) Continue past left (north) turn to the Eagle Nest mines.

164.1 (1.5) A block of gypsum marks the paved road to Inca Siding on the right (southwest). Mines in the Little Maria Mountains produced gypsum and anhydrite.

165.9 (1.8) Continue past the left (northeast) turn to the Black Hill quarries.

166.7 (0.8) Pass under double-pole powerline running north to the Black Hill quarries.

169.8 (3.1) Continue past a left (northeast) turn to to Big Maria quarries (the sign reads "Levy's Marble – $CaCO_3$"). The Blythe graben to the northeast cuts older Pleistocene sediments (QTa_2) and Holocene or late Pleistocene sediments (Qa_3) (Stone, 2006).

171.0 (1.2) Continue past the Midland long-term BLM visitor area to the northeast.

173.1 (2.1) Mesaville. There is a gravel pit on the east side of the road.

173.4 (0.3) Pass a land fill on the east side of the road. Mid-

Figure 1-4. Colorado River sediments near Midland Road.

land Road is on the "Upper Mesa" at elevation 400'. Drop off the terrace and pass through Colorado River sediments (Fig. 1-4).

173.6 (0.2) Cross the railroad tracks. We are on Lovekin Blvd.

175.9 (2.3) 4th Avenue.

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Alternate Trip to Blythe Intaglios

Turn left (east) on 4th Avenue. Proceed east to CA Highway 95.

(1.9) STOP at Highway 95 TURN LEFT (north) and travel on Highway 95 to the intaglios (Leska, this volume).

(10.5) TURN LEFT (west) to the Blythe intaglios. Retrace to Hwy 95. Proceed south to Blythe.

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176.9 (1.0) Continue past 6th Avenue.

177.9 (1.0) Continue past 8th Avenue.

178.9 (1.0) Continue past Riverside Avenue.

179.4 (0.5) **Stop** at the intersection of Hobson Way at Lovekin Blvd. in Blythe. Fill your gas tank south of I-10. Pick up dinner, food, and drink for tomorrow at markets (east) and fast food sources clustered at this intersection. **RECONVENE** and review directions to reach the starting point for Day 2.

End of Day 1

What did we see? Our 180 mile route crossed high elevations of the eastern Mojave Desert and then dropped into lower elevations of the Colorado Desert. Drainages north of Granite Pass drain into Soda Basin, while the Bristol–Danby trough drains to the Colorado River near Vidal. At Amboy, we saw outcrops of Bouse sediments containing the early Pliocene Lawlor Tuff (4.83 Ma) indicating that the Bristol–Danby trough was filled to an elevation of approximately 950 feet, which would have allowed it to connect with the Blythe basin to the southeast. On our trip southeast through the Bristol–Danby trough we saw sediments containing middle Pleistocene vertebrate faunas near Cadiz and late Pleistocene mammal fossils at Danby Lake, suggesting moisture in the form of groundwater discharge was available to support complex biotic communities.

Day 2

What we will see

The "Big Meander" of the Colorado River left polished cobbles and cross-bedded sands in Plio-Pleistocene outcrops between the McCoy and Mule mountains. These cobble barriers may have dammed drainage in the Chuckwalla Basin to the west. Mid-day on Day 2, we will see Bouse Formation sediments that contain both freshwater and brackish/marine fossils. The sediments are younger than the Tuff of Wolverine Creek (5.6 Ma, Pearthree and House, this volume) and filled the Blythe Basin to an elevation of 1080 feet by time the Lawlor Tuff (4.83 Ma) was deposited. Late in the day, we will pass the southern margin of the Salton Trough half-graben. Young rhyolite domes, Obsidian Butte, and mud volcanoes are testimony to its current activity.

Directions from Blythe to start of Day 2

Proceed to the I-10 onramp at Lovekin Blvd. Fill gas tank and gather food, drinks, and sunscreen.

(0.0) (0.0) **ENTER** I-10 westbound toward Indio.

(3.0) (3.0) Continue past the Highway 78–14th Street offramp.

(6.0) (3.0) **EXIT** at Mesa Drive for Mesa Verde and the Blythe airport.

(6.3) (0.3) Stop at the end of the offramp and **TURN LEFT** (south).

(6.6) (0.3) **Stop** at the intersection with Blythe Avenue. **TURN RIGHT** (west). Pavement ends ahead. Proceed west on the utility road.

() (0.7) Continue past the double-pole powerline road.

Figure 2-1. Cobbles deposited at the Big Meander, stop 2-1.

() (0.6) **STOP** at the intersection with the road that runs south to the Vor-Tac station.

Reset odometer to 0.0 miles.

CONVENE north of Vor-Tac Station on the east/west utility road. Reset odometer.

0.0 (0.0) Stay east of the single-pole powerline road and proceed north up the brown cobble hill.

0.3 (0.3) **PARK** on top of the hill.

STOP 2-1. Big Meander. We are looking at Plio-Pleistocene deposits of rounded Colorado River cobbles (QTmw; Stone, 2006) at an elevation of 128 m (420 ft). The elevation of the Colorado River to the east is 79 m (260 ft), or 43 m (140 ft) lower than where we stand. Cuts 500 feet north expose northeast-dipping, imbricated, cross-bedded cobbles indicating that these rounded cobbles were deposited by a Colorado River meander coming from the northeast (Fig. 2-1). The mapped outcrop pattern (Stone, 2006) indicates an arc of cobble deposits from a major river channel that trends southwest from the southern tip of the Big Maria Mountains to this spot. The outcrops of channel gravels have roughly concordant elevations around 122 m (400 ft). The cobbles are 14 m (46 ft) higher than the adjacent upper terrace. Channel gravels at this stop would have made an effective barrier to constrain flow eastward from Chuckwalla basin.

Playa High Stands. Pliocene sediments on the southwest margin of the Palen Mountains (QTs, Stone and Pelka, 1989) are exposed between elevations of 134 and 183 m (440 and 600 ft), more than 108 m (354 ft) higher than the surface of Ford Dry Lake Playa in Chuckwalla basin. These sediments (QTs), thin to thick-bedded, subrounded quartz and silt, suggest a playa deposit that received wind-blown sand. The sediments may have been ponded against the river cobble barrier on which we stand before erosion planed it to its current elevation. However, no dates are available for the Palen QT sediments or the river cobbles. Any definitive statement concerning the relation of gravel deposits in the McCoy and Mule mountains to the QT sediments in the southwestern Palen Mountains must await such correlation.

Mule Mountain River Gravels. Look southwest toward the northern tip of the Mule Mountains. At Stop 2-2 we will inspect shallow dipping sands containing polished, well-rounded river cobbles (QTmm, Stone, 2006) that may have been deposited by early flows of the Colorado River. These deposits sit at an elevation of 189 m (620 ft). If their outcrop pattern is similar to that of the QTmw on which we stand, they too would have provided a drainage barrier at the east end of Chuckwalla Valley with an elevation that would have allowed deposition of sediments at the 183m (600 ft) elevation along the southwest margin of the Palen Mountains(Fig. 2-2). No age relations are available. Return to vehicles. **PROCEED SOUTH** to the utility road.

0.6 (0.3) **TURN LEFT** (west) at utility road. Proceed to double-pole powerline road.

1.2 (0.6) **TURN RIGHT** (southeast) on double-pole powerline road.

1.8 (0.6) Proceed southerly at the well where the double-pole powerline bears west. Continue past a jojoba farm on the right.

2.2 (0.4) Continue south at the southeast corner of the jojoba farm.

2.7 (0.5) Continue past a right fork in the road.

3.2 (0.5) **TURN RIGHT** (west) at the "T" intersection.

3.5 (0.3) Continue past a reverse right intersection.

3.7 (0.2) **TURN LEFT** (south) at the "T" intersection.

4.0 (0.3) **BEAR RIGHT** (southwest) through the bushes.

5.4 (1.4) Cross under the powerline.

6.3 (0.9) Continue past the east end of the fence for the Mule Mountains archaeological site.

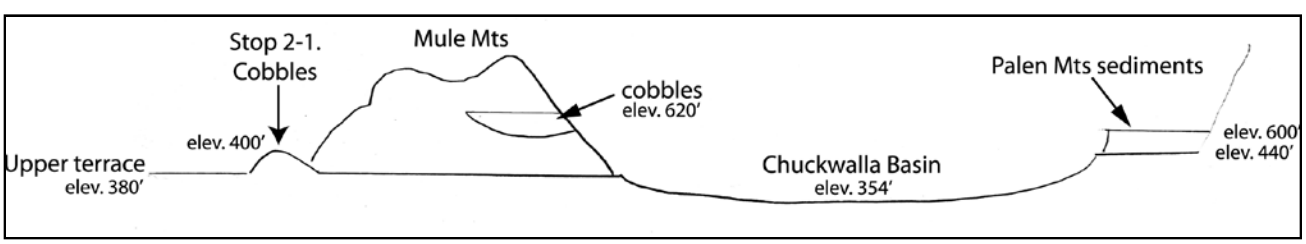


Figure 2-2. Sketch of relationships between sediments at Stop 2-1, the Mule Mountains, Chuckwalla basin, and the Palen Mountains.

Figure 2-3. Cobbles at Stop 2-2.

6.7 (0.4) Continue past the west end of the fence for the Mule Mountains archaeological site.

7.3 (0.6) The road bears south at a rock outcrop.

7.7 (0.4) **BEAR RIGHT** at the fork.

8.0 (0.3) **PARK** on the narrow terrace (UTM NAD 83, Zone 11 702784mE, 3714292mN).

STOP 2-2. Cobbles. Walk northeast to the slope of the terrace that exposes well-sorted, coarse sandstones containing rounded river cobbles of chert, jasper, quartzite, and silicified Paleozoic limestone (Fig. 2-3; UTM NAD 83, Zone 11 702831mE, 3714373mN). The elevation here is 188 m (617 ft). The elevation of the Colorado River to the east is 79 m (260 ft). These shallowly south-dipping deposits (QTmm, Stone, 2006) were possibly deposited by a former channel of the Colorado River that cut through the Mule Mountains (Stone, 2006). Channel deposits of sands and gravel from the Mule Mountains north to the McCoy Mountains at this elevation would have made an effective barrier against drainage from Chuckwalla basin to the Colorado River. From another perspective, if this QTmm represents a major channel deposit, are the QTs deposits (Stone and Pelka, 1989) in northwestern Chuckwalla basin distal overbank deposits from this meander? No data about age relationships between the Palen Mountain sediments and the Mule and McCoy mountain cobbles has yet been found. The local QTmm (189 m , 620 ft) and the QTmw deposits at Stop 2-1 (122 m , 400 ft) are both below the maximum high stand of Bouse Formation sediments (329 m , 1080 ft), and significantly above the current 40 m (130 ft) elevation of the Colorado River at Yuma, Arizona.

The Mule Mountains Thrust to the south places Jurassic plutonic rocks (Jp) over Jurassic volcanic rocks (Jv) (Tosdal, 1990; Stone, 2006). **RETRACE** to the BLM archaeological site.

(9.7) (1.7) The west end of the fence for the Mule Mountains archaeological site.

PARK at the entrance gate.

Stop 2-3. Mule Mountains Archaeological Site. Compare the extent of desert varnish on desert pavement with that on an ancient trail and on clasts in circular impressions (Fig. 2-4). Also compare the desert varnish on pavement and in rings with that in the rectangular clearings for circa 1950s pup tents (Fig. 2-5), and with the “fresh” look of fox holes in adjacent washes (Fig. 2-6) and on the hill north (Fig. 2-7). The lack of silt in the depressed linear trail supports its antiquity. Silt remaining in the arc of circles is

Figure 2-4. Ancient trail and circular impressions on desert varnish at Stop 2-3.

Figure 2-5. Tent impressions on desert varnish at Stop 2-3.

Figure 2-6. Fox hole in desert varnish at Stop 2-3.

Figure 2-7. Fox hole on hill north of Stop 2-3.

consistent with that in the pup tent clearings. **PROCEED WEST** toward Mesa Verde.

12.0 (2.3) Cross under the powerline.

13.4 (1.4) **TURN LEFT** (north) at the intersection.

13.7 (0.3) **TURN RIGHT** (east).

14.2 (0.5) **TURN LEFT** (north) toward the jojoba farm.

15.2 (1.0) Continue past the southeast corner of the jojoba farm.

15.6 (0.4) Continue past the well and north to the utility road.

16.1 (0.5) **TURN RIGHT** (east) on the utility road, which becomes Blythe Avenue.

16.8 (0.7) Stop, **TURN LEFT** (north) at the intersection with Mesa Drive.

17.1 (0.3) **TURN RIGHT** onto Interstate 10 and proceed eastward to Blythe. Downcutting by the ancestral Colorado River developed this upper terrace at 118 m (388 ft).

18.5 (1.4) Highway 10 drops to middle river terrace at 101 m (330 ft).

21.1 (2.6) Highway 10 drops to lower river terrace at 79 m (260 ft), the elevation of the Colorado River ahead (east).

21.3 (0.2) **EXIT** Interstate 10 at Neighbors Boulevard/Highway 78.

21.6 (0.3) **Stop** at Neighbors Boulevard. Gas and supplies can be obtained three miles east at Lovekin Boulevard. Proceed south on Neighbors Boulevard (Hwy 78) toward the communities of Ripley and Cibola.

26.0 (4.4) Slow through the community of Ripley.

27.6 (1.6) Stop, **PROCEED STRAIGHT** on Neighbors Blvd as Highway 78 jogs right (southwest). The Bradshaw Road (Brunzell, this volume) crosses our route. It ran from Banning Pass along the north side of the Chocolate Mountains and through the Mule Mountains, crossing the Colorado River to reach Ehrenberg, Arizona.

32.6 (5.0) Imperial County line.

33.6 (1.0) Slow: road bends right.

34.0 (0.4) Cross the Colorado River on Cibola Bridge. Welcome to La Paz County, Arizona. **PROCEED SOUTH** on River Road (Cibola Road).

36.5 (2.5) Stop at Baseline Road in the community of Cibola. **PROCEED SOUTH**.

37.5 (1.0) Cibola National Wildlife Refuge–Visitors Center.

41.4 (3.9) Cibola Sportsman's Club.

42.2 (0.8) **Stop** at "Cibola Crossroads:" the intersection with a road west to "South Bridge Crossing" of the Colorado River that reaches Highway 78 on the west side of the river in California. **TURN LEFT** (east).

44.5 (2.3) Cross a tributary of Hart Mine Wash.

44.6 (0.1) **PULL LEFT** into the barnacle locality and **PARK**.

STOP 2-4. Barnacles. Silty marl at this site contains disarticulated valves of freshwater clams. The valves were distributed by the current, and were subsequently used as anchors by barnacles looking for a solid substrate. Barnacles can tolerate brackish but not fresh water (Reynolds and Berry, this volume). If time permits, walk southwest down-drainage to look at barnacle coquina— beach deposits of disarticulated barnacle plates similar to recent deposits at Corvina Cove on the east side of the Salton Sea (Fig. 2-8). **RETRACE** to Cibola Crossroads.

47.0 (2.4) Stop, **TURN LEFT** (south) at Cibola Crossroads.

Figure 2-8. Cibola barnacle locality, Stop 2-5.

Proceed south toward the Hart Mine turnoff.

48.0 (1.0) **BEAR 15° LEFT** (southwest) at the Hart Mine turnoff.

48.1 (0.1) **TURN RIGHT** (southwest). Do not drive up the hill.

48.2 (0.1) **TURN LEFT** (south).

48.4 (0.2) **TURN LEFT** (east) into Marl Quarry wash.

48.5 (0.1) Continue past Marl Quarry, which is near the location of the fossil False Grunion (Todd, 1976). Proceed east up Marl Quarry Wash.

49.1 (0.6) **PARK** off the tracks. **STOP 2-5. Quarry Wash**. Walk southeast to the gully that cuts through white marl to expose yellow, cross-bedded sands with disarticulated brackish water invertebrates (Reynolds and Berry, this volume). These invertebrate-rich sands (Fig. 2-9) are similar to those at Earp, California and at Osborne Wash east of Parker, Arizona, and to sands that we will see at the next two stops. **RETRACE** to the north/south road.

49.8 (0.7) Stop, **TURN LEFT** (south) at the north/south road.

50.1 (0.3) Rejoin Cibola Road (River Road).

50.2 (0.1) Continue straight past the right (west) turn to the historic homestead cabin (Fig. 2-10). This road provides access to Levee Road on the east side of Colorado River.

50.3 (0.1) Don't stop on this sandy portion of the road.

50.5 (0.2) **TURN LEFT** (east) onto the dirt track that leads up "Cibola Wash."

51.1 (0.6) **STOP 2-6. "Cibola Wash."** We are at the junction of three washes. The sedimentary section on the north side of the wash contains a sub-angular volcanic fanglomerate overlain by Bouse Formation basal marl, then cross-bedded sediments in turn overlain by white marl (Fig. 2-11). The basal marl contains freshwater mollusks and ostracodes (Reynolds and Berry, this volume). Cross bedded sands to the west contain disarticulated brackish water invertebrates like those at Stop 2-5. Although the river plain is choked with salt cedar (tamarisk), the tributary washes contain dense stands of smoke tree, palo verde and mesquite (Gardner, this volume). **RETRACE** to Cibola Road.

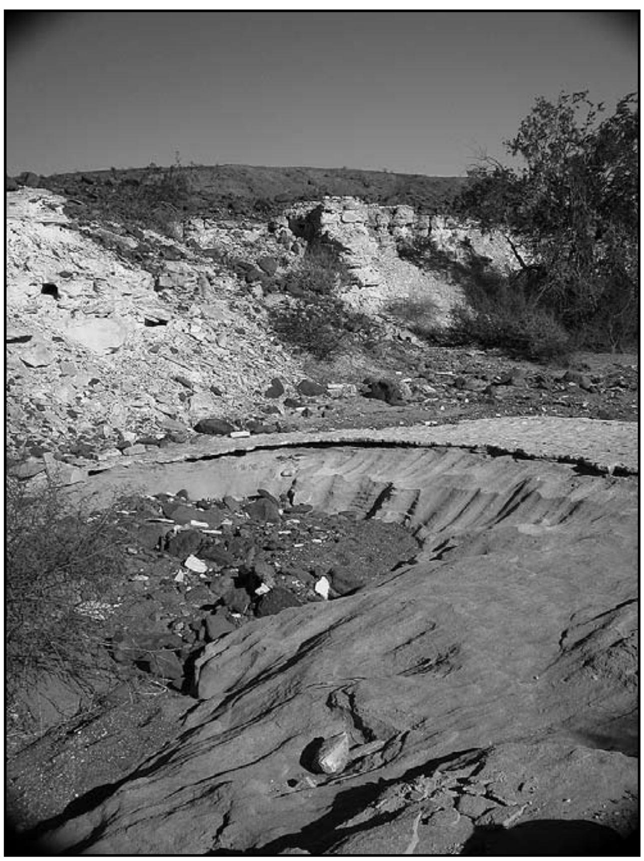


Figure 2-9. Invertebrate-rich sands at Quarry Wash, Stop 2-5.

Figure 2-10. "Dog trot" cabin built of cottonwood trees in 1910.

Figure 2-11. Cross-bedded sandstone in "Cibola Wash," Stop 2-6. Jon E. Spencer photograph.

51.8 (0.7) Stop, **TURN RIGHT** (north) at Cibola Road and drive toward Cibola Crossroads.

52.5 (0.7) Continue past Hart Mine Road.

53.5 (1.0) Stop, **TURN LEFT** (west) at Cibola Crossroads and head toward the Colorado River.

54.4 (0.9) Cross East Levee Road.

54.6 (0.2) Cross the Colorado River on a single-lane bridge.

54.7 (0.1) **TURN RIGHT** (north) on Levee Road on the west side of the Colorado River.

58.1 (3.4) **TURN LEFT** (west) toward Marlow Road and Highway 78.

58.5 (0.4) Proceed northwest on Marlow Road to Highway 78.

60.1 (1.6) **Stop** at the pavement (Highway 78). Look for cross traffic and **TURN LEFT** (south) onto the highway.

60.7 (0.6) Continue past Stallard Road.

61.3 (0.6) Highway 78 passes through green Miocene volcanic rocks.

61.5 (0.2) Highway 78 crosses over a ridge of Miocene volcanic rocks. Watch for fast oncoming traffic around curves.

61.7 (0.2) Note the cross-bedded sands on the left (east) side of the highway.

62.1 (0.4) Continue past, but notice, a left turn. We will return to this road by a safer route.

62.7 (0.6) Prepare for left turn across traffic in 0.1 miles.

62.8 (0.1) **TURN LEFT** (east) off Highway 78 and stop. Either make a "U" turn and return north to "first left turn" via Highway 78, or take the dirt pole line road north to the site. Watch for mud along the latter route.

63.5 (0.7) **TURN RIGHT** at the "first left turn."

Figure 2-12. Branching tufa structures at Palo Verde Point, Stop 2-7.

63.6 (0.1) **TURN LEFT** (north) and proceed into a rock lined cove.

63.9 (0.3) **PARK** outside the fenced Palo Verde Point BLM Archaeological Site.

STOP 2-7. Palo Verde Point. This rocky cove is the downstream side of a ridge of early Miocene volcanic and volcaniclastic rocks. In latest Miocene time, it was submerged by clear waters of a Bouse lake filling the Blythe basin. Branching tufa structures (Fig. 2-12).were deposited by blue-green algae on eastern outcrops. Blue-green algae require relatively clear, sunlit, shallow water to deposit tufa (Li, 2003). Subsequently, cross-bedded sands with mollusks and barnacles covered the tufa deposits. This sequence suggests that the clear water lake was replaced by shoreline activity that mixed a variety of fresh and brackish water invertebrates (Reynolds and Berry, this volume). RETRACE to Highway 78.

64.2 (0.3) **Stop** at the pavement, look for cross traffic, and **TURN LEFT** onto Highway 78.

66.3 (2.1) View to the west of Bouse Formation marl.

68.4 (0.3) Continue past Mitchell Camp Road.

69.5 (1.1) Continue past 3 Slashes Road.

70.1 (0.6) Continue past a left turn.

70.6 (0.5) Continue past a left turn.

71.3 (0.7) Continue past Walters Camp Road on the left.

71.4 (0.1) Continue past Milpitas Wash Road. Drop down the bluff into Milpitas Wash. From the start of Day 2, drainage into the Colorado River rrough from the west has been from sources no more distant than 10 miles. Milpitas Wash is a major drainage that reaches the Black Hills and Little Mule Mountains 25 miles to the west.

Figure 2-13. Bouse marl at Stop 2-8 contains impressions of fossil water grasses and carbonate coatings (stromatolites) around stems.

72.9 (1.5) Continue past Old Palo Verde Road.

77.5 (4.6) Continue past Midway Well Road.

79.9 (2.4) Continue past the turnout on the right.

81.2 (1.3) Continue past Gold Basin Road on the south side of the wash.

81.5 (0.3) Slow for a right turn and memorial marker.

81.6 (0.1) **PARK** at Ben Hulse Memorial Marker on the right.

STOP 2-8. Hulse Memorial Marker. Hike 30 minutes east-southeast to an outcrop with Lawlor Tuff in Bouse Formation sediments (Fig. 2-13). This outcrop demonstrates that the high stand of water here reached 330 m (1080 ft) when the Lawlor Tuff was deposited at 4.83 Ma (Spencer and others, this volume). Return to vehicles and **PROCEED SOUTH** on Highway 78.

82.2 (0.6) Buzzard Peak is at 10:00.

83.5 (1.3) Continue past the Border Patrol station.

84.4 (0.9) Continue past Black Mountain Road.

87.3 (2.9) Continue past the junction with Hwy 34 south to Ogilby. Drainage in this region runs east into the Colorado River in the Picacho Peaks area. The historic Tumco Mining District and Obregon Mining District are to the south in the Cargo Muchacho Mountains. Mining started in the 1890s and continued through the 1930s. The American Girl Mine was reactivated as a cyanide heap leaching operation in 1989. Proceed southwest on Highway 78.

93.9 (6.6) The Mesquite Mine is on the right (north) (Lange, 2006; Lange and others, 2007).

96.2 (2.3) Continue past BFDC Mine Road.

99.4 (3.2) **Stop** at Glamis and Ted Kipf Road. **PROCEED WEST** on Highway 78.

103.2 (3.8) The Osborne scenic overlook.

105.6 (2.4) The Cahuilla visitor center and ranger station at Gecko Road. Cross the Coachella Canal and proceed west on Hwy 788 (the Ben Hulse Highway).

106.6 (1.0) Pass through the gunnery range.

112.8 (6.2) Cross the East Highline canal.

114.1 (1.3) Continue past Hwy 33.

116.6 (2.5) Continue past Hwy 32.

118.6 (2.0) Continue past Hwy 115 south.

121.0 (2.4) Continue past Hwy 115 north.

123.4 (3.2) **Stop** at the junction of Hwy 111 South. Continue south and enter downtown Brawley. Fill gas tank.

126.6 (1.2) **Stop** at the junction of Hwy 111 North. **TURN RIGHT** (north) and follow Hwy 111.

127.8 (0.5) Continue past Shank Road.

128.3 (0.2) Continue past the New River bridge.

131.4 (3.1) Continue past Rutherford Road.

131.7 (0.3) Cross the New River, created by an historical agricultural experiment that caused Colorado River to flow into the Salton trough (Oglesby 2005).

134.3 (2.6) The Finley Kremer Waterflow Wildlife Area.

136.6 (2.3) **SLOW** for Calipatria.

140.6 (4.0) **TURN LEFT** (west) onto Sinclair Road.

143.2 (2.6) The Leathers power plant of the California Energy Company is on the right.

145.0 (1.8) Continue past, but notice, Garst Road. We will return for a trip to the "mud pots."

145.2 (0.2) The Elmer power plant of the California Energy Company is on the right.

146.0 (0.8) **RECONVENE** at the Sonny Bono Salton Sea National Wildlife Refuge (water, toilets, visitor center, gift shop) at the corner of Sinclair and Gentry roads. **RETRACE** east on Sinclair Road to Garst Road for a tour of mud pots and mud volcanoes (Lynch and Hudnut, this volume).

147.0 (1.0) **TURN LEFT** (north) on Garst Road. The pavement will end soon.

147.4 (0.4) Pavement ends.

147.7 (0.3) View west-northwest of Red Hill: two rhyolitic domes dating to 16,000 BP. Another small volcano, Rock Hill, can be seen to the southwest.

148.4 (0.7) Continue past Red Hill Road on the left (west) to Red Hill County Park and Marina. Cross the Alamo River. The Alamo River and New River empty seasonally into the Salton Sea. Both apparently formed by northward overflow of the Colorado River from Mexico in the late 1800s.

Figure 2-14. Mud volcanoes at Stop 2-9.

148.5 (0.1) **TURN RIGHT** (east) on Schrimpf Road. Look northwest toward Mullet Island, a low, white structure in the sea. If it is a clear day, you will see a plume of steam coming from the sea—an active volcanic vent to the right of Mullet Island.

149.5 (1.0) **STOP 2-9. Mud Volcanoes.** The mud volcano field is immediately northeast of the junction of Davis Road and Schrimpf Road. (Fig. 2-14). **TURN LEFT** (north) on Davis Rd, proceed 0.1 and **PARK. The volcanoes are on private land, pay appropriate respect!** Do not drive into the field. **CAUTION!!** Boiling mud and water are **hot** and **soft**. Do not climb on mud volcanoes. Return to vehicles. **PROCEED NORTH** on Davis Road.

Figure 2-15. Ruins of the CO_2 processing plant, Stop 2-10.

149.9 (0.4) Continue past McDonald Road.

150.9 (1.0). **PARK** at Pound Road. **Stop 2-10: CO_2 Mine.** The crumbling adobe building was part of a factory that extracted CO_2 to make dry ice (Fig. 2-15). There are many mud pots within 200 yards of the adobe. **PROCEED NORTH** on Davis Road.

153.8 (2.9) **TURN RIGHT** (east) onto the southern-most dirt track, south of Beach Rd and south of the water delivery channel. Drive 0.3 miles to the 6th levee on the right.

154.4 (0.6) .**Stop 2-11. 6th levee at Beach Road**. Walk southwest on the levee to mud pots that straddle the footpath. Mud pots exhibit different colors and evaporation rings that are a seasonal response to fluctuating sea level and rainfall. The levee and partitioned wetlands are maintained by the California Department of Fish and Game. Fields are flooded at different times to provide rest and roosting areas for migratory birds. The maintenance is funded by duck hunting license fees. Cautiously **RETRACE** to Davis Road.

154.7 (0.3) **TURN RIGHT** (north) at the junction of Davis and Beach Roads onto Davis Road.

155.7 (1.0) The pavement begins.

157.0 (1.3) Continue past the Wister Unit visitor area of the Imperial Wildlife Area.

157.1 (0.1) **Stop** at Hwy 111, watch for cross traffic, and **TURN RIGHT** (south) on Hwy 111. Proceed to Sinclair Road.

160.5 (3.4) Pass through Niland.

Figure 2-16. View toward Obsidian Butte, Stop 2-12.

161.8 (1.3) Continue past Pound Road.

162.7 (0.9) Continue past McDonald Road.

163.2 (0.5) Continue past Schrimpf Road.

164.4 (1.2) Slow, prepare to turn right . on Sinclair Road.

164.6 (0.2) **TURN RIGHT** (west) onto Sinclair Road and proceed west.

170.1 (5.5) **TURN LEFT** (south) on Gentry at the entrance to the Bono Salton Sea National Wildlife Refuge.

170.5 (0.4) **TURN RIGHT** (west) on McKendry Road.

171.4 (0.5) Cross Boyle Road.

171.9 (0.9) Veer to the right.

172.3 (0.4) **PARK** at Obsidian Butte (Fig. 2-16)

STOP 2-12: Obsidian Butte. Discuss the rift basin (McKibben, this volume), recent volcanism, the relationship of obsidian sources to Native American lithic sources, and current hydrothermal energy sources (McKibben, this volume; Lindsay and Hample 1998, Oglesby 2005). **RETRACE** to Gentry Road.

174.1 (1.8) Stop, **TURN RIGHT** (south) on Gentry Road.

174.5 (0.4) Pass the Hoch 79 Plant, Unocal Geothermal Salton Sea Unit 2.

177.1 (2.6) Stop at Eddins Road, Hwy 30.

180.4 (3.3) **Slow** as Hwy 30 jogs west, where it is called Walker Road.

180.7 (0.3) **Slow** as Hwy 30 jogs south and is called Forrester Road.

182.4 (1.7) Continue past Bannister Road (the Sonny Bono Salton Sea National Wildlife Refuge is to the west)

183.1 (0.7) Stop sign at 7th Street.

183.4 (0.3) **Stop** at Highway 86 in Westmorland. Check your gas gauge: this is the last gas available until Borrego Springs. Pick up dinner at the market. **TURN RIGHT** (west) on Hwy 86 and **PROCEED WEST** on Hwy 86 and Hwy 78, to Ocotillo Wells.

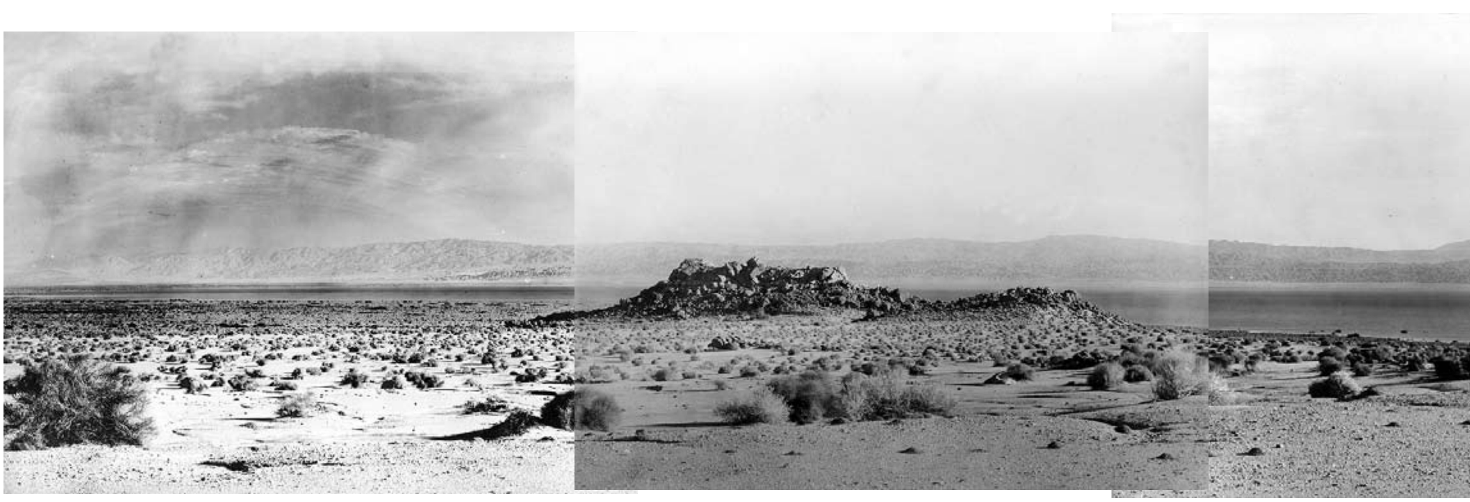
188.4 (5.0) Hwy 86 bears right (northwest). We are approximately 55 m (180 ft) below sea level. The shoreline of Lake Cahuilla, 12.5 m (+40 ft) above MSL, cuts into the Superstition Hills to the southwest.

197.3 (8.9) Continue past artesian Kane Spring with "water full of soda …being hardly fit for use" (Mendenhall, 1909).

199.6 (2.3) Cross San Felipe Creek, which drains Fish Creek Wash and Lower Borrego Valley.

Move to the left lane and prepare to turn left immediately past the Border Patrol check station

199.9 (0.3) Pass through the Border Patrol check station. Watch for oncoming traffic and **TURN LEFT** (west) on



General view of the Salton Sea from back of Figtree Johns. Riverside or Imperial Counties, California. October, 1906. Panorama with USGS photos mwc 00517, mwc00518, mwc00519, mwc00520, and mwc00521.

Hwy 78 immediately past the check station. Ahead, the highway crosses silts deposited by Lake Cahuilla below the 12.5 m MSL (+40 ft) high shoreline. These silts cover Plio-Pleistocene fluvial sediments of the Borrego and/or Brawley formations.

204.0 (4.1) Flowing Wells (artesian springs) are located three miles north.

206.2 (2.2) Cross sea level. We will cross the high shoreline of Lake Cahuilla at elevation 12.5 m (+40 ft) one-half mile ahead on the right (north) side of the road. Look for shoreline terraces and beach bars.

207.1 (0.9) Cross under a powerline.

210.6 (3.5) Continue past the Blue Inn Café.

211.1 (0.5) Continue past Payne Road on the left (south).

214.4 (3.3) Los Puertecitos Historical marker is on the left (south). Named "The Little Pass" by Anza, his expedition camped here on Monday, December 18, 1775 while en route through Borrego Valley to Coyote Canyon.

215.8 (1.4) **Slow**; prepare to turn left across oncoming traffic.

216.0 (0.2) **TURN LEFT** (south) on Split Mountain Road in Ocotillo Wells. The Split Mountain Store on Split Mountain Road is south of H-78. The Desert Ironwoods Resort, 2.9 miles west of Split Mountain Road on H-78, has supplies and may have rooms available. Services such as gas stations, markets, motels are about 35 miles to the northwest in Borrego Springs. Proceed south 8.1 miles from Ocotillo Wells on Split Mountain Road to the Fish Creek Canyon dirt road.

216.5 (0.5) The Split Mountain Store is on the left.

218.6 (2.1) The road bends southeast and becomes Old Kane Spring Road.

219.7 (1.1) **BEAR RIGHT** (south) on Split Mountain Road.

221.6 (1.9) Enter Anza-Borrego Desert State Park.

221.8 (0.2) Continue past a right (west) turn to the Elephant Tree area. Information on this and other interesting hikes and places to visit are available at the park Visitor Center in Borrego Springs.

224.0 (2.2) **TURN RIGHT** (southwest) onto a dirt road in Fish Creek Canyon wash.

225.4 (1.4) **TURN LEFT** (east) and up the bank at the sign. PARK at Fish Creek Campground. No water is available. Keep all open fires within the fire rings. If additional camp sites are needed, camping is also permitted along Fish Creek Canyon road. Vehicles must remain within one-car-length of the road and ground fires are not permitted.

Split Mountain Road dead-ends at the US Gypsum mine, visible to the east from the Fish Creek Campground (see Stop 3-1 below). The hills north of Fish Creek Canyon road and west of the south end of the pavement on Split Mountain Road were mined for celestite during World War II (Durrell 1953). Discuss Fish Creek Gypsum, celestite and the base of the Imperial Group deposits and Elephant Trees Conglomerate. Compare fauna and age to the Bouse Formation. Please note that collecting specimens of any kind is not permitted within the state park.

End Day 2 – Dry Camp at Fish Creek Campground

Day 2 – What did we see?

Early on Day 2 we saw the Big Meander of the Colorado River that left polished cobbles and cross-bedded sands in Plio-Pleistocene outcrops between the McCoy and Mule mountains. These cobble barriers may have dammed drainage in the Chuckwalla basin to the west. Bouse Formation sediments near Cibola contain both fresh water and

brackish/marine fossils. They are younger than the Tuff of Wolverine Creek (5.6 Ma, Pearthree and House, this volume) and filled the Blythe basin to 1080 feet at today's Hulse Memorial Marker by time the Lawlor Tuff was deposited (4.83 Ma). On Day 3 will have discussions about the timing of fresh water filling the Salton Trough. Late in Day 2, we passed the southern margin of the Salton trough half-graben. Young rhyolite domes, Obsidian Butte, and mud volcanoes are a testimony to its activity.

Questions

Stop 2-2. How Colorado River cobble deposits at elevation 188 m (617 ft) relate to Unit B of Metzger? At this elevation, what constrained the downstream base level? Is there a way to estimate relative age ranges for these gravels?

Stops 2-4 through 2-7. The Bouse faunas and facies appear to alternate from fresh to brackish water, and from carbonate to clastic facies. What type of barrier would allow fluctuations of fresh and brackish/marine water? Where did fresh water enter the Blythe basin?

Stop 2-8. Hulse Memorial Marker. The Bouse sediments here contain the Lawlor Tuff at a similar elevation to outcrops in Bristol basin (Stop 1-1). If a full Blythe basin backed water into the Bristol–Danby trough, what was the source of the marine water? What was the nature of a postulated dam that allowed fresh water fluctuations to enter? Must tectonic lowering of the Colorado River trough and subsequent uplift of sedimentary deposits be invoked to produce this 800-foot stack of basin-filling sediments?

Day 3

Please note that collecting specimens of any kind is not permitted within the State Park.

What we will see: The third day of our trip covers the lower part of the Fish Creek/Vallecito Creek Basin 5 km-thick stratigraphic section. These sediments largely fall within the Imperial Group (Figure 3-1), record the opening of the Salton Trough, filling by the ancestral Gulf of California, and deposition of the Colorado River delta across the trough. We will cover about 5 million years of this continuous stratigraphic record starting with pre-marine terrestrial deposits at ca. 7–8 Ma. The marine depositional record lasts from about 6.3 to 4 Ma, and the earliest evidence of input from the ancestral Colorado River is at 5.3

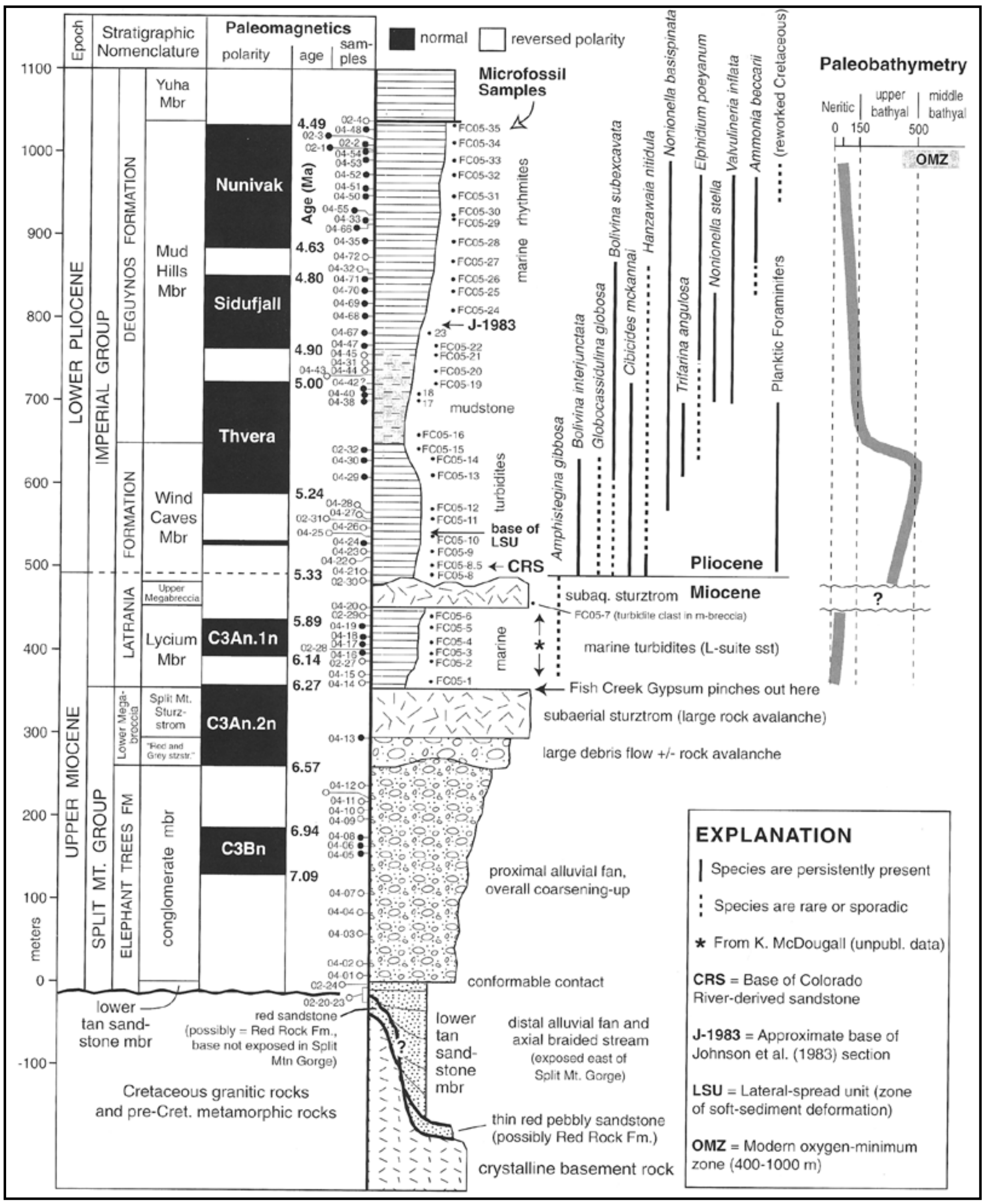


Figure 3-1. Generalized stratigraphic column for the Vallecito Creek/Fish Creek stratigraphic section. (from Dorsey 2006)

Ma (Winker 1987, Dorsey et al. 2007).

We will cross the marine prodelta, delta front, near-shore marine delta, and will finish with the transition to the terrestrial deltaic deposits at ca. 4.0 Ma. This section is summarized in Figure 1 (from Dorsey et al. 2007). The stratigraphic nomenclature of Neogene deposits within the Salton Trough has undergone numerous revisions and it remains controversial (see Remeika 1998, Lindsay 2006). Also see Winker and Kidwell (1996) and Dorsey (2006, Dorsey et al. 2007) for a discussion of the regional geologic setting. A systematic list of fossil taxa from the Imperial Group is found in Table 1 (Appendix I) (from Jefferson and Lindsay 2006).

Break camp early, and be prepared for lunch at STOP 3-6. We will start the trip on the east side of the campground at 8AM (with incessant horn honking).


Figure 3-2. Elephant Trees Conglomerate, Stop 3-2.

WALK 1/4 mile west from the Fish Creek Campground to outcrops of the Fish Creek Gypsum.

STOP 3-1. Fish Creek Gypsum, celestite, base of Imperial Group, and Elephant Trees Conglomerate (Figure 3-1). The marine Imperial Group includes the Latrania Formation and overlying Deguynos Formation (Winker and Kidwell 1996) (equivalent to the Mud Hills, Yuha and Camels Head Formations of others, Remeika 1998). Paleomagnetic dates range from 6.27 to 4.0 Ma (Dorsey 2006, Dorsey et al. 2007). The Fish Creek Gypsum is present at the base of the Imperial Group. It interfingers with the top of the Elephant Trees Conglomerate at its base and is laterally equivalent to the fossiliferous near-shore Latrania Formation. It has been interpreted as a sabkah-like deposit (Dean 1996) but largely lacks calcite, and otherwise has a distinctive metallic trace element signal of a geothermal vent (Peterson and Jefferson 1996). The gypsum is 90% pure, over 30 m-thick, and has been mined since 1920s. The celestite to the north, which is lens-shaped within the Latrania or Mud Hills, was mined during World War II (Durrell, 1953). The gypsum yields marine nanoplankton (Dean 1996) and other microfossils (Table 1). Elsewhere, the base of the Latrania Formation yields a diverse tropical invertebrate fauna with east Atlantic and Caribbean Ocean affinities (Deméré and Rugh 2006) (Table 1). The Isthmus of Panama was not present during Latrania time, allowing Atlantic and Caribbean molluscs to occupy eastern Pacific tropical waters. Remember that the brackish/marine snail *Batillaria* sp. with Atlantic Ocean affinities (Taylor 1983) occurs in 4.8 + Ma Bouse sediments from Parker to Cibola, AZ. **RETURN** to the camp ground.

0.0 (0.0) Leave Fish Creek campground and **TURN LEFT** (southwest). Drive up Fish Creek Canyon dirt road to the Red Cliffs. Compare the large clast size in the Miocene conglomerate with the intermediate size of clasts in late Pleistocene/Holocene conglomerate plastered to canyon walls (note smaller clasts in wash).

(0.5) (0.5) View ahead of a truncated anticline. Older sediments of the Elephant Trees Formation appear low on the canyon wall. These were anticlinally folded, perhaps compressionally elevated, and then truncated.

0.6 (0.1) **PARK** on the left side of the road.

STOP 3-2. Elephant Trees Conglomerate, "Red Rock," sturzstroms, and Split Mountain Anticline. The Elephant Trees Conglomerate is cut by the antecedent Fish Creek drainage, which is perpendicular to the Split Mountain anticline. This exposes the conglomerate, primarily debris flows and fanglomerates, at the core of the fold. The pale red conglomerate is about 8 to 6.5 Ma, and coarsens upward. The largely fluvial sandstone base to this unit was previously correlated with the early Miocene, 22 Ma, "Red Rock" formation that crops out several km to the south. Locally two lower megabreccias or struzstroms (Abbott 1996) separate the top of this unit from the base of the Latrania. A third, upper megabreccia occurs within the top of the Latrania. The struzstroms crop out along the south (left) side of the canyon en route to Stop 3-3. Note the very large, house-sized clasts in this unit. **CONTINUE WEST** along Fish Creek Canyon.

1.9 (1.3) **PARK** on the left side of the road.

STOP 3-3. Base of the Latrania Formation, Imperial Group. Here the olive brown locally derived silty sandstones in the base of the Latrania (southwest) lap onto the top of the lower megabreccias (northeast) and over the white to pink Fish Creek Gypsum. The gypsum is seen pinching out between these units several hundred meters to the southeast. An invertebrate ichnite-rich, near-shore facies of the Latrania (Table 1) is not present in these exposures, but crops out above the Elephant Trees Conglomerate about 1 km to the northeast along strike from Stop 3-1.

Figure 3-3. Base of the Latrania Formation, Stop 3-3.

CONTINUE along Fish Creek Canyon. From miles 2.0 to 2.5 observe turbidites in the upper Latrania Formation on both sides of the canyon. These relatively deep water marine turbidite medium brown sands and silts are locally derived and devoid of Colorado River transported clastic materials such as chert. They have been variously called the Lycium or Wind Caves member of the Latrania Formation (Lindsay 2006), yield marine microfossils (Dorsey et al. 2007, Figure 3-1), and contain invertebrate ichnites.

(2.1) (0.2) Cross axis of drag fold below the upper sturzstrom and adjacent to the Split Mountain fault to its right.

2.5 (0.4). **PARK** at the right side of the road.

STOP 3-4. First evidence of the ancestral Colorado River. These sands within the middle of the Latrania Formation and below the Coyote Mountain clays, or Mud Hills member of the Deguynos Formation, yield the first evidence of the Colorado River transported clasts. The quartz-rich sands are better sorted and rounded than the locally derived sediments. Quartz grains exhibit syntaxial quartz overgrowths, are hematite stained, and the sediments contain distinctive chert and metavolcanic lithic fragments. These sands typically lack appreciable amounts of locally derived biotite, which is present in the underlying sediments that crop out immediately down section. Based on paleomagnetic analyses (Dorsey et al. 2007), this horizon is 5.3 Ma (Figure 3-1).

CONTINUE west and south along Fish Creek Canyon.

(2.7) (0.2) Pass a sign on the left for Wind Caves.

3.0 (0.3) **PARK** on the right side of the road at the interpretive marker.

STOP 3-5. Coyote Mountain Clays or Mud Hills member of the Deguynos Formation (Figure 3-1). The Mud Hills member comprises all but the top-most beds of the prominent strike ridge to the southwest called the Elephant Knees. The dark olive and chocolate brown Mud Hills member is a relatively deep-water, very fine-grained marine sediment that largely predates progradation of the ancestral Colorado River delta front to the west across the Salton Trough. It yields a small, primarily molluscan invertebrate assemblage, bony fish, and the deep water shark *Squalus* sp. (Roeder pers. comm. 2007).

CONTINUE to the west along Fish Creek Canyon.

3.7 (0.7) **PARK** on the left side of the road.

STOP 3-6 at 3.7 mile. Colorado River delta rythmites. These primarily yellowish and medium brown cyclic silty sandstones occur in the top of the Coyote Mountain Clays or Mud Hills member and through the lower part of the Yuha member of the Deguynos Formation. They are ancestral Colorado River delta front sediments, about 4.8 to 4.5 Ma, and crop out for 1.5 km along Fish Creek Canyon. The physical drivers for this depositional phenomenon (climatic, tidal or other) and the duration of a single cycle are presently undetermined. Do you have any ideas?

CONTINUE to the west along Fish Creek Canyon.

5.2 (1.5) **PARK** at the left side of the road.

STOP 3-7 at 5.2 mile. Yuha Formation or member of Deguynos Formation (Figure 3-1). These reddish brown tempestite, clast-supported coquinas are primarily composed of mixed single valves of *Dendostrea vespertina*, *Anomia subcostata*, and *Argopecten deserti* (Demere and Rugh 2006). The deposits are lens-shaped and have a short outcrop pattern along strike. This, and taphonomy of the bivalve taxa, suggest high-energy erosion of estuarine ma-

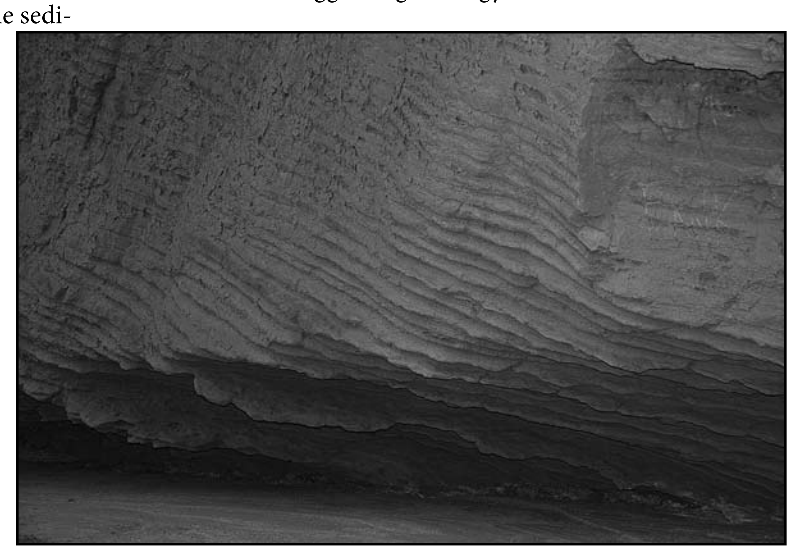


Figure 3-4. Colorado River delta rythmites, Stop 3-6.

terials and re-deposition into channels on the distal marine delta plain or upper delta front. Most marine vertebrate taxa (Table 1), including several newly discovered specimens of *Valenictus imperialensis* (Imperial walrus) and crocodile, have been recovered from similar shelly sand lenses near the top of the Yuha Formation (Atterholt and Jefferson 2007).

TURN RIGHT (west) into Loop Wash. Continue west along Loop Wash.

(5.9) (0.7) From 6.0 to 7.0 miles west, drive-by Camels Head transition. The Camels Head member in the top of Deguynos Formation records the transition from the marine delta to the terrestrial delta plane. It contains what are probably near-shore mudflat silty claystones and sandy beach deposits. Along strike, about 3.5 km south of Loop Wash and Fish Creek Canyon, Yuha-like silty sands containing estuarine molluscan taxa are interbedded with well-sorted deltaic medium-grained very pale yellow brown sands that yield abundant fossil woods (Remeika 2006), an Arroyo Diablo-like deposit (see below). Note the ranges in color from pink through pale green, and massive to laminar bedding of the deposits through this marine/subaerial transitional part of the section.

(7.2) (1.3) **PARK** along the roadside.

STOP 3-8. Arroyo Diablo Formation (Figure 3-1). The Arroyo Diablo Formation is primarily sandstone, and in some exposures south of Fish Creek Wash is comprised of a series of fining upward sand-silt sequences. It represents the terrestrial delta plane and interfingers with locally derived deposits of the Olla Formation along the basin margin. A variety of different shapes of sandstone concretions and fossil woods typify the unit. The fossil wood assemblage contains taxa whose modern relatives occupy lowlands and coastal areas with up to 50 cm (20 in) of annual precipitation. Fossil vertebrates include an elephant-like gomphothere and the Pliocene horse *Dinohippus*. The ancestral Colorado River extends its delta across the ancestral Gulf during Arroyo Diablo time, isolating the Salton Trough to the north about 3.9 Ma ago. To the north, the unit interfingers with the pale reddish clays and silts of the lacustrine and playa deposits of the Borrego Formation. To the south, the delta deposits spilled into the Gulf of California as they do today. The unit has also been called "Diablo", a preoccupied (Miocene of northern California and Permian of Nevada) and invalid name (Cassiliano 2002).

CAUTION: Important left turn ahead!! Continue southeast a short distance to the upper intersection of Loop Wash and Fish Creek Canyon. Enter Fish Creek Canyon and **TURN LEFT**, downstream, and continue back toward Fish Creek Camp.

(7.4) (0.2) **TURN LEFT** 300 degrees (east) into Fish Creek and continue east and north returning back through Split Mountain Gorge to Split Mountain Road. Upper Loop Wash is in the process of joining Fish Creek, and captures some drainage during floods.

() (4.0) (1.8) Pass a left turn to the lower end of Loop Wash road.

() (8.4) (4.4) View ahead (west) of red sandstone and a truncated anticline.

(9.1) (0.7) Pass the right turn to Fish Creek Camp.

10.5 (1.4) Stop at paved Split Mountain Road. Watch for truck traffic from the US Gypsum mine. **TURN LEFT** and drive north on paved Split Mountain Road.

18.6 (8.1) **STOP** at Highway 78 at Ocotillo Wells.

End Day 3 at Ocotillo Wells, intersection of SR-78 and Split Mountain Road.

Day 3 – What did we see?

How does the depositional history in the southern Salton basin compare to the depositional history in the Colorado River trough? The third day of the trip covered the lower part of the Fish Creek/Vallecito Creek Basin 5 km-thick stratigraphic section. These sediments of the Imperial Group (Figure 3-1) record the opening of the Salton trough, filling by the ancestral Gulf of California, and deposition of the Colorado River delta across the trough. A 5 million-year continuous stratigraphic record starts with pre-marine terrestrial deposits at ca. 7-8 Ma. The marine depositional record lasts from about 6.3 to 4 Ma, ending with terrestrial deltaic deposits at ca. 4.0 Ma. The earliest evidence of input from the ancestral Colorado River is at 5.3 Ma (Winker 1987, Dorsey et al. 2007). This is a period when fresh water input into the Blythe basin was alternating with input of marine water, producing alternating environments for fresh, then brackish water fauna.

Question: If the Blythe Basin continued filling with water (particularly marine water) from 5+ Ma to 4.83 Ma (Lawlor Tuff deposition), how did a proto-Colorado River reach and fill the portions of the Salton trough at 5.3 Ma without leaving a significant depositional record in the Blythe basin? Is the record present but unrecognized? Did Colorado River-like sediments come from a different source such as the Gila River?

Your Route Home

The park visitor center and services such as gas stations, market, motels, and restaurants are about 35 miles northwest in Borrego Springs. Continue west 6.7 miles on SR-78 to Borrego Springs Road, turn right (north), and continue to the Borrego Springs traffic circle in the center of town.

Exit Trip East (right turn) on H-78 to H-86 north (left turn) to I-10 west (left turn) and Riverside and Los Angeles Counties, and north (right turn) on I-15 to San Bernardino County, or I-10 east (right turn) to Arizona. A south (right turn) on H-86 south to I-8 returns to Yuma (left turn) or San Diego (right turn).

Exit Trip West (left turn) on H-78 to H-67 in Ramona into San Diego County, and I-8.

Visit Anza-Borrego Desert State Park. Visitor Center (closes at 5:00p), exit trip west (left turn) on H-78 to Borrego Springs Road (right turn 6.7 miles) to Borrego Springs, at traffic circle go west (left turn) on SR-22, Palm Canyon Drive, the Colorado Desert District Stout Research Center, State Park Visitor Center and Palm Canyon Campground (developed, reservation required).

From Visitor Center continue on SR-22 west (left turn) to S-2 west (right turn) to H-79 west (right turn) to Temecula and north (right turn) on I-15 to H-91 west (left turn) into Orange and Los Angeles Counties. Or, you can travel east on SR-22 to H-86 (See **Exit Trip East** above).

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Appendix I
Day 3 Faunal Lists

Table 1. Systematic list of fossil taxa from the Imperial Group, Anza-Borrego Desert State Park® and the Salton Trough Region, San Diego, Imperial, & Riverside Counties.

Explanation: * = type specimens from the Salton Trough Region; † = extinct taxon;; cf. = compares favorably with; nr. = near; sp. = single species; spp. = two or more species present. Taxonomic names have been revised to conform with current usage. Higher taxonomic categories are included where known, and common names are provided where known. Subgenera are not listed. Authors and dates for invertebrate species are included when known. Extracted from Jefferson et al. (2006); Jefferson and Remeika (2006) (see Deméré and Rugh 2006).

Fish Creek Gypsum Assemblage
(late Miocene)

Division Haptophyta
Class Coccolithophyceae (calcareous nannoplankton)

Order Isochrysidales
  Family Gephrocapsaceae
    Dictyococcittes scrippsae (?)
    D. minutes
    Reticulofenestra pseudoumbilica
    Crenalithus doronicoides (?)
Order Discoasterales
  Family Sphenolithaceae
    Spenolithus abies
    S. moriformis
  Family Braarudosphaeracea
    Braarudosphaera bigelowii
Order Eiffellithales
  Family Helicosphaeracea
    Helicosphaera kamptnen
Order Coccolithales
  Family Coccolithaceae
    Calcidiscus macintyrei
    Coccolithus pelagicus

Imperial Group Western Salton Trough, Coyote Mountains, and Vallecito Creek/Fish Creek Basin Assemblages
(late Miocene)

Subkingdom Protozoa
Phylum Sarcomastigophora
Subphylum Sarcodina (foraminifers)
Class Granuloreticulosea

Order Foraminifera
  Family Amphisteginidae
    Amphistegina gibbosa
    A. lessoni
  Family Miliolidae
    Quinqueloculina sp.
  Family Buliminidae
    Bolivina interjuncta
    B. subaenariensis mexicana
    B. vaughani
    Reussella pacifica
    Uvigerina peregrina
    Trifarina bella
    T. angulosa
  Family Cassidulinidae
    Cassidulina delicata
    C. laevigata
    C. subglobssa
    C. tortuosa
  Family Anomalinidae
    Cibicides fletcheri
    Hanzawaia nitidula
    H. basiloba
    Planulina ornata
  Family Discorbidae
    Epistominella subperuviana
  Family Globigerinidae
    "Globigerina pachyderma"
    G. quinqueloba
    Globigerinita uvula
    Sphaeroidinella subdhiscens
  Family Nonionidae
    Elphidium gunteri
    Elphidium sp.
    Nonion basispinata
    N. miocenica stella
    N. glabratalia californica
  Family Planorbulinidae
    Planorbulina acervalis
  Family Rotaliidae
    Ammonia beccarii
    Ammonia sp. cf. *A. parkinsonia*
    Siphonina pulchra
  Family Textulariidae
    Textularia schencki
    Textularia spp.

Phylum Cnidaria
Class Anthozoa
Subclass Zoantharia (corals)

Order Scleractinia
  Family Meandrinidae (starlet, brain, and flower corals)
    Meandrina bowersi (Vaughan, 1917) * †
    Dichocoenia merriami (Vaughan, 1900) * †
    D. eminens Weisbord, 1974 †
    Eusmilia carrizensis Vaughan, 1917 * †
  Family Siderastreidae (starlet corals)
    Siderastrea mendenhalli Vaughan, 1917 * †
  Family Rhizangiidae (= Astrangiidae) (cup corals)
    Astrangia haimei Verrill, 1866 †
  Family Faviidae (star corals)
    Manicina sp.
    Plesiastrea californica (Vaughan, 1917) †
    Solenastrea fairbanksi (Vaughan, 1900) * †
  Family Poritidae (finger corals)
    Porites carrizensis Vaughan, 1917 * †

Phylum Mollusca
Class Gastropoda (marine snails)

Order Patellogastropoda
  Family Lottiidae (limpets)
    "Patella" sp. †

Order Vetigastropoda
Family Fissurellidae (keyhole limpets)
Diodora alta (C.B. Adams, 1852)
D. cayenesis (Lamarck, 1822)
D. sp.
Fissurella sp.
Hemitoma emarginata (Blainville, 1825)
Rimula cancellata Schremp, 19981 * †
Family Haliotidae (abalones)
Haliotis pourtalesii Dall, 1881
Haliotis sp.
Family Turbinidae (turban snails)
Mirachelus imperialis Schremp, 1981 * †
Turbo magnificus Jonas, 1844
T. mounti Schremp, 1981 * †
Turbo sp.
Homalopoma maiquetiana (Weisbord, 1962) †
Family Liotiidae
Arrene stephensoni Schremp, 1981 * †
Family Trochidae (top snails)
Calliostoma bonita Strong, Hanna, and Hertlein, 1933
C. olssoni Schremp, 1981 * †
Tegula mariana Dall, 1919
Order Neritopsina
Family Nertidae (nerites)
Nerita scabricosta Lamarck, 1822
N. funiculata Menke, 1851
Theodoxus luteofasciatus Miller, 1879
Order Neotaenioglossa
Family Cerithiidae (ceriths)
Cerithium incisum Sowerby, 1855
Liocerithium judithae Keen, 1971
Family Potamididae (horn snails)
Cerithidea mazatlanica Carpenter, 1857
Family Modulidae (button snails)
Modulus catenulatus (Philippi, 1849)
Family Turritellidae (tower snails)
Turritella gonostoma Valenciennes, 1832
T. imperialis Hanna, 1926 * †
Vermicularia pellucida (Broderip and Sowerby, 1829)
Family Littorinidae (periwinkles)
Littorina varia Sowerby, 1832
Family Strombidae (conchs)
Strombus galeatus Swainson, 1823
S. granulatus Swainson, 1822
S. gracilior Sowerby, 1825
S. obliteratus Hanna, 1926 †
Family Hipponicidae (horse-hoof limpets)
Cheilea cepacea (Broderip, 1834)
Hipponix panamensis C.B. Adams, 1852
Family Calyptraeidae (cup and saucer snails)
Crepidula onyx Sowerby, 1824
Crucibulum scutellatum (Wood, 1828)
C. spinosum (Sowerby, 1824)
Family Cypraeidae (cowries)
Macrocypraea cervinetta (Kiener, 1843)
Muracypraea sp.
Zonaria sp.
Family Naticidae (moon snails)
Natica chemnitzii Pfeiffer, 1840
N. unifasciata Lamarck, 1822
Polinices bifasciatus (Griffith and Pidgeon, 1834)
P. uber (Valenciennes, 1832)
Family Cassidae (helmet snails)
Cassis subtuberosus Hanna, 1926 * †
Family Tonnidae (tuns)
Malea ringens (Swainson, 1822)
Family Ficidae (fig snails)
Ficus ventricosa (Sowerby, 1825)
Family Personidae (distorsio snails)
Distorsio constricta (Broderip, 1833)
Family Epitoniidae (wentletraps)
Epitonium efferum Bramkamp *in* Durham, 1937
Order Neogastropoda
Family Muricidae (murex snails)
Hexaplex brassica (Lamarck, 1822)
Eupleura muriciformis (Broderip, 1833)
Family Turbinellidae (vase snails)
Vasum pufferi Emerson, 1964 * †
Family Buccinidae (welks)
Solenosteira anomala (Reeve, 1847)
Family Melongenidae (crown conchs)
Melongena patula (Broderip and Sowerby, 1829)
Family Fascolariidae (tulip snails and horse conchs)
Fusinus dupetitthouarsii (Kiener, 1840)
Pleuroploca princeps (Sowerby, 1825)
Latrius concentricus (Reeve, 1847)
Leucozonia cerata (Wood, 1828)
Family Nassariidae
Nassarius sp.
Family Columbellidae (dove shells)
Strombina solidula (Reeve, 1859)
Family Olividae (olive snails)
Oliva incrasatta [Lightfoot, 1786]
O. porphyria (Linnaeus, 1758)
O. spicata (Röding, 1798)
Olivella gracilis (Broderip and Sowerby, 1829)
Family Mitridae (miter snails)
Mitra crenata Broderip, 1836
Subcancilla longa (Gabb, 1873) †
S. sulcata (Swainson *in* Sowerby, 1825)
Family Cancellariidae (nutmeg snails)
Cancellaria cassidiformis (Sowerby, 1832)
C. coronadoensis Durham, 1950 †
C. obesa Sowerby, 1832
C. urceolata Hinds, 1843
Family Terebridae (auger snails)
Terebra dislocata (Say, 1822)
T. elata Hinds, 1844
T. robusta Hinds, 1844
Family Turridae (turrid snails)
Knefastia olivacea (Sowerby, 1833)
Polystira oxytropis (Sowerby, 1834)
Family Conidae (cone snails)
Conus arcuatus Broderip and Sowerby, 1829
C. bramkampi Hanna and Strong, 1949 * †
C. californicus Reeve, 1844
C. durhami Hanna and Strong, 1949 * †
C. gladiator Broderip, 1833
C. fergusoni Sowerby, 1873
C. patricius Hinds, 1843
C. regularis Sowerby, 1833
C. ximenes Gray, 1839
Order Heterostropha
Family Architectonicidae (sundials)
Architectonica nobilis discus Grant & Gale, 1931†

Order Cephalaspidea
Family Bullidae (bubble snails)
Bulla punctulata A. Adams in Sowerby, 1850
B. striata Bruguière, 1792
Order Basommatophora
Family Melampidae
Melampus sp.

Class Scaphopoda (tusk shells)

Order Dentalioida
Family Dentaliidae
Dentalium sp.

Class Bivalvia (marine clams)

Order Nuculoida
Family Nuculidae (nut clams)
Nucula sp.
Family Nuculanidae
Nuculana acuta (Conrad, 1831)
N. santarosaensis Perrilliat, 1976 †
Order Arcoida
Family Arcidae (ark clams)
Arca mutabilis (Sowerby, 1833)
A. pacifica (Sowerby, 1833)
Barbatia reeveana (Orbigny, 1846)
Anadara carrizoensis Reinhart, 1943 * †
A. concinna (Sowerby, 1833)
A. formosa (Sowerby, 1833)
A. multicostata (Sowerby, 1833)
A. reinharti (Lowe, 1935)
Family Glycymerididae (bittersweet clams)
Glycymeris bicolor (Reeve, 1843)
G. delessertii (Reeve, 1843)
G. gigantea (Reeve, 1843)
G. maculata (Broderip, 1832)
G. multicostata (Sowerby, 1833)
Order Mytiloida
Family Mytilidae (mussels)
Lithophaga sp. aff. *L. plumula* (Hanley, 1844)
Order Pterioida
Family Pinnidae (penshells)
Pinna latrania Hanna, 1926 * †
P. mendenhalli Hanna, 1926 * †
Atrina stephensi Hanna, 1926 * †
Order Limoidea
Family Limidae (file shells)
Ctenoides floridana (Olsson and Harbison, 1953)
Limaria sp. †
Order Ostreoida
Family Ostreidae (true oysters)
Myrakeena angelica (Rochebrune, 1895)
"Dendostrea" angermani (Hertlein and Jordan, 1927)
Dendostrea? *vespertina* (Conrad, 1854) * †
Crassostrea columbiensis (Hanley, 1846)
Saccostrea palmula (Carpenter, 1857)
Undulostrea megodon (Hanley, 1846)
Family Gryphaeidae (oysters)
Pycnodonte heermanni (Conrad, 1855) * †
Family Pectinidae (scallops)
Antipecten? praevalidys (Jordan and Hertlein, 1926)
Argopecten circularis bramkampi (Durham, 1950) * †
A. deserti (Conrads, 1855) * †
A. mendenhalli (Arnold, 1906) †
A. sverdrupi (Durham, 1950) †
A. ventricosus (Sowerby, 1842)
Chlamys corteziana Durham, 1950 †
C. lowei (Hertlein, 1935)
C. mediacostata (Hanna, 1926) * †
Cyclopecten pernomus (Hertlein, 1935)
Euvola keepi (Arnold, 1906) †
Flabellipecten carrizoensis (Arnold, 1906) * †
Flabellipecten sp.
Leptopecten palmeri (Dall, 1897)
L. velero (Hertlein, 1935)
Lyropecten tiburonensis Smith, 1991 †
Family Plicatulidae (kitenpaws)
Plicatula inezana Durnam, 1950
P. penicillata Carpenter, 1857
Plicatula sp.
Family Spondylidae (thorny osters)
Spondylus bostrychites Guppy, 1867 †
S. calcifer Carpenter, 1857
S. princeps Broderip, 1833
Family Anomiidae (jingles)
Anomia subcostata Conrad, 1855 * †
Placunanomia hannibali Jordan and Hertlein, 1926 †
Order Veneroida
Family Lucinidae (lucine clams)
Calucina quincula Olsson, 1961 ?
Codakia distinguenda (Tryon, 1872)
Miltha xantusi (Dall, 1905)
Pegophysema edentuloides (Verrill, 1870)
Divalinga eburnea (Reeve, 1850)
Parvilucina mazatlanica Carpenter, 1857
Family Crassatellidae (crasstellas)
Crassinella mexicana Pilsbry and Lowe, 1932
Eucrassatella digueti Lamy, 1917
E. subgibbosa (Hanna, 1926) * †
Family Chamidae (jewelbox clams)
Chama frondosa Broderip, 1835
Arcinella arcinella (Linnaeus, 1767)
A. californica (Dall, 1903)
Family Carditidae (carditas)
Cardites crassicostata (Sowerby, 1825)
C. megastropha (Gray, 1825)
Carditamera laticostata Sowerby, 1833
Family Corbiculidae (marshclams)
Polymesoda notabilis (Deshayes, 1855)
Family Cardiidae (cockles or heart clams)
Trigoniocardia sp. aff. *T. guanacastensis* (Hertlein and Strong, 1947)
Laevicardium sp.
Lophocardium gurabicum (Maury, 1917)
Family Veneridae (Venus clams)
Chione hannai Parker, 1949
Chione sp.
Cyclinella cyclica (Guppy, 187x)
Dosinia dunkeri (Philippi, 1844)
D. ponderosa (Gray, 1838)
Gouldia californica Dall, 1917
Irus ellipticus (Sowerby, 1834)
Megapitaria sp.
Periglypta multicostata (Sowerby, 1835)
Pitar sp. ? *P. catharius* (Dall, 1902)
Globivenus isocardia (Verrill, 1870)

Family Tellinidae (tellens)
Tellina ulloana Hertlein, 1968
T. pristiphora Dall, 1900
T. ochracea Carpenter, 1864
Florimetis dombei (Hanley, 1844)
Macoma siliqua (C.B. Aams, 1852)
Family Donacidae (bean or wedge clams)
Donax sp. cf. *D. gracilis* Hanley, 1845
Family Semelidae (semele clams)
Semele bicolor (C.B. Adams, 1852)
S. sayi Toula, 1909
Family Solecurtidae (tagelus clams)
Tagelus californianus (Conrad, 1837)
T. violascens (Carpenter, 1857)
Solecurus gatunensis Toula, 1909
Order Myoida
Family Myidae (softshell clams)
Crpytomya sp.
Family Corbulidae (corbulas)
Corbula mexicana Perrilliat, 1984 †
Corbula sp. †
Family Haitellidae (geoducks)
Panopea abrupta (Conrad, 1849)
Family Pholadidae (rock piddocks)
Cyrtopleura costata (Linnaeus, 1758)
Order Pholadomyoida
Family Thraciidae (thracia clams)
Cyathodonta undulate Conrad, 1849

Phylum Echinodermata
Class Asteroidea (sea stars)

Order Paxillosida
Family Astropectinidae (sand stars)
Astropecten armatus Gray, 1840
Subclass Ophiuroidea
Family,Genus and species indeterminate (brittle stars)

Class Echinoidea (sea urchins and sand dollars)

Order Cidaroida
Family Cidaridae (club-spined urchins)
Cidaris sp.
Eucidaris thouarsii (Valenciennes, 1846)
Order Diadematoida
Family Diadematidae (sea urchins)
Centrostephanus sp.
Order Arbacioida
Family Arbaciidae (regular sea urchins)
Arbacia incisa (Agassiz, 1863)
Order Temnopleuroida
Family Toxopneustidae (white urchins)
Lytechinus sp. cf. *L. anamesus* Clark, 1912
Toxopneustes roseus (Agassiz, 1863)
Tripneustes californicus (Kew, 1914) †
Order Echinoida
Family Strongylocentrotidae (sea urchins)
Strongylocentrotus purpuratus (Stimpson, 1857)
Order Clypeasteroida
Family Clypeasteridae (Sea biscuits)
Clypeaster bowseri Weaver, 1908 * †
C. carrizoensis Kew, 1914 * †
C. deserti Kew, 1915 * †
Clypeaster sp. cf. *C. rotundus* (Agassiz, 1863)
Family Echinarachniidae (sand dollar)
Vaquerosella sp. †
Family Mellitidae (Key-hole sand dollar)
Encope arcensis Durham, 1950 †
E. sverdrupi Durham, 1950 †
E. tenuis Kew, 1914 * †
Family Echinoneidae (regular heart urchins)
Echinoneus burgeri Grant and Hertlein, 1938 †
Order Spatangoida
Family Schizasteridae (puffball heart urchins)
Agassizia scrobiculata Valenciennes, 1846 †
Agassizia sp.
Schizaster morlini Grant and Hertlein, 1956 †
Family Brissidae (heart urchins)
Brissus obesus Verrill, 1867
Metalia spatagus Linnaeus, 1758
Meoma sp.
Family Loveniidae (Porcupine heart urchins)
Lovenia hemphilli Israelsky, 1923 †

Phylum Bryozoa
Class Gymnolaemata (bryozoans)

Order Cheilostomata
Family Membraniporidae
Conopeum commensale Kirkpatrick and Metzelaar, 1922

Phylum Brachiopoda
Class Inarticulata

Order Artremata
Family Lingulidae
Glottidia? sp.

Phylum Arthropoda
Subphylum Crustacea
Class Maxillopoda

Order Sessilia
Family Balanidae
Megabalanus tintinnabulum (Linnaeus, 1758) (acorn barnacle)

Class Malacostraca

Order Decapoda
Family Goneplacidae
Speocarcinus berglundi Tucker, Feldman, and Powell, 1994 (crab)

Class Ostracoda (marine water fleas)

Order Podocopida
Family Trachyleberididae
Puriana sp.
Hermanites sp.
Family Loxoconchidae
Loxocorniculum sp.
Loxoconcha sp.
Family Xestoleberideidae
Xestoleberis sp.
Family Cytheruridae
Cytheura sp.
Anterocythere sp.
Family Hemicytheridae
?Aurila sp
?Ambostracon sp.
Caudites sp.

Family Cytheridae
Perissocytheridea sp.
Family Microcytheridae
Microcytherua sp.

Phylum Vertebrata
Class Chrondricthyes (sharks, skates, and rays)

Order Galeomorpha
Family Cetorhinidae
Cetorhinus sp. (basking sharks)
Family Carcharinidae
Carcharhinus sp. (requiem sharks)
Hemipristus serra (east Indian Ocean shark)
Family Lamnidae
Carcharocles megalodon † (great white shark)
Carcharodon sp. (white sharks)
Family Odontaspididae
Odontaspis ferox (sand shark)
Squalus sp. (deep water shark)

Order Mylobatiformes
Family Myliobatidae
Myliobatis sp. (bat rays)

Class Actinopterygii (bony fish)

Order Culpeiformes
Family Clupeidae
Genus and species indeterminate (herrings)
Order Tetraodontiformes
Family Tetraodontidae
Arothron sp. (puffer fish)
Family Balistidae
Genus and species indeterminate (triggerfish)
Order Perciformes
Family Labridae
Semicossyphus sp. (sheepshead)
Family Sphyraenidae
Sphyraena sp. (barracudas)

Istiophoridae (billfish)
(tuna)

Class Reptilia (reptiles)

Order Testudines
Family Cheloniidae
Genus and species indeterminate (sea turtles)

Class Mammalia (mammals)

Order Carnivora
Family Odobenidae
Valenictus imperialensis * † (Imperial walrus)
Order Sirenia
Family Dugongidae
Genus and species indeterminate (dugong)
Order Cetacea
Family Balaenopteridae
Genus and species indeterminate (baleen whale)
Family Cetotheriidae
Genus and species indeterminate (whale-bone whale)
Family Delphinidae and/or Phocaenidae
Genus and species indeterminate (dolphins and porpoises)

Typanites Marine Ichnofauna (borings and tracks)
(late Miocene Latrania Formation)

Entobia (clionid sponge boring)
cf. *Gastrochaenolites torpedo* (clam boring)
Maeandro polydora (polychaete worm boring)
Typanites (polychaete worm or barnacle boring)
Echinoid (boring)

The vegetation of the Mojave and Colorado deserts

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Introduction

Many travelers perceive the California desert as little more than a desolate wasteland, inhabited by a monotonous expanse of creosote bush (*Larrea tridentata*). In spending time off the beaten path, with a greater attention to detail, one uncovers an amazing diversity of plant life which exhibits a fascinating array of adaptations to the challenges of surviving in the desert. Variations of climate, substrate, and elevation support a mosaic of different vegetation associations, with many of the species found only here in the California Desert ecoregion.

The flora of the California deserts as we see it today is of relatively recent origin, developing in response to rapid drying and warming trends over the past 10,000 years. Species now restricted to the high elevations of the desert mountains, such as pinyon pine (*Pinus monophylla, P. edulis*) and juniper (*Juniperus* spp.), were widespread throughout the lowlands when the dry basins contained freshwater lakes. The heat- and drought-tolerant species that dominate today's desert landscapes were confined to the lowest elevations and more southerly latitudes before expanding their ranges with increasing temperatures and decreasing rainfall.

Contrasts between the Mojave and Colorado deserts

The California Desert province is divided into the Mojave and Colorado Deserts, a division based on climate, elevation, and latitude. The Mojave receives less summer rainfall and endures longer periods of freezing temperatures in the winter than the Colorado Desert with its more southern location, lower elevation, and exposure to a summer monsoon rainfall pattern. Precipitation also increases with elevation so that greater plant diversity and abundance can be found in the desert mountains. In addition to the influence of topography, variations occur north to south and east to west across the landscape.

The Mojave Desert supports an estimated 2500 plant taxa, with over 200 of them endemic to California (Keeler-Wolf, 2007). The Colorado Desert is roughly half as rich in species. Some distinctive plants of the Colorado Desert that are not found elsewhere in California—and thus considered indicator species—include ocotillo (*Fouquieria splendens*), ironwood (*Olneya tesota*), desert lavender (*Hyptis emoryi*), desert agave (*Agave deserti*), chuparosa (*Justicia californica*), and California fan palm (*Washingtonia filifera*) (Baldwin, 2002). Joshua tree (*Yucca brevifolia*) and Mojave yucca (*Yucca schidigera*) are considered indicator species for the Mojave Desert, as are burro bush (*Ambrosia dumosa*) and teddy-bear cholla (*Opuntia bigelovii*).

The transition zone between the Colorado and Mojave deserts occurs approximately between Banning to the west and Needles to the east (Barbour et al., 1991). South of this imaginary line, plants distinctive to the Colorado Desert become more prevalent. However, many species cross this imaginary line, making the transition zone a subtle blending rather than a sharp contrast.

The Mojave Desert

The Mojave is the smallest and driest of the four North American deserts, covering approximately 50,000 square miles including portions in California, Nevada, Arizona, and Utah (MacKay, 2003). The region is topographically diverse, composed of a series of mountains and valleys as part of the Basin and Range Geomorphic Province. Elevations range from 282 feet below sea level in Death Valley to high mountain peaks above 11,000 feet, but generally lie between 2,000 and 6,000 feet. The Mojave is often considered a transitional zone between the Great Basin to the north and the Colorado Desert to the south, exhibiting some of the characteristics of each region.

The division between the eastern and western Mojave Desert runs through the Cadiz and Bristol Dry Lake valleys, up through Broadwell Dry Lake and Soda Lake, then north through Death Valley (Keeler-Wolf, 2007). The Mojave is a rainshadow desert, with most of the winter storm precipitation off the Pacific Ocean intercepted by the Sierra Nevada. The western Mojave receives an average of 4–8 inches of precipitation annually during the winter months, while the eastern Mojave receives up to half of its rainfall during the summer months. Winter temperatures are too low in the Mojave for most species of cacti. The growing season lasts between 200 and 300 days.

The Colorado Desert

The Colorado Desert is a portion of the larger Sonoran Desert lying in the lower Colorado River Valley of southeastern California. Most of the Colorado Desert lies between sea level to 3,000 feet elevation, with a low point of 275 feet below sea level in the Salton Trough and high peaks reaching nearly 10,000 feet. Encompassing approximately 7 million acres, the Colorado is lower, flatter, and warmer than the Mojave (Hickman, 1993). The Colorado Desert's latitude, low elevation, and proximity to the sea give it a more subtropical desert climate with infrequent freezing temperatures. With precipitation blocked by the Peninsular Range, a meager 2–3 inches of rain falls on the Colorado River Valley. Most of it comes in winter, but the summer monsoonal rains off the Gulf of Mexico and Gulf of California through Arizona and Mexico spill over into this region and can account for roughly half of the annual precipitation (Spellenberg, 2002). Summer temperatures can exceed 120 degrees Fahrenheit and the growing season lasts from 250 to 350 days.

Cacti and succulents are common throughout the greater Sonoran Desert, but southeastern California is too hot and dry to support the large columnar cacti such as saguaro (C*arnegia gigantean)* that characterize the landscapes of Arizona (as an exception, a few populations occur near the Colorado River). Trees in the legume family such as honey mesquite (*Prosopis glandulosa*) and smoketree (*Psorothamnus spinosus*) are also common throughout the greater Sonoran Desert, but in California are restricted to watercourses. Ocotillo (*Fouqueria splendens*) is often considered an indicator species for the Colorado Desert. Other indicators for the Colorado Desert include catclaw (*Acacia greggii*) and palo verde (*Cercidium microphyllum*) (MacMahon, 2000).

Plant Adaptations to Desert Conditions

Due to the low rainfall and high temperatures found in deserts, evaporation exceeds precipitation. To cope with this situation, desert plants have evolved a wide range of structural and physiological adaptations to minimize water loss. These drought-tolerant plants, called “xerophytes,” may escape, avoid, or endure drought conditions, resulting in a wide assortment of strange and beautiful plant forms.

Annuals

An annual plant germinates, grows, flowers, sets seed, and dies in less than one year, avoiding drought in a dormant state within the seed. Annuals are also referred to as “ephemerals” due to their short lifespans. Seeds of desert plants remain viable for long periods, only germinating when conditions are right. Winter ephemerals germinate and grow in response to sufficient fall and winter rainfall, while summer annuals respond to adequate amounts of summer monsoon rains, blooming in late summer and early fall when the rest of the desert plants are dormant. Desert winter ephemerals typically live for 8 months, and desert summer ephemerals typically live for 2–3 months.

During most years, the annuals are absent or few. Rarely, perhaps once in a decade, above-average precipitation triggers widespread germination of annual plants which blossom into spectacular carpets of wildflowers. One such event occurred in 2005, causing millions of tourist to descend on Death Valley to view the breathtaking spring floral displays.

Herbaceous perennials

Herbaceous perennials are plants that live for more than one year, but their tops die back to an underground portion. The underground root may be enlarged into a bulb or tuber for storing extra carbohydrates. This allows them to avoid the drought by surviving underground during the hot, dry season. Examples of desert herbaceous perennials are desert lily (*Hesperocallis undulata*), jimson weed (*Datura wrightii*), and various desert bunch grasses.

Succulents

Succulent plants are able to store water in their leaves and stems and have a waxy coating to retard water loss. Leaf succulents may have a rosette form, such as in the yuccas and agaves. The leaves are arranged on the stem so as to funnel water towards the plant’s roots. Stem succulents have a cylindrical or spherical shape to reduce surface area relative to volume. Most stem succulents in North America are members of the cactus family. Further adaptations in the cactus family are the reduction of leaves to spines, ribs that can expand or contract accordion-like for water storage, and a special type of photosynthesis that allows the plants to open their pores only at night. Cacti with flat pads, such as beavertail (*Opuntia basilaris*), angle their pads for the least amount of exposure to the summer sun. The tops of barrel cacti have a similar mechanism for minimizing heat by bending to the north.

Shrubs

Shrubs are the most common life form in the California deserts and display the widest assortment of adaptations to drought and heat stress. Many are drought-deciduous, with the ability to drop their leaves to stop water loss through transpiration when conditions become too unfavorable. Those that retain their leaves year-round are the drought-enduring evergreen shrubs. They withstand the heat with diminished or divided leaf surfaces or have pale-colored or hairy leaves to reflect sunlight. Waxy coatings or very small pores to minimize water loss are also common adaptations. Leaves may also be oriented upright for minimum exposure to the sun. Look for a combination of these characteristics when examining desert shrubs. Shrubs can be subdivided into evergreen shrubs such as creosote bush, drought-deciduous shrubs such as bur-sage, and winter-deciduous shrubs that have deep roots in riparian habitats.

Trees

Because of their larger structure, trees require greater amounts of water to survive and can only endure in the deserts where extra amounts of moisture are available—in desert mountains, washes, and riparian zones. “Phreatophyte” is a term applied to deep-rooted plants that obtain water from a permanent underground supply. Roots of honey mesquite (*Prosopis glandulosa*) can tap into water at a depth of 160 feet (Barbour et al., 1991). These trees are winter-deciduous, losing their leaves and going into a semi-dormant state during the winter months.

Desert Sage – This shrub, found throughout the California deserts in rocky habitats, bears small, whitish leaves to reduce water loss. Leah Gardner photograph.

Bladderpod – An example of a shrub that favors wash habitats, the yellow flowers of this species are visited by bees and hummingbirds in the springtime. Leah Gardner photograph.

California Fan Palms—California Fan Palms in a small palm oasis community on the north side of the Coachella Valley. Jonathan Mistchenko photograph.

Dune Evening-Primrose—A common herbaceous perennial of dunes and sand flats. Leah Gardner photograph.

Panamint Dunes—Creosote Bush Scrub covers the landscape approaching the Panamint Dunes in Death Valley National Park. Leah Gardner photograph.

Telescope Peak—A land of contrasts, snow-covered Telescope Peak towers over Death Valley. Brittlebush blooms in the foreground. Leah Gardner photograph.

Yucca—The Mojave yucca has longer leaves and a shorter stature than the Joshua tree, both indicator species for the Mojave Desert. Leah Gardner photograph.

Oriented—The flat pads of this prickly pear cactus are oriented upright to minimize exposure to the overhead sun. Leaves of cacti are reduced to protective spines and the succulent stems carry on photosynthesis. Leah Gardner photograph.

Rosette—This desert agave is a leafy succulent in the form of a rosette which funnels moisture towards the base of the plant. Leah Gardner photograph.

Death Valley—Carpets of winter ephemerals such as desert marigold created spectacular displays in Death Valley in the spring of 2005. Leah Gardner photograph.

Pinyons—Pinyon Juniper Woodland with an understory of Mormon tea and other shrubs occurs at higher elevations of the Granite Mountains. Leah Gardner photograph.

Wild burros in Creosote Bush Scrub. The shrubs with light-colored foliage are desert holly and all-scale while the darker green leaves belong to the creosote bush. Leah Gardner photograph.

Vegetation types

Plant assemblages are categorized into vegetation types based on a combination of life forms, dominant species, and habitat types. Several classification schemes have been developed by botanists over the years. The following is a simplified summary of currently accepted vegetation types for the Mojave and Colorado deserts.

Desert Scrub

This vegetation type, dominated by shrubs, dominates most of the low elevation areas of both deserts. It can be further broken down by species associations.

Creosote Bush Scrub. Creosote Bush Scrub is the most common desert scrub type, covering approximately 60–70% of the desert floors and alluvial fans across the Mojave and Colorado deserts of California (Barbour et al., 2007). Creosote bush is an evergreen shrub, able to withstand a wide range of conditions, but typically occurs in areas receiving between 2 to 8 inches of rainfall in both the Mojave and Colorado deserts. Common associates include burro bush (*Ambrosia dumosa*), brittle bush (*Encelia farinosa, E. actoni, E. virginensis*), and cheesebush (*Hymenoclea salsola*). Mojave yucca (*Yucca schidigera*), silver cholla (*Opuntia echinocarpa*), and beavertail cactus (*Opuntia basilaris*) are often encountered amid the broadly spaced shrubs.

Blackbush Scrub. This vegetation association, dominated by blackbush (*Coleogyne ramosissima*), gives the landscape a drab color across a range of elevations up to 5,000 feet. It can be found in large dense stands on north-facing slopes or as an understory with Joshua Tree Woodland or Pinyon-Juniper Woodland throughout the Mojave Desert. Some of the associated species include Mormon tea (*Ephedra nevadensis, E. viridis*), hop-sage (*Grayia spinosa*), winter fat (*Krascheninnikovia lanata*), and horsebush (*Tetradymia stenolepis*).

Alkali Sink. In the lowest desert basins, water collects and evaporates, leaving behind salts and soils with a high pH. These dry lakebeds are also known as an alkali sinks, salt flats, or playas. While the playa itself may be devoid of vegetation, they are commonly ringed by salt-tolerant plants. Plants that can live in these alkali sinks are called "halophytes," literally meaning salt loving. Examples of halophytes include saltgrass (*Distichlis spicata*), arrow-scale (*Atriplex phyllostegia*), iodine bush (*Allenrolfia occidentalis*), bush seepweed (*Suaeda moquinii*), and yerba mansa (*Anemopsis californica*).

Saltbush Scrub and Shadscale Scrub. These communities are frequently associated with moderately alkaline soils. Dominant species of the Saltbush Scrub include several members of the *Atriplex* genus including saltbush (*Atriplex canescens*), shadscale (*A. confertifolia*), and allscale (*A. polycarpa*). These species, along with hop-sage and winter fat, make up the Shadscale Scrub vegetation community at higher elevations in the northern Mojave and around Death Valley.

Cactus Scrub. This community is dominated by a variety of cactus species alone or in a mixture of cacti, drought-deciduous shrubs, and succulents. Occurring on dry, rocky south-facing slopes, this plant community is found more commonly in the Colorado Desert than in the Mojave. The Mojave is home to over 20 species of cactus while the Colorado contains more than 125 species (Schoenherr and Burk, 2007).

Joshua Tree Woodland

Joshua trees (*Yucca brevifolia*) are unique to the Mojave and are found between 2,500 and 4,500 feet elevation in areas receiving 6 to 15 inches of rainfall. Other interesting plants found among these dramatic Mojave indicators are the Mojave yucca (*Yucca schidigera*), bladder sage (*Salazaria mexicana*), boxthorn (*Lycium andersonii, L. cooperi*), desert sage (*Salvia dorrii*), and many species of wild buckwheat (*Eriogonum* spp.). The leaves of the Joshua tree are much shorter than those of the Mojave yucca, thus the name "brevi folia". Cima Dome is home to one of the largest intact expanses of Joshua Tree Woodland in the world.

Pinyon-Juniper Woodland

An open woodland composed of pinyon pines and junipers occurs above 4,500 feet elevation where they can receive over 10 inches of precipitation annually, some of it falling as snow. These evergreen conifers were much more widespread throughout southeastern California in the past but have retreated to their mountain refuges as the climate dried and warmed. This woodland is also a common vegetation type in the mountains of the Great Basin. Shrubs found in the understory include many from the Great Basin such as sagebrush (*Artemisia tridentata*), bitterbrush (*Purshia tridentata*), mountain mahogany (*Cercocarpus* sp.), and Mormon tea (*Ephedra viridis*).

Desert Dune

Sand dunes in the desert can absorb and store water like giant sponges. Water rapidly percolates down from the surface, to be retained at depth in the dune. Furthermore, dry sand at the surface acts as mulch, preventing evaporative loss. The dune may also act like a riparian habitat, with water at depth. Plants growing on the dunes need to have deep roots to reach this valuable resource. They must also tolerate the challenges of heat, wind, abrasion, and sand movement. Plants tend to be widely scattered with low cover, except during the rare explosions of wildflowers during years of excessive precipitation. Dune plants include many of those common to other areas of the desert, as well as some found only on the dunes.

Plants found only on sand dunes and sand flats are referred to as psammophytes or psammophytic vegetation. The plants tend to be low-growing herbaceous perennials, including rhizomatous grasses, because woody plants are too stiff and grow too slowly to remain above the shifting sand. Examples of herbaceous perennials common to the dunes are desert sand-verbena (*Abronia villosa*) and desert evening-primrose (*Oenothera deltoidea*). Nonetheless, honey mesquite, desert willow, and a variety of other shrubs and small trees do occur sporadically or in dense aggregations on the dunes.

Eureka Dunes are home to three endemic species found nowhere else: Eureka dunes grass (Swallenia alexandrae), Eureka Dunes evening-primrose (Oenothera californica ssp. eurekensis), and Eureka milkvetch (Atriplex lentiginosus var. micans). The Kelso Dunes, the largest dune system in the Mojave Desert, supports 75 indigenous species with several endemics. The Algodones Dunes, largest in the entire United States, host six unique taxa, including Peirson's milkvetch (Astragulus magdelenae var. peirsonii) (Keeler-Wolf, 2007).

Desert Wash Woodland or Microphyll Woodland

Washes occur in canyons and drainages subject to infrequent but sometimes severe flooding. Assemblages of shrubs and trees that can successfully establish in these conditions are found in and along the washes. Many of these plants are winter-deciduous. Desert willow (*Chilopsis linearis*), catclaw (*Acacia greggii*), honey mesquite (*Prosopis glandulosa*), smoketree (*Psorothamnus spinosus*), and palo verde (*Cercidium floridum*) are examples of trees commonly found along desert washes. Wash shrubs include desert waterweed (*Baccharis sergiloides*), bladderpod (*Isomeris arborea*), chuparosa (*Justicia californica*), desert lavender (*Hyptis emoryi*), and indigo bush (*Psorothamnus schottii*). The desert wash community is better developed in the Colorado Desert and often goes by the name "Microphyll Woodland" due to the dominance of small-leaved trees in the legume family.

Desert Riparian

Extensive riparian zones are found along some stretches of the Mojave, Colorado, and Amargosa Rivers where water is available year-round. Elsewhere, springs provide water for year-round creeks in isolated canyons of desert mountains. Cottonwoods (*Populus fremontii*), several species of willows (*Salix* spp.) and mesquite are the most common trees of the riparian areas. Desert broom (*Baccharis sarothroides*) is common along with many other shrubs, grasses, and herbs.

Palm Oasis

The Palm Oasis is a special type of riparian community found only in the Colorado and Sonora deserts. The California fan palm, *Washingtonia filifera*, is the dominant characteristic species although other riparian plants are present. Chuparosa is common in the understory, its red tubular flowers attracting hummingbirds during spring. Individual palms may grow up to 30 meters tall and live for 250 years or more. Palm groves are found along geologic faults where breaks in the bedrock allow fresh water, as hot or cold springs, to come to the surface. California fan palms are now commonly grown as ornamentals, but their natural distribution is limited to widely separated groves in southeastern California, southern Nevada, southern Arizona, and northwest Mexico. Unlike other vegetation types of the Mojave and Colorado deserts, palm oases are adapted to surface fires; many of the ground-layer species do not occur unless the large palm leaf litter is burned. Several good examples of this rare ecological community can be accessed from Borrego Springs and throughout Anza Borrego State Park.

Invasive Species

The spread of invasive exotic plants and animals has become an urgent environmental threat throughout California, second only to habitat loss as the cause of species endangerment. While many non-native plants are not harmful, the noxious weeds crowd out native plants, compete with natives for limited resources, lower productivity for agriculture and grazing, and alter fire regimes. The worst culprits in our desert ecosystems are tumbleweed or Russian thistle (*Salsola tragus*), cheatgrass (*Bromus tectorum*), Saharan mustard (*Brassica tournefortii*), giant reed (*Arundo donax*), and tamarisk or saltcedar (*Tamarix ramosissima*).

The latter two weeds have overtaken riparian zones along river channels, irrigation canals, and other wetland habitats, eliminating native species by outcompeting them for water, increasing soil salinity, and decreasing habitat values. A prime example of this can be seen at the Cibola National Wildlife Refuge along the Colorado River where native mesquite and willow have been almost totally supplanted by giant reed and tamarisk.

Saharan mustard is problematic in the Colorado Desert, especially in sensitive habitat areas such as washes and dunes in the Imperial Valley. In the Algodones Dunes, Saharan mustard is threatening several rare plant species (DoTomaso et al., 2007). Cheatgrass is mostly a problem in the Great Basin but extends into the California deserts. Its presence provides a continuous cover, allowing the spread of wildfires in ecosystems that have not evolved adaptations to frequent fires. Two other exotic grasses, Arabian grass (*Schismus barbatus*) and Mediterranean grass (*Schismus arabicus*), are also common desert weeds.

Invasive species are not the only threat to native plants of the California deserts. Other threats include suburban expansion, power generation, military training, off-highway vehicles, grazing, mining, and agriculture—the latter due to both land conversion and the lowering of the water table (Barbour et al., 1991). Global warming and climate change are also current and future threats over the next 100 years and beyond. Once damaged the desert, as a fragile ecosystem, is extremely slow to recover; natural revegetation can be measured in centuries (Carpenter et al).

At least for the present, there are many beautiful intact desert ecosystems for us to enjoy and study. Large tracts of desert land are protected as national and state parks, monuments, natural areas, and reserves. With their unique assemblages of plants, geomorphological diversity, rich history, and wide open spaces, the Mojave and Colorado deserts of California are waiting for us to explore, appreciate, and protect.

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Southern California vanadate occurrences and vanadium minerals

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Introduction

There are about 95 known vanadium minerals, 41 of which are vanadates that contain the $(VO_4)^{-3}$ ion. There are very few common vanadate minerals. The most common are vanadinite [$Pb_5(VO_4)_3Cl$], descloizite [$PbZnVO_4(OH)$], mottramite [$PbCuVO_4(OH)$], and carnotite [$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$]. They most likely formed as a result of vanadium in magnetite finding its way into ground water which then oxidized primary lead minerals, most likely galena (W. Wise, pers. comm.). Vanadium is primarily used to harden steel.

The seventeen southern California vanadate occurrences and four vanadate minerals reported by 1983 (Pemberton, 1983) are indicated with asterisks in the following list. Since 1983, eight new occurrences and four new vanadate/vanadium minerals have been reported in southern California. These are denoted in bold. Most of these have been documented in Inyo and San Bernardino counties (Adams, 1999, 2000, 2003a, 2003b, 2005; Housley and Reynolds, 2002; Reynolds and Housley, 1995; White, 2000).

Inyo County

- Blue Monster Mine, Saline Valley (**vanadinite, descloizite**)
- Brown Monster Mine, Owens Valley (**vanadinite, mottramite, descloizite**)
- Reward Mine, Owens Valley (**vanadinite, mottramite**)
- Green Monster Mine, Owens Valley (**volborthite, vesigneite, tangeite)**
- Ubehebe Mine, Death Valley National Park (vanadinite*, **descloizite**)
- Thompson Mine, Darwin (vanadinite*)
- Opir Mine, N of Trona (vanadinite+)

San Bernardino County

- AO Prospect, Lenwood (**vanadinite, descloizite, mottramite**)
- Leiser Ray Mine, near Goffs (vanadinite*, mottramite*, **tangeite**)
- Blue Bell Mine, near Baker (**mottramite**)
- Bear Claw Well, Providence Mountains (vanadinite*)
- War Eagle Mine, 29 Palms Marine Base (vanadinite*)
- Giant Ledge Mine (**mottramite**)
- New York Mountains (**vanadinite**)
- Kramer Hills (carnotite*)
- Jeep #2 claim/Mammoth Mine (carnotite*)

Riverside County

- New Eldorado Mine, Joshua Tree National Park (vanadinite*)
- Black Eagle Mine, Black Mountain (vanadinite*)
- Lone Star Quarry, Crestmore (mottramite*)
- Ram deposit, Old Dale (carnotite*)

Imperial County

- McKnight Clay Mine, Chocolate Mountains (carnotite*)
- Bluebird Hill (Vitrifax) kyanite deposit (carnotite*)

Kern County

- Miracle Mine (carnotite*)
- Knoll Prospect (carnotite*)
- Vanuray Claim (carnotite*)

San Diego County

- Tourmaline King, Tourmaline Queen etc. (pucherite)*

** Pemberton (1983)*
+ Norman and Stewart (1951)

Most of these occurrences (and all the new occurrences) are associated with small, secondary lead–copper–zinc deposits. This paper summarizes and briefly describes these newly discovered occurrences of vanadate minerals in southern California.

Inyo County occurrences

The **Blue Monster Mine**, formerly known as the Monster Mine, was a lead prospect discovered in 1907 and worked until the mid 1930s (A. Knopf, 1918; Tucker and Sampson, 1938). The workings consist of several short tunnels and surface pits at an elevation of 4800 feet on the east slope of the Inyo Mountains, east of Independence. The country rock is limestone and spotted schist adjacent to plutonic igneous rocks; the main ore body was a 3.5-foot

Figure 1. Vanadinite crystals (to 3 mm) in subparallel growth from the Blue Monster Mine, Inyo Co., CA.

Figure 2. Pyramidal vanadinite crystals (to 2 mm) from the Brown Monster Mine, Inyo Co., CA.

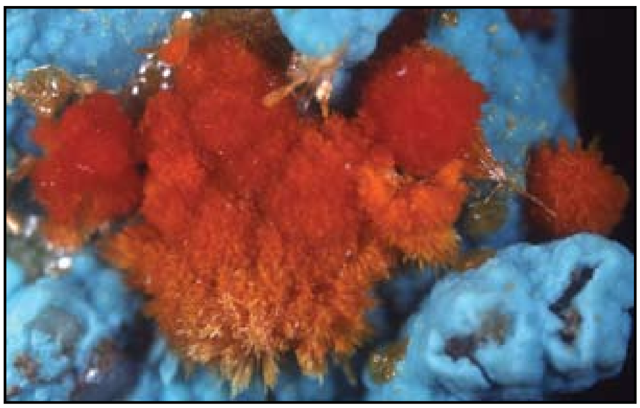

Figure 3. Vanadinite crystals (to 0.5 mm) on chrysocolla from the Reward Mine, Inyo Co., CA.

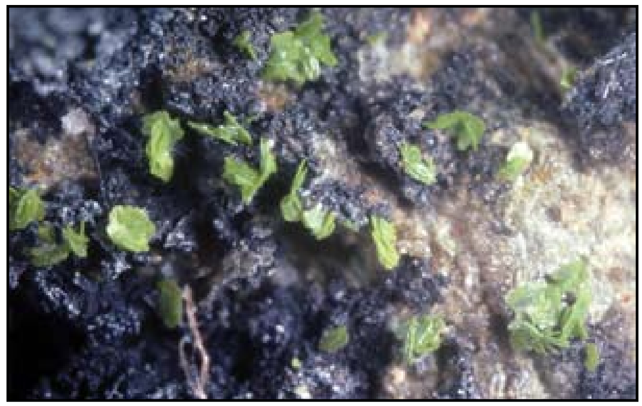

Figure 4. Intergrown tangeite, volborthite and vesigneite crystals (to 0.25 mm) from the Green Monster Mine, Inyo Co., CA.

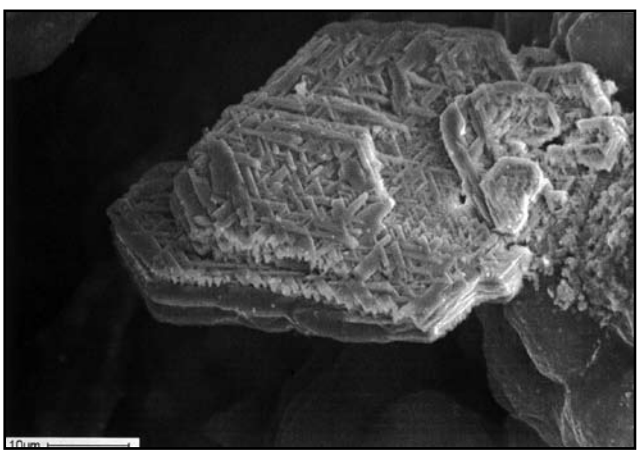

Figure 5. Scanning electron microscope image of intergrown tangeite, volborthite and vesigneite crystals from the Green Monster mine, Inyo Co., CA.

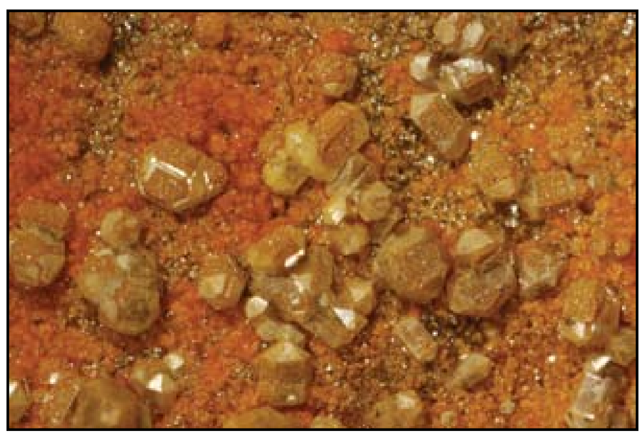

Figure 6. Dipyramidal vanadinite crystals (to 2 mm) on descloizite from the Ubehebe Mine, Inyo Co., CA. Natural History Museum of Los Angeles County specimen.

wide by 40-foot long galena vein in milky quartz. The ore was transported to the base of the canyon by means of a 1500-foot long tram. The ore was carried by pack animals west, up (4000 feet) and over the crest of the Inyo Mountains to Mazourka Canyon and then hauled to the railroad siding at Kearsage (Citrus) five miles east of Independence in the Owens Valley. The Blue Monster Mine may now be in the Inyo Wilderness and access may be blocked by the BLM. The most interesting crystallized mineral from the Blue Monster Mine is one that was not even originally reported—vanadinite. Vanadinite crystals occur in a number of different colors and habits (Adams, 2005). The most common are dark gray tapering prisms that often have a cream colored outer layer and coat limestone breccia fragments. Light brown simple hexagonal prisms, cream-colored equant to tabular hexagonal crystals (to 1 mm), and very rounded, almost botryoidal light gray aggregates (0.5 mm) were also found. The most interesting habit, represented by a single specimen found on the dumps, is that of subparallel aggregates of crystals forming a sort of "pineapple" structure (Figure 1). Other microminerals that occur, but not in abundance, include pyromorphite as small (0.25 mm) cream colored crystals, often associated with reddish-brown micro-mottramite.

The **Eclipse Mine** (later named the **Brown Monster**) was one of the first three gold claims in the southern Owens Valley (1861). It was worked during the Indian Wars in the early-mid 1860s and later taken over by a group of English investors in the 1870s. It was sold in 1878 as a result of a law suit and the name was changed to the Brown Monster. The Brown Monster and **Hirsch** mines (later named the **Reward**) were patented in 1882. A mill operated on the site and a small town with a post office and school was present in the early 1900s. Major operations ceased about 1914 (W. Irelan, Jr., 1888; A. Knopf, 1918). Small time, intermittent operations continued until the mid 1950s (Tucker and Sampson, 1938; Norman and Stewart, 1951). The mines are located nine miles southeast of Independence and can be reached by the Manzanar–Reward road, east of Highway 395. The Brown Monster Mine is located on the north side of the gulch; the Reward Mine is on the south side. Both of the mines explore mildly dipping quartz veins 4–8 feet thick that contain small amounts of gold, but veins of galena are also present in the hanging walls. At the Brown Monster Mine, vanadinite occurs as transparent reddish-brown crystals (to 2 mm) associated with mottramite and wulfenite (Adams, 1999). The dark, red-brown crystals usually have steep pyramidal terminations that often have light yellow tips (Figure 2). These crystals often have a second generation of oriented, acicular vanadinite growing from the tips. In one small area the vanadinite crystals were perched on micro-bladed deep red to dark brown mottramite, while in another, light orange mottramite forms crusts (casts) that cover vanadinite and calcite crystals. Late stage micro drusy quartz has also formed casts covering 2–3 mm prismatic vanadinite crystals. Vanadinite crystals with similar appearances and associations to those at the Brown Monster Mine are also found at one location near the portal of the Reward Mine (Figure 3) (Adams, 2000). At both mines, the darker red varieties are usually arsenian vanadinite while the lighter orange to yellow crystals are usually vanadian mimetite, but exceptions exist. At the Brown Monster Mine, mottramite is relatively common at certain locations. The mottramite forms botryoids and crusts that range in color from light yellow green through, tan, brick red, and chocolate brown. It is commonly associated with mimetite and wulfenite. Locally it was found as dark brown botryoidal coatings to 2 mm thick or individual brown balls (to 1 mm) associated with dark reddish brown vanadinite. Multiple episodes of growth are relatively common and mottramite has been observed overgrowing mimetite, quartz, and calcite crystals. A similar occurrence is found in a localized vanadate assemblage in the Reward Mine. Small balls (0.25 mm) of brown calcian mottramite have been found on rubble near the portal to the Reward Mine. In addition to mottramite, descloizite has also been found at the Brown Monster Mine. It is brown in color and tends to form larger crystals (to 0.25 mm) than the mottramite, which is typically more micro-botryoidal. Micro-fibrous cuprian descloizite has also been found covering small quartz crystals.

The **Green Monster** (a.k.a. Green Eyed Monster) Mine is located about 7 miles northeast of the town of Independence in Inyo County, CA. It can be reached by taking the Mazourka Canyon Road east from Route 395, just south of Independence. After about 4 miles, on the right is an old wooden ore bin near the road and a small hill. A short distance past the bin, a dirt road leads north, through a gate, and towards the mine. The Green Monster Mine was discovered in the late 1800s and was worked for copper until about 1910. It was described as "the most notable deposit of contact-metamorphic copper ore" in the Inyo Mountains, even though it was not of particular economic importance (Aubury, 1908; Knopf, 1918). The name of the mine probably came from the conspicuous yellow-green minerals seen in the outcrop, some of which had been described as being a hydrous ferric silicate analogous to chloropal (nontronite?). The mine is along the contact between an aplite intrusive and limestone, presumed to be Carboniferous in age. The copper ores occur in a garnetized zone along the contact. The total production from the property was reported as 300 tons of 12% copper ore, carrying $4.50 per ton in gold and silver. Mineral collectors had reported volborthite occurring at the Green Monster Mine (F. DeVito, pers. comm.). When minute yellow green platy crystals (Figure 4) of suspected volborthite were examined in the scanning electron microscope (SEM), an unusual reticulated surface structure was revealed (Figure 5) and the composition, as determined by energy dispersive X-ray spectroscopy (EDXS) in the SEM, did not match volborthite (Adams, 2003b). A polished cross section of the crystals showed a complicated interlayering of what appeared to be volborthite and vesigneite, based on EDXS. This was confirmed by X-ray diffraction analysis. A very thin (microns) surface layer, which showed the reticulation, had a composition consistent with tangeite. Volborthite, vesigneite and tangeite have very similar crystal structures and it has been proposed that the crystals from the Green Monster Mine are epitactic intergrowths (Adams, 2003b).

The **Ubehebe Mine** is located at the northwest end of Racetrack Valley in Death Valley National Park. It was discovered in 1906, started production in 1908, and was worked sporadically for lead, zinc, and copper until the early 1960s (McAllister, 1955). The ore deposits occur in the Ely limestone about 600 feet from the contact with a small syenite stock. The deposit is developed by the south, north, and main workings, the latter which consists of

Figure 7. Vanadinite crystals (to 2 mm) on descloizite from the AO prospect, San Bernardino Co., CA.

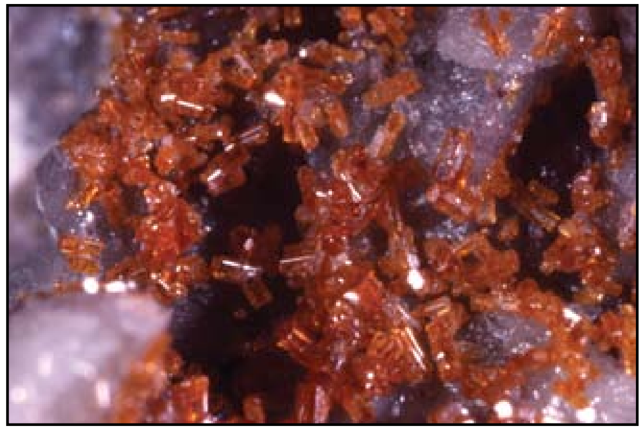

Figure 8. Vanadinite crystals (to 1 mm) from the Leiser Ray Mine, San Bernardino Co., CA.

Figure 9. Descloizite crystals (to 0.5 mm) from the Leiser Ray Mine, San Bernardino Co., CA.

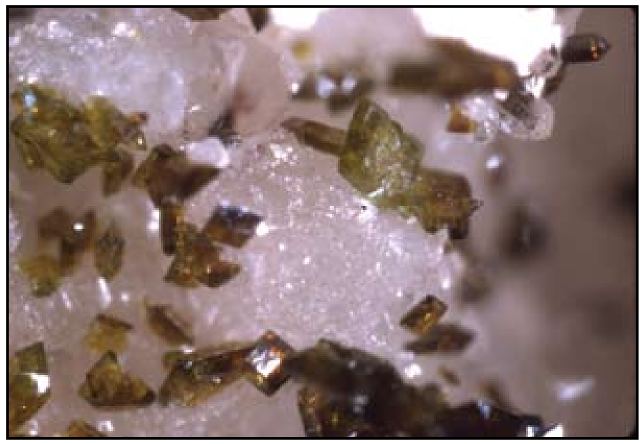

Figure 10. Vanadinite crystals (to 2 mm) from the Leiser Ray Mine, San Bernardino Co., CA. San Bernardino County Museum specimen.

the south and north stopes (McAllister, 1955). Secondary lead and zinc minerals are found there including cerussite, hemimorphite, vanadinite, wulfenite, and descloizite. Vanadinite crystals occur in a variety of colors ranging from red to brown to yellow and in habits ranging from simple hexagonal prisms to rice-shaped crystals (to 2 mm). They often occur on micro drusy descloizite (Figure 6), which had not been previously reported.

San Bernardino County occurrences

The **AO prospect** is located about 2 miles southeast of Mount General. It was apparently first recorded by Bezore and Shumway (1986) but is named for Al Ordway who collected there and called it to the attention of other collectors (Housley and Reynolds, 2002). It consists of a small open pit with minimal underground workings. Vanadinite crystals occur in a wide range of habits and colors. They are usually grayish brown hexagonal prisms that may taper at the terminations, have subparallel growth, or exhibit multiple generations of growth. They often occur on yellow micro crystalline descloizite (Figure 7). Mottramite has also been found at a nearby prospect (Housley and Reynolds, 2002).

The **Leiser Ray Mine** is located about 8 miles northeast of Goffs in eastern San Bernardino County, California. It was part of the Camp Signal district and has been known by a number of other names, including the Vanadium King, California–Comstock, Lombard and Main, and Louisiana–California. Fred Leiser was the mine manager for the Louisiana–California Mining Company (Cloudman, et al., 1919; Wright et al., 1953). The Leiser Ray Mine was the only deposit worked primarily for vanadium in San Bernardino County, but production of copper, lead, silver, and gold was also reported. The original workings were probably known before 1891 but most of the activity occurred between 1905 and 1915 (Hewett, 1956). In 1915 several mills and other equipment were installed. The workings consisted of several shafts which explored two parallel quartz veins, 4–12 feet wide, in granite. Ten to fifteen years ago interesting microminerals could still be found on the north dumps which are associated with the 925-foot deep vertical shaft (Adams, 2003a). These included vanadinite, mottramite, mimetite, cerussite, brochantite, chrysocolla after brochantite (?), and less common linarite, caledonite, and chlorargyrite. The vanadinite was found as groups of reddish-orange hexagonal prisms (to 2 mm, Figure 8) that often graded to a more yellow color at the ends. These were found either on fracture surfaces or in vugs in milky quartz. Mimetite was infrequently found as more tabular yellow crystals. Mottramite occurs as olive-green colored tabular crystals (0.2-0.5 mm, Figure 9) and druses that are occasionally found with vanadinite. Wulfenite occurs as reddish-orange to yellow tabular crystals (to 1 mm) in quartz vugs. The south workings consist of a short vertical shaft that is intersected by a north-plunging incline, with a crosscut at about 50 feet depth. An interesting suite of minerals came from these workings in the late 1960s (R. Reynolds, pers. comm.). The San Bernardino County Museum (Redlands, CA) has an excellent suite of these specimens. While similar minerals are found in the south workings, their habits are significantly different than those from the north. The forms of vanadinite are much more varied. Radiating sprays and jack straw masses of gray to whitish opaque endlichite (arsenian vanadinite) crystals produced striking micromounts (Figure 10). These are often associated with mottramite which occurs as botryoidal masses of microscopic yellow green rosettes. The vanadinite–mimetite was also found as transparent light orange to sherry-colored elongated prisms that formed random or radiating groupings. The habit of the wulfenite is also quite different from that in north workings. Here it is found as yellow-orange bipyramidal prismatic crystals. Tangeite (calciovolborthite) has also been reported from the Leiser Ray Mine (R. Reynolds, pers. comm.). In 1997 the area surrounding the Leiser Ray Mine was incorporated into the East Mojave National Preserve and mineral collecting is no longer allowed.

The **Blue Bell Mine**, 8 miles southwest of Baker, was a small lead–silver–copper producer opened prior to 1920. It was worked on a small scale until the 1950s. It is well known for its suite of secondary lead–zinc–copper minerals (Maynard, 1984). At locality 2E or 2F a couple of small samples consisting of minute yellow green rosettes of mottramite on bladed hemimorphite have been collected. The material is uncommon. Tiny black crystals and crystal balls of mottramite have also been found in the 2C adit where they occur with green pyromorphite and clear plumbogummite (R. Housley, pers. comm.).

Acknowledgements

I would like to thank the San Bernardino County Museum and the Natural History Museum of Los Angeles County for allowing access to their collections and Dr. Robert Housley for reviewing this paper and bringing additional vanadate occurrences to my attention.

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The Iron Hat (Ironclad) ore deposits, Marble Mountains, San Bernardino County, California

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Introduction

The Marble Mountains are located in the eastern portion of the Mojave Desert Province approximately 22.5 km (14 miles) east of Amboy, California on Historic Route 66. They extend about 27 km (17 miles) in a northwesterly direction beginning in the vicinity of the Cadiz railroad station and culminating close to the junction of Interstate 40 and Kelbaker Road. As one travels northeast, they gradually increase in width from 1.6 km (1 mile) in the southeast to approximately 8 km (5 miles) in the northwest (Figure 1).

Rising from the desert floor with elevations of 280 m (920 ft) to 1158 m (3800 ft) the Marble Mountains silhouette the horizon with a banded appearance resembling a layered cake. Marble outcrops are prominent throughout the range and that along with its appearance played a role in naming it (Kilian, 1964) (Figure 2).

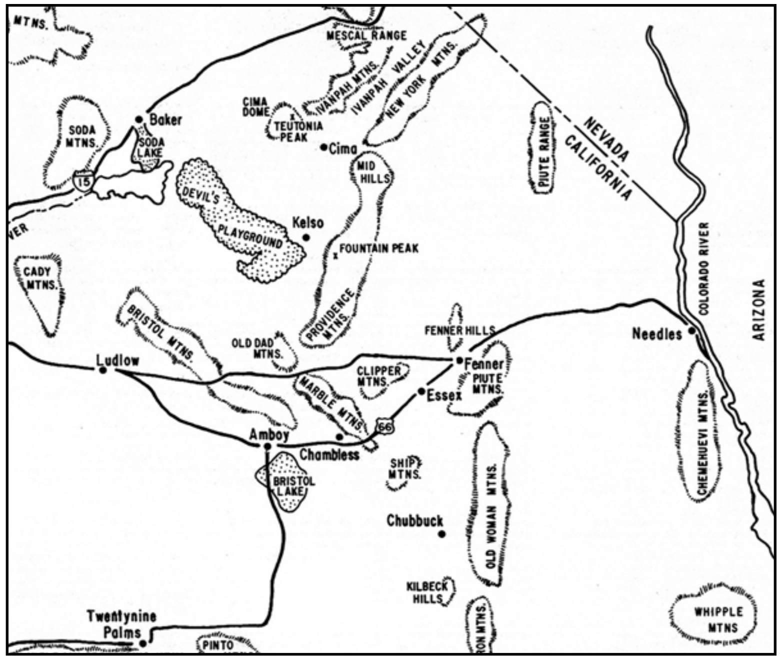

Figure 1. Location of the Marble Mountains, from DeCourten (1979).

Proterozoic (Precambrian) igneous and metamorphic rocks lie unconformably below Paleozoic marine sedimentary rocks in many of the ranges located in the Eastern Mojave Desert. Such is the case in the southeastern section of the Marble Mountains where granite and gneiss lie below rocks of Lower Cambrian to Devonian or younger age (Hazzard and Crickmay, 1933). These sediments are primarily limestone and dolomite with lesser amounts of shale and quartzite. Except for faulting, this section of the Marble Mountains shows little structural activity and lacks the folding and metasomatism associated with ore emplacement.

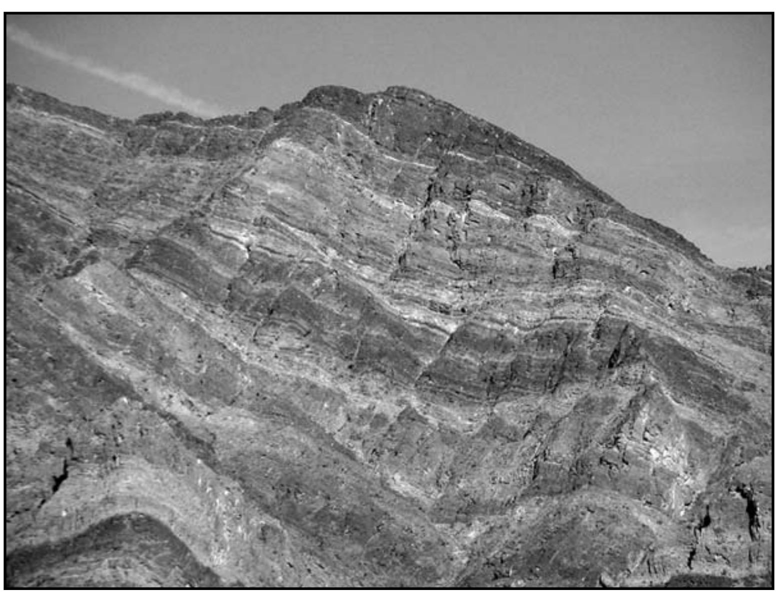

Figure 2. View of the Marble Mountains south of Chambless, California. Photo by Bruce Bridenbecker.

In the south-central Marble Mountains, the sedimentary section has been intruded by Middle Jurassic granitic rocks and a series of felsic and mafic dike complexes (Hall, 1985). This is where the Iron Hat ore deposits are located (Figure 3), which appear to have formed in northeastern-trending zones of contact metamorphism and skarn formation along zones of structural weakness. The lithology of these zones will be discussed in a separate section of this paper.

In the northern section of the Marble Mountains, volcanic rocks of Tertiary age dominate the landscape. These overlap older outcrops or occur as fault contacts with granite, marble, meta-igneous, and various clastic or detrital rocks (Hall, 1985). The Miocene

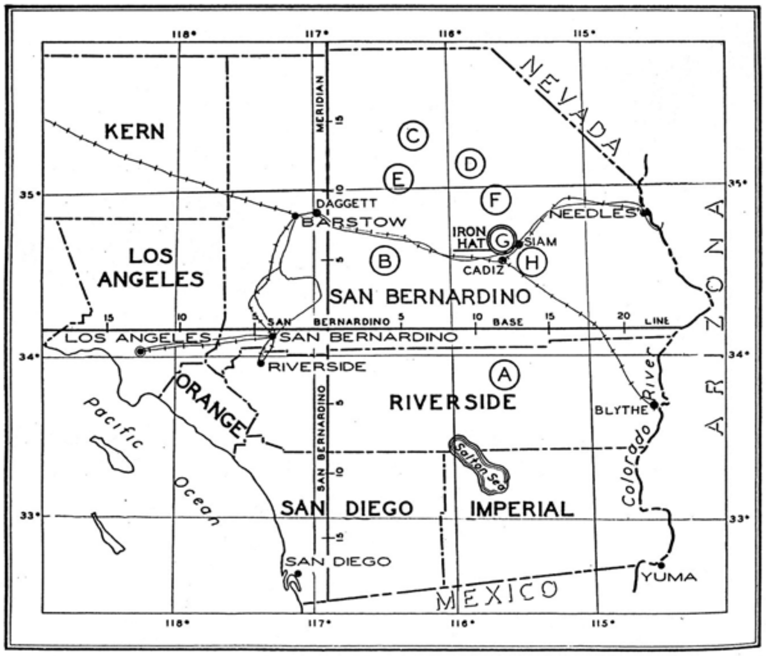

Figure 3. Location of the Iron Hat Mine from Lamey (1948). A) Eagle Mountains; B) Iron Mountain (Lava Bed); C) Iron Mountain (Silver Lake); D) Old Dad Mountain; E) Cave Canyon; F) Vulcan; G) IRON HAT (Ironclad); H) Ship Mountains.

Period of the Tertiary Epoch appears to be the time when volcanism was most prominent. Approximately 700 m (2000 ft) of basalts, dacites, and andesites were deposited along the northern and eastern portions of the area during this time (Kilian, 1964).

As this paper is specifically addressing the ore bodies of the ore deposits, emphasis will be placed upon pre-Tertiary stratigraphy. As a result, a detailed discussion of Tertiary stratigraphy will not be included in this paper.

Stratigraphy

Proterozoic (Precambrian) rocks

Most of the Proterozoic (Precambrian) igneous and metamorphic rocks crop out along the foot of the mountain range in the south and central portion of the Marble Mountains. Granite, granodiorite, and diorite are the predominate rocks found in this area. Of these three, the diorite crops out most frequently. Metamorphism and dike emplacement lace the granitic rocks with chlorite that replaces ferromagnesian minerals in many localities. Lanphere (1964) and Silver (1964) dated samples of the granite at 1400 to 1450 mybp using K-Ar, Rb-Sr, U-Pb methods on biotite, potassium feldspar, and zircon grains. Lanphere wrote that he dated one of the youngest intrusions in the area and that the age of the rocks is most likely much older.

Paleozoic rock sequence

Most of the Proterozoic (Precambrian) rocks appear to be the remnants of a paleohigh, which was covered as the Cambrian sea transgressed eastward throughout the region. As a result, the lower Cambrian rocks consist of a conformable sequence of shallow marine, clastic, and carbonate sediments in the area (Mount, 1980). Figure 4 is a photograph of the Paleozoic section in the southern Marble Mountains.

The Zabriskie Quartzite (Hazzard, 1937), also referred to as the Wood Canyon Formation (Nolan, 1929) or the Prospect Mountain Quartzite (Hazzard, 1937), is the lowermost Cambrian age rock unit found in the area and consists of a basal quartz pebble conglomerate grading upward into a cross-bedded sandstone in the southern part of the Marble Mountains. The cross-bedded sandstones are slightly metamorphosed. The nomenclature Zabriskie Quartzite seems to be the preferred name for the rock unit so it will be used in this paper.

Conformably above the Zabriskie Quartzite lies the Latham Shale (Hazzard, 1954). Consisting of grey-green shale, micaceous siltstone, sandstone, and minor carbonate lenses, the Latham Shale weathers to red thin fragments displaying an assemblage of fossils. The most notable are Early Cambrian olenellid trilobites (Mount, 1980).

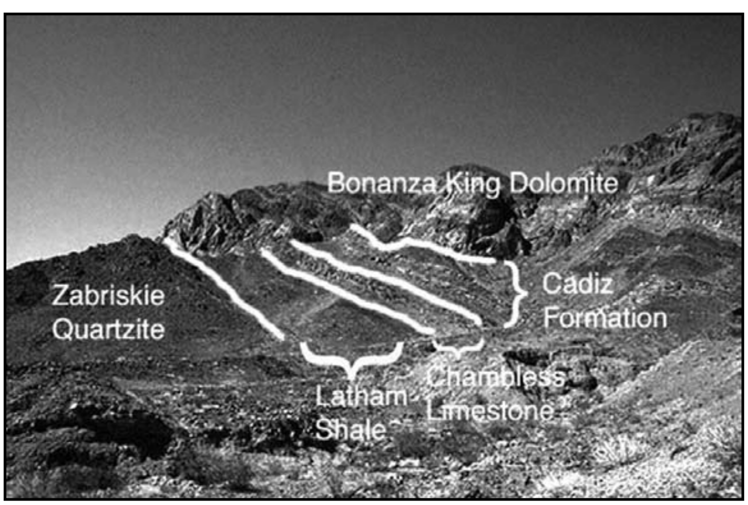

Figure 4. Labeled Paleozoic Section Southern Marble Mountains from Waggoner (n.d.).

Above the shale is the light gray to dark gray cliff-forming Chambless Limestone described by Hazzard (1954). Composed mostly of fine-grained limestone muds, the most conspicuous feature in the rock unit is algal oncolites of genus *Girvanella* (Hazzard, 1937).

The Cadiz Formation was originally proposed by Hazzard and Mason (1936) to describe the cliff-forming upper rock units composed of quartzite, limestone, and shale in the Marble Mountains. It has been assigned a lower to middle Cambrian age based on fossil content and lies conformably above the Chambless Limestone (Kilian, 1964). Distinguishing features of the

Figure 5. Large Pit NE1/4 Section 19. Photo by Bruce Bridenbecker.

Cadiz Formation are the red to brown colored shales and quartzites found at its base, grading upward into tan shales and limestones interlaced with green shales, and culminating in a bluish gray cliff-forming limestone in its upper regions.

The cliff-forming Bonanza King Formation is tan to gray colored dolomite and limestone. It is the cap rock in much of the southern to central Marble Mountains, including the area around Marble Peak just southeast of the Iron Hat ore deposits (Kilian, 1964).

Contact metamorphism and regional tectonics resulted in the formation of Paleozoic marble described by Hall (1985). This marble crops out in sections 16, 17, 18, 19, 20, and 21, T6N, R14E (Lamey, 1948).

Mesozoic rocks

Jurassic granitic rocks either intrude or are in fault contact with Proterozoic (Precambrian) and Paleozoic marble in the vicinity of the Iron Hat ore deposits. Hall, Cohen, and Schiffman (1988) describe these rocks as a mixture of equigranular granite, alkali feldspar granite, and older porphyritic granite to granodiorite with a minimum age of 165 mybp. They also describe a series of felsic dikes that appear to have an origin related to the Jurassic granites and a series of mafic dikes injected along preexisting structural weaknesses with a K-Ar age of 160 mybp.

Iron Hat (Ironclad) ore deposits

Occurrence and origin

According to Hall, Cohen, and Schiffman (1988) the hydrothermal alteration that formed the skarn deposits in the Marble Mountains occurred in three distinct episodes. All of these are found in calcareous wall rocks adjacent to granitic intrusions. Iron-poor contact skarns were the first to form. The second episode is marked by iron-rich skarn envelopes that encircle the felsic dikes. Hall (1985) believes these are the result of late-stage differentiates of the pluton. The third skarn formed at fault contacts between dolomitic marble and granite. It is probable that ore formation occurred when deep, iron-bearing solutions circulated up along normal faults, reacted with shallow fluids and/or adjacent marble, and deposited magnetite as both vein-filling material and replacement ore bodies (Hall, Cohen, and Shiffman, 1988).

Mineralogy

Magnetite and both specular and massive hematite are reported by Lamey (1948) to be the chief ore minerals found at the seven claims reported to be the Iron Hat Group, formerly called the Ironclad Group (Tucker and Sampson, 1930). Hall (1985) states that traces of copper, gold, and silver were also found at the site. Brown garnet, epidote, serpentine, calcite, wollastonite, tremolite, quartz, and even small traces of chalcopyrite have been found in the tailings by the author.

Distribution and extent

Lamey (1948) reports that the ore bodies are small and very shallow, that they are irregular and scattered throughout an area 1829 m (6000 feet) long and 305 m (1000 feet) wide, and that they occur as three principle deposits. The largest ore body, in the NE ¼ of section 19, was reported to have a surface area of 9144 m (30,000 feet) (Figure 5).

Ore reserves and mining history

Estimates ranging from 152,410 metric tons (150,000 long

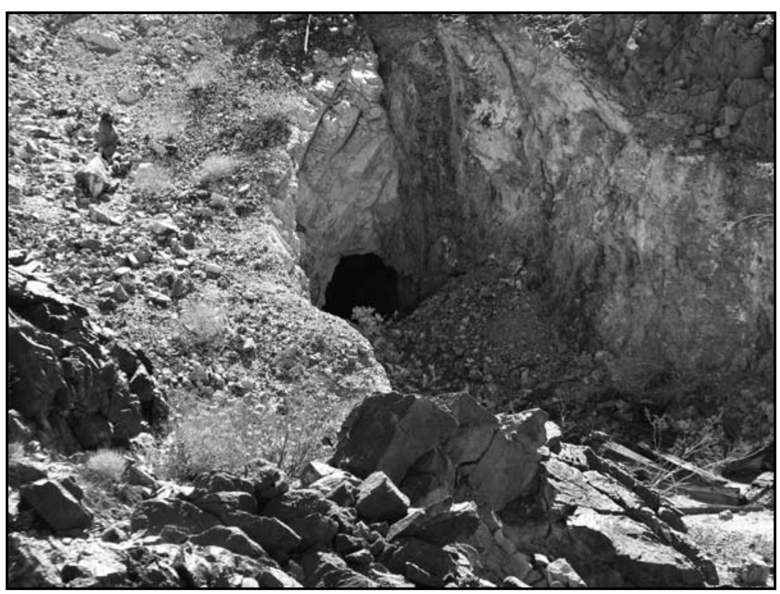

Figure 6. Large Shaft SE1/4 Section 18. Photo by Bruce Bridenbecker.

tons) to 289,578 metric tons (285,000 long tons) of ore reserves at depths of 7.6 m (25 feet) to 30.5 m (100 feet) were reported by Lamey (1948). Approximately 1814 metric tons (2000 tons) of ore was shipped to Llewellyn Iron Works in Los Angeles and was reported to have averaged 65% iron (Tucker and Sampson, 1930).

Development work consists of two tunnels, one 12.2 m (40 feet) long and the other 30.5 m (100 feet long)(Figure 6). The 30.5 m (100 foot) tunnel is reported to be a crosscut, passing through quartz porphyry into the ore at a distance of 18.3 m (60 feet) from the entrance (Tucker and Sampson, 1930). Several open pits were also used to mine the area.

T. Schofield of Amboy, California is listed by Lamey (1948) and Tucker and Sampson (1930)as the first owner of the claims. Arthur L. Doran of Barstow, California appears to be the present owner and has leased the claims to Riverside Cement Company of Los Angeles, California (Wright, Stewart, Gay, and Hazenbush, 1953). Recent visits to the sites indicate that someone is still working the claim in the NE1/4 of section 20.

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Possible Bouse Formation in the Bristol Lake basin, California

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Abstract: Sediments similar to those of the Bouse Formation lie north of the town of Amboy in Bristol Lake Basin, southern Mojave Desert, California. The deposits lie at an elevation of 290 m (951 ft) at the northwest end of the Bristol–Cadiz–Danby Trough. The Amboy outcrops contain the Lawlor Tuff (4.83 Ma). The same tephra was found in an outcrop attributed to the Bouse Formation in the Blythe Basin near the Chocolate Mountains, 180 km southeast from Amboy.

The Bouse exposure at Amboy contains the ostracodes *Cyprideis beaconensis*, and tentatively *Limnocythere staplini* and *Heterocypris fretensis*. These species have not been identified from the Bouse Formation between Parker and Cibola, but *C. beaconensis* and *L. staplini* live today along the shoreline of the Salton Sea, suggesting that the Bristol Basin may have held a saline lake or marine waters in early Pliocene time. Beds of the outcrop dip southward and lie 113 m (370 ft) above the surface of Bristol Playa, where similar age sediments lie buried 270+ m deep, suggesting active faulting in the last four million years. This timing coincides with times inferred for dextral faults of the eastern California shear zone. However, fault locations near the Bristol Lake basin are cryptic. This outcrop provides one more piece to this tectonic puzzle and may also bear on the early history of the Colorado River.

Previous work

Twentieth century debates about the distribution mechanism of freshwater fishes (Blackwelder, 1933; Hubbs and Miller, 1948; Miller, 1981) postulated drainages from the central Mojave Desert through the Bristol–Cadiz–Danby Trough to the Colorado River (Fig. 1). Minimal evidence of either freshwater or brackish-water organisms in Bristol Lake sediments from the surface to 270 m depth (~3.65 Ma, Rosen 1992) refutes this concept of a freshwater drainage system (Bassett et al., 1959; Brown and Rosen, 1992; Rosen, 1992). However, in Danby Basin and perhaps into the Cadiz Basin, sediments containing brackish-water ostracodes and foraminifera (Smith, 1970; Brown and Rosen, 1992, 1995) have been interpreted as an extension of the Pliocene Bouse embayment. Recent studies of the Bouse Formation support Blackwelder's (1934) idea that downstream-integration of the

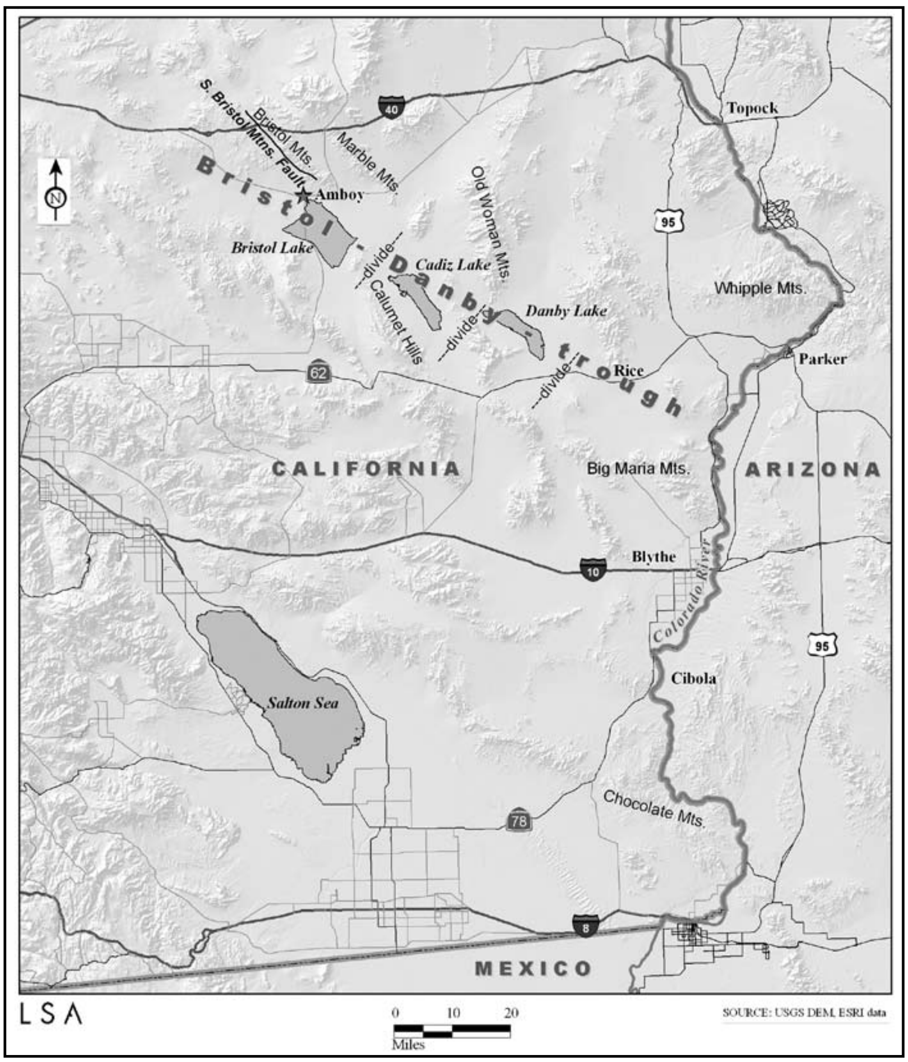

Figure 1. Map of the Bristol–Danby trough region showing locations of the Lawlor tuff outcrop at Amboy and features referred to in text.

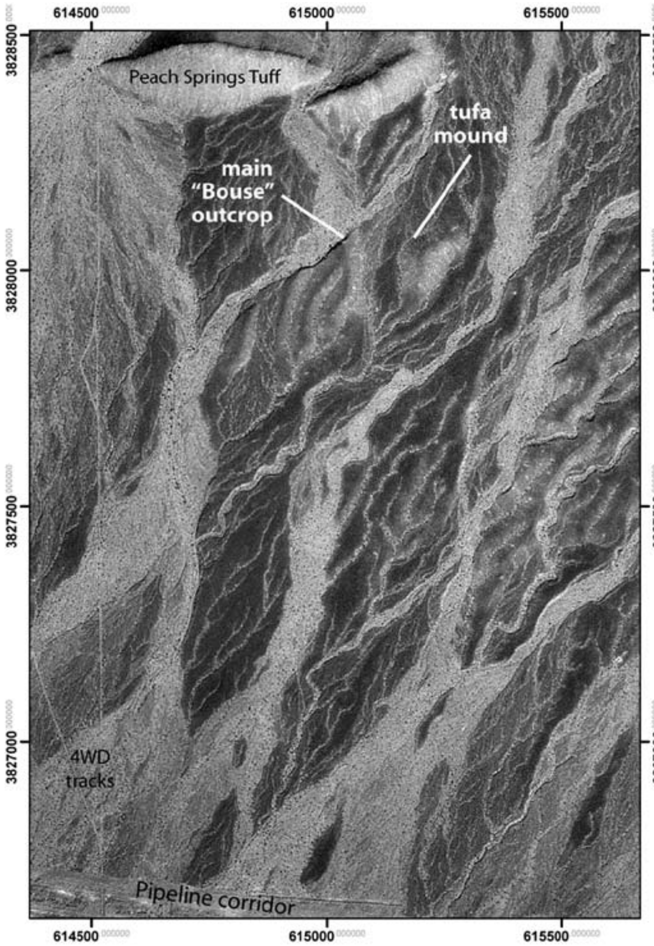

Figure 2. Aerial image showing location of the deposits similar to the Bouse Formation north of Amboy.

Colorado River occurred by successive lake overflow, creating freshwater lakes in several basins north of a barrier at Topock (Spencer and Patchett, 1997; House et al., 2005, 2007). However, the Bouse basin south of Topock, from Parker to Cibola, may reflect interplay of fresh and estuarian to marine conditions (Smith, 1970; Metzger et al., 1973; Todd, 1976; Spencer et al., this volume; McDougall 2005, 2008). The extent, paleoenvironment, and evolution of the Bouse sediments remain unresolved.

Geology

During the 1980s, Miller identified outcrops of probable lacustrine deposits north of Amboy during regional geologic mapping in the area. Recently these sediments were revisited to better evaluate their age and paleoenvironment. Silty to sandy marl containing tephra identified as the Lawlor Tuff (4.83 Ma; Sarna-Wojcicki, 2005, written commun.) is exposed in outcrops 3 km north of the town of Amboy (Fig. 2; UTM Zone 11, NAD 83 615026 m E 3828006 m N) in Bristol Lake Basin. The outcrop lies near the northwest end of the Bristol–Cadiz–Danby trough, a topographic low that trends southeast to the Earp–Parker area on the Colorado River. The attitude of beds in the Amboy exposure (strike N 72° E, dip 22° SE) is similar to that for an outcrop of the early Miocene Peach Spring Tuff (18.5 Ma, Nielson et al., 1990) 0.3 km to the north (Fig. 2). The similar attitudes suggest that both beds and intervening alluvial gravels were tilted by folding or faulting after 4.83 Ma. Although deformation may have elevated the outcrop, it now sits at 290 m (951 ft) altitude, within the maximum elevation range of Bouse outcrops along the Colorado River from Parker to Cibola (Spencer et al., this volume).

Stromatolitic algal mounds (Fig. 3) sit on locally derived alluvial fan gravels near the base of the section. The mounds are overlain by white silty and sandy marl, a gray, glassy tephra, and thin-bedded, silty marl and diatomite with ostracodes. The top of the fine-grained section is unconformably overlain by sands and gravel (Figs. 4, 5, 6). A tephra found in the Bouse marl at the southeast end of the Chocolate Mountains (Metzger and Loeltz, 1973) also correlates with the Lawlor Tuff. The strontium ratios in the Amboy marl overlap those of the Bouse marl at the Chocolate Mountains established by Spencer and Patchett (1997), strengthening the identification of the Amboy locality as the northwestern most outcrop of the Bouse Formation (Spencer et al., this volume).

The date of 4.83 Ma for the Lawlor Tuff indicates an early Pliocene age for the Amboy sediments, which is very close to the Hemphillian/Blancan North American Land Mammal Age boundary. Sea level from 6 Ma to 4.4

Figure 3. Photograph of an algal mound in outcrops north of Amboy.

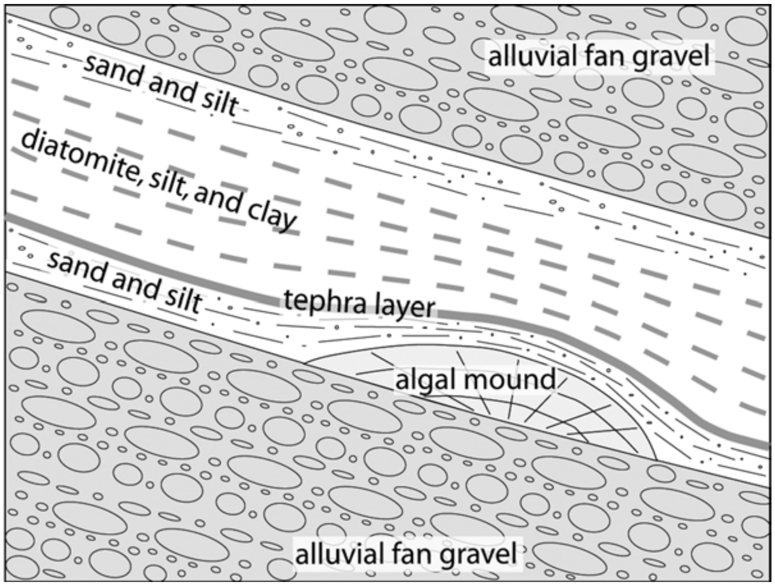

Figure 4. Drawing of stratigraphic section for deposits north of Amboy (not to scale).

Ma was transgressing landward (Woodburne and Swisher, 1995). An expanding still-water estuary would be ideal for receipt and burial of volcanic ash, as would a freshwater lake.

Paleontology and environment

Algal mounds in the Amboy section have no counterparts in the thicker Bouse section in the Blythe Basin, but in the Bouse tufa, occurs on near-shore "bedrock" anywhere in the section where water was shallow and clear (Metzger and Loeltz, 1973; Metzger et al., 1973; Buising, 1990, 1992, Reynolds et al., 2007). The silty marl in the Amboy exposures shows near-shore features such as soft sediment deformation from sediment loading. The near-shore position is supported by the presence of indistinct wading bird tracks that might be referable to ichnogenera *Avipeda* sp. (Sarjeant and Reynolds, 2001).

Fossils in deposits north of Amboy include ostracodes *Cyprideis beaconensis* and probable *Limnocythere staplini* and *Heterocypris fretensis*, and a suite of marine to estuarine diatoms. *C. beaconensis* is not known from the Bouse Formation and is similar to *C. Castus* in the Bouse, so we carefully studied these ostracodes to determine species. The ostracode *C. beaconensis* has morphometric valve characteristics that distinguish it from *C. castus*, which has been reported from Bouse sediments near Parker.

It is larger than *C. castus* (Sandberg, 1966; Benson, 1959). The males of *C. castus* (0.77 mm) are smaller than the females (0.80–0.84 mm). *C. beaconensis* females are smaller (0.95–0.90 mm; LeRoy, 1943) than males (0.97–1.05 mm). The female *Cyprideis* valves at Amboy (0.95 mm–1.0 mm) are smaller than the males (1.0 mm–1.1 mm).

Both male and female *C. castus* have a broad concave and smooth hinge area, with apex approximately mid-valve (Sandberg, 1966). *C. beaconensis* has a straighter hinge, with a prominent inflection point slightly anterior of the central muscle scar field. The valves at Amboy have a straight hinge with a prominent inflection point slightly anterior of the central muscle scar field.

C. castus has a prominent sulcus above the central muscle scar field. The sulcus in *C. beaconensis* is less pronounced. There's no sense of a prominent sulcus in Amboy valves.

In dorsal view, the *C. castus* female carapace is smooth with no inflection points, except at the prominent sulcus (Sandberg, 1966). *C. beaconensis* females, in dorsal view, have a very noticeable bulge at the posterior end of the left valve, less so on the right valve. Several of the Amboy females have the noticeable bulge on the left valve.

Within the Cyprideis group, the common environmental theme (whether continental or marine) is a persistent environment with low alkaline/calcium solutions, such as estuaries, the perennial springs and marshes surrounding the Great Salt Lake, and the Salton Sea. *Limnocythere staplini* has similar hydrochemical requirements as the Cyprideis group but it rarely occurs in estuaries and can survive in places that dry out annually. The presence of probable marine diatoms in the Amboy sediments narrows the environment to an estuary or saline lake. Both *Cyprideis beaconensis* and *C. castus* occur in estuaries along the Pacific coast of North America (LeRoy, 1943; Benson, 1959; Sandberg, 1966; McKenzie and Swain 1967). *Cyprideis castus,* present in the Bouse Formation in the Colorado River trough, is less able to withstand transport from marine

Figure 5. Photograph of outcrop of deposits north of Amboy. View is to the east.

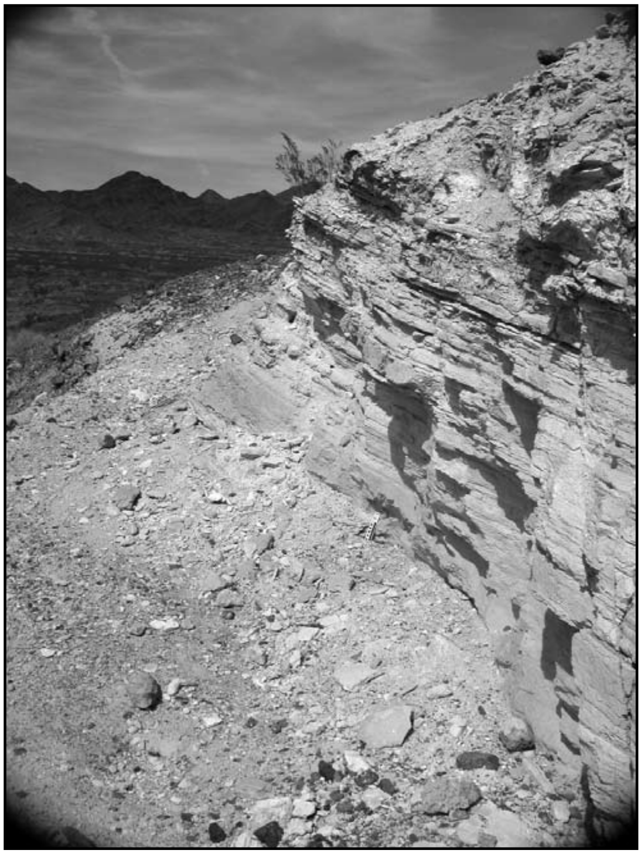

Figure 6. Photograph of the sedimentary section. Gray bed at top of scale chart (near base of section) is the Lawlor tuff.

settings to lakes because of limited brood pouches, than is *C. beaconensis*. *Cyprideis beaconensis* has not been found in the Bouse Formation from Parker to Cibola (R. Forester, pers. comm., 2008). Neither *C. beaconensis* or *C. castus* has been reported in the modern sediments of the Gulf of California, whereas *L. staplini* [incorrectly identified as *L. sanctipatricii*] has been reported from 2 near-shore locations (Swain, 1967). At both locations *L. staplini* was very rare, comprising only 2% or less of the ostracode fauna. It is possible, with such low numbers, that the *L. staplini* were washed into the Gulf from nearby streams. Both *C. beaconensis* and *L. staplini* have been collected from near-shore facies around the margins of the Salton Sea (Forester, 1983: Hurlbert et al., 2001; Detwiler et al., 2002) but they are absent from Salton Sea sediments following flooding events by the Colorado River (R. Forester, pers. comm., 2008). *Cyprideis castus* and *L. staplini* have been recovered in late-Pleistocene and younger sediments cored from Laguna Salada, within the Salton Trough (Romero-Mayen, 2007). Fresh water from a source such as the Mojave River would be lethal to *C. beaconensis, C. castus* and *L. staplini* (R. Forester, pers. comm., 2008) and the Colorado River is apparently incompatible with the environmental requirements of these ostracode, as to date none of them have been collected from that river. Shallow, brackish waters under high rates of evaporation at the northwest end of a lacustrine or estuarine embayment would have been suitable habitat for *C. beaconensis* and *L. staplini*.

Diatoms recovered from one ostracode sample were studied by Scott Starratt of USGS. He identified about a dozen species, most of which indicate brackish water conditions, either marine or estuarine. However, saline lakes could support the species and could possibly have been populated by individuals transported by avifauna.

Discussion

The Bristol Basin lies in the northwestern end of the Bristol–Cadiz–Danby Trough. The modern trough is partitioned by low divides at the Arica–Turtle Mountains, Kilbeck Hills–Iron Mountains, and at the northern Calumet Mountains (Bishop, 1963). It is possible that rising sea level or freshwater lakes filled the basins, but the barriers restricted circulation. After Bouse intrusion, evaporation could have produced "Salton Sea-like" hyper-saline conditions. Core logs from Cadiz and Danby lakes (Fig.3 in Brown and Rosen, 1992) suggest that evaporite deposits (indicating increased salinity due to evaporation) sit above strata referred to as "Bouse sediments" (Brown and Rosen, 1992, 1995) containing microfossils suitable for brackish water conditions. However, significant tectonism in the Bristol-Danby trough (discussed below) permits the interpretation that these modern divides formed after the lake/estuary occupied the basin. By this scenario, a long arm of the Bouse Lake had restricted circulation and high evaporation rates, but was not separated from the main lake/estuary.

Correlations of tephra recovered from deep cores in Bristol Basin indicate that basin filling started before 3.7±0.2 Ma (Rosen, 1991, 1992). Conservative estimates based on depositional rates suggest that the basin might have started filling earlier than 6 million years ago (Rosen, 1992). Lack of deposits equivalent to those north of Amboy is puzzling. However, marine or lacustrine deposits containing a brackish water fauna occur in Cadiz Lake, suggest that the Bouse Formation might exist in that basin. Fauna and stratigraphy strongly suggest that that the Bouse is present below 80 m in Danby Lake (Brown and Rosen, 1992).

This report recognizes the potential for the Bouse Formation in the subsurface section of the Bristol Basin, south of the surficial Amboy outcrops. The deposits we studied north of Amboy lie 205 m (670 ft) above similar age sediments that are buried under playas 5 km (3 mi) southeast of Amboy. This elevation differential can be accounted for by basin topographic configuration and by tectonism. There are three possible candidates for structural elevation. Several northwest-striking dextral faults have been active during the Quaternary (Howard and Miller, 1992; Bedford et al., 2006). The most likely candidate is the south Bristol Mountains fault, which strikes northwest along the southwest side of the Bristol Mountains and projects southeastward along the west side of Cadiz Lake. A barrier between saline water (west, in Bristol Basin) and fresh water introduced along Fenner Wash from Lanfair Valley lies approximately at this position (Rosen, 1992, 2000). The northeast Bristol Lake playa margin is 8 m (25 ft) higher than the southwest playa margin (Rosen, 1992, 2000), consistent with elevation along a fault-controlled ground water barrier. Other structural possibilities include a projection of northwest striking faults mapped in the Calumet Mountains (Bishop, 1963; Howard, 2002). The broad area of Holocene distal fan deposits (Bedford et al., 2006) adjacent to Bristol Lake may mask buried faults and folds, essentially permitting multiple poorly constrained tactic scenarios. The elevation of the Amboy Bouse outcrops at 290 m (951 ft) does not necessarily require vertical tectonic displacement, since the outcrops are within the maximum elevation range of Bouse outcrops in the Blythe Basin.

Summary

The outcrops of sediments north of Amboy bear similarity to other Bouse Formation outcrops in the Blythe Basin along the Colorado River Trough. Similarities are:

- Elevation (290 m) similar to the maximum Bouse elevation of 330 m.
- Presence of the Lawlor Tuff (4.83 Ma) similar to Chocolate Mountains Bouse outcrops.
- Presence of marl and tufa, fine-grained sediments, and near-shore lacustrine or marine features.
- Strontium isotope ratios that overlap other Bouse outcrop data.
- Presence of the ostracode *Limnocythere staplini*.

The Amboy Bouse-like sediments differ from other Bouse outcrops in the presence of the ostracode species *Cyprideis beaconensis*, which lives today in saline-brackish waters at the margin of the Salton Sea. A saline environment is supported by the presence of marine diatoms. The fauna and tephrochronologic age constraints support the presence of brackish to saline waters in Bristol Lake Basin at a time when Cadiz and Danby Lake basins contained fauna and sediments deposited correlated with the Bouse Formation. More study of cores from these lake basins is warranted, as are geophysical studies to identify buried structures.

Acknowledgements

We thank Rick Forester and George Jefferson for constructive discussion of ideas presented. Scott Starratt kindly examined diatoms and provided insight into environmental conditions. We appreciate the tephra identification by Andrei Sarna-Wojcicki. The authors also thank M. Rosen and D. Malmon for thorough reviews and helpful suggestions with the paper, and Margaret Gooding of LSA for preparing Figure 1.

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Review of freshwater mollusks from the Bouse Formation, Lake Havasu area, California

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Abstract: Exposures of the Miocene–Pliocene Bouse Formation near Chemehuevi Wash southwest of Lake Havasu consist of basal marl overlain by silts of the basin-filling member of the formation. Resistant layers of the basal marl contain tracks of wading birds and the snails (*Succinea* sp. and *Valvata* sp.) that suggest fresh, shallow water conditions. These fossils are consistent with previous reports of freshwater mollusks from the Chemehuevi basin. The maximum elevation of Bouse Formation sediments in the Chemehuevi basin is approximately equal to that of Bouse Formation sediments in the downstream Blythe basin to the south and west. The presence of freshwater mollusks and the lack of brackish or marine invertebrates in the Chemehuevi basin contrasts with the mix of fresh and marine invertebrates downstream in the Blythe basin. These differences raise the question of whether a physical barrier was present between the basins or if there was temporal separation of the two basins.

Paleogeography and regional history

House and others (2004, 2005, 2007) described the Bouse Formation (Fm) as having been deposited in lakes filling a series of post-extension basins occupied sequentially by overtopping of the early Colorado River (Figure 1). Tephra dates indicate that the basins filled during late Miocene–early Pliocene time (House and others, 2004, 2005, 2007), with Bouse Fm sediments in Cottonwood and Mojave basins being bracketed by the Tuff of Wolverine Creek (5.59 ±.05Ma) and the Lower Nomlaki tephra layer (4.1± 0.05Ma, Pearthree and House, this volume; Reynolds and others, 2007), a range of 1.5 Ma. Bouse Fm deposits crop out in Cottonwood Valley north of Bullhead City. Downstream, north of Topock, Mojave Valley has been filled by Bouse Fm sediments to an elevation of 536 m (1760 ft), approximately concordant with the sill at Topock. House and others (2004, 2005, 2007) characterize Bouse Fm sediments as having been deposited in freshwater environments, a fact

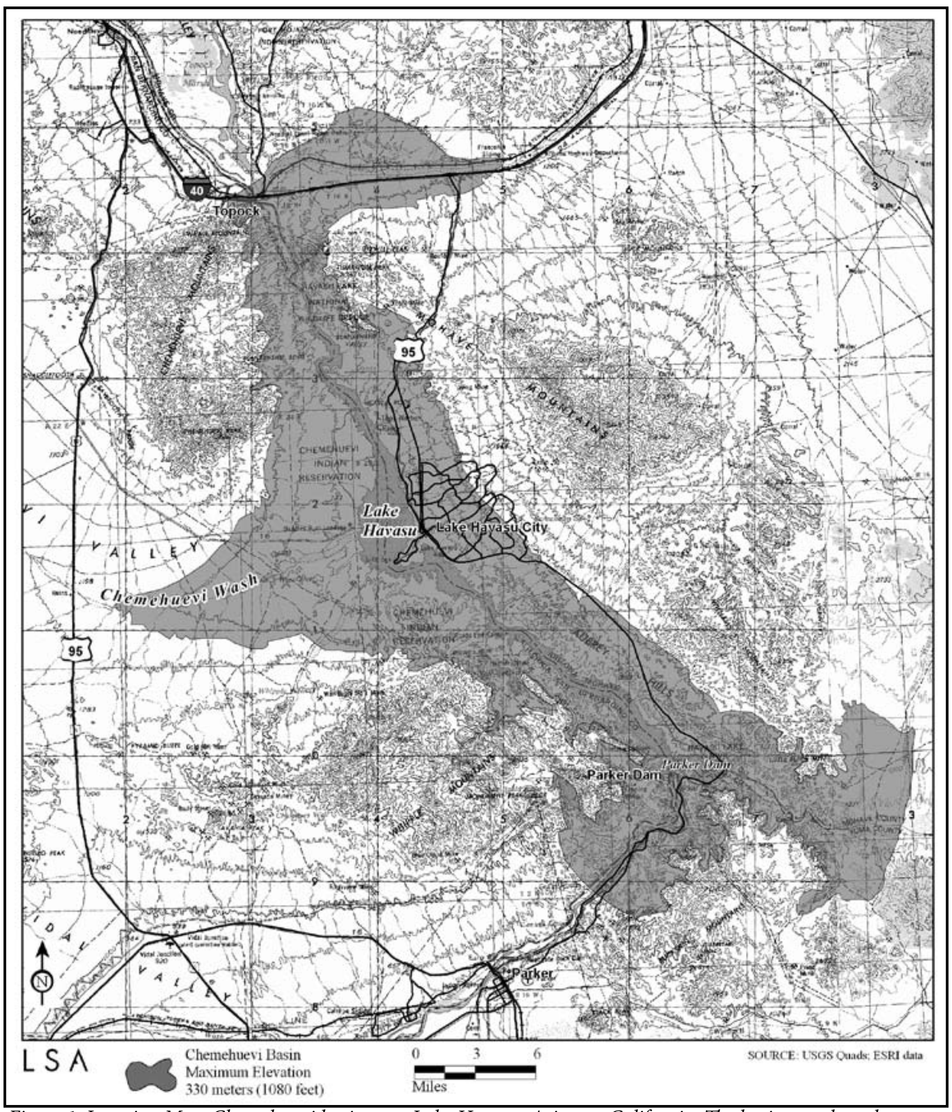

Figure 1. Location Map, Chemehuevi basin near Lake Havasu, Arizona–California. The basin may have been filled to a depth of 330 m (1080 ft).

TABLE 1. Summary of fossils from Chemehuevi basin.

Taxa/Ichnotaxa	This Report	USGS 20227	USGS 20226	Habitat
Bird tracks				
Aviadactyla vialovi	X			Shoreline
Alaripeda lofgreni	X			Shoreline
Gastropods				
Valvata sp. cf. *V. nevadensis*	X	X	X	Freshwater
Lymnaeidea		X		Freshwater
Physa sp.			X	Freshwater
Succinea sp.	X			Shoreline
Pelecypods				
Anodonta californiensis		X		Freshwater

supported by fossil charophytes in Lost Cabin Wash, on the east margin of Cottonwood Valley.

Bouse Fm sediments in Blythe basin reached a high stand of at 330 m (1080 ft), which allowed the basin to extend from a paleodam in the southern Chocolate Mountains (Arizona [AZ]) to Blythe, Parker, AZ, and northwesterly to Bristol Lake basin, (Spencer and others, this vol.; Reynolds and others, this vol.). The Bouse Fm sediments in Bristol Lake basin and near Buzzards Peak in the southern Chocolate Mountains, (California [CA]) contain the Lawlor Tuff of 4.83Ma at 308 m (1010 ft) (Spencer and others, this vol.; Reynolds and others, this vol.), suggesting that lacustrine filling of the Blythe basin was approaching its maximum geographic extent and high stand around that time.

The term "Chemehuevi basin" as used herein, is south of Lake Mojave basin and the Topock barrier, and north of the Blythe basin and Black Canyon Gorge (Figure 1). In Chemehuevi basin, Bouse Fm sediments reach elevations of over 317 m (1040 ft) in drainages south of West Well, four miles west southwest of the community of Havasu Lake. This paper speculates that Chemehuevi basin was filled first by freshwater Colorado River overflow after Mojave basin breached the sill at Topock, and before Blythe basin filled with brackish water to its high stand and inundated the Bristol-Danby trough and Chemehuevi basin.

The Blythe basin extends from the Chocolate Mountains, AZ barrier, north of Yuma (Spencer, this vol.) to the Earp–Parker area south of Black Canyon Gorge (Spencer and others, this vol.; Reynolds and others, this vol.). Outcrop data indicate that the Blythe basin filled to elevations of 330 m (1080 ft) near Buzzards Peak in the southern Chocolate Mountains, CA and at outcrops north of Amboy at the northwest end of the Bristol–Danby trough (Reynolds et al., this vol.; Spencer et al., this vol.). The similar elevations of Bouse Fm sediments in Chemehuevi basin and Blythe basin suggest that they may have been connected and filled contemporaneously in late Miocene to Pliocene time, the time of deposition of the Lawlor Tuff (4.83 Ma) (Spencer and others, this vol.).

Bouse Fm sediments in the extensive Blythe basin from the Earp–Parker area to Cibola have been described as estuarian to brackish water based on the presence of barnacles, a mixture of brackish and fresh-water mollusks, and the marine fish, *Colpichthys* (Smith, 1970; Metzger and others,1973; Todd, 1976; Taylor, 1983; Buising, 1990, 1992), from fossil localities that range in elevation from 73 to 165 m (240 to 540 ft).

Fossil occurrences in Chemehuevi basin

The previous record of fossils from Chemehuevi Valley includes unspecified ostracode species and charophytes (Metzger and Loeltz, 1973). Charophytes are encapsulated green algae that are compatible with fluctuations in freshwater levels. Fossil freshwater mollusks have previously been reported in Bouse Fm from the Chemehuevi basin (Taylor, 1983) from USGS Locality 20226 on the Arizona side of the Colorado River and from USGS Locality 20227 on the California side, 5.6 km (3.5 miles) southeast of the

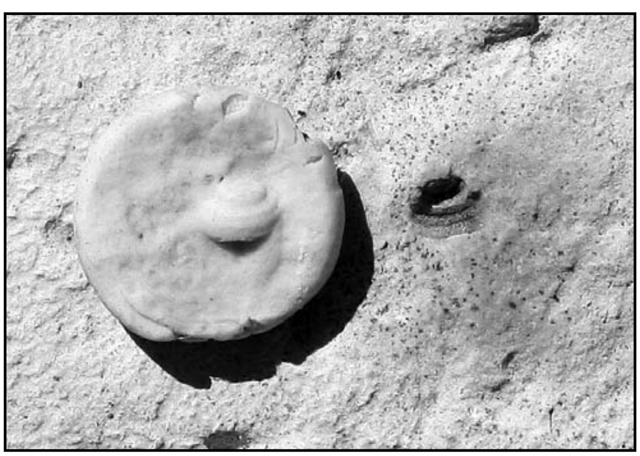

Figure 2. Cast of gastropod Valvata *sp., cf.* V. nevadensis.

Figure 3. Cast of land snail Succinea *sp.*

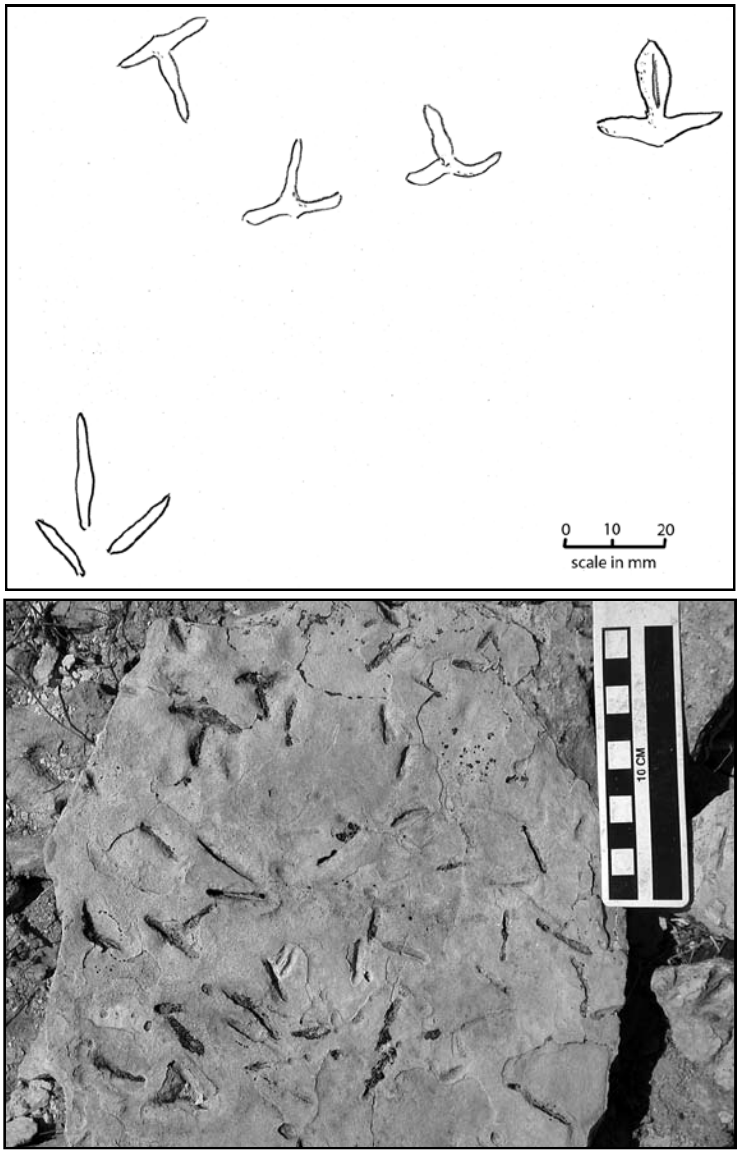

Figure 4. A:*Drawing of wading bird tracks:* Avidactyla vialovi *(lower left),* Alaripeda lofgreni *(upper left), undescribed ichnospecies of* Alaripeda *(upper right).* B: *Bird tracks:* Avidactyla vialovi *(lower left),* Alaripeda lofgreni *(middle left), and undescribed* Alarpida *(upper left).*

new locality reported herein. This additional locality is in a drainage south of Chemehuevi Wash, where Bouse Fm basal marl sits at 207 m (680 ft). The Bouse Fm basal marl unconformably overlies a conglomerate of locally derived angular volcanic clasts. Bouse Fm basal marl is conformably overlain by Bouse Fm silts and silty sands (Bouse Fm interbedded unit: Metzger and others, 1973). The Bouse Fm outcrops are exposed in Section 14 (Projected), T 4 N, R 24 E, San Bernardino Base Line and Meridian, as shown on the Lake Havasu 7.5 USGS Quadrangle map.

This new locality contains tracks of wading birds, casts of the snails *Succinea* sp. and *Valvata* sp. cf. *V. nevadensis*, casts of water grasses, and invertebrate burrows. "Living species of *Valvata* are restricted to perennial fresh water" (Taylor, 1983). The specimen described herein (Fig. 2) closely resembles figures of *Valvata nevadensis* (Plate 3, Taylor and Smith, 1981) where the body whorl is sculptured by spiral carinae of rounded cords. These spiral cords are not as pronounced as in *V. idahoensis* (Plate 3, Taylor and Smith, 1981). The land snail, *Succinea* sp. (Fig. 3) can survive in moist, non-saline habitats such as leaf litter. *Physa* sp. (known from USGS Loc. 20226) is a freshwater snail (Moore, Lalicker and Fischer, 1952) and *Anodonta* sp. (known from USGS Loc. 20227) is a freshwater mussel that requires perennial rivers and lakes with sandy bottoms (Taylor, 1983; Schneider, 1989). These aquatic mollusks suggest that initial deposition of the Bouse Fm sediments in Chemehuevi basin was by fresh water, at least to the elevation of 250 m (820 ft, USGS Loc. 20227).

Bird tracks (Fig. 4A, B) in the Chemehuevi Wash area are referable to *Aviadactyla vialovi* and *Alaripeda lofgreni* (Fig. 7 and Fig. 12 in Sarjeant and Reynolds, 2001). A third print morphology indicates an undescribed ichnospecies of *Alaripeda* (Fig 4B). Birds that made the tracks were probably wading birds similar to sandpipers, which forage along pond, lake, estuary or marine shorelines for small mollusks and crustaceans.

Discussion and inferences

All the molluscan species known from Chemehuevi basin require fresh water to survive. These freshwater habitat requirements contrast sharply with the molluscan fauna of the Blythe basin, which contains a mixture of fresh and brackish water species along with a marine fish (Todd, 1976). The lack of marine taxa in basins north of the Blythe basin, including the extension through the Bristol–Danby trough (Reynolds and others, this vol.), is consistent with distribution of marine microorganisms (McDougall, 2008). Taxa from Blythe basin include mussels (*Pisidium* sp., *Sphaerium californica*) gastropods (*Amnicola longinqua, Fluminicola* sp., *Tyronia protea, Batillaria californica*) and barnacles (*Balanus* sp.) (Reynolds and Berry, this vol.). This assemblage has little in common with the list known from the Chemehuevi basin (Table 1). There are several scenarios that may account for these differences:

1. The Chemehuevi basin could have filled with Colorado River water that deposited the lacustrine sediments, after which the basin breached spilling river waters to the Blythe basin. This scenario suggests that fresh water from the Chemehuevi basin spilled downstream into a marine estuary at a lower elevation. A subsequent rise in sea level or tectonic depression could have then filled both the Chemehuevi and Blythe basins to an elevation of 330 m (1080 ft). This scenario implies that lower Chemehuevi sediments are older than Bouse Fm sediments downstream and suggests that Chemehuevi basin sediments should transition upward from fresh to brackish water conditions;

2. Both the Blythe basin and the Chemehuevi basin were contemporaneously joined and initially filled with fresh Colorado River water. Sea level rise caused estuarine sedimentary depositional facies and fauna to inundate first the Blythe basin and then the Chemehuevi basin. However, such an estuarian facies has not been found in the Chemehuevi basin, and the faunas of the respective basins are not comparable (Reynolds and Berry, this vol.). This scenario lacks the robust outcrop data supportive of scenario 1.

Preliminary data for molluscan habitats based on fossil taxa suggests that Chemehuevi basin was initially filled with fresh water, at least to elevation 250 m (820 ft). When the Blythe basin filled to the 330 m (1080 ft) level, around Lawlor Tuff time (4.83 Ma), it may have overflowed into and became contiguous with the Bristol–Danby trough and the Chemehuevi basin.

Acknowledgements

I thank David Miller and George Jefferson for their insightful suggestions and reviews of this paper, and Margaret Gooding of LSA Associates for preparing Figure 1.

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The age and character of the northern Bouse Formation, Mohave and Cottonwood Valleys, Arizona, California and Nevada

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Introduction

Deposits of the fine-grained late Miocene to early Pliocene Bouse Formation in eastern California, western Arizona and southern Nevada represent a dramatic change in depositional environment that is related to the inception of the Colorado River. Bouse deposits are exposed in the Colorado River Valley and the eastern Mojave Desert south of Parker, Arizona, but also extend northward in a narrower strip through Chemehuevi Valley (Lake Havasu area), Mohave Valley, and Cottonwood Valley (Figure 1). Detailed geologic mapping and related investigations in Mohave and Cottowood Valleys during the past decade have more fully characterized northern Bouse deposits and their relationships to underlying and overlying deposits (Faulds et al, 2004; House et al, 2005). The primary purposes of this short paper are to describe the extent and character of Bouse deposits in these valleys and their relationships to older basin deposits and younger Colorado River deposits, summarize new age constraints on the Bouse Formation and the arrival of Colorado River sand and gravel, and briefly consider the implications of this evidence for the alternative hypotheses of Colorado River development.

The Bouse Formation was described and defined by several reconnaissance geohydrology studies conducted in the 1960's and 1970's (Metzger, 1968; Metzger and Loeltz, 1973). They correlated discontinuous outcrops of Bouse deposits within and between basins based on strikingly similar facies, including basal calcareous marl, scattered tufa deposits, in some places spatially associated with the marl, and much thicker fine-grained clastic deposits overlying the marl in many outcrops. The presence of a few fish fossils and forams interpreted to be marine organisms (Smith, 1970) led to the conclusion that the late Miocene Bouse Formation was deposited in a subsiding trough related to the opening of the Gulf of California that was filled by a marine incursion (Metzger, 1968; Metzger and Loeltz, 1973). Lucchitta (1972; 1979; Lucchitta et al, 2001) hypothesized that this trough then guided the development of, and was filled by sediment supplied by, the Colorado River. Because Bouse deposits exist at altitudes as high as 550 m above sea level (asl) today, this interpretation implies that substantial regional uplift occurred in the lower Colorado River region subsequent to Bouse deposition (Lucchitta, 1979; Lucchitta et al, 2001). Isotope ratios determined for Bouse marl deposits are similar to modern Colorado River values, however, and are not consistent with late Miocene marine water (Spencer and Patchett, 1997; Poulson and Jahn, 2003; Roskowski et al, 2007). In addition, maximum altitudes of Bouse deposits rise in a step-wise fashion to the north, rather than a gradual increase that would be consistent with regional warping (Spencer and Patchett, 1997; Spencer et al., in press). These results support an alternative interpretation that the Bouse Formation was deposited in a series of lakes that were filled by the Colorado River as it as it spilled through an area of internally-drained basins.

The distribution, character and age of northern Bouse Deposits

New mapping and investigations lend increased confidence to the original characterization of the northern Bouse Formation (Metzger and Loeltz, 1973). Marl / white limestone or calcareous sandstone (referred to as "carbonate" in this paper) exists at virtually every outcrop where the base of the Bouse Formation is exposed. This basal carbonate is always less than 3 m thick, typically is less than 1 m thick, and is absent completely in a few outcrops. On the flanks of Mohave Valley, basal carbonate deposits are draped on paleo-alluvial fan surfaces and locally mantle bedrock paleo-hillslopes and pediments, at altitudes ranging from about 180 to 550 m asl. In the axis of northern Mohave Valley, basal carbonate conformably overlies coarse, southward-directed flood deposits that contain only local gravel at an altitude of ~190 m asl. The lowest basal carbonate outcrops (~180 m asl) are draped on alluvial fan deposits on the southern margin of Mohave Valley. These basal carbonate outcrops project into the subsurface beneath thick, fine-grained clastic Bouse deposits. The lowest clastic Bouse exposures are at 150 m asl, and the base of the Bouse in this area is not exposed. These thick, fine-grained clastic Bouse deposits are widespread in the central and southern parts of the valley, where they are found at altitudes below 300 m asl. They consist primarily of clay and silt beds but include some up to 1 m thick sand beds in southern Mohave Valley. Fine-grained clastic deposits are uncommon in northern Mohave Valley or anywhere in the valley above 300 m. An exception to this is in Secret Pass Canyon on the flank of

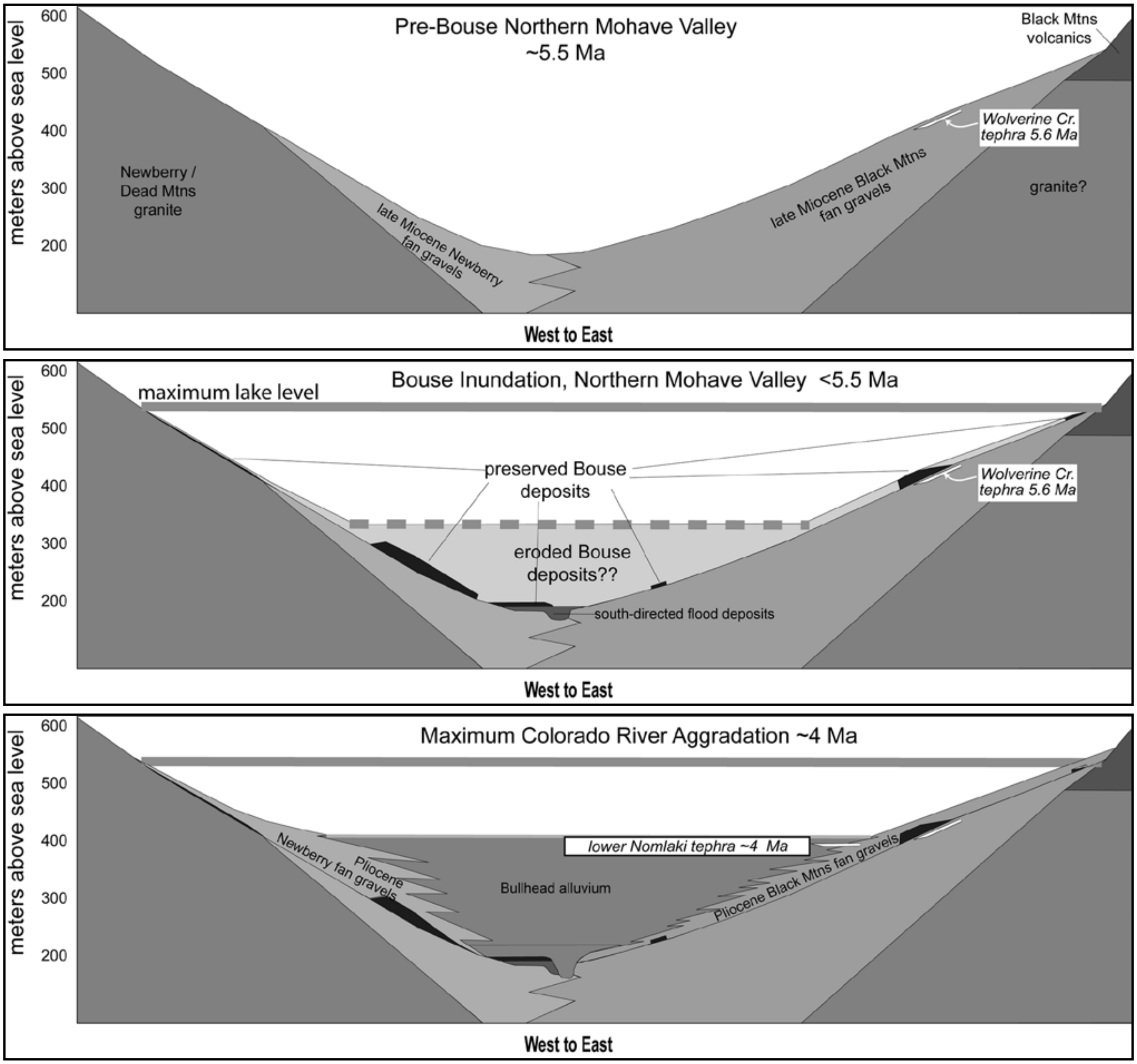

Figure 1. Schematic cross sections across northern Mojave Valley prior to and during Bouse deposition, and at the maximum early Pliocene Colorado River aggradation.

the Black Mountains, where a ~20-m-thick section of carbonate, mudstone, siltstone and sandstone grades upward into fanglomerate (House et al, 2005; Reynolds et al., 2007). Tufa deposits have been discovered primarily on bedrock outcrops or hillslopes between 370 and 550 m asl.

In Cottonwood Valley, basal Bouse carbonate beds range in altitude from ~340 m asl near the valley axis to 550 m on the valley margins. The basal carbonate most commonly rests on minimally eroded alluvial fan surfaces, but locally mantles bedrock pediments. In southern Cottonwood Valley, the basal carbonate overlies a fining-upward sequence of fan deposits from both sides of the valley, mixed fine gravel axial deposits, and sand/silt/clay beds that probably represent floodplain or playa margin deposits informally termed the Lost Cabin beds (House et al, 2005). The Wolverine Creek tephra (House et al., in press) was deposited in Lost Cabin beds several tens of meters below the basal Bouse carbonate. Fine-grained clastic Bouse deposits overlying the basal carbonate are uncommon and the thickest preserved sections are less than 10 m thick.

In most outcrops in both valleys, local tributary fan deposits overlie Bouse deposits above an unconformity, although Bouse deposits grade upward into gravel beds of overlying fan deposits at a few localities. The character of the overlying fan deposits is variable. In many outcrops, the induration of pre- and post-Bouse fan deposits is quite similar, suggesting a similar age. In some outcrops, induration of overlying fan deposits is substantially less or soil development associated with a preserved alluvial surface suggests a Quaternary age. It is clear in some outcrops that erosion completely removed Bouse deposits prior to renewed alluvial fan deposition. Thus, the Bouse deposits we have observed are a small remnant of a once continuous depositional unit. Direct contacts between Bouse deposits and obvious Colorado River sand and gravel deposits are rare. In the axis of northern Mohave Valley, however, a substantial erosional unconformity separates Bouse deposits from Colorado River deposits (House et al, 2005). In Cottonwood Valley, the oldest Colorado River deposits fill erosional topography substantially below the base of the Bouse Formation. Thus, it appears that substantial erosion occurred in both valleys after Bouse deposition and prior to the first arrival of Colorado River bedload sediment. A period of major aggradation occurred in the early Pliocene after the development of the through-going Colorado River. The ~ 4 Ma lower Nomlaki tephra has been found in association with Colorado River deposits at altitudes of 365 to 395 m in Mohave Valley (House et al, 2005); the very highest Colorado River sand and gravel deposits in this area have been found at 400 m asl.

The age of the northern Bouse Formation

The Wolverine Creek and Lower Nomlaki tephras constrain the age of the Bouse Formation in Mohave and Cottonwood valleys to <5.6 Ma and >4 Ma. In Secret Pass Canyon in northern Mohave Valley, 10 m of cobbly, sandy alluvial fan deposits separate the Wolverine Creek tephra and the basal Bouse carbonate. There are no obvious, well-developed paleosols in this 10 m section, which suggests that the interval between deposition of the tephra and the Bouse deposits may not have been very long. In Cottonwood Valley, several tens of meters of fine-grained deposits (the upper part of the Lost Cabin beds) separate the same tephra and the basal Bouse deposits. This intervening section includes several moderately developed paleosols, suggesting intermittent deposition of fine-grained deposits with prolonged periods of surface stability. A period of substantial erosion followed by major river aggradation occurred after Bouse deposition and prior to 4 Ma.

Bouse paleogeography and the development of the Colorado River

The distribution and character of Bouse deposits in Cottonwood and Mohave Valleys and their relationships to underlying deposits reveals much about the paleogeography of this area and the nature of the entrance of water that filled this deep body of water. Several key pieces of evidence indicate that water entered this region from the north. Evidence in northern Mohave Valley indicates that water spilled into the valley from the north just prior to, and probably associated with, earliest Bouse deposition there. Based on the lowest outcrops of Bouse Formation in the basin axes, the altitude of the floor of Cottonwood Valley (~340 m asl) was substantially higher than that of Mohave Valley (<150 m asl in southern Mohave Valley). Prior to deposition of the Bouse Formation, these valleys were not connected via surface drainage, and the local depocenters were in southern Mohave Valley and central Cottonwood Valley. The fact that the highest Bouse outcrops in each valley are the same altitude indicates that one large, deep body of water eventually filled both valleys. The isotopic composition of basal Bouse carbonate is virtually the same throughout the entire altitude and geographic range within these valleys, and is indistinguishable from modern Colorado River water (Roskowski et al, 2007). The most plausible scenario to explain these relationships is that water supplied by the developing Colorado River spilled into Cottonwood Valley from the north, overtopped a low paleodivide and flooded into Mohave Valley, and eventually filled both valleys with a lake that was at least 400 m deep. When the lake filled to 550 m asl, a divide at the southern end of Mohave Valley (the Topock Gorge area) was overtopped and eroded as the larger Bouse basins to the south gradually filled.

The thick, fine-grained clastic sections of the Bouse Formation are all in southern and central Mohave Valley, and all are below 330 m asl. It is possible that similar thick sequences existed in other parts of Mohave and Cottonwood valleys and were removed by subsequent erosion. An alternative explanation for this distribution of clastic deposits is that they represent delta deposits associated with filling of the southern Bouse basins. Assuming the modern flow of the Colorado River and modern evaporation rates, tens of thousands of years would have been required to fill the extensive and complex southern Bouse basins (Spencer et al, in press). If the Topock divide was lowered by erosion below 330 m asl as the southern Bouse basins filled, lake water would have eventually backed into areas of Mohave Valley that are below 330 m, causing delta deposition in the lower portions of Mohave Valley.

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Preliminary review of invertebrate fossil localities from the Bouse Formation, Blythe basin, California

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Abstract. Eight new invertebrate fossil localities have been found in the Bouse Formation in the Blythe basin between Parker, Arizona and the southern Chocolate Mountains north of Yuma, Arizona. The localities are between 74 m and 178 m elevation in the Blythe basin that was eventually filled to 330 m. Fossil localities containing freshwater mollusks are low in the section, and interspersed between other localities that yield a mix of fresh and brackish/marine fossil taxa. Two fresh-water fossil assemblages are found in marl facies. Elsewhere, a marine fish is reported from marl, as are barnacles and fresh-water mussels. Cross-bedded sands produce a mix of fresh and brackish/marine fossil taxa. Faunas and sedimentary facies suggest interplay between fresh water and marine water early in the basin history.

Paleogeography and regional history

The Bouse Formation in the Colorado River trough was deposited in a series of post-extension basins (House and others 2004, 2005, 2007) that successively filled from north to south. Tephra dates indicate that the basins filled during late Miocene–early Pliocene time (House and others, 2004, 2005, 2007). Bouse sediments in northern Cottonwood and Mojave basins are bracketed by the Tuff of Wolverine Creek (5.59 ± 0.05Ma) and the Lower Nomlaki tephra layer (4.1± 0.05Ma, Pearthree and House, this volume; Reynolds and others, 2007), a range of 1.5 Ma. The central basin, the Chemehuevi basin may have been filled by Colorado River overflow after the Mojave basin breached the basin sill at Topock (Reynolds, this vol.) and before water level in the southern basin, the Blythe basin reached its high stand. Bouse sediments in Blythe basin reach a height of 330m (1080 ft), at which the basin extended from a barrier in the southern Chocolate Mountains to Parker and northwesterly to Bristol Lake basin (Spencer and others, this vol.; Reynolds and others, this vol.). The Bouse sediments in Bristol Lake basin and near Buzzards Peak in the south-

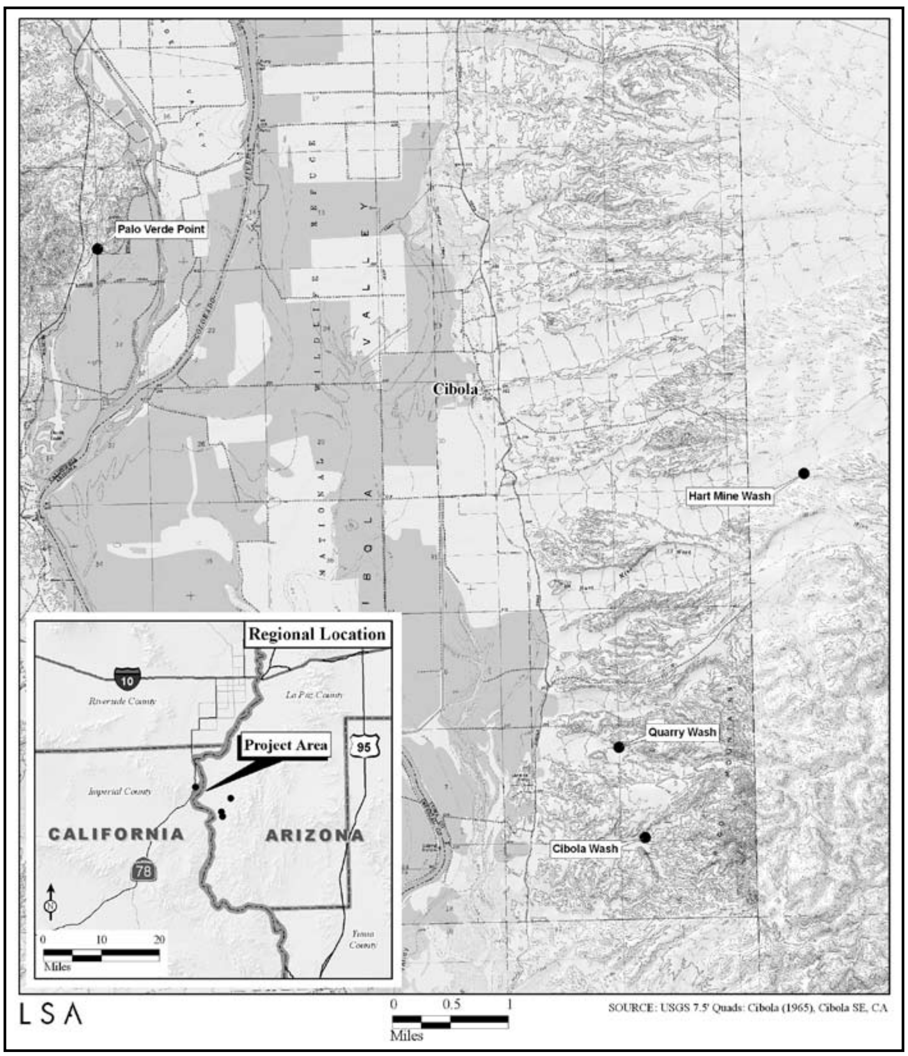


Figure 1. General location of invertebrate fossil localities in the Cibola area.

Table 1. USGS Localities (Metzger and others, 1973; Taylor, 1983)

	Taxon	Habitat	M3091 elev. 165m	M3090 elev. 177m	M3089 elev. 165m	Cibola Lake elev. 85m
G	*Batillaria californica*	brackish	X	X	X	X
B	*Balanus* sp.	brackish-marine	X			
C	crab	brackish	X			
G	?*Barleeia* sp.	marine	X			
P	*Diplodonta* sp.	marine	X			
P	*Halodakra* sp.	marine	X			

B = barnacle, C = crustacean, G = gastropod, O = ostracode, P = pelecypods, elev. = elevation

ern Chocolate Mountains, Arizona contain the Lawlor Tuff of 4.83Ma at 330 m (1080 ft) elevation (Spencer and others, this vol.; Reynolds and others, this vol.) suggesting that water in the Blythe basin was approaching its maximum geographic extent and high stand around this time.

The Blythe basin, extending from the Earp–Parker area to Cibola, contains many outcrops of the Bouse Formation. Bouse sediments have been described as estuarian to brackish, or even marine, based on the presence of fresh-water mollusks, barnacles, a mixture of estuarian/marine mollusks, and the marine fish *Colpichthys* sp. (Smith, 1970; Metzger and others, 1973; Todd, 1976; Taylor, 1983; Buising, 1990, 1992). The sedimentary facies containing each fauna (fresh-brackish-marine) have yet to be placed in a stratigraphic or temporal framework. This paper encourages continued research that would do so.

Invertebrate localities

Previously-reported localities

The U.S. Geological Survey (Metzger and others, 1973; Taylor, 1983) reported four invertebrate localities in the study area. These localities, summarized in Table 1, were not inspected during this preliminary field study.

USGS locality M3091 sits at elevation 167 m (549 ft) on the north side of Milpitas Wash south of the community of Palo Verde in Imperial County, California. Fossil barnacles, crab, snails, and clams were found in marl deposits (Taylor, 1983). The taxa represent a mixture of marine and brackish water species.

USGS localities M3090 and M3089 are at elevations 177 m (580 ft) and 165 m (540 ft) on the north side of Osborne Wash, east of Parker, La Paz County, Arizona. The Cibola Lake locality is at elevation 85 m (280 ft), 0.4 km (1/4 mi) east of Cibola Road and approximately 8 km (5 mi) south of the community of Cibola, south of the Cibola Wash localities (below). The brackish water snail (*Batillaria* sp.) is the only taxon reported from these localities.

Osborne Wash Sands locality (Buising, 1992) at elevation 177 m (580 ft) is east of Parker, Arizona, 1.6 km (2 mi) southeast of USGS M3090. Fossiliferous yellow cross-bedded sands are the lowest deposits of the Bouse, and sit on a volcanic coarse-grained fanglomerate (Osborne Wash strata, Buising, 1992), and are overlain by marl. The fossils include a mixture of disarticulated freshwater clams and snails as well as brackish water forms, with one type (*Tyronia* sp.) that today is usually found in alkaline streams.

Table 2. Osborne Wash Sands - (close to USGS M3090) Elevation 178 m (580 ft)

Organism Type	Taxon	Habitat
pelecypod, small-size, toothed hinge	*Sphaerium californica*	fresh water
gastropod, high spired reduced shoulders, aperture notch, ornamentation	*Batillaria californica*	brackish
gastropod, high spired, shoulders, round aperture,	*Tyronia* sp.	alkaline streams
barnacle	*Balanus* sp.	brackish-marine

New localities

Earp Bridge Sands, at elevation 122 m (400 ft), is located on the northwest side of the Colorado River at Earp, San Bernardino County, California. Road cuts on Highway 95 about 154 m (500 ft) south of California State Route 62 contain fossiliferous yellow cross-bedded sands underlain by marl and gravel and overlain by marl. The fossils represent a mixture of fresh and brackish water environments.

Hart Mine Wash Marl is south of Cibola, La Paz County, Arizona. The locality is 3.8 km (2.4 mi) east of Cibola Road on the north side of South Bridge Road just east of a tributary of Hart Mine Wash. A cut at an elevation of 146 m (480 ft) exposes friable, silty marl and blocks of resistant marl. The silty marl contains disarticulated valves of mussels (*Pisidium* sp.) that barnacles (*Balanus* sp.) have used

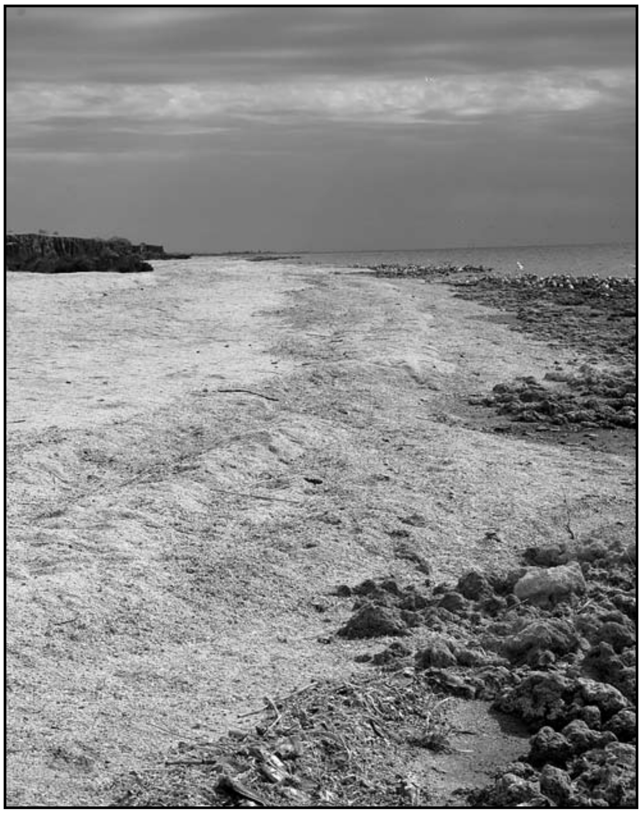
Table 3. Earp Bridge Sands - Elevation 123 m (400 ft)

Organism Type	Taxon	Habitat
pelecypod, small-size, toothed hinge, disarticulated	*Sphaerium californica*	fresh water
gastropod, high spired reduced shoulders, aperture notch, ornamentation	*Batillaria californica*	brackish
barnacle	*Balanus* sp.	brackish-marine

Table 4. Hart Mine Wash Marl - Elevation 148 m (480 ft)

Organism Type	Taxon	Habitat
pelecypod, medium-size, toothed hinge	*Pisidium* sp.	fresh water
barnacle covering *Pisidium* sp.	*Balanus* sp.	brackish-marine

*Figure 2 Hart Mine Wash disarticulated, freshwater mussels (*Pisidium *sp.) covered by barnacles (*Balanus *sp.).*



for anchors (Fig. 2). About 0.5 km (1/4 mi) south-southwest downstream in the wash are white, resistant barnacle beds deposited as shoreline features (Fig. 3A). Similar barnacle beach concentrations can be seen today at Corvina Beach on the east shore of the Salton Sea (Figure 3B).

"Quarry Wash" is an informal name for the first major wash south of Hart Mine Road. The **Quarry**

Figure 3. A *(above): Hart Mine Wash barnacle coquina;* B *(left): Corvina Beach barnacle beds.*

Wash Sands locality, south of Cibola, is 0.8 km (1/2 mi) south of Hart Mine Road and approximately 1.6 km (1 mi) east up-drainage from Cibola Road at elevation 104 m (340 ft). Fossiliferous yellow cross-bedded sands are overlain by marl (Figure 4). The fossils represent a mixture of taxa from fresh and brackish water habitats. Pelecypod valves are all disarticulated, supporting the reworked nature of the concentration. The base of section is not exposed.

Quarry Wash Marl is represented only by rounded, stream-transported slabs of dense, resistant, marl "float" found in the main wash 154 m (500 ft) north of the Quarry Wash Sands locality. The source for these materials remains to be found, but it is apparently upstream at an elevation greater than 104 m (340 ft). The fossils consist of freshwater snails and articulated mussels. Mussels with articulated valves suggest that there has been minimal transportation. The false grunion (*Colpichthys regis*, Todd, 1976), a marine fish, is reported to have been collected in marl along this wash, but no precise stratigraphic locality was published.

"Cibola Wash" is an informal name for the first major wash south of Quarry Wash, approximately 1.7 km (1.1 mi) on Cibola Road south of Hart Mine Road. Outcrops in this wash may be those depicted by Metzger (Fig. 6, Metzger and others, 1973). The Cibola Wash Marl consists of fri-

Table 5. Quarry Wash Sands - Elevation 105 m (340 ft)

Organism Type	Taxon	Habitat
pelecypod, small-size, toothed hinge	*Sphaerium californica*	fresh water
gastropod, high spired reduced shoulders, aperture notch, ornamentation	*Batillaria californica*	brackish
gastropod, high spired, shoulders, round aperture,	*Tyronia protea*	alkaline streams
gastropod, medium-high spired	*Fluminicola* sp.	fresh water streams
gastropod, medium-low spired	*Amnicola longinqua*	fresh water lakes
barnacle	*Balanus* sp.	brackish-marine

Table 6. Quarry Wash Marl - Elevation m 105+ m (340+ ft)

Organism Type	Taxon	Habitat
pelecypod, small-size, toothed hinge	*Pisidium* sp.	fresh water
gastropod, medium-low spired	*Amnicola longinqua*	fresh water
Fish, false grunion	*Colpichthys regis*	marine

Table 7. Cibola Wash Marl - Elevation 92 m (300 ft)

Organism Type	Taxon	Habitat
pelecypod, small-size, toothed hinge	*Sphaerium californica*	fresh water
gastropod, medium-low spired	?*Physa* sp. or ?*Amnicola* sp.	fresh water
ostracode	?*Limnocythere* sp.	fresh water

Table 8. Cibola Wash Sands - Elevation 95 m (310 ft)

Organism Type	Taxon	Habitat
pelecypod, small-size, toothed hinge	*Sphaerium californica*	fresh water
barnacle	*Balanus* sp.	brackish-marine
gastropod, high spired reduced shoulders, aperture notch, ornamentation	*Batillaria californica*	brackish

Table 9. Palo Verde Point Sands - Elevation 74 m (240 ft)

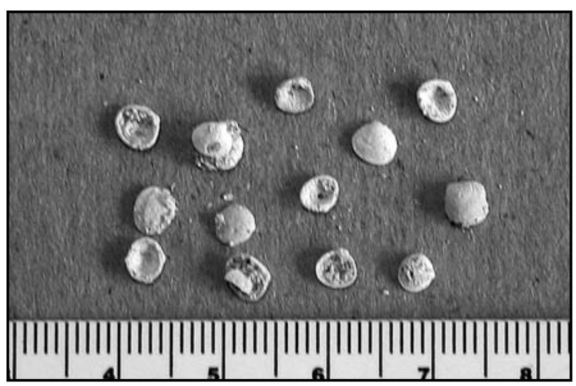
Organism Type	Taxon	Habitat
gastropod, high spired reduced shoulders, aperture notch, ornamentation	*Batillaria* sp?	brackish
gastropod, high spired, shoulders, round aperture	*Tyronia* sp.?	alkaline streams
barnacle	*Balanus* sp.	brackish-marine

able, silty marl that rests disconformably on volcanic sub-rounded gravels (Figure 5). The lower marl, at 91 m (300 ft), is overlain by cross-bedded sands and gravels that are in turn overlain by a higher layer of marl. A cap of barnacle coquina is reported higher in the section (Fig. 6, Metzger and others, 1973). The fossils reported herein were collected only from the lower (91 m) marl layer and include three freshwater taxa.

The **Cibola Wash Sands** site is in Cibola Wash, approximately 154 m (500 ft) downstream (west) from the Cibola Wash Marl locality at elevation 94 m (310 ft). Volcanic sub-rounded gravels at the base of the section are overlain by gray marl that is in turn overlain by three feet of white marl capped by yellow-brown, cross-bedded sands that contain a mix of disarticulated freshwater mussels and brackish water snails.

Palo Verde Point Sands is on the east side of Highway 78 approximately 11.2 km (7 mi) south of the community of Palo Verde in Imperial County, California. This locality at elevation 73 m (240 ft) contains yellow, cross-bedded sands with brackish water mollusks and barnacles (Figure 6A). Oncoidal tufa structures (Figure 6B) are adjacent to the east and north of the site. Tufa consists of calcium carbonate precipitated by algae in clear, sunlit water (Li, 2003).

Figure 4. View east of Quarry Wash Sands.



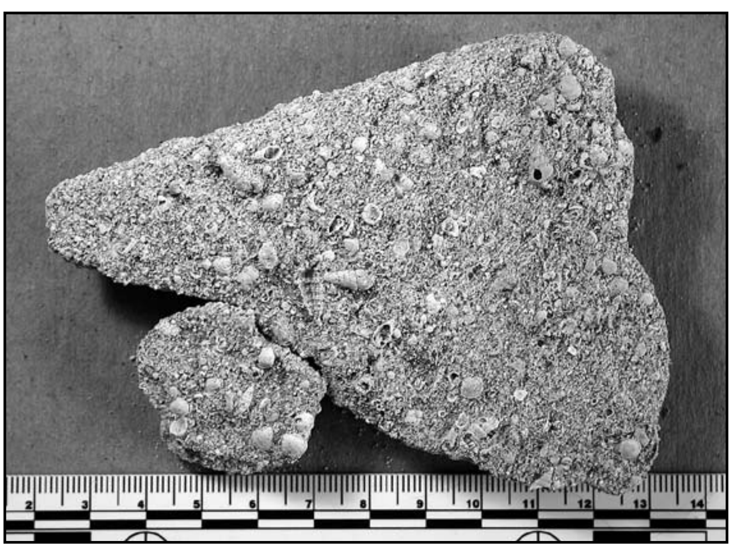


Figure 5. A *(above right): small, disarticulated, fresh water clams (*Sphaerium californica*).* B *(above): freshwater clams and brackish water snails in cross-bedded sands exposed in Quarry Wash.* C *(below right): ornamented conispiral, brackish-water snails (*Batillaria californica*).*

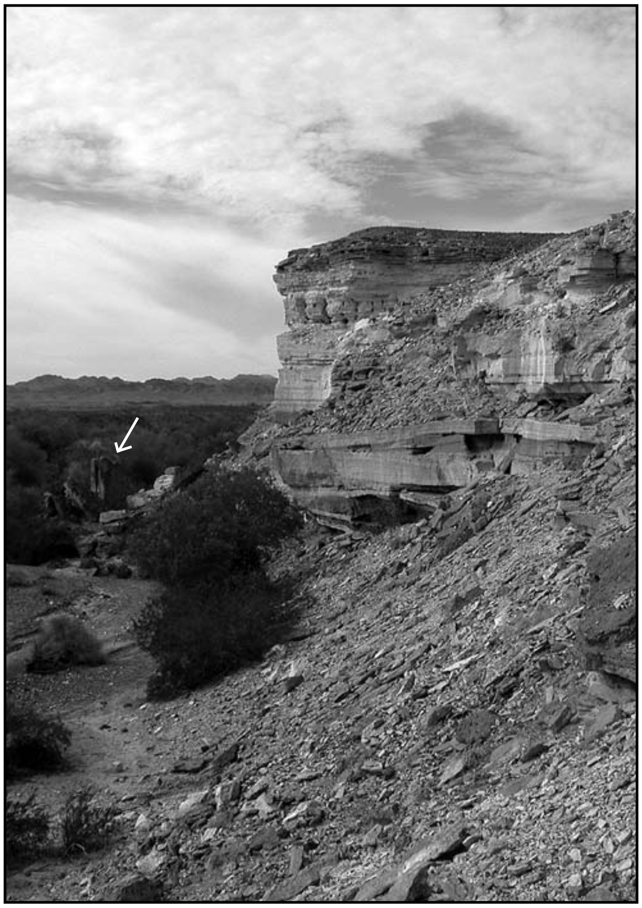


Figure 6. View west of cross-bedded sands overlain by marl in Cibola Wash. The vertical block of marl (left, designated with arrow) contains fresh-water mollusks and ostracodes.

The depositional sequence at this outcrop suggests that tufa formed on a substrate of Miocene volcanic rocks in unagitated, clear water. Subsequently, the area was inundated by cross-bedded sands deposited as shoreline features.

Discussion

Invertebrate Habitats

Invertebrate fossil taxa from the Blythe basin have modern counterparts that provide habitat data. Certain snails such as *Tyronia* sp. prefer alkaline springs and streams. *Fluminicola* sp. prefers freshwater streams and *Amnicola* sp. freshwater lakes.

Other taxa represent estuary/marine water, and were introduced from marine sources. For instance, the brackish/marine snail *Batillaria* sp., has Atlantic/Caribbean Ocean affinities (Taylor 1983) and cannot tolerate fresh water. Crabs and barnacles can tolerate water with low salinity, and are recorded from brackish estuaries with stream and tidal interplay. Barnacles with unusual morphology attributed to freshening of estuary waters have been noted north of Parker, Arizona (Zullo and Buising, 1989). The brackish-water snail (*Batillaria* sp.,) is widely distributed through the Blythe basin localities (Taylor, 1983). Localities with marine fossil clams (*Macoma* sp. and *Mulinia*? sp.) have been reported, but no locality data or descriptions were provided (Metzger and others, 1973; Taylor, 1983).

The Quarry Wash Marl and Cibola Wash Marl localities contain only freshwater species. Hart Mine Wash Marl contains freshwater bivalves that have become disarticulated by current and subsequently were used as anchors by barnacles. All cross-bedded sands (Earp Bridge, Osborne Wash, Quarry Wash, Cibola Wash, Palo Verde Point) contain brackish water taxa or a mixture of fresh and brackish water taxa. The marine False Grunion was found in marl (Todd, 1976). Outcrops of deposits that yield these fossil taxa occur at variable elevations and have not been placed into a stratigraphic framework.

As water levels rose in a freshwater Blythe basin, similar depositional facies and faunas would have moved laterally upslope through time, transgressing bedrock topography and volcaniclastic fanglomerate. Deposits of Bouse Formation basal marl may represent $CaCO_3$ deposition in still water during this transgressive phase. Marl facies contain both fresh- and brackish-water faunas. The freshwater assemblages may have come from up stream sources, but the brackish/marine faunas must have come from marine sources (southerly) and suggest an interplay of basin filling regimes. This implies a transient (not bedrock) barrier at the marine end of the basin that leaked marine water early in basin history, and allowed marine waters to be the major

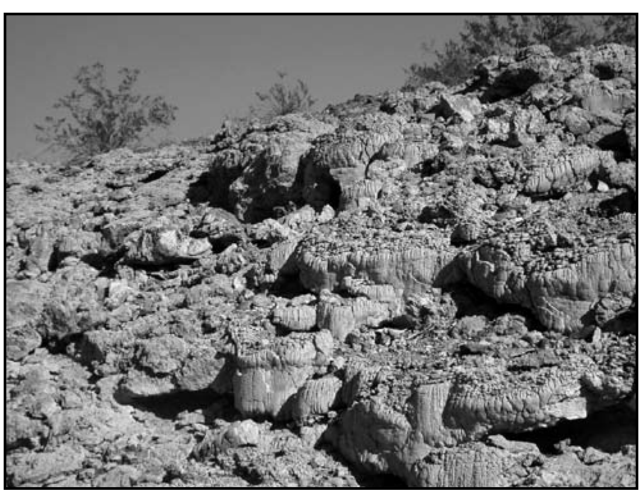


Figure 7. A *(left): tufa structures and* B *(above): cross-bedded sands at Palo Verde Point.*

component late in basin history.

Cross-bedded shoreline sands near the basin center, interfingering with marl deposits, suggest a draw-down event, where water level lowered and shoreline deposits migrated down slope. As the area of the basin decreased, salinity would increase if fresh water influx was limited and remains of brackish water species would dominate the record. Continued draw-down of surface level would move shoreline deposits such as cross-bedded sands and barnacle coquina toward the center of the basin, mixing the fresh and brackish /marine invertebrate shells from previously deposited sedimentary facies.

Elevation of Fossiliferous Outcrops

Fossil localities in the Blythe basin between Parker and Cibola range in elevation from 74 to 177 m (240 to 600 ft).

The Blythe basin localities are at least 146 m (480 ft) below the maximum elevation of Bouse sediments containing Lawlor Tuff (4.83 Ma) at Buzzard Peak in the southern Blythe basin. This research did not find records of fossil localities between 183–330 m (600–1080 ft) in the Blythe basin. Therefore, the salinity of the water filling the upper half of the Blythe basin is currently unknown.

Facies

Where the base of section is exposed, Bouse Formation outcrops all appear to sit on sub-angular to subrounded gravels, often dominated by locally-derived Miocene volcanic clasts. These gravels are overlain by alternating layers of marl, cross-bedded sands, marl, and layers of barnacle coquina (Fig. 6, Metzger and others, 1973). Except for Cibola Wash, the outcrops discussed above do not have the base of the section exposed. However, marl can be interpreted as having been deposited in still water (House and others, 2005), a contention supported locally by partially intact fish skeletons (Todd, 1976) and articulated mussel valves. The marl in Blythe basin can not be interpreted as exclusively a fresh water precipitant since some outcrops contain freshwater mollusks while others are reported to contain marine fish (Todd, 1976). Tufa deposits at Palo Verde Point suggest deposition in relatively clear, sunlit, shallow water. Cross-bedded sands and barnacle coquina may represent shoreline deposits.

Interpretation of habitats

Fossil assemblages are helpful in the interpretation of environmental conditions in the Blythe basin. Seven freshwater mollusks suggest fresh streams or lakes, while one gastropod (*Tyronia* sp.) suggests alkaline conditions. Barnacles and one snail (*Batillaria* sp.) suggest brackish water. The False Grunion (Todd, 1976) suggests a marine incursion, since they have not been reported in estuaries (Swift and others, 1993). The report of crabs and marine mollusks (USGS M3091) was not verified during this study. The Blythe basin does not have any taxa in common with the freshwater invertebrate assemblages (*Anodonta* sp, *Physa* sp., *Succinea* sp. *Valvata* sp., Reynolds, this volume) reported from the Chemehuevi basin to the north. The lack of marine fauna in Chemehuevi, Mojave, and Cottonwood basins north of the Blythe basin and its extension through the Bristol–Danby trough (Reynolds and others, this vol.; Spencer and others, this vol.) is consistent with marine microorganism distributions (McDougall, 2008).

Basin filling

Filling of the lowest half of the Blythe basin (early basin) involved an interplay of fresh, brackish, and marine waters. The marine water probably came from the newly formed Gulf of California (6.3 Ma, Dorsey and others, 2007), allowing certain marine taxa (*Batillaria* sp. and False Grunion) access to the Blythe basin. Fresh water entering the early basin may have come from Chemehuevi basin (Reynolds, this volume), lateral drainages, or even from the meandering Gila River. The barrier between the early basin and the Gulf of California appears to have been transient, as it allowed variable input of marine water and taxa, creating fluctuations that caused shoreline features to migrate basinward. A solid "bedrock" barrier in the vicinity of the Chocolate Mountains might allow marine water leakage, but would probably prevent introduction of brackish/marine taxa until it was breached

Early basin filling may have started prior to 5 Ma, and "late" basin filling proceeded until the high stand at 330 m (1080 ft) that contains the Lawlor Tuff (4.83 Ma). The period between 6 Ma and 4.5 Ma records a sea level rise (subcycle 3.4 of Sea level Super Cycle TB3, Woodburne and Swisher, 1995). The filling of the Blythe basin may not have been as simple as the breaching of an upstream (Chemehuevi) basin to fill a downstream basin with a sill at 330 m (1080 ft). Brackish/marine taxa are present in the early Blythe basin and near the high stand of basin filling that reached Bristol basin at the north end of the Bristol–Danby trough. The filling of Bristol–Danby trough, and the Blythe basin required an enormous volume of water. The presence of mixed marine/brackish/freshwater faunas in the Blythe basin suggests a transient or "filter" barrier that might have been a result of sea level rise and interplay with the developing Gila River delta. However, Bouse sediments filled the Blythe basin to thicknesses from 74–330 m (240–1080 ft), which suggests that basin filling must have involved tectonic depression and subsequent elevation of the Colorado River trough in addition to the interplay of water sources and the transient nature of the southern barrier.

Summary

This preliminary review of selected invertebrate faunas from the Blythe basin hints at the following history of basin filling:

1. Lowest assemblages, (74 m and 178 m in elevation), in the early basin contain a mixture of fresh and brackish/marine taxa, suggesting that the early basin had contact with marine waters.
2. Interspersed layers of marl with exclusively freshwa-

ter taxa suggest a transient barrier with marine water sources.

3. Cross-bedded sands and barnacle coquina indicate near shore deposits near the basin center. This suggests fluctuation of the early basin water level.

4. The maximum water level reached an elevation of 330 m (1080 ft) and extended through Blythe basin to Danby, Cadiz, and Bristol basins. Saline-tolerant invertebrates are recorded in Bristol basin. The presence of brackish/ marine taxa as far northwest as Bristol basin (Reynolds and others, this vol.) throughout the history of filling the Blythe basin suggest that a marine source of water played an important part in filling basins to the maximum level.

5. The strong influence of marine water during basin filling implies tectonic depression and subsequent elevation of the Colorado River trough in addition to the interplay of water sources caused by a transient barrier.

Future work

This preliminary study examined fossil assemblages from Bouse Formation outcrops that were not related by a stratigraphic framework. Such a framework will permit correlation of fossil locations and more precisely document the sequence of faunal and sedimentary depositional changes. Inventory of invertebrate fossils should include collection and analysis of diatoms and ostracodes to provide supporting paleoenvironmental data. Additional studies would benefit from a tephro-stratigraphy tied to magnetostratigraphic analyses.

Acknowledgements

The authors wish to thank David Jessey, David Miller, and George T. Jefferson for careful review and constructive comments. We also thank Tom Howe, who spent winter months helping prepare invertebrate specimens using the freeze-thaw method of matrix disaggregation, and Margaret Gooding, LSA Associates, for preparing Figure 1.

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Extent and age of the Bouse Formation as indicated by strontium isotopes and tephrochronology in Blythe basin

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The Bouse Formation consists of latest Miocene to earliest Pliocene travertine, marl, and siltstone in the lower Colorado River Valley. The formation is well-exposed along the flanks of the valley where it has been uncovered by incision associated with entrenchment of the Colorado River (Metzger et al., 1973; Metzger and Loeltz, 1973; Buising, 1990). The Bouse Formation contains fossils of several marine species and was originally interpreted as deposited in an estuarine extension of the early Gulf of California (Smith, 1970; Lucchitta, 1979; Lucchitta et al., 2001). However, strontium isotopes, elevation distributions, and coincidence with fluvial sedimentation derived from northern sources all support Bouse deposition in a chain of lakes fed by first-arriving Colorado River waters (Spencer and Patchett, 1997; House et al., 2005; Spencer et al., 2008). These river waters were delivered to closed basins inherited from earlier tectonic extension.

The Blythe subbasin of the Bouse Formation is the largest and southernmost of the inferred Bouse lake basins, and is the only subbasin to contain marine fossils. The maximum elevation of Bouse deposits in this basin is 330 m (Figure 1). If deposited in a lake filled to this elevation, the Bouse Formation should have been deposited in several closed basins in the eastern Mojave Desert after water spilled westward over several passes that are lower than 330 m elevation. Examination of cuttings from drill holes in Cadiz, Danby, and Bristol Lake basins identified some marine foraminifera (Bassett et al., 1959; Smith, 1970). However, there were no identified outcrops that could reflect a westward extension of the Bouse Formation until USGS geologist David Miller identified marl and tephra (volcanic ash) in a small outcrop north of

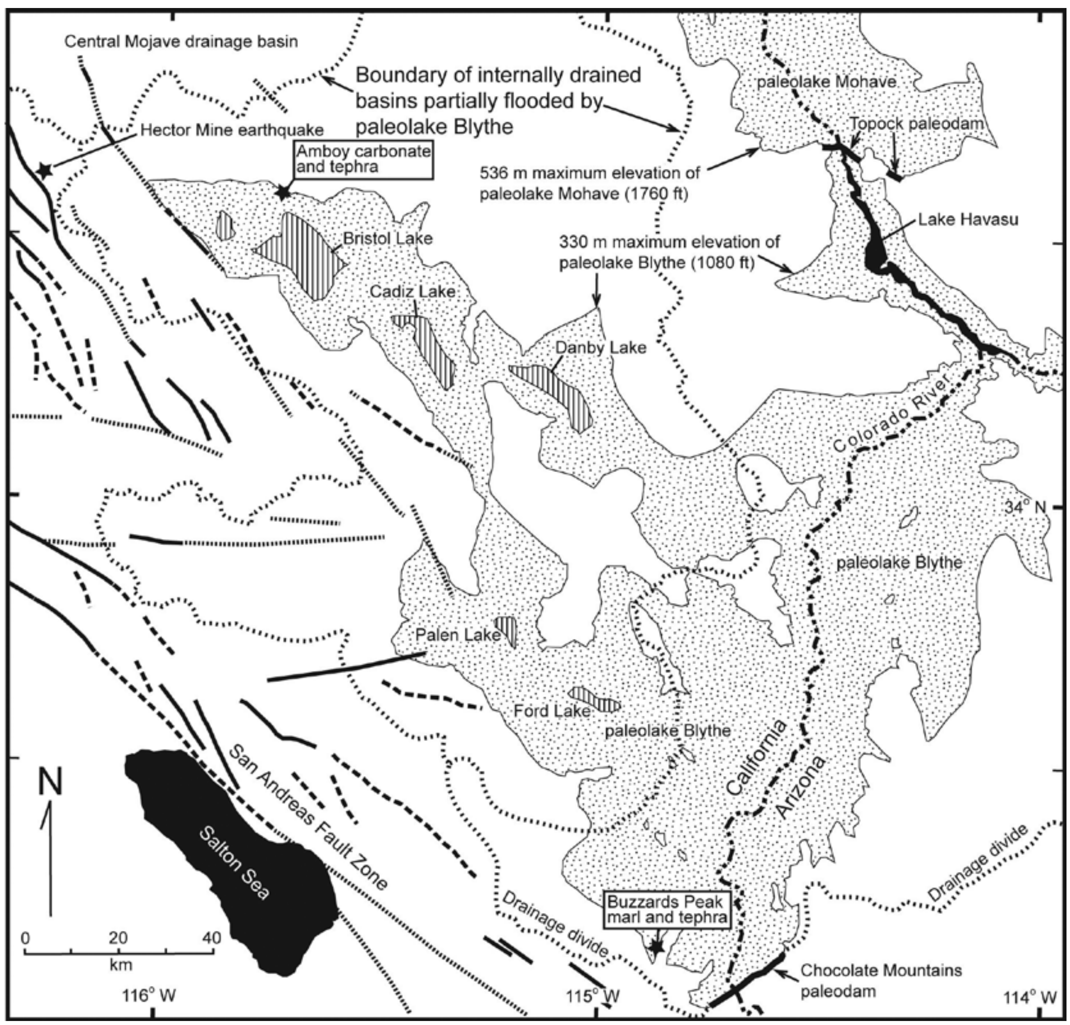

Figure 1. Map showing extent of paleolake Blythe and the southern end of paleolake Mohave (speckles). Also shown are modern playas (ruled), modern lakes and reservoirs (black), and active faults (heavy solid, dashed, and dotted lines for mapped fault, approximate mapped fault, and concealed fault, respectively). Note that active faults are sparse or absent in the area of the Blythe basin, which suggests that the original outline of the lake can be approximated from modern topography.

the town of Amboy on the north flank of the Bristol Lake basin (Figure 1). Five analyses of strontium isotopes from marl and travertine from this outcrop, done by M.S. student Jen Roskowski at the University of Arizona, indicate $^{87}Sr/^{86}Sr$ of 0.7107 to 0.7123, which overlap partially with values of 0.7100 to 0.7112 determined elsewhere for the Bouse Formation (Spencer and Patchett, 1997; Roskowski et al., 2007).

Geochemical and petrographic analysis of tephra from this outcrop and from an outcrop within the Bouse Formation in the Chocolate Mountains at the south end of the Blythe subbasin (Figure 1) indicate that both are the same tephra (Elmira Wan and Andrei Sarna-Wojcicki, USGS, written communication, 2008). On the basis of this tephra correlation, and lithologic and Sr isotopic similarity of host carbonates, we correlate the marl and travertine at Amboy with the Bouse Formation. This correlation is consistent with a lacustrine origin for the Bouse Formation wherein filling of the Blythe subbasin by Colorado River water led to deposition of Bouse carbonates over all of the areas that could have potentially been reached by a lake filling to 330 m elevation. The elevated $^{87}Sr/^{86}Sr$ of the Amboy carbonates relative to typical Bouse carbonates is attributed to the influence of local Proterozoic bedrock and incomplete mixing of local and Colorado River waters in Bristol basin. The tephra has been correlated with the Lawlor tuff originating from north of the San Francisco Bay Area, which yielded an $^{40}Ar/^{39}Ar$ date of 4.83 ± 0.02 Ma (Elmira Wan and Andrei Sarna-Wojcicki, written communication, 2008).

The Bouse lake system was terminated by filling with sediment from the Colorado River and by incision of outflow reaches. Termination was followed by delivery of petrographically distinct Colorado River sand to the Salton Trough, where its abrupt appearance is identified within the Imperial Formation on the west side of the trough (Kerr and Kidwell, 1991; Dorsey et al., 2007). First-arrived sands are placed at a stratigraphic horizon nine meters above the 5.33 Ma Mio–Pliocene boundary as identified by micropaleontology, and almost a hundred meters below the 5.24 to 5.00 Ma Thvera normal-polarity magnetochron (Dorsey et al., 2007). This age assignment is in conflict with the 4.83 Ma date derived from the Lawlor tuff because all Colorado River sand delivered to the Salton Trough should be younger than the Bouse Formation (which contains the 4.83 Ma tephra), and none should be older.

Three possible resolutions to the apparent ~0.5 m.y. discrepancy in ages determined for first delivery of Colorado River sands to the Salton Trough are as follows:

1. Both determined ages are correct. In this case, Colorado River sands were delivered by the newly formed Colorado River to the incipient Salton Trough at 5.3 Ma. This was followed by a period when the lower reach of the Colorado River was dammed by tectonic uplift of the Chocolate Mountains associated with early San Andreas fault displacement and related deformation. This tectonic event trapped river waters and associated sands, forming Lake Blythe, which was almost at its maximum level when the Lawlor Tuff was deposited at 4.83 Ma. This was followed by overflow, outflow incision, and eventual renewed sand delivery to the Salton Trough. One of the many problems with this interpretation is that basal Bouse marl in the Blythe subbasin does not overlie river sediments anywhere except possibly for very thin sands in the Parker area where the early Colorado River entered and filled lake Blythe. Other problems are lack of evidence for either a pre-Bouse river channel through the Chocolate Mountains (Sherrod and Tosdal, 1991), for a tectonic event that uplifted the Chocolate Mountains and blocked the early Colorado River, or for a hiatus in Colorado River sand delivery to the Salton Trough.
2. The age assignment for first arriving Colorado River sands is incorrect. To accommodate the 4.83 Ma date of the Lawlor tephra , the reverse-polarity magnetochron which was extant at the time of first-delivered Colorado River sands would have to be at least as young as the 4.8-4.63 Ma period between the Sidufjall and Nunivak normal-polarity magnetochrons. In the chronology determined by Dorsey et al. (2007), the Sidufjall (4.9-4.8 Ma) and Thvera (5.24-5.0 Ma) normal-polarity magnetochrons are after, rather than before, first delivery of Colorado River sands. Shifting the assignments of magnetochrons by two complete reversals would severely conflict with the paleontological identification of the Miocene–Pliocene boundary.
3. Correlation of the Chocolate Mountains and Amboy tephra with the Lawlor tuff, or the age determination for the Lawlor tuff, is in error. This possibility is not evaluated here as analytical data for the 4.83 Ma date for the Lawlor tuff, the field location of the dated sample, and the geochemical and petrologic bases for correlation of the dated tuff to the Amboy and Bouse tephras were not available to us.

In conclusion, new tephrochronologic and Sr isotopic data provide a firm basis for correlation of the Amboy marl with the Bouse Formation in the Blythe basin, as predicted by the lacustrine interpretation for the Bouse Formation. However, a half-million year geochronologic discrepancy for constraints on the time of first Colorado River sand delivery to the Salton Trough remains unresolved.

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Early geological excursions and observations of the Colorado Desert region by William Phipps Blake, 1853 and 1906

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Introduction

William Phipps Blake was the first professional geologist to conduct a geological examination of the Colorado Desert area. Blake's efforts and accomplishments in the early exploration of the west, and in California and internationally, are less known and undervalued in comparison to those individuals that comprised the first California Geological Survey headed by Whitney in the early 1860s, and the later regional surveys of Ferdinand V. Hayden, Clarence King, John W. Powell and George M. Wheeler during the 1880s, but are of no less importance. Blake's role and numerous contributions to our understanding of California geology, and the role geology played in the growth and development of the state, is significant and has been previously discussed by Testa (1996) and Testa (2002).

In the course of nearly 60 years Blake contributed to the public and scientific community both domestically and internationally. As a student and assistant to Benjamin Silliman, Sr. and James D. Dana, he was one of the first six graduates of the Sheffield Scientific School, having already published several articles for Silliman's American Journal of Science before he graduated. Following his instrumental role with the Pacific Railroad Survey he, along with Raphael Pumpelly, served as mining engineer consultants to the Japanese government in 1861, going on to organize the first school of science in Japan. Blake was also connected with the Paris Exposition of 1897, the Vienna Exploration of 1873, the United States Centennial Exposition of 1876 where he would develop a means to catalogue and classify information—a system we commonly refer to as the Dewey Decimal System, and the Columbian Exposition in 1893 where he drafted the system of classification of United States ores and minerals.

Blake continued to conduct explorations not only throughout the United States as a mining consultant, but also visited China and explored Alaska where his report influenced Secretary Seward in the procurement of Alaska. In 1895 at the age of 70, he was appointed Professor of Geology and Mining and Director of the School of Mines at the University of Arizona, Tucson, where he served with vigor and success for 10 years. He resigned to Professor Emeritus in 1905. Blake died in 1910 while attending a semi-centennial anniversary of the University of California and receiving the degree of Doctor of Laws.

In a brief biographical notice prepared shortly after Blake's death by his friend Rossiter W. Raymond (1910), Raymond stated:

> *In conversation, he was fascinating, by reason of his own keen interest in what he was saying. He told a fact as if he had only just discovered it. In the art of delivering in oral abstract the substance of a technical paper, and illustrating his remarks by rapid black-board sketches, he had no superior. He did*

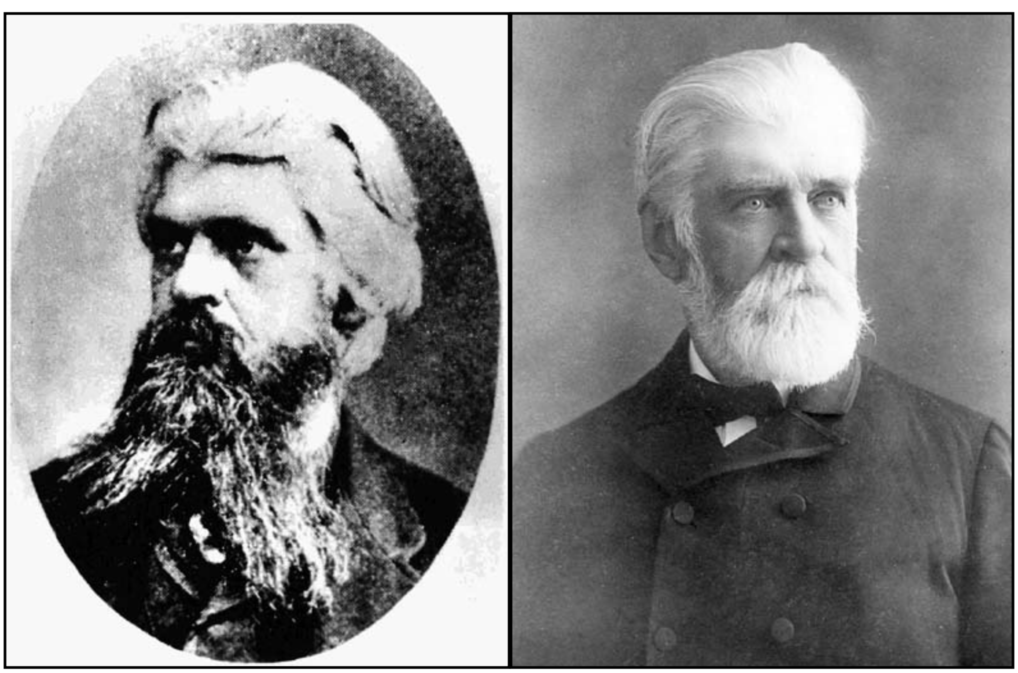


Figure 1. Portrait of W. P. Blake as a young man (left) and while at the University of Arizona (right) in June, 1890 (Photo N-6385 and N-11,549; University of Arizona, Special Collections Department, Tucson, Arizona).

such things with the grace, directness, and lucidity of a generation not pampered with stenographers, type-writers, and lantern-slides. Out of our earthly life he has departed—stalwart, versatile, tireless, brave, and gentle to the last;—but from my soul, at least, his splendid presence and his serene yet eager spirit will never depart.

Blake's excursions to the Colorado Desert region

Blake actually made two trips to the Cahuilla Basin and Colorado Desert area. His first excursion was conducted as part of the Williamson's expedition of 1853, commonly referred to as the Pacific Railroad Survey. Blake's second trip to the region was in May 1906, 53 years later, at the request of the Carnegie Institute.

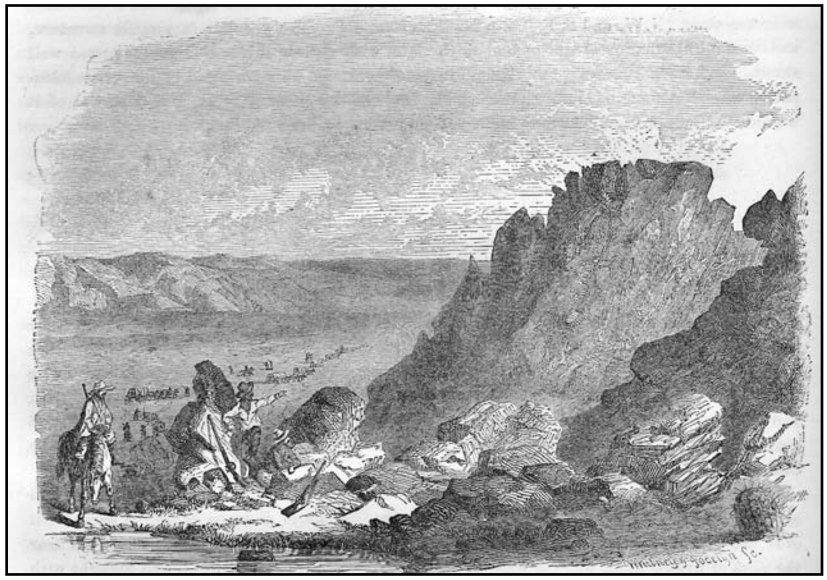
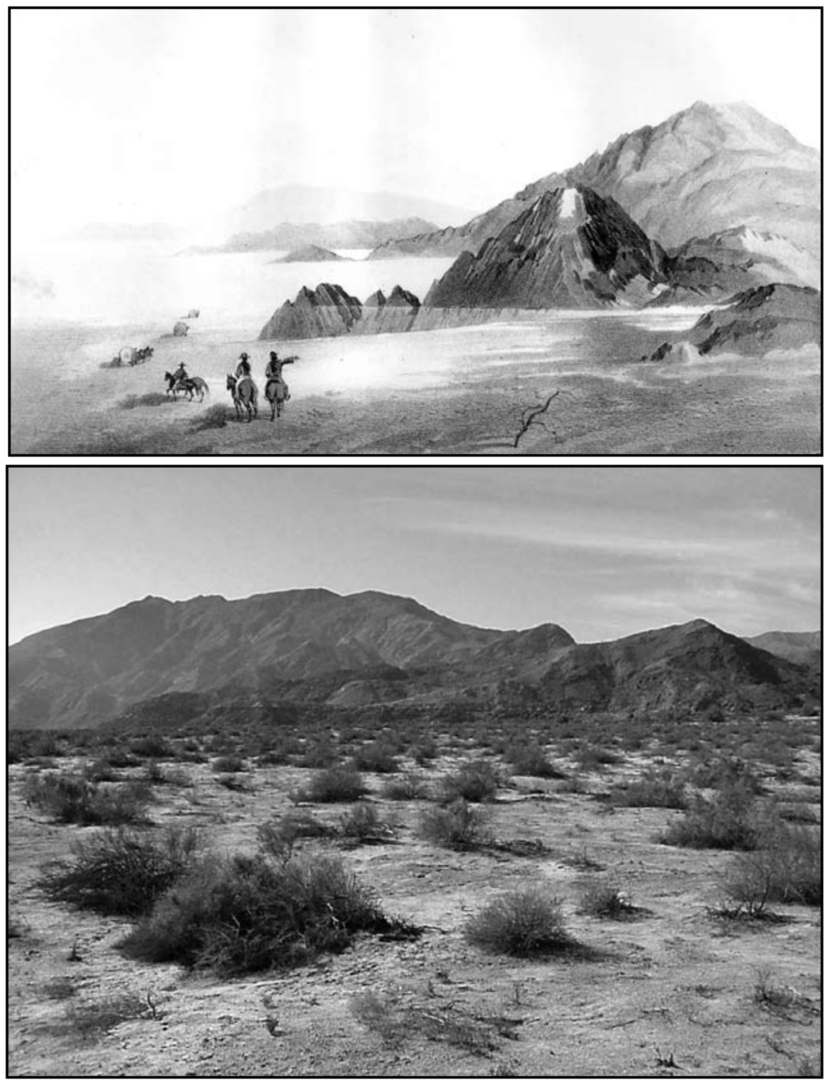


Figure 2. A view by Koppel of the camp near the desert (Williamson, 1856).

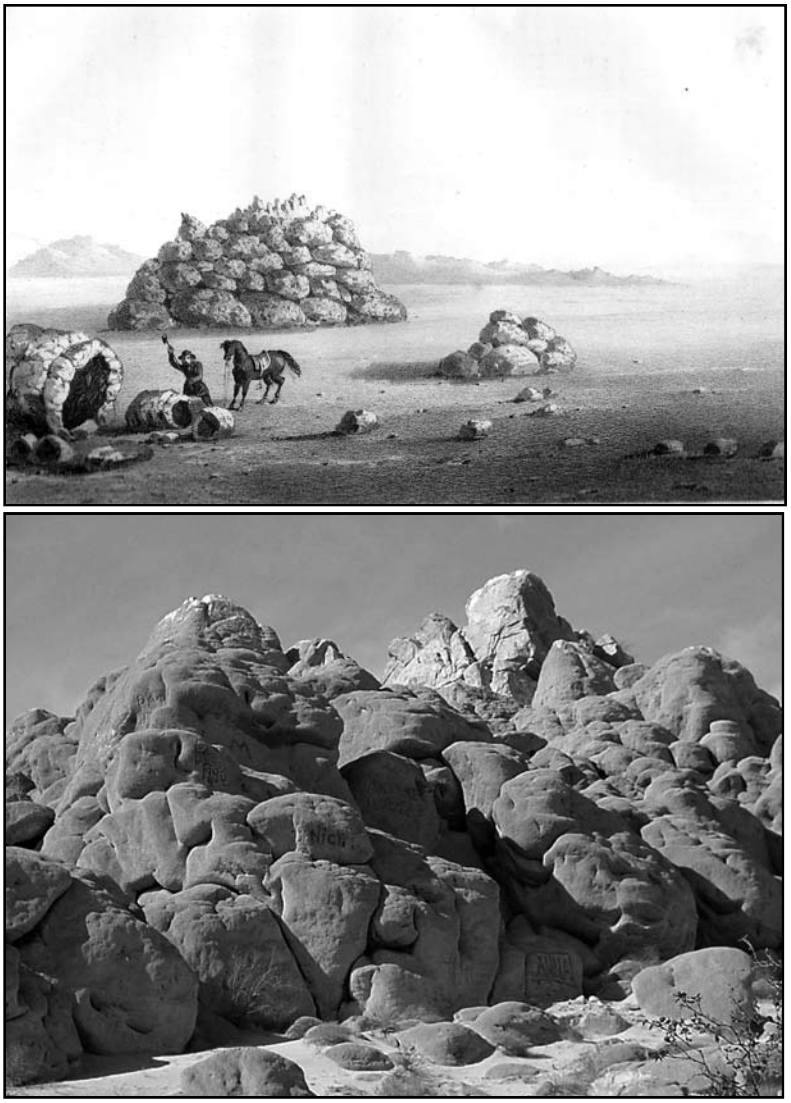
The Pacific Railroad Survey

In 1853, four expeditions as authorized by Congress under the administration of President Pierce and Jefferson Davis as Secretary of War were implemented to explore the span of country virtually unknown at the time lying between the Mississippi River and the Pacific Ocean. These explorations, commonly referred to as the Pacific Railroad Survey, had the mandated purpose to assess and determine a practicable route for a railway, although the expeditions actually more resembled topographic reconnaissances than surveys. Their objective was not to map out the exact routes the railroads would potentially follow, but rather collect information regarding anticipated engineering difficulties, economic potential, and availability of water and timber, both essential resources required for railroads of the times. In addition, the parties were to collect information about the soil, rocks, natural history, and climate. As a result of such surveys and much political maneuvering, railroads were eventually built from the east to Los Angeles through the San Gorgonio Pass, and to the Central Valley and San Francisco through the Tehachapi Pass.

One of these expeditions was placed under the charge of Lieutenant R. S. Williamson of the United States Topographical Engineers, with Lieutenant J. G. Parke as second in command and topographic engineer, and W. P. Blake as geologist and



Figures 3a and 3b. View by Koppel of water line and shores of the Ancient Lake, Colorado Desert - Plate VII of Williamson, 1856 (a) and recent photograph taken by author (b).



Figures 4a and 4b. View of point of rocks covered with a calcareous incrustation, Ancient Lake, Colorado Desert - Plate VIII of Williamson, 1856, by Koppel from sketch by Blake (a) and recent photograph taken by author (b).

mineralogist (Williamson, 1856). The party also included Dr. A. L. Heermann as physician and naturalist, Mr. Isaac W. Smith as civil engineer, Mr. Charles Koppel as assistant civil engineer and artist, Mr. Charles Preuss as draughtman, and Lieutenants G. B. Anderson (soon to leave the expedition due to illness) and George Stoneman of the 2nd and 1st Dragoons, respectively, as escort. Williamson was already in Benicia, ready to proceed with the expedition, but did not as yet have a geologist and mineralogist despite efforts to obtain one. Blake, who had graduated from the Yale Scientific School a year earlier (1852), was holding minor technical positions until Professor Silliman and Dana encouraged him to serve as organizer and collector of minerals for the New York City's Exhibition of the Industry of all Nations, scheduled to open in May of 1853 (Dill, 1991). Josiah D. Whitney, a distant cousin of Blake and a Yale alumnus, mentioned Blake to Professor Spencer F. Baird, Assistant Secretary under Joseph Henry of the Smithsonian Institute, who recommended him to Williamson's Senior Officer, Lieutenant Amiel W. Whipple, who concurred.

Blake arrived in the San Francisco bay area on July 8, 1853, a 27-year-old Chief Scientist, imposing but disarmingly charming, six feet tall, piercing blue eyes, and an abundance of hair already turning white. The Williamson expedition commenced in Benicia on the morning of July 10, examined the passes of the Sierra Nevada from the San Joaquin and Tulare valleys, then proceeded southeast to Walker Pass, the Tehachapi, Tejon, Canada de las Uvas (the Grapevine), the passes north of Los Angeles, and the Cajon from the Mojave to San Bernardino. Blake's party traveled with a sextant, two chronometers, two syphons, two cisterns, and an aneroid barometer, and a spirit level. These instruments were hauled in a wagon or carried by mules. Blake also carried out certain chemical analyses of rocks and soils, in addition to collecting material for further study to be performed later by others.

On November 15, 1853, the party entered the desert from San Bernardino through San Gorgonio Pass (Figure 2). From San Bernardino, the expedition first camped at Hot Springs (in the vicinity of Palm Springs), not knowing when water would be available to them again. They then proceeded to Indian Wells, in the northwestern end of the desert, now referred to as the Coachella Valley. On November 16, they traveled 12 miles from the Hot Springs to Deep Well (Agua Dulce). Both springs were former Indian centers, and as of the turn of the century were included as part of Indian reservations. On November 17, 13 miles from Deep Well to the Cahuilla Villages, Blake first recognized the evidence of an ancient lake (Figures 3a and 3b). On November 18, they traveled 35 miles to Salt Creek, observing calcareous incrustations nearly two feet thick in places (Figures 4a and 4b). It was from this general location that Blake, after taking a barometric measurement, determined that he was at or below sea level. Dry ravines resembling fissures 20 to 30 feet deep in the bed of the ancient lake were also observed and traversed (Figure 5).

Proceeding south on November 19, difficulties were encountered below Figtree John, along the west side of the Salton Sea area, during the expedition's attempt to reach the old stage road which followed the Carrizo Valley from the desert floor to the base of the Peninsula Range. Water was scarce and after several of the pack train animals became nearly exhausted, they found water on November 30 in the vicinity of Salton Creek, near what is now known as McCain Springs. The expedition proceeded to Salt Creek, then to the Emigrant Road leading from the north of the Gila along Carrizo Creek. The party headed toward War-

Figure 5. View by Koppel of ravines in the beds of the Ancient Lake (Plate IX of Williamson, 1856).

ner's Ranch along Carrizo Creek to Vallecito, San Felipe, and Warner's Pass, and then was to head back to San Felipe and Carrizo Creek and on to Fort Yuma.

On December 1, the expedition departed Warner's Valley to San Felipe, a distance of 16 miles, heading for Fort Yuma at the mouth of the Gila River. On December 2, the party reached Vallecito, on the 3rd reaching Carrizo Creek, on the 4th traveling a distance of 25 miles to Big Lagoon, and a distance of 26 miles to Alamo Mocho on the 5th (Figure 6). Observations of dry but vegetated streams, wells, and the first mention of the New River were made. On December 6 the party reached Cook's Well, a distance of 22 miles, and on the 7th arrived at the Colorado River, a distance of 15 miles. On December 8 the party reached Fort Yuma. The expedition left Fort Yuma on December 11, arriving in San Diego on December 23, and onto a steamer heading for San Francisco, arriving on the 26th of December.

Blake named the region the Colorado Desert, since the desert owed its origin to the river by the deposition of sediment and displacement of the sea-water. Blake was clear not to include the Mojave Desert, since the name was to strictly apply to "*the typical desert area of the lacustrine clays and alluvial deposits of the Colorado where extreme characteristic desert conditions prevail, such as arid, treeless plains, old lake beds, and sand hills*" as found in the Sahara of Africa and in the delta region of the Nile.

Following completion of the Williamson expedition, an extensive report was prepared by Blake in San Francisco which included summaries of his observations en route, geologic maps and sections, illustrations, and collections of materials that were later analyzed, identified, and provided as illustrations in his report (Williamson, 1956). Many of the wood engravings, 87 sketches in all, were created by Blake himself, along with several views; he collaborated with Koppel on others. Further study and examination of specimens collected during the expedition were subsequently performed by Professor L. Agassiz, Mr. T. A. Conrad (Tertiary shells), and Dr. T. A. Gould (shells of living species), and Dr. J. Torrey (botanical specimens). Blake's report is Part II of the Williamson report, and was dated 1857. As Coash (1992) points out, some confusion of dates exist in the publication of this report. Williamson's report is dated 1855, a letter of transmittal is dated 1854, and the published report (Volume V of the Pacific Railroad Survey Reports) is dated 1856. In addition, Blake had a number of copies of his report covering California bound up separately (Blake, 1858). This report included some additions and corrections, with an additional view, and as with his previous report, was divided into two parts: the first being an itinerary or notes and general observations upon the geology of the route, and the second being geology of portions of the route.

Carnegie Institute of Washington excursion

Blake's second trip to the Colorado Desert area in May of 1906 was at the invitation of Dr. D. T. MacDougal of the Carnegie Institute of Washington (Blake, 1914). Blake crossed the valley from Mecca on the Southern Pacific Railway, visiting the then-rising Salton Sea, and skirting the body of water to Travertine Point which he ascended after 53 years on May 23, 1906 (Figures 7a and 7b), where Blake observed:

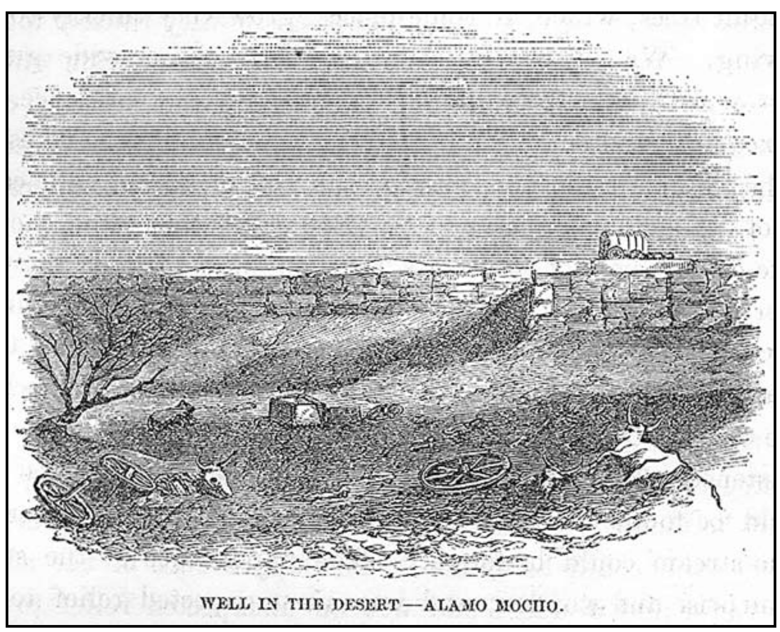
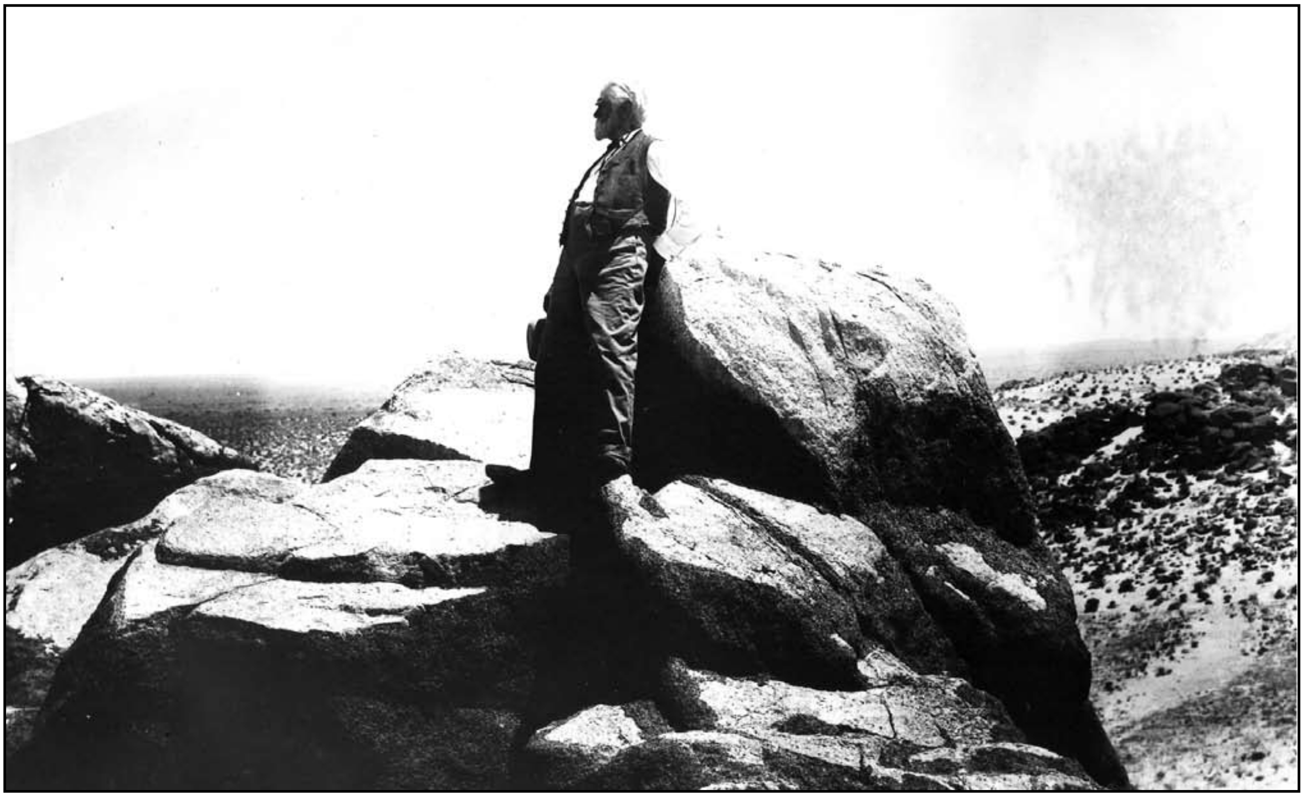


Figure 6. Wood engraving by Blake of well in the desert at Alamo Mocho (Williamson, 1856).



Figures 7a and 7b. Blake standing on summit of Travertine Rock on May 23, 1906, 53 years after his original discovery of this formation (a), and current view from same point (b) (Photograph by author).

The old water-lines and beaches were comparatively unchanged in appearance. Concentric lines of sparse vegetation marked where the waters had stood centuries before. Looking out from the summit across the Salton Sea, it was difficult to realize that the old-traveled trail across the desert lay 15 fathoms deep under water, where before not a drop could be found.

Blake observed the rapidly-rising water level of the Salton Sea (estimated at 3 inches a day). He was overwhelmed en route from Mecca to Palm Springs by the agricultural and industrial development that had taken place since 1853. He rested in Palm Springs and left for Los Angeles on May 24, and continued by rail to San Diego.

A summary of Blake's final thoughts, which reflected many original opinions set forth in his early report (Williamson, 1856), was also prepared two years prior to his death in 1910 (Blake, 1919). Some general perceptions of the surveys conducted in California, and Blake's role in such surveys, are provided by Coash (1992).

Geological observations and notes

Blake had very little time to veer any significant distance from the proposed route during his 1853 traverse through southern California and the desert country, and still he managed to record many important and significant observations. Some of the more significant observations reflected on topographic setting, geology, origin of pebble-covered plains, deposition and erosion, differential weathering, wind abrasion, superficial blackening and discoloration of rocks, volcanism and seismicity, availability and quality of water, and economic, agricultural, and engineering considerations. A few salient observations are summarized below.

Topographical setting

Blake traversed the desert taking barometric measurements with Lt. Parke as a member of the Williamson expedition in 1853 and first established the fact that the region was an

Figure 8. Photograph of wind mill farms situated just north of the City of Palm Springs (Photograph taken by author).

enclosed basin, the lowermost part of which was below sea-level (Blake, 1891). The parallelism of the valley with the Pacific Ocean, and the linear succession of narrow valleys of Vallecito, San Felipe, Warner's, and San Luis River, and with the Bernardino Pass, was noted. The overall northwest–southeast trend of the coastal ranges was also evident.

He also correctly described the general cause of the persistent winds in the upper Coachella Valley area. As stated by Blake,

> *. . . They both (the San Francisco Golden Gate and San Gorgonio Pass) appear to be great draught channels from the ocean to the interior, through which air flows with peculiar uniformity and persistence, thus supplying the partial vacuum caused by the ascent of heated air from the surface of the parched plains and deserts . . .*

In regards to wind abrasion (Figure 9), Blake goes on to state:

> *I had before me remarkable and interesting proofs of the persistence and direction of this air-current, not only in the fact that the deep sand-drift was on the east side of the spur, but in the record which the grains of sand engrave on the rocks in their transit from one side to the other.*

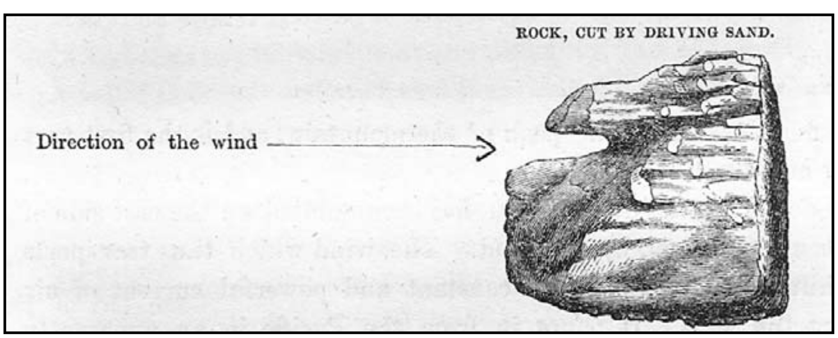


Figure 9. Wood engraving by Blake showing differential wind erosion. Persistent quartz within less resistant mass of feldspar with the whole having a smooth surface (Williamson, 1856).

Geology

Blake's geologic map of the country between San Diego and the Colorado River was produced at a scale of 1 inch = 25 miles (1:608228 feet) and is reproduced in Figure 10. Units delineated, from youngest to oldest, include sandhills and drifts, desert alluvial, Tertiary and detritus, erupted trapped rocks, and granitics and metamorphics.

The most areally extensive is alluvium, which includes bluish clay of alluvial or lacustrine origin, and the surrounding gravelly plains or low hills that occur along the base of the surrounding mountains. Fossil shells were submitted to Dr. H. A. Gould in Boston and analyzed. The fossil shells retrieved from the bluish clay included *Gnathodon lecontei*, *Planorbis ammon*, *Physa humerosa*, *Amnicola protea*, and *Amnicola*, four of which were new (Figure 11). *Anodonta californiensis* was also found to be abundant, especially in the northern part of the desert. These fossils were representative of a fresh-water origin with the exception of *Gnathodon* which is a brackish water genus and found in the mud of estuaries. Tertiary fossils were also found in Carrizo Creek. Tertiary fossil shells were found at Carrizo Creek, including new species of *Ostrea*, *Pecten* and *Anomia*, were inferred to be Miocene in age (Figure 12).

The Colorado Desert was found to be bordered on both sides by mountains comprised chiefly of granitic and metamorphic rocks. The Peninsula (Sierra) Ranges are delineated north of the United States–Mexico border, and were described as chiefly granitic and syenitic rocks, with unusual amounts of schorl (black tourmaline). Gneiss and micaceous schist were described as largely developed and sharply upraised and plicated, forming extremely rough and jagged outcroppings along the border of the desert (Figure 13). Mention is made of superb gems including red, green and pink colored tourmaline, spodumene, kunzite, garnets, and beryls, notably in his later writings.

Blake described the sandhills where principal accumulations were encountered between Pilot Knob and Alamo Mocho, between Carrizo Creek and Salt Creek, at Deep Well in the Bernardino Pass and on the north side of the desert opposite Deep Well. The sands were found to form a belt less than a mile in width, and about 20 miles in length. Blake concluded that the sands which comprised the hills were derived from the

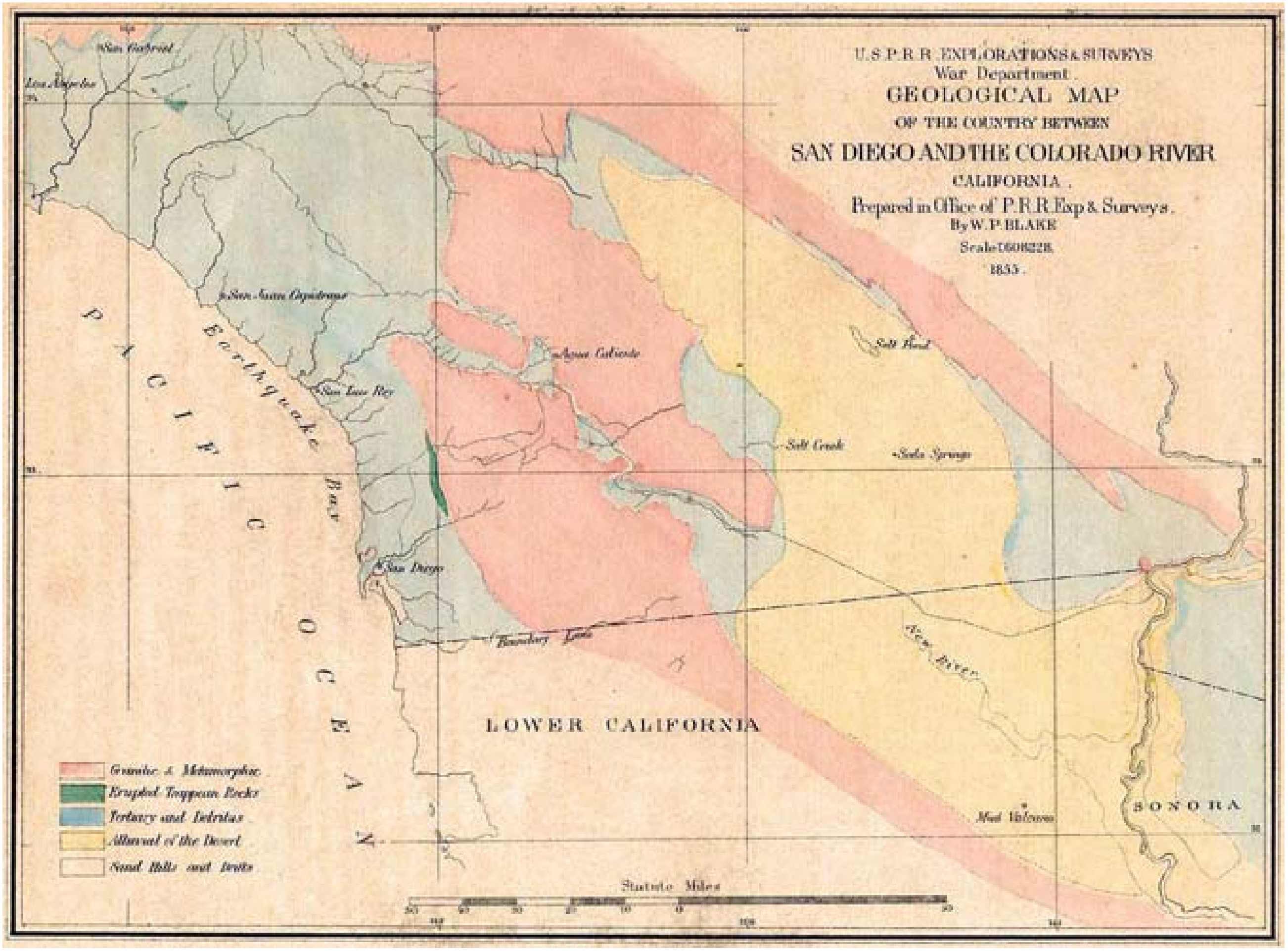


Figure 10. Geological map of the country between San Diego and the Colorado River, California, by Blake, 1855 (Williamson, 1856).

surface of the upper gravelly plain by the continued action of the northerly winds. The hills seldom reach a height of 60 feet, being composed chiefly of sand, and are underlain by a high bank of clay and gravel, with a covering of sand. Blake inferred that the clay and gravel terrace, which forms the margin of the plain overlain by sand, acted as an effectual bar to further development and migration.

Evidence of uplift

Blake concluded that the presence of marine and fresh water fossils above tide-level clearly indicated that there must have been considerable uplift of the whole region, and a change from marine to fresh water conditions during Middle Tertiary. Blake deduced that uplifting culminated in the Pleistocene, or Glacial period, when the precipitation of rain and snow was believed to have attained their maximum. The Colorado River at this time had its greatest volume and transporting power. Silt was distributed far and wide in the interior sea, then only partially cut off from the broad Pacific by a chain of islands which now form the rest of the Peninsula Mountains from San Jacinto to Cape St. Lucas.

Entering the Gulf just below where the mouth of the Gila River now is, it began dropping its load of debris and silt, forming a raised delta which gradually extended westward and southerly across the upper end of the Gulf toward the Cocopah Mountains and finally to the higher ridges beyond the Pattie Basin, even to the eastern face of the Peninsula Mountains. Building up of the delta proceeded rapidly.

Ancient Lake Cahuilla

Blake clearly deduced that the valley was formerly occupied by sea-water as shown by reefs of fossil oysters and other marine shells. Considering the configuration of the valley and its relation to the Colorado River, Blake inferred that the Gulf once covered the region, extending nearly 170 miles further inland; and possibly reaching as far as the face of San Gorgonio and San Bernardino.

The head of the Gulf, being cut off by the buildup of deltaic deposits, resulted in an inland sea of salt water or brackish water. The influx of fresh water from the Colorado, though variable in quality and quantity, exceeded the loss by evaporation, thus raising the level of the lake with excess overflow to the Gulf by a lower outlet. He noted at least three terraces marked by abrupt descents: the first or lowest bordering the Colorado and forming its bank, the second forming a bluff as evident at Cook's Well and be-

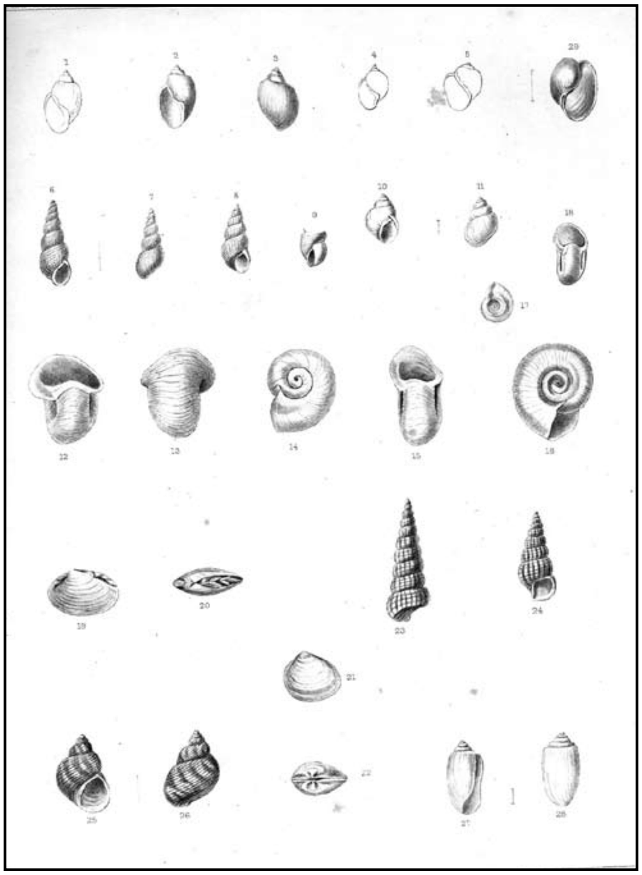


Figure 11. Engraving by Conrad of fresh-water fossil shells from the Colorado Desert – Plate XI, Figures 1, 2, 3, 4 and 5 (Williamson, 1856).

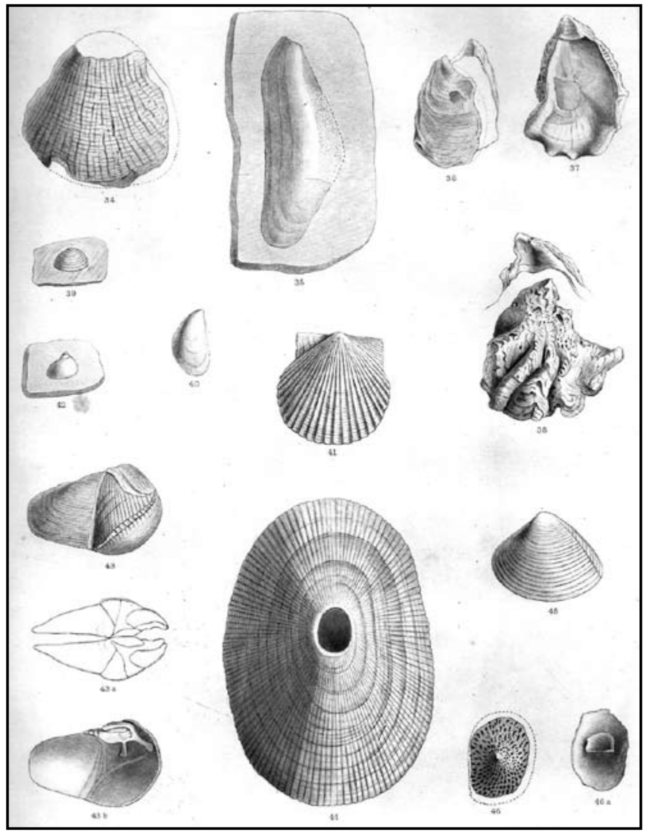


Figure 12. Engraving by Conrad of fossil shells of Tertiary (Miocene) age from Carrizo Creek – Plate V, Figures 34, 35, 36, 37, 38 and 41 (Williamson, 1856).

yond (older alluvium), and the third being the high pebbly plain of the desert (post-Tertiary). Blake inferred that such lacustrine conditions continued for centuries considering the enormous accumulation of fossiliferous sediment within the old beach lines, with a record of salt-water displacement and final occupation of the valley by fresh water. With variable flow and sediment accumulation and eventual loss of water from the Colorado, the lake disappeared via evaporation very slowly. Blake compared his observations with the rapid increase in delta formation associated with the Mississippi, Nile, Ganges, and other rivers. Crossing the desert, several banks or terraces and their relationship relative to the Colorado River were also observed. Blake also compared the desert area north of the Gulf of California to other areas such as the Gulf of Suez at the north end of the Red Sea, the Indus Delta of Central Asia, the Rann of Kachh, and at the head of the Persian Gulf.

Origin of pebble-covered plains

During Blake's exploration of the Colorado Desert area, he first observed in 1853 broad stretches of pebble-covered plains. In a paper read before the AIME in February 1903 (Blake, 1903), he stated:

> *The attention of travelers, upon the desert bordering the Great Colorado of the West, is often arrested by broad stretches of pebble-covered plains, or mesas, glittering in the sunlight from the myriads of polished surfaces, giving, at a distance, the appearance of a sheet of water. It is not alone the well-rounded, polished surface of these pebbles which commands attention, but, in addition, their nearly black or dark-brown color; and, above all, their uniform distribution in a level sheet, covering the plain in a continuous layer or pavement like a vast mosaic without sand or soil.*

Such occurrences were observed to occur in Yuma County, Arizona, and on the borders of the Colorado Desert. Blake inferred that phenomenon was much more extensive historically, but had been reduced in extent due to formation of numerous dry arroyos or washes which were formed during precipitation events.

Blake inferred that the surface-sheet of accumulated pebbles, and in many localities small fragments of rock and bits of fossil silicified wood, resulted from the gradual removal of silt and finer material by wind. Such action undermined the pebbles, thus removing their support and causing them to fall and accumulate at lower levels. Eventually, the accumulation of pebbles would be such that the surface would be covered by fragments too large and heavy to be moved via wind. Such deposits of pebbles and fragments represented all that was originally distributed

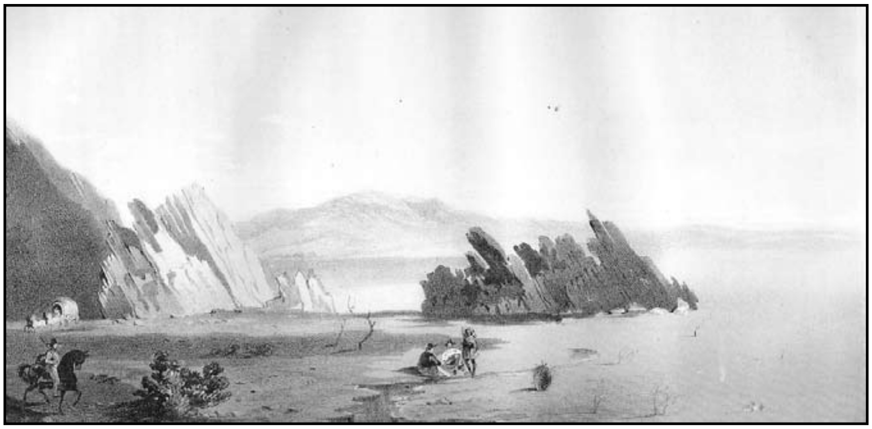


Figure 13. View of metamorphic rocks – borders of the desert by Koppel – Plate XIII (Williamson, 1856).

through several feet of thickness of sand and lighter alluvials. Once the entire area was covered and thus protected, aeolian denudation would be arrested and the further lowering of the surface stopped.

Superficial blackening and discoloration of rocks

Blake observed the general blackening of rock outcrops and of boulders and pebbles that occurred on the surface of the mesa along the Colorado River. Such outcrops and rock fragments were also commonly observed to be polished or lacquered, characteristic of attrition of wind-driven sand and dust.

Blake in his discussion of this phenomenon compared his observations with those of Humboldt in granitic rocks of Orinoco in tropical America, Rozier in the syenitic rocks of the Nile, Captain Tuckey in Saire, and Sir Robert Schomburk at Berbice (Blake, 1905). Blake attributed such discoloration as proceeding from within the rock as a result of chemical changes, with some contribution from the influence of the atmosphere and of the sun's rays in the production of the film. The process was considered primarily endogenetic rather than exogenetic. The discoloration commonly observed was thus due to the formation of a thin coating of ferric oxides, such as magnetite, which is derived from the interior of the rock by osmotic flow—a kind of rock transpiration tending upwards and outward to supply the excessive evaporation under hot arid conditions. Performing chemical examination of the outer film, the composition was found to be iron sesquioxide; whereas, in some specimens manganese oxide predominated.

The explanations provided above were not viewed by Blake so easily explained in regards to the loose pebbles of the Colorado mesas. The varying degrees of hardness, composition, and mass were not consistent with the amount of coloring solution required to adequately produce the change. One explanation offered by Blake was the assumption that there was osmotic flow from the subjacent earth to the pebbles, and the solutions though small in volume and weak in composition are uniform in nature and eventually become concentrated at the exposed surfaces.

Evidence of volcanism and seismic activity

Blake directly observed evidence of volcanism in the lower Delta region of the Colorado and on the Sonora side of the head of the Gulf of California. He also observed numerous faults and fractures in Carrizo Creek which he associated with earthquakes, and speculated that a local earthquake may have modified the direction of the New River and the quantity of water admitted to its channel (Blake, 1854). In addition, during his second visit to the area in 1906, Blake was aware of an earthquake which occurred in the Imperial region of the Delta at the time of the earthquake of 1906 in San Francisco. He suggested the probable continuation of a fault plane (now commonly known as the San Andreas Fault Zone) passing along the great interior valley of California and southward through the valley of the Gulf (Blake, 1914). Blake did map evidence of faulting in the Carrizo Creek area, and it seems that large regional-scale faulting may have been suspected.

Artesian wells, springs, wells, and streams

The condition of most wells observed by Blake was abominable. These wells were described as very shallow (i.e., less than 18 feet in depth), unlined, and muddy. An inventory of all known and observed wells was produced and, despite their condition, there was no interval over 25 miles without available water. Blake recommended that such wells be improved and others dug at convenient distances. He concluded that a persistent water supply may be obtained and relied upon by wells. This conclusion was based on the presence of a deep clay which occurs primarily below the elevation of the Colorado River, and at times is replenished and the land irrigated by overflow of the Colorado River via the New River. The deep clay is very retentive of water with evaporation from its surface slow. Thickly wooded mesquite and other plants located at the lower level or terrace bordering the Colorado and extending far inland showed the presence of water at shallow depths. In addition, water being found at various locations throughout the desert area at about the same level suggested that the supply is derived in part from the New River via infiltration.

Blake also believed that because of the presence and apparent lateral continuity of the clay and the apparent rise of water at springs situated in the lower and central portions of the desert, an artesian condition was most likely present. The presence of artesian conditions would undoubtedly be invaluable for irrigation purposes.

Agricultural considerations

Blake in 1853 considered the upper gravelly plains of the desert in the vicinity of the mouth of the Gila as too arid and sandy to be useful for agricultural purposes (Figures


Figures 14a and 14b. Impact of water availability of soil conditions along the southern perimeter of the Salton Sea (Photograph by author).

14 a and 14b). However, most of the desert area was immediately underlain by alluvial and lacustrine clay and, with irrigation, would be very suitable for agricultural development. The soil was considered by analysis to be very rich and adaptable to a variety of crops, and only limited by the need for an adequate water supply and climatic concerns. Irrigation was, however, postulated during seasons of high water and overflows of the Colorado, deepening of the channel of the New River or cutting another channel. Blake also postulated the refilling of the dry ancient lake.

Economic consideration

Blake also evaluated during his travels the occurrence and distribution of natural resources for construction and use of the potential railway and for regional development. Granite and limestone were found in sufficient quantities. Also of notable interest was the dry lake-bed of salt situated in the lowest part of the northern portion of the Colorado Desert area, which had the potential of being worked. These deposits were ultimately worked for many years by the East Liverpool Salt Company until destroyed by overflow from the Colorado River in the early 1900's (Blake, 1908).

Engineering accomplishments

The Williamson party ascertained the correct Walker's Pass, previously thought to be the gateway into California, and confirmed the correct locations of the Mojave River and the Old Spanish Trail through the desert. The party concluded that Walker's Pass was not feasible for a railroad. However, the party as a whole did determine that not one but several practicable routes existed. Two passes were eventually determined to be practical: the Tehachapi Pass and the Canada de las Uvas or Grapevine, the former ultimately being selected. The San Gorgonio Pass was recommended as the best route to connect the east to Los Angeles. The party also concluded that there was no suitable route to San Diego from the east, but confirmed the potential of a route from Los Angeles to San Francisco, west of the coast ranges.

Summary

Blake was a renaissance man, characteristic of many educated men of his times, and was a significant geologic figure during the latter half of the 19th Century (Figures 15a and 15b). He was a scholar and a man of action, well-read, and very familiar with the geologic literature of his time. He was a keen observer, and consistently and successfully combined local detail with regional interpretation and global analogies. He was careful to include only those details he personally observed, thus what gaps, omissions, or generalizations are made should be understandable from a brief reconnaissance of this nature. In the course of his involvement with the Williamson expedition, Blake spent less than a month in the area under conditions of hardship and deprivation. The daily responsibilities required of the expedition did not allow extended observations or excursions of any great distance on either side of the route explored. In this short time, however, Blake most importantly demonstrated that this region, as well as California, had more potential and was more valuable than anyone previously imagined. As of 1909, "*50 years later, Blake's report remained the most complete and graphic scientific account of the physical features of this area*" (Mendenhall, 1909).

A summary of Blake's contributions to our knowledge and understanding of this region includes:

- Described the physical aspects of the desert and explained in a clear manner and to a satisfactory degree the geological phenomena that existed in the region and its origin;
- Discovered the San Gorgonio Pass which provided an all-weather southern route, and had vast implications for the opening of Arizona and the southwest;
- Described the general cause for the persistent winds in the area;
- Described the effects of wind erosion, discoloration, differential weathering, and the origin of pebble-covered plains in the area;
- Discovered ancient Lake Cahuilla and observed and recorded the old water line along its western border;

Figures 15a and 15b. Views of Blake in his office while at the University of Arizona in Tucson.

Figure 16. Nondescript historical marker overlooking the ancient shoreline (Photograph by the author).

- Mentioned springs which he visited and of which he could obtain and provide reliable information;
- Predicted that the presence of artesian water would eventually be found beneath the surface of the desert. Such prediction was fulfilled 35 years later, although the water was found within Pleistocene alluvium instead of the consolidated Tertiary rocks as he inferred;
- Suggested the probable existence of a fault-plane extending from San Francisco to the Gulf of California. This fault system was later recognized as the San Andreas Fault System;
- Produced maps which provided the basis for further travels and studies; and
- Indicated that not one but several extremely practicable railroad routes existed.

In 1906, as he stood on top of Travertine Rock along the west side of the Salton Sea, Blake—then 76 years of age—would remark:

> *The old water lines and beaches were comparatively unchanged in appearance. Concentric lines of sparse vegetation marked where the water has stood centuries before. Looking out from the summit across the Salton Sea, it was difficult to realize that the old traveled trail across the desert lay 15 fathoms deep under water, where before not a drop could be found.* (Blake, 1906)

In a letter dated January 14, 1854, immediately following completion of the Williamson Survey and having arrived in San Francisco on Christmas Day in 1853, Blake informed Spencer Baird of the Smithsonian that he "*discovered that the desert or a great part of it was formerly the bed of an immense fresh water lake - now dry --.*" Blake obviously thought that this single fact was the most important discovery resulting from his survey throughout California.

In a recent visit in the footsteps of Blake through the Colorado Desert region, my wife Lydia and I came across a monument just south of Travertine Rock and overlooking the ancient shoreline to the west (Figure 16). The plate to the historical marker was apparently removed or vandalized some years ago. This is unfortunate for I do not know what words were expressed on the marker, but it was clear to me that this discovery and event was important enough to have been noted at this place.

Mendenhall (1909) proposed that the ancient body of water discovered by Blake, now occupied by the Salton Sea, be called "*Blake's Sea*." Blake himself, however, proposed the name Lake Cahuilla from the name of the valley and the Indian tribe that occupied it, which name remains today. As stated by Mendenhall "*I realize that no other man has an equal right to name the now vanished water body, that the name is especially appropriate, and that it now has priority . . .*"

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The Great Steamboat Race from Yuma to the Grand Canyon

Paul F. Smith, *29 Palms Inn, 7773950 Inn Avenue, Twentynine Palms, CA 92277*

Preparations for the race

In 1857 the United States was trying to understand the great American West—what it contained, who lived there, how to open up better routes of travel by railroads, and what obstacles existed to improved commerce between east and west. One of the great mysteries was the unpredictable Colorado River.

So, the War Department commissioned Lieutenant J. C. Ives of the Topographical Engineers to put together an expedition to solve the mystery of the river. A key part of the journey was to go by steamboat up the river as far as practicable. Ives' official report describes some of the difficulties he encountered and solved.

At this time there were commercial boats making their way up from the Gulf of California but they were only going as far as Yuma. Ives was working for the government and did not have much capital to obtain a boat, but he did the best he could.

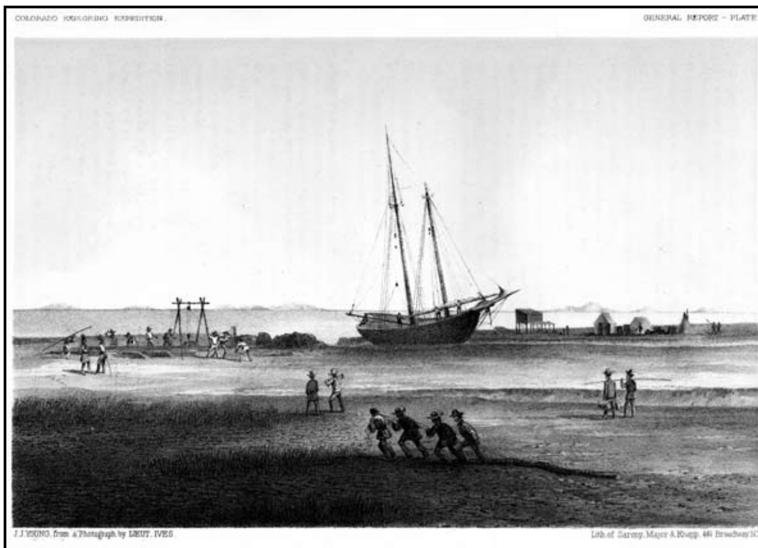
> *A boat of suitable construction had, therefore, to be built on the Atlantic coast and transported to San Francisco, and thence to the mouth of the river. In order that the survey should be made at the worst and lowest stage of the water, I had been directed to commence operations at the mouth of the Colorado on the 1st of December (1857). This left little time for preparation, considering that it was necessary to build a steamer and carry the parts to so great a distance.*
>
> *In the latter part of June I ordered of Reaney, Neafie & Co., of Philadelphia, an iron steamer, fifty feet long, to be built in sections, and the parts arranged that they could be transported by railroad, as the shortness of tie required that it should be sent to California, via the Isthmus of Panama. About the middle of August the boat was finished, tried upon the Delaware, and found satisfactory, subject to a few alterations only. It was then taken apart, sent to New York, and shipped on board of the California steamer which sailed on the 20th of August for Aspinwall. Mr. A. J. Carroll, of Philadelphia, who had engaged to accompany the expedition as steamboat engineer, went out in charge of the boat."*

Their arrival in San Francisco was not the end of the adventure. Ives and Carroll loaded the structural components of the steamboat on the schooner Monterey and sailed to the Gulf of California. For the next thirty days they sailed up the gulf, encountering strong gales, heavy billowing ocean swells, and the "desolate grandeur" of the Baja desert shoreline.

On November 30, 1857, the party reached Montague Island where they could see Robinson's Landing dead ahead, the usual anchorage for vessels reaching the mouth of the Gulf of California. It was at Robinson's Landing that they heard one of the early California gold treasure stories.

> *There is a tradition that, a few miles up the river, a large amount of gold was sunk in a vessel belonging to the ill-fated party of the Count Rousset de Boulbon. After an unsuccessful attempt to revolutionize Sonora, the count tried to escape by way of the Colorado; but, mistaking the channel, got into what is called Hardy's, or the false Colorado, where the vessel was lost, and most of the individuals on board killed by the Indians. The hope of recovering the lost treasure has, it is said, influence Mr. Robinson in the selection of the singular locality he has chosen for his residence.*

The men were now at the gateway of the great California desert and they prepared to reconstruct their steamboat, known as the *Explorer*. Other members of the expedition sailed from San Francisco to San Diego. There they loaded supplies on mules and traveled over the southern Colorado Desert to Yuma where they would meet the *Explorer*. A



ROBINSON'S LANDING, MOUTH OF COLORADO RIVER.

COCOPAS.

third contingent landed in San Pedro and went north to Fort Tejon where they gathered various animals and took them to Yuma.

The United States had a small commercial and military presence at Yuma to handle a growing traffic across the Colorado Desert. But conditions to the north of Yuma still remained somewhat of a mystery to the Topographical Engineers. The navigability of the river was uncertain. The possibility of sudden flooding was present; and so was the reverse, with the chance that the water level of the river could decline and leave them stranded in a little known country. And the possibility of hostile Indians was always present.

By the morning of December 30, 1857, the *Explorer* had been outfitted with additional timbers to strengthen its hull and was ready for the trip up the river to Yuma and then beyond. The Ives' report describes the situation.

> *This morning the 'Explorer' underwent a critical inspection. She is fifty-four feet long from the extremity of the bow to the outer rim of the stern wheel. Amidships, the hull is left open, like a skiff, the boiler occupying a third of the open space. At the bow is a little deck, on which stands the armament—a four-pound howitzer. In front of the wheel another deck, large enough to accommodate the pilot and a few of the surveying party, forms the roof of a cabin eight feet by seven.*
>
> *. . . . The night promises to be perfectly quiet, or we would not be able to start with our present load. The proper time for a steamboat to leave is two or three hours before the ebb. This evening the tide is coming in with great force and rapidity. At low water the surface was one or two feet below the low-water mark of the last full moon tide, which portends a corresponding increase of elevation at high water.*
>
> *Our task has not been completed a day too soon, for there is every indication that by 3 o'clock to-morrow morning the country will be entirely submerged. Before that time, however, we trust to have bidden a final farewell to Robinson's Landing and the mouth of the Colorado.*

On their way up the Colorado they encountered another boat coming down which warned them that the condition of the river below Yuma was the worst that they had ever seen. It was suggested that they leave a portion of their cargo with some friendly Indians further up the river so that they would not be overloaded when they ran into troublesome waters. This later stop with the friendly Cocopa Indians gave Ives the opportunity to record a cultural snapshot of these native inhabitants.

> *We found a large party of Cocopas—men, women, and children—waiting on the bank, with grinning faces, for the arrival of the 'chiquito steamboat,' as they call our diminutive vessel. They have been thronging about the camp fires all the evening, chattering, laughing, begging, and keeping a sharp lookout for chances to appropriate any small articles. I had no hesitation, however, in leaving the packages of provisions and stores taken from the skiffs piled in a conspicuous place near the edge of the bank . . . One of the Cocopas seemed to apprehend that my mind might be ill at ease in regard to the safety of the property, and disinterestedly offered to remain and watch it . . . . I gave him a piece of cotton, of which he was much in need. A few are provided with blankets, but nearly all, males and females, are on a scanty allowance of clothing. The women generally have modest manners, and many are good looking. They have a custom of plastering their hair and scalps with the soft blue clay from the river bank, the effect of which is not at all pretty, but the clay is said to be a thorough exterminator of vermin, and as such must give them a great deal of comfort."*

They continued up the river. The water shifted in depth and it was necessary to pole themselves forward in certain areas. They obtained fuel for the steamboat boiler wherever it grew naturally. "There is plenty of excellent fuel all along the bank. The dead mesquite, willow, and cottonwood trees, instead of rotting become seasoned in the pure dry atmosphere. The mesquite has a particularly close, fine grained texture, and makes a hot fire."

A small contingent left the boat and went on by land. The *Explorer* would catch up with them in town. They finally arrive at Yuma on January 5, 1858, cold , exhausted, and ready for some rest and reorganizing.

> *Fort Yuma is build upon the west side of the river, on the top of a gravelly spur that extends*

Fig 1.—Yuma Shoals.

with a steep bluff to the edge of the stream. A corresponding precipice upon the opposite side forms, with the other, a gate through which the united waters of the Gila and Colorado flow in a comparatively narrow bed. The mouth of the Gila is just above. The southern emigrant route to California crosses the river at this place. For ten or fifteen miles north and south the valley is inhabited by the Yuma Indians, a few years ago the most powerful and warlike of the Colorado tribes. Opposite to the fort an anticipated town has been located and denominated Colorado City. At present there are but a few straggling buildings, the principal of which are a store, blacksmith's shop, and tavern.

Several days later the *Explorer* arrived in Yuma. It had been stopped by a broken rudder and the crew had to make a new one. They set to work preparing for the next leg of their expedition several days later.

The race

Enterprising traders had been using steamboats on the lower Colorado River since 1852 to move supplies to the military garrison at Fort Yuma. George A. Johnson was one of those traders and had been working on the river as a steamboat operator. In 1856 Johnson had traveled to Washington and obtained a government appropriation of $75,000 to investigate the river above Yuma. However, he did not obtain the financing immediately and in some mysterious lobbying maneuver the Army managed to steer the appropriation to Ives to fund his investigation. Johnson was determined to get even with Ives and be the first steamboat explorer north from Yuma. He got the jump on Ives and started up the Colorado River on December 20, 1857 on board his *General Jessup*. The great steamboat race was on.

Ives finally assembled the *Explorer* and was ready to start on January 11, 1858. Friends from the garrison as well as Indian men, women, and children were gathered to watch them get everything on board and get their steam up.

The men grinned, and the women and children shouted with laughter, which was responded to by a scream from the Explorer's whistle; and in the midst of the uproar the line was cast off, the engine put in motion, and, gliding away from the wharf, we soon passed through the gorge ahead abreast of the fort and emerged into the open valley above.

The river was shallow at this time of the year and the *Explorer* was only several hours into the trip before it ran into trouble on the Yuma shoals. It happened in full view of their well wishers on shore.

The channel became at each moment more difficult to find, and when we had made but two miles we were brought to a dead stop by a bar. An anchor was put out ahead; but the bed being quicksand, it would not hold. It was necessary to lighten the boat, and finally most of the men were overboard, and having thus further diminished the drought, succeeded, after four hours and a half of hard labor, in forcing the steamer in the deeper waters beyond the bar.

The delay would have been less annoying if it had occurred a little higher up. We were in plain sight of the fort, and knew that this sudden check to our progress was affording an evening of great entertainment to those in and out of the garrison.

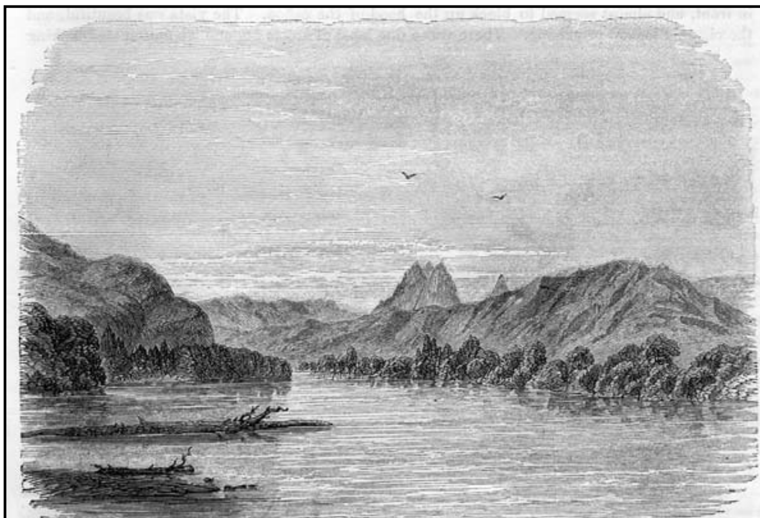
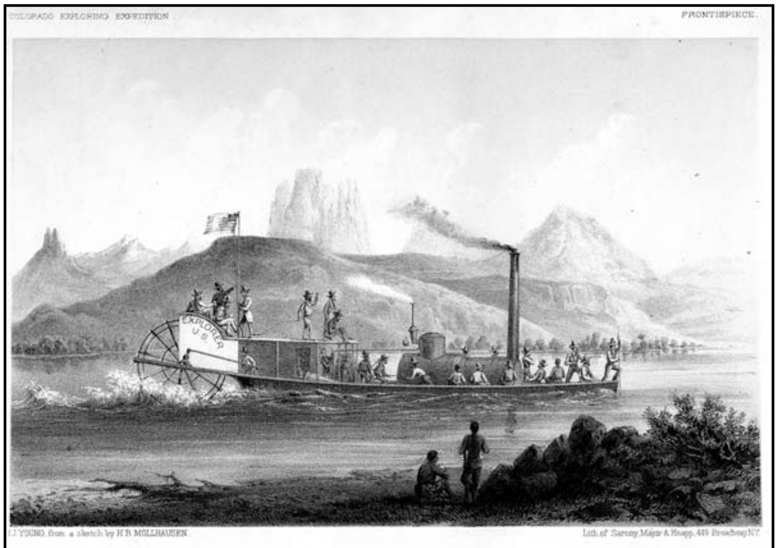


Fig. 2.—Explorer's Pass.



CHIMNEY PEAK

The next day (January 12, 1858) Ives' party was able to make another fifteen miles or so, passed some Indian huts with cattle and mules grazing, and reached a pass which they named after their steamboat, Explorer's Pass. They were still within easy land travel of the garrison, and a Yuma Indian arrived carrying mail which had arrived from San Diego. By January 15 they had traveled through rugged and colorful country with beautiful desert vistas and purple colored hills.

> *Just before reaching our present camp, which is little more than 20 miles from Explorer's Pass, a sudden turn brought Chimney Peak full in view. Its turretted pinnacles towered directly in front, and almost seemed to block up the head of the canyon . . . . In the rocks which comprise the Purple Hills, Dr. Newberry has discovered the presence of gold, iron, and lead. Veins of copper and argentiferous galena have been already worked, and with the prospects of successful returns.*

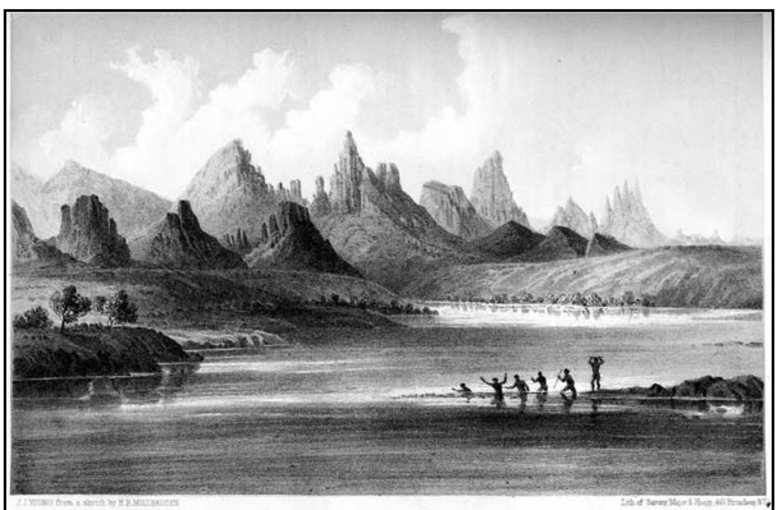
The General Jessup was nowhere in sight and probably had a commanding lead.

It would not be an easy trip for either party. They encountered shallow sand bars which grabbed on to their hulls and necessitated much maneuvering to get free. And they went up apparent easy channels to find that they were blocked by giant impassable rock formations which required them to retreat. And, although the currents of the river permitted navigation, they could be deadly strong on occasion—frequently by surprise.

We are fortunate to have the official report of the Ives expedition to experience in their own words what they encountered. For the most part, Ives' encounters with the Indians were friendly, although they had to be constantly vigilant to protect their expedition assets. On January 23, 1858 they set up camp, approximately 70 miles above Yuma.

> *A small party belonging to a tribe called the Chemehuevis came into camp this evening. They live in the valley we are now traversing, but are altogether different in appearance and character from the other Colorado Indians. They have small figures, and some of them delicate, nicely-cut features, with little of the Indian physiognomy. Unlike their neighbors—who, though warlike, are domestic, and seldom leave their own valleys—the Chemehuevis are a wandering race, and travel great distances on hunting and predatory excursions. They wear sandals and hunting shirts of buckskin, and carry tastefully-made quivers of the same material. They are notorious rogues, and have a peculiar cunning, elfish expression, which is a sufficient certificate of their rascality. One of them tried to cheat me while fulfilling a bargain for a deer-skin; but I detected him at it, and, in spite of his denial, proved the fraud on him. He was highly amused at being fairly caught, and it raised me very much in his estimation; if I had tried to cheat him, and had succeeded, his admiration would have been unlimited.*

For the next several weeks the Ives expedition continued to make good progress up the river. They passed the mouth of the Bill Williams Fork, the only tributary of any note between the Virgin and Gila rivers. Ives had accompanied the Whipple overland expedition which had reached this point the river in 1853. The Bill Williams was almost dry and they were surprised that they could not locate any remaining sign of the Whipple expedition. The Whipple expedition had been comprised of one hundred men, several hundred mules, and four wagons, but no indication



THE NEEDLES (MOJAVE RANGE)

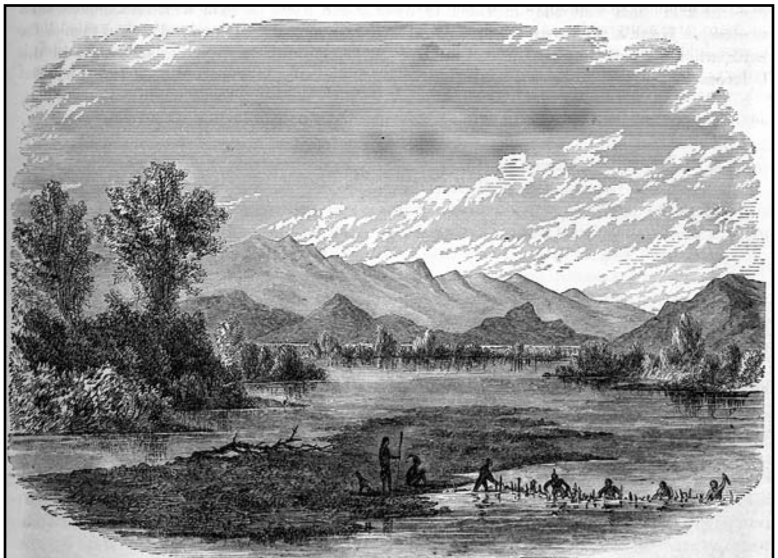


Fig. 21.—Cottonwood Valley.

remained that they had visited this spot.

In early February the Ives party had their first encounter with the Mojave Indians. Their reputation as skilled warriors had become well known ever since the second Jedediah Smith exploration in 1828 when Smith barely escaped with his life.

> *As Captain Robinson and myself were walking out this evening we suddenly came upon two Indians reclining on the top of the bank, in sight of the steamer. I at once knew them to be Mojaves. One of them must have been nearly six feet and a half in height, and his proportions were herculean. He was entirely naked, excepting the ordinary piece of cotton about his loins, and his chest and limbs were enormously developed. A more scowling, sinister looking face than that which surmounted this noble frame I have seldom seen; and I quite agreed with a remark of the captain, that he would be an unpleasant customer to encounter alone and unarmed. His companion was smaller, though a large man, and had a pleasant face. Neither took the slightest notice of us, but both continued looking at the steamboat, the taller man with an expression that indicated a most unamiable frame of mind. Doubtless they were sent down from the valley above to learn something in regard to our party. I am sure that the report of one of the two will be anything but complimentary to the steamboat and ourselves. I can scarcely blame him for his disgust, for he must suspect that this is the first step towards an encroachment upon the territory of his tribe.*

After passage through the rest of Chemehuevi territory, the Ives party entered Mojave Valley on February 10, 1858. As they did throughout the trip, careful note was made of the physical and natural features of the landscape through which they passed. They met with Chief Jose and at least three other chiefs of the Mojaves and visited and traded with the men, women and children of the tribe.

They continued on, having seen no sign of Johnson's *General Jessup*. Of course they knew that Johnson had a considerable lead on them and must have been guessing that there was still a considerable length of navigable waters ahead of them.

Johnson enjoyed a head start and ultimately piloted his

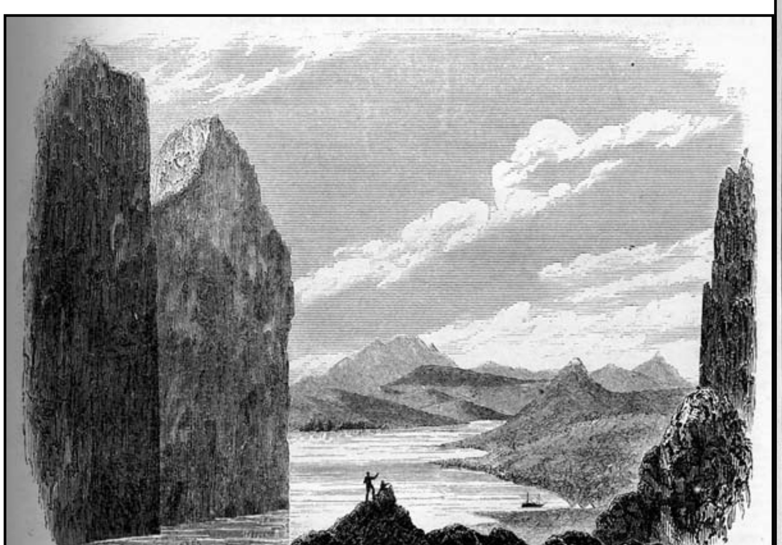
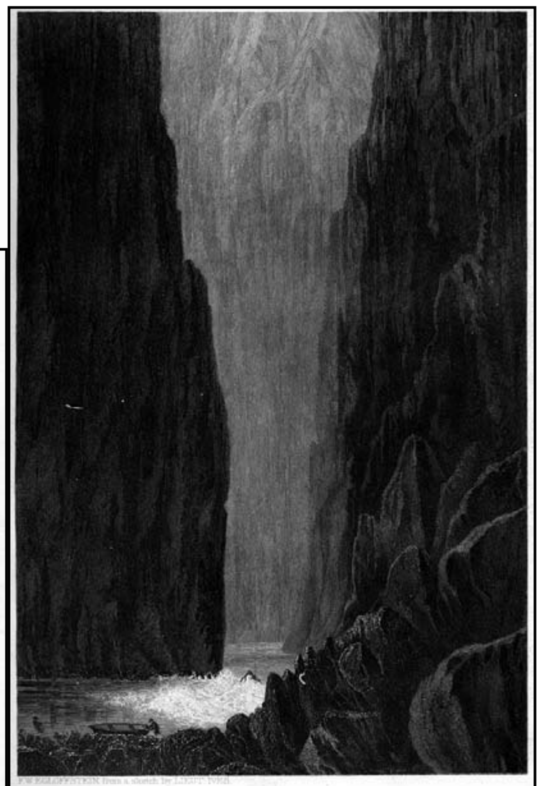


Fig. 25 —Mouth of Black Cañon.



BLACK CAÑON.

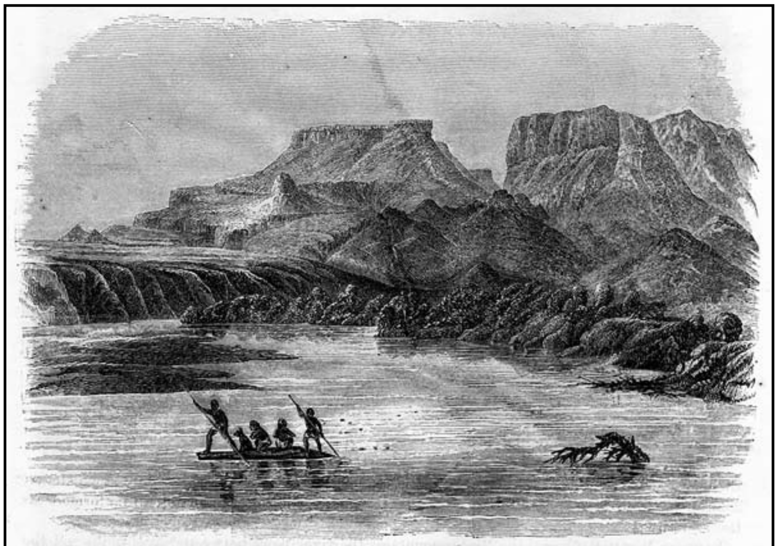


Fig. 24.—Gravel Bluffs south of Black Mountains.

boat as far as the mouth of El Dorado Canyon, approximately 350 miles north of Yuma. Ives never caught him and they undoubtedly passed each other as Ives chugged up the river while Johnson was coming down the river to return to Yuma.

On February 24, 1858 Lt. Ives reached the foot of Cottonwood Valley and began the dangerous portion of the journey to the mouth of Black Canyon. On March 8 they reached the mouth of Black Canyon. By now they had passed the farthest point where the *General Jessup* had traveled and so, despite losing that race, had the satisfaction of knowing that they had made the longest distance. During this leg of the journey, one the Mojave Indians, Ireteba, kept warning Lt. Ives of dangers ahead, both from the river itself as well as from the Paiute Indians.

> *Ireteba . . . , while admitting that we may reach the mouth of Black Canyon, still maintains that we can never get the steamboat through it. Since leaving the Cottonwood Valley he has appeared uneasy, and has given me constant warnings to exercise precaution, for that 'the bad Pai-utes' are prowling about. He says that great numbers of them live near the Mormon road from which we are not far distant; that there are many white men among them, and that some Pai-utes who lately visited the Mojaves told them that they intended to destroy our party as soon as it should enter their territory. He thinks that we are too few in number, and looks dubiously at us and then at the bank, when we come to places where the river is narrow and the formation of the gravel hills is favorable for an ambuscade.*

But then it happened!

> *A rapid, a hundred yards below the mouth of the canyon, created a short detention, and a strong head of steam was put on to make the ascent. After passing the crest the current became slack, the soundings were unusually favorable, and we were shooting swiftly past the entrance, eagerly gazing into the mysterious depths beyond, when the Explorer, with a stunning crash, brought up abruptly and instantaneously against a sunken rock. For a second the impression was that the canyon had fallen in. The concussion was so violent that the men near the bow were thrown overboard; the doctor, Mr. Mollhausen, and myself, having been seated in front of the upper deck, were precipitated head foremost into the bottom of the boat; the fireman, who was pitching a log into the fire, went half-way in with it; the boiler was thrown out of place; the steam pipe doubled up; the wheel-house torn away; and it was expected that the boat would fill and sink instantly by all, but Mr. Carroll, who was looking for an explosion from the injured steam pipes.*

By some miracle the *Explorer* did not sink. Ives and his crew decided that this was as far as the steamboat could safely travel, particularly at this time of year when the water level was at its lowest. So they put the carpenter to work and in several days had a small skiff ready so that they could ascend the canyon in safety for their final exploration. For the next two days they traveled in the skiff and made about thirty miles up the lower reaches of the Grand Canyon before halting. Their exploration was completed and they headed back down river.

On their return trip they were visited by a Mormon who asked many questions but supplied few answers as to who he was and why he was there. Within the next several days they encountered more Mojave Indians—but, this time they showed signs of hostility.

> *Two Yumas, who had acted as guides, had a talk with the Mojaves, and told Mr. Tipton that the*

YUMAS

Mormons had been endeavoring in every way to excite the hostility of the last-mentioned Indians against the expedition, and had urged them to commence an attack by stampeding the animals.

Mormons had indeed been trying to incite an incident but their efforts failed when Ives had discussions directly with the Mojave leaders and avoided any confrontation. These same Mojaves were not without experience in dealing with Euroamericans and had recently concluded the Olive Oatman incident. In 1851 the Yavapais Indians had attacked a small party of immigrants and killed six members of the Oatman family. They kidnaped a young girl named Olive Oatman and her sister (who later died) and traded both of them to the Mojave Indians. In 1856 the Mojaves had reluctantly returned the tattooed teenage Olive Oatman to the soldiers at Fort Yuma.

This writer is not aware of any written diary of George Johnson's first steamboat trip above Yuma. He was in it to further his business career on the Colorado River, not to make grand and detailed reports. However, Lt. Ives left a detailed diary with maps and drawings as part of his official report to the Secretary of War, Officer in Charge of the Office of Explorations and Surveys. It is from Ives that we learn what it was like to personally experience such an adventure with its day-to-day hardships and joys, encounters with the various Indian tribes along the Colorado, and the geography, botany, biology, and geology of the region.

It is hard to declare a winner of the great steamboat race. The *General Jessup* certainly came in first on the return to Yuma. But the *Explorer* went farther, having penetrated into the Grand Canyon, and returned with substantial recorded information about the country which would be shared with others. Both expeditions proved that steamboat travel was feasible for hundreds of miles above Yuma, even when the river was at its lowest ebb.

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Introduction to the Salton Trough Rift

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The Salton Trough rift, manifested geomorphically as the Imperial Valley in southern California and the Mexicali Valley in northern Baja California (Figure 1), possesses an abundance of natural resources. These valleys are major areas for agriculture, game fish, and waterfowl migration and management. Major nonrenewable resources include metallic minerals (primarily gold) and industrial minerals (primarily gypsum and aggregate). Finally, two of the world's largest liquid-dominated geothermal energy fields are located in the rift: the Salton Sea field in California and the Cerro Prieto field in Mexico. The rift is therefore of major economic importance to the population of southwestern North America.

Viewed in the simplest way the Salton Trough consists of an active continental rift, underlain by a fragmented oceanic ridge spreading system, into which has been deposited the delta of the Colorado River. Deposition of the delta has significantly influenced the character of economic mineralization in the rift. The combination of magmatic heat sources, thick porous sediments, tectonic activity, and saline lakes has provided a unique environment for the accumulation and movement of metalliferous hydrothermal brines. Before considering these aspects, a summary of the tectonic evolution of the Gulf of California and Salton Trough is presented.

Tectonic history of Gulf of California and Salton Trough

For this article, only a cursory review of the regional Tertiary geologic evolution is provided. I have drawn heavily on the more comprehensive reviews by Elders et al. (1972), Elders (1979), Fuis et al. (1982), and Lonsdale (1989).

The Salton Trough is located within a unique tectonic transition zone between the divergent tectonics of the East Pacific Rise (which dominate the Gulf of California) and the strike–slip tectonics of the San Andreas fault system (which dominate California) (Figure 2). Presently, Baja California and the portion of California west of the modern San Andreas fault system are part of the Pacific plate, moving northwest relative to the North American plate.

Before the end of the Miocene, the area corresponding to the Gulf of California largely consisted of an andesitic volcanic arc overlying the zone of subduction of the Farallon plate under the North American continent. Near the end of the Miocene, the spreading center separating the western Farallon plate from the eastern Pacific plate was obliquely subducted under the North American continent. This resulted in a complex series of tectonic changes that essentially "captured" Baja California and part of southern California, rafting them away from the North American plate (Lonsdale, 1989).

The Oligocene Mesquite deposits formed in dilatent shear zones associated with strike–slip faulting (Tosdal et al., 1991). Thus their genesis appears to be tied more to the pre-Gulf tectonic environment than the post-Miocene extensional regime.

The setting for formation of the modern Gulf of California and Salton Trough was set at about 12 Ma, when subduction ceased and an inland belt of east–west extension, alkali basalt volcanism, and subsidence and basin sedimentation was initiated. Marine evaporites in the Fish Creek

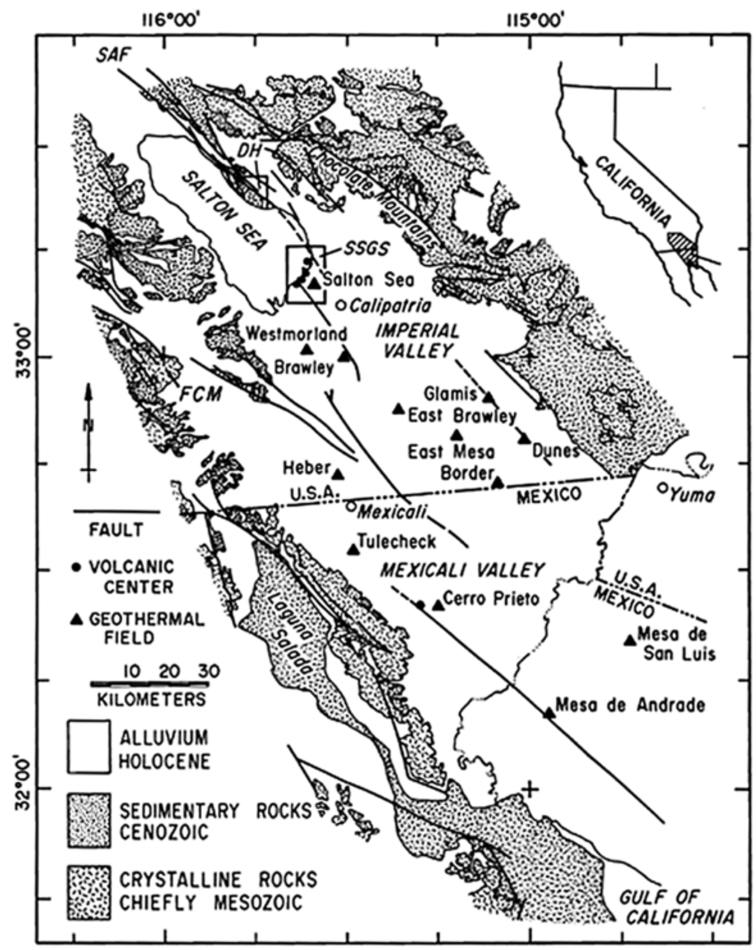

Figure 1. Map of the Salton Trough, showing features discussed in the text. SAF: San Andreas fault; SSGS: Salton Sea Geothermal System; FCM: Fish Creek Mountains; DH: Durmid Hills.

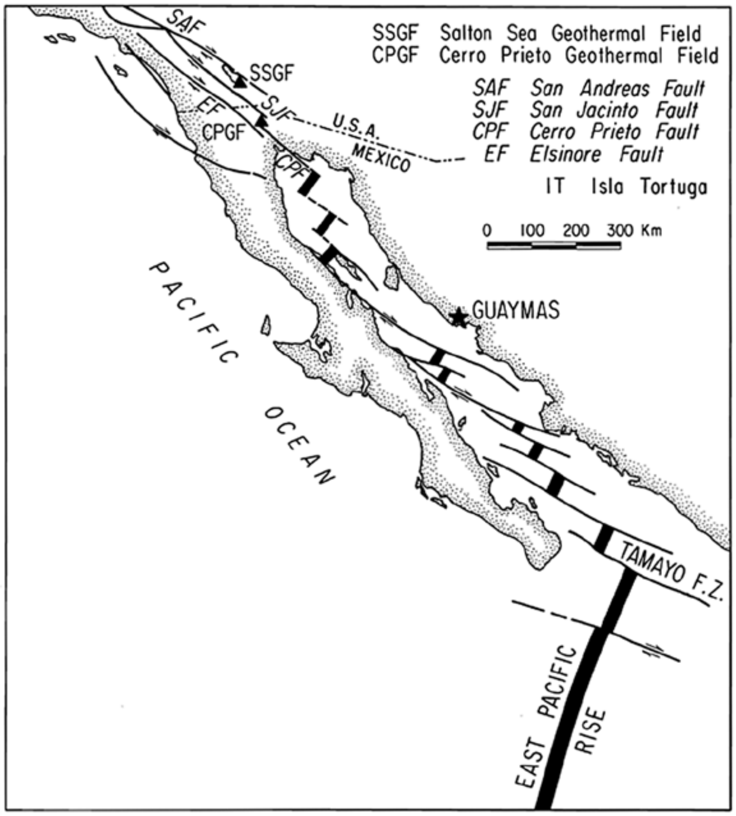

Figure 2. Map showing plate tectonic features of Southern and Baja California.

Mountains (Figure 1) and marine sediments in the Yuma Basin may have formed by early incursion of seawater into these proto-Gulf structures. The shear zone comprising the principal tectonic boundary between the Pacific and North American plates appears to have shifted about 250 km inland into this weakened belt by about 6 Ma, and the opening of the modern Gulf of California and Salton Trough began.

Because of the 10–20° angle between the shear zone and the relative motions of the Pacific and North American plates, the Gulf of California and Salton Trough are characterized by oblique rifting that is distinct from more typical styles of continental rifting (Lonsdale, 1989). The modern tectonics are therefore dominated by a series of en echelon transform faults connecting spreading center fragments (Figure 2).

It appears that the highest intensity modern hydrothermal systems tend to occur in sediment-filled pull-apart basins (rhombochasms) overlying these spreading center fragments (e.g., Salton Sea, Cerro Prieto, Guaymas Basin) (Figure 3). These systems exhibit high heat flow, strong gravity and magnetic anomalies, and often have surface manifestations such as Quaternary volcanoes and mud pots. The geothermal and base metal exploration significance of this type of tectonic control on past and present high temperature hydrother-

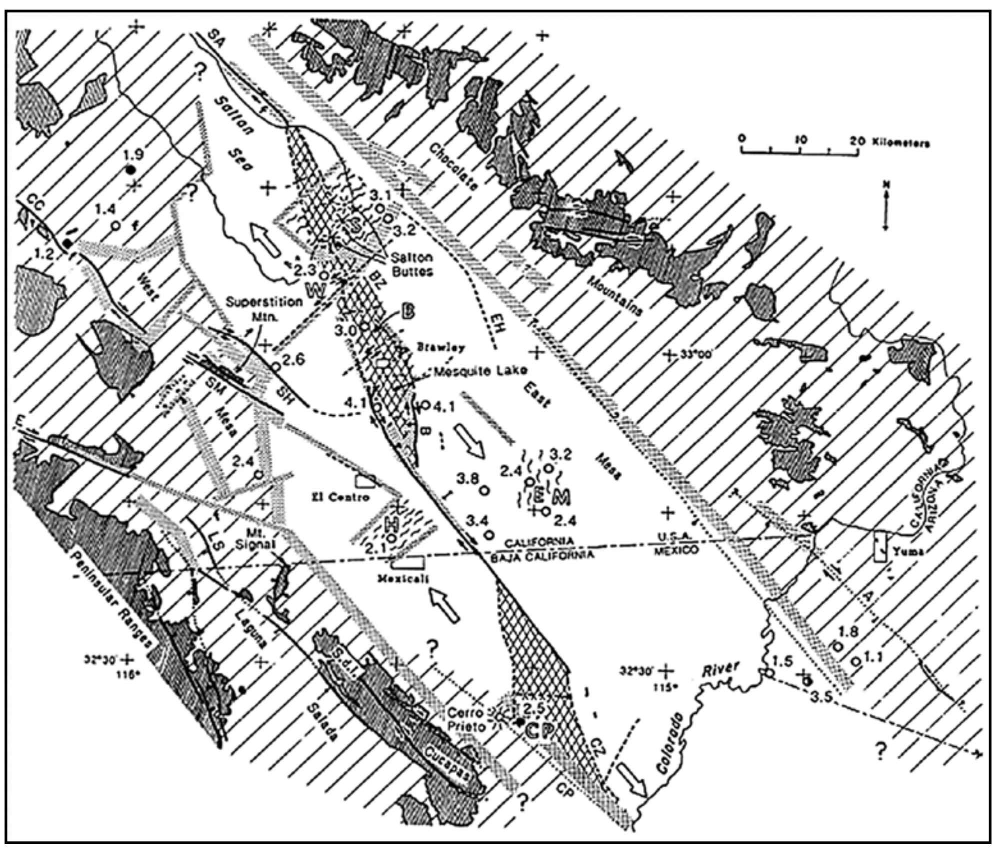

Figure 3. Structure and tectonic summary map of Salton Trough (Figure 6 from Fuis and Kohler, 1984). Circles denote wells with depths in km: open circles penetrated only Cenozoic sedimentary rocks, filled circles penetrated crystalline rocks. Outcrops of pre-Cenozoic crystalline basement are indicated by closely spaced lines; inferred extent of crystalline basement beneath Cenozoic sedimentary rocks is indicated by widely spaced lines. Zones with high (greater than 16 percent) gradient in depth to basement are indicated by stippled bands of different lengths. "f" refers to areas of Cenozoic folding and/or reverse faulting. Geothermal fields are indicated by block letters: S=Salton Sea, W=Westmorland, B=Brawley, H=Herber, EM=East Mesa, CP=Cierra Prieto. Seismic zones are crosshatched: BZ=Brawley seismic zone, CZ=Cerro Prieto seismic zone. Wavy lines indicate apparent basement shallowing under geothermal fields. Large open arrows indicate direction of spreading in Brawley and Cerro Prieto spreading centers.

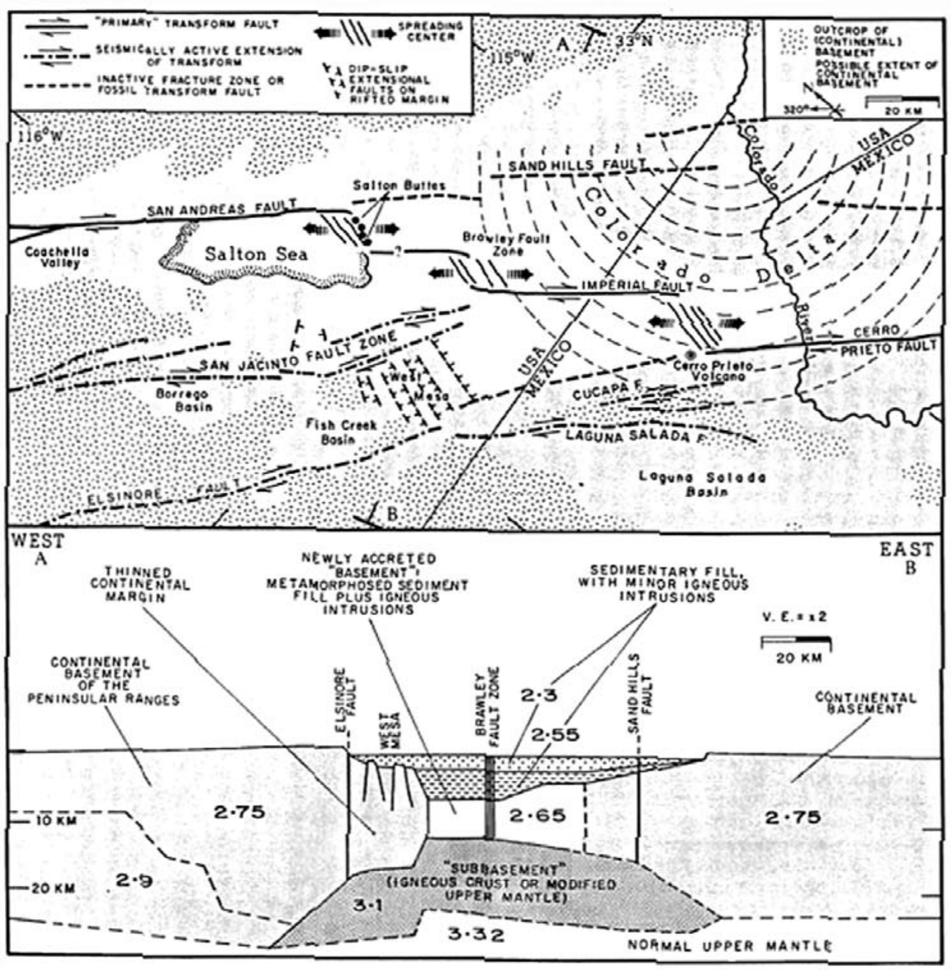

Figure 4. Sketch map and crustal section of the Salton Trough (Figure 6 from Lonsdale, 1989, modified from Fuis et al., 1982). Dashed boundaries in the section are controlled by gravity modeling only (not by refraction). Numbers are estimated densities (g/cm³).

mal systems in the Salton Trough and Gulf provinces should not be overlooked.

Lower intensity hydrothermal systems such as Dunes, Heber, and East Mesa (Figures 1 and 3), and their fossil analogs such as the Modoc Prospect (Hillemeyer et al., 1991), tend to occur along more rift-marginal normal and strike–slip faults, where shallow ground and lake waters are convectively heated above basement highs. In the case of Modoc, structural control along reactivated portions of an older rhombochasm may have been important. Typically these systems have little surface expression and only moderate geophysical signatures: they are essentially blind systems. Some of these systems are gold-bearing, and thus considerable exploration potential exists along the margins of the Salton Trough southward into Baja California.

Sedimentation in the Salton Trough

As the Salton Trough has opened, it has been filled with sediment derived from the delta of the Colorado River. The river has been building its delta from the east into the trough since about 5 Ma, and sedimentation has apparently kept pace with subsidence. Beginning about 4 Ma the delta had prograded southwestward (transaxially) across the Salton Trough (Figure 4), so that no marine sediments younger than this are found in the now hydrologically closed northern trough (Winker and Kidwell, 1986). Since then, waters of the Colorado River have alternately flowed north and south through time, resulting in the repeated generation and desiccation of freshwater lakes (collectively termed Lake Cahuilla) in the northern trough. This lacustrine evaporitic environment has dominated Pliocene and Quaternary sedimentation in the northern trough, resulting in the downward percolation and accumulation of saline formation brines ("rift basinal brines") which characterize the Salton Sea and Brawley geothermal systems (McKibben et al., 1988; Osborn et al., 1988). The hypersaline nature of these fluids exerts important physicochemical controls on the topology and heat budget of metalliferous hydrothermal brine reservoirs in these systems (Williams and McKibben, 1989).

Crustal spreading and accompanying subsidence continues in the central part of the Trough, where sediments accumulate at rates of 1-2 cm/yr. Along the margins of the trough, equivalents of these young sediments are being uplifted near strike–slip faults. For example, in the Durmid Hills east of the Salton Sea (Figure 1) (Babcock, 1974), movements along the San Andreas fault have exposed tightly folded but unmetamorphosed Pleistocene lacustrine evaporite sediments. These sediments are laterally equivalent to undeformed metasediments found at depths of 2 km in the Salton Sea geothermal field (Herzig et al., 1988), where they have been converted into greenschist and amphibolite facies hornfelses. This contrast in the deformation and metamorphism of stratigraphically equivalent sediments reflects the rapid and diverse tectonics of the rift.

Deep structure of the trough

In the central part of the northern trough, fluvial and lacustrine sediments have been penetrated by drilling to depths of at least 4 km. Seismic refraction measurements by Fuis et al. (1982) suggest that north of the present delta apex about 4 km of sediments overlie about 10 km

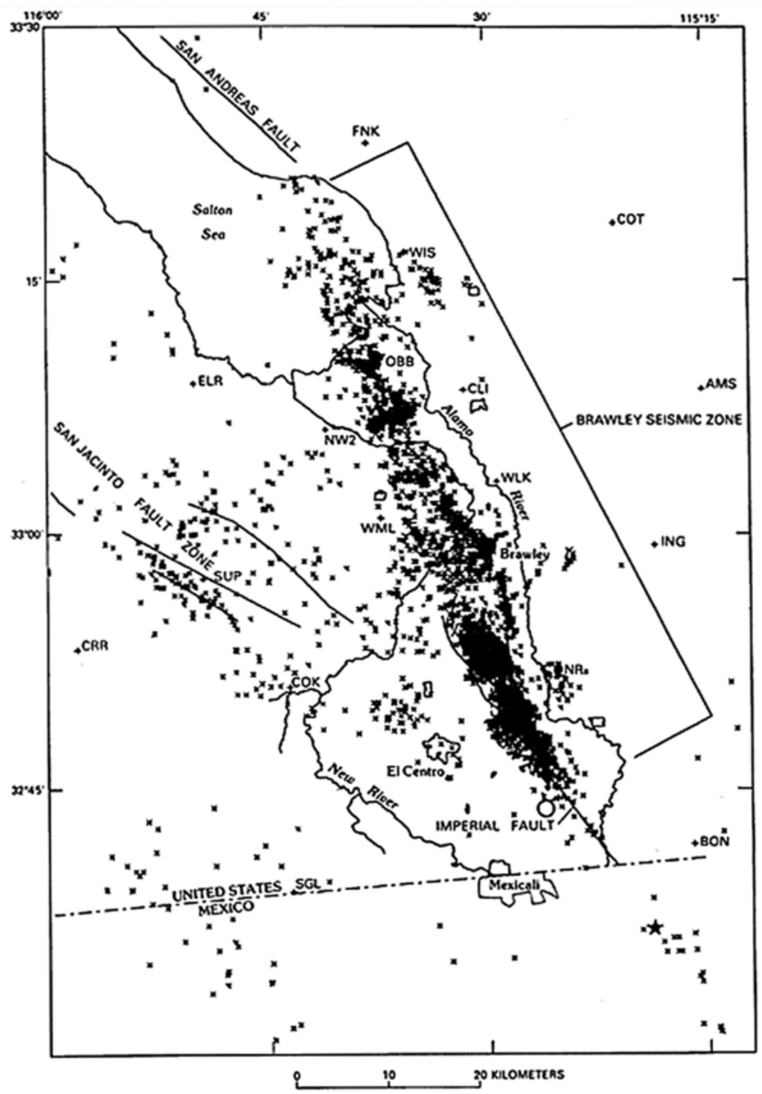

Figure 5. Seismicity of Imperial Valley from Johnson and Hill (1982, Figure 7). Shown are all epicenters with relative horizontal location errors less than 2.5 km (A– and B– quality solutions) for interval June 1973 through November 1978. Circle north of Mexicali marks instrumental epicenter of 1940 Imperial Valley earthquake (M_L=7.1), dot at left edge of 1942 Superstition Mountain earthquake (M_L=6.5), and star in lower right corner of 1979 Imperial Valley earthquake. Letters refer to station localities in southern California seismic network.

of "basement" crustal rocks, which may consist of metamorphosed post-middle Miocene sediments (Figure 4). However, because of the densification of sediments caused by hydrothermal metamorphism, it may be difficult to seismically distinguish metasediments from mafic intrusions related to the crustal spreading. Dikes and sills of MORB-type basalt and diabase are encountered in several geothermal wells at depths of 2–4 km (Elders, 1979; Herzig and Elders, 1988). Beneath the 14–15 km of sediments occurs a high-velocity "subbasement" layer, at least 10 km thick, which may consist either of a largely gabbroic igneous crustal layer (Fuis et al., 1982) or altered upper mantle (Nicolas, 1985).

Quaternary rhyolitic domes near the Salton Sea contain xenoliths of granitic rocks, but recent Sr isotopic data and U-Pb age dates on zircons indicate that these are cognate xenoliths having ages less than 100,000 years (Herzig and Jacobs, 1991). Thus, there is no evidence for significant amounts of granitic continental crust underlying the central part of the Salton Trough.

Seismic activity

Five major earthquakes have occurred in the Salton Trough in the 20th century (Ellsworth, 1990). The Cerro Prieto fault ruptured in November of 1915 (magnitude 7.1), resulting in a steam eruption at Volcano Lake near the fault's northern terminus. The fault moved again in December of 1934 (magnitude 7.0). In May of 1940 the Imperial Valley earthquake (magnitude 7.1) generated a surface rupture at least 60 km long, showing a peak right-lateral strike–slip offset of 6 m at the U.S.-Mexico border. This event resulted in the discovery of the Imperial fault (Figure 4). In October of 1979 the northern part of this fault moved again (magnitude 6.5), resulting in 30 km of surface rupture and 1 m of strike–slip offset. More recently, the Superstition Hills fault moved in November of 1987 (magnitude 6.6), resulting in rupture along its entire length and offset along numerous conjugate faults at its northern terminus. Interestingly, there was no reported interruption of geothermal power production during the 1987 event.

Seismicity patterns in the Salton Trough (Figure 5) support the concept that the Salton Sea, Brawley, and Cerro Prieto high-intensity hydrothermal systems overlie discrete spreading center fragments having shallow igneous activity. A distinct pattern of shallow («7 km) microearthquake swarms, likely caused by dike intrusions, can be distinguished from deeper shocks related to regional strike–slip motions (Hill et al., 1990).

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Geothermal structures southeast of the Salton Sea*

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Abstract. We report the results of a survey of geothermal features (mud pots, mud volcanoes) in the Brawley Seismic Zone (BSZ) in and adjacent to the southeastern Salton Sea. Hundreds of features were located, photographed and described. Many were found to cluster along the postulated Sand Hills fault (Wister fault), an area that is historically aseismic. An extrapolation of the trace of the San Andreas Fault southeastward from its accepted terminus north of Bombay Beach very nearly coincides with the mud pot lineament and may represent a surface manifestation of the San Andreas Fault. Other mud pots were are? arranged along several other NW trending faults, notably the Red Hill and Calipatria faults. Together the faults appear to form an en echelon structure.

Introduction

Mud pots and mud volcanoes are geothermal features produced when water and/or gas is forced upward through soil and sediments (e.g. Guliev 2007). They are usually associated with volcanic and seismic activity and thus reveal activity at plate boundaries and hot spots (Martinelli and Panahi 2005). The most common gases are H_2O and CO_2 although significant amounts of H_2S, CH_4, C_2H_{10}, and NH_3 may also be present, as well as other noble gases such as He, Ar, Rn, Ne and Kr.

Mud pots can assume a variety of morphologies, typically being depressions or enclosed basins containing gas seeps, bubbling water, or viscous mud (Figures 1, 3, 4 & 5). They can also be water-laden and appear as bubbling muddy water. Mud volcanoes are elevated conical structures composed of accumulations of viscous mud extruded from a central vent. According to Milkov (2003), "mud volcanoes often occur at the surface and the seafloor as a result of migration of fluidized sediment along active faults due to overpressure, and may also form on top of seafloor-piercing shale diapirs." Mud volcanoes can range from finger-sized to several km across and the eruption of some may be associated with earthquake activity (Mellors et al. 2007). Small mud volcanoes on land (1–3 meter tall) are usually called mud cones or gryphons.

In the Salton Trough, a relatively shallow magma body results in high heat flow in the area, hydrothermal alteration of near-surface sediments (Sturz 1989), as well as a number of active geothermal features including mud pots, mud volcanoes, and gas vents (Sturz et al. 1997; Svensen et al. 2007). Wells in the area were formerly a commercial source of CO2 that was used to manufacture dry ice. For a good historical review of mud volcanoes in the Salton Trough and Colorado River delta region see Strand (1981).

Methods and results

We first searched satellite imagery in the study area (Figure 2) and identified possible mud pots in the rectangle defined above. The survey was unbiased in the sense that we searched the area without regard for possible fault locations. Visibility of many pots was enhanced because

Figure 1. Large mud pot pool in the W10 field, Imperial County, CA. (See Table 1)

** Adapted from "The Wister Mud Pot Lineament: Southeastward Extension or Abandoned Strand of the San Andreas Fault?" BSSA (in press 2008)*

Figure 2. Known and inferred faults in the southern Salton Trough region. Most were taken from the qfauts database (http://earthquake.usgs.gov/regional/qfaults/). SA San Andreas, HS Hot Springs, CC Coyote Creek, ER Elmore Ranch, C Calipatria, RH Red Hill, W/SH/A Wister/Sand Hills/Algodones, SM Superstition Mountain, SH Superstition Hills, B Brawley, I Imperial, CP Cerro Prieto. LM is the fault inferred by Lohman and McGuire (2007) from the 2005 earthquake swarm.

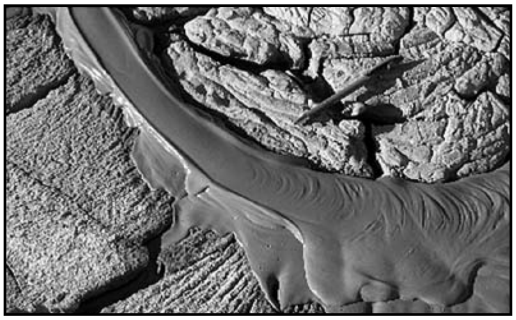
of earthen dams that were erected around them by the California Dept. of Fish and Game (CDF&G). With these sites in hand, we asked personnel of the CDF&G (Imperial Wildlife Area, Wister Unit) if they knew of any mud pots or related geothermal features in the area that we might visit. They kindly led us to about a dozen, some of which we had identified from the satellite imagery. Further *in situ* reconnoitering revealed many other mud pots (in? throughout?) the region (Table 1). We also surveyed vents in the Salton Sea between Mullet Island and the mainland. Several entries in Table 1 refer to clusters of pots, some with too many pots to count, e.g. W10, W27 and M9. Most features were ordinary mud pots and a few were small mud volcanoes or gas venting through shallow water. We visited each site and measured the pot's geographic position, photographed it, and characterized its structure.

Most of the mud pots in the Wister area had similar morphologies: they are composed of a circular depression that is usually shallower than the diameter of the pot, typically 1:2, probably representing the angle of repose for the poorly consolidated sediments of the Salton Trough. The walls of the pot often show collapsed material and incised rings indicating a changing water level. Such rings may be found as high as the lip of the pot, a probable sign of overflow by ground water. Many pots are circumscribed by partial or complete ring scarps that form as the pots grow and their walls begin to collapse inward. Some pots are wet and show recent activity, others appeared to be completely dry with significant collapse and aeolian debris suggesting little or no recent activity. It seems likely that dry pots continue to emit gas, their absence of moisture probably being due to a lack of ground water. Indeed, some dry pots are heard to "hiss."

We have broadly referred to many features as "mud pots" because of the bubbling mud—or evidence of it—but many of them have morphologies that are more similar to sinkholes (dolines) or collapse pits (Delle Rose, Federico, and Parise 2004). Sinkholes are basin-like, funnel-shaped, or vertical-sided depressions in the ground's surface that have formed with essentially

Figure 3. Typical large mud pot (W12 - see Table 1).

Figure 4. Mud volcanoes near the corner of Davis and Schrimpf roads, Imperial County, CA. (M9, See table 1)



no horizontal material transport. They are the result of subsidence (Abbass Fayad et al. 2003) and can occur by any of several mechanisms such as dissolution of rock or withdrawal of ground water. Like sinkholes, virtually all the mud pots in the study area are circular and most lack crater rims or obvious ejecta blankets. Even in the loosely consolidated sediments, many have steep sides and circumscribed ring scarps. This suggests recent formation or perhaps frequent renewal. Even if occasionally filled with sediments by flooding, the continuous emission of CO_2 from below would probably reform the structures. In all likelihood, the subsidence mechanism is local compaction as upwelling CO_2 is displaced by collapsing soil. This is similar to the "bathtub model" of sinkhole formation (Kochanov 1999).

The distinction between pots and volcanoes is not always clear, with some mud pots being slightly elevated shield-like structures overflowing with water or having a central pool in the caldera. There seems to be a continuum of features between pots and volcanoes and one may evolve into the other as water levels and gas supply change. Rains and flooding can also significantly alter the surface morphology of pots and volcanoes without affecting the subsurface forces that produce them. In their early

Table 1. Known mud pots, mud volcanoes and related geothermal features in the survey area

name	latitude	longitude	short description
W1	33 16.548	-115 35.633	4 large pots w/parking area (local attraction)
W1A	33 16.487	-115 35.661	2 large active pots, 2 small in active pots, trending N30W
W1B	33 16.598	-115 35.621	gully of ~10 pots trending N6W, younger to south and 1 large active pot
W1C	33 16.567	-115 35.604	2 small inactive mud volcanoes
W2	33 15.913	-115 34.789	(bubbles in water delivery ditch (new 2006)
W3	33 14.733	-115 33.379	3 large pots
W4	33 14.706	-115 33.228	small pot (private)
W5	33 14.911	-115 33.448	very large pot Spoony Rd.
W6	33 15.713	-115 34.424	2 large pots straddling road
W7	33 16.270	-115 35.238	small pot, little activity
W8	33 14.216	-115 33.366	large active pot
W9	33 17.117	-115 34.620	large active shield-like pot (private)
W10	33 17.295	-115 34.630	large area of active shield-like pots (private)
W11	33 17.580	-115 35.144	5 small pots, one of them outside fence
W12	33 17.355	-115 36.263	large active pot
W12E	33 17.356	-115 36.218	2 medium active pots
W13	33 17.030	-115 35.846	2 dry pots
W14	33 16.833	-115 35.827	1 dry pot
W15	33 16.851	-115 35.761	small gas vent and bubbles
W16	33 17.085	-115 36.050	small volcano
W16A	33 17.085	-115 35.864	small volcano
W17	33 17.013	-115 36.063	large pot (6' across) little activity
W18	33 17.218	-115 36.260	4 medium active pots, many small ones
W19	33 16.281	-115 35.386	wet spot with perimeter of vegetation
W20	33 13.804	-115 30.059	large shield pot in alfalfa field (private) Niland
W21	33 17.160	-115 36.245	New (1year?) bubbles in pond near W18 (inaccessible)
W22	33 17.118	-115 35.496	several bubbling vents in WDC
W23	33 17.165	-115 36.233	loud gurgling in brush (new) near W18
W24	33 14.684	-115 34.743	bulldozed ring in pond (inaccessible)
W25	33 16.623	-115 35.806	2 large dry pots
W26	33 16.608	-115 35.858	3 pots, main & SW attached pots wet.
W27	33 16.574	-115 35.881	very large field of wet & dry pots and volcanoes
W28	33 16.376	-115 35.271	1 large pot, wet but not active
W29	33 16.516	-115 35.568	1 large dry pot
W30	33 16.278	-115 35.315	wet semicircle of vegetation
W31	33 16.960	-115 36.062	1 6' pot, 1 1' pot , 2 small vents, all dry
M1	33 13.466	-115 36.376	3 bubble vents, east end of Mullet Island
M2	33 13.260	-115 36.204	5-10 bubble vents
M3	33 13.180	-115 36.114	several bubble vents
M4	33 13.121	-115 36.077	main vent, hot, steam, black mud, 1 acre
M5	33 13.134	-115 36.126	smaller vent, hot, steam, black mud
M6	33 12.732	-115 35.723	hundreds of bubble vents, ½ acre
M7	33 12.810	-115 35.596	several dozen bubble vents, H2S odor
M8	33 12.895	-115 35.616	another cluster
M9	33 12.048	-115 34.687	Large field of volcanoes and pots (well known)
R1	33 11.434	-115 35.120	~dozen bubbles in water with "mud pot" sign
R2	33 11.354	-115 35.104	~dozen bubbles in water with "mud pot" sign
R3	33 11.305	-115 35.188	bubbles (approximate location)
R4	33 11.294	-115 35.134	100 m long line of bubbles striking ~N12E

Prefix "W" refers t the Wister area.
Prefix "M" refers to vents SE of Mullet Island in the Salton Sea, except for M9, the well-known field of mud pots and volcanoes at the corner of Davis and Schrimpf roads.
Prefix "R" refers to mud pots SE of Red Island.
For completeness, mud pots and vents associated with the former CO_2 wells are listed in Appendix I

Figure 5. Violent expulsion of hot gas and water from major vent in the Salton Sea (M4 in Table 1). The surrounding pool is about three meters across.

To our knowledge, the existence of the Wister fault or Sand Hills fault has never been confirmed to exist at depth or by surface rupture (faulting), but their apparent correlation with the Wister Field mud pots may provide some evidence for such a structure. Because of the relative lack of seismicity, and hence the uncertainty about whether this is a deep structure, we shall refer to this alignment of geothermal features as the Wister Mud Pot Lineament (WMPL).

Summary and conclusions

The arrangement of geothermal features can sometimes be used as tracers of faults. The geothermal lineament in the Wister Unit of the Imperial Wildlife Area in Imperial County, CA (the so-called Wister Mud Pot Lineament—WMPL) defines the postulated Sand Hills fault (Wister fault, Algodones fault). Within the

stages, both may begin their lives as small wet spots on otherwise dry, unremarkable ground. As subsurface conditions change, the pots and volcanoes may grow inactive and eventually be erased by erosion.

Mud pots in the Wister Unit fall along a lineament about 16 kilometers long that strikes about N45W (Figure 6), a feature previously suggested by Meidav and Furgerson (1972, attributed by Schroeder 1976) that they called the Wister Fault (WF). The mud pot lineament was also noted by Muffler and White (1969) based on sixteen mud pots. The indicated WF (dotted line) would seem to be good linear fit to the pot locations. Except for three mud pots—two of whose structure is quite different from the others (W9, W10 & W11)—the mud pots define a lineament that we suppose to be a fault, possibly the previously-postulated WF, and arguably coincident with the Sand Hills/Algodones fault. Citing Muffler and White (1969), "These lines of hot springs probably mark upward leakage of hot water from faults at depth."

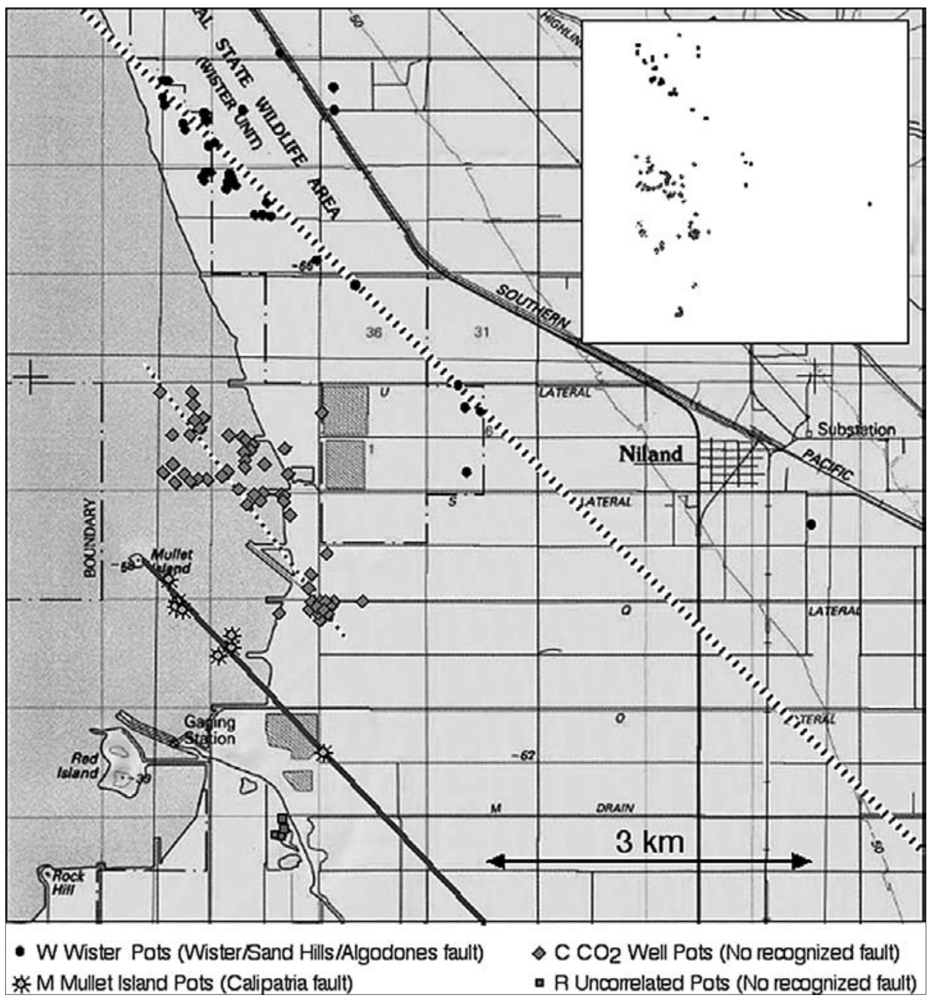


Figure 6. All known geothermal features in the area. The upper dotted line indicates mud pots and vents in the Wister Unit. Those along the lower solid line are associated with the Calipatria Fault that is presumed to pass through Mullet Island. In the middle are old CO_2 wells indicated on the USGS topographic map based on NAD83/WGS84. For reference, the inset (upper right) shows all the features in map projection without lines or base map. See Table 1 and Appendix I for the mud pot locations.

narrow uncertainties of its location, this fault lies along a southeastward extension of the San Andreas Fault and may be indicative of an inactive or abandoned strand of the fault.

Appendix I

Listed here are mud pots and vents associated with former CO_2 commercial production and identified on the UGS84 UTM topographic survey as "CO_2 well". Though not geothermal structures in themselves, the wells are indicative of significant CO_2 emissions and therefore are suggestive of geologic features. Most of the accessible pots are within a few hundred meters of the intersection of Davis Road and Pound Road (33° 13.214′ – 115° 34′.788′) where remains of the old CO_2 plant are found. There are many smaller pots and vents in the area that are not listed here.

In the table above, prefix C indicates that the pot locations were taken from identifiers on topographic maps. Prefix A indicates that the pot is clearly visible in modern aerial imagery. S indicates that the vent is in the Salton Sea or in the marshes immediately adjacent to the sea.

Table A-1

name	latitude		longitude		
C1	33	13.018	-115	34.752	
C2	33	13.053	-115	34.753	
C3	33	13.055	-115	34.682	S
C4	33	13.077	-115	35.151	
C5	33	13.085	-115	34.807	S
C6	33	13.099	-115	34.861	S
C7	33	13.110	-115	34.752	S
C8	33	13.115	-115	34.795	S
C9	33	13.132	-115	34.812	S
C10	33	13.132	-115	34.644	S
C11	33	13.147	-115	34.696	S
C12	33	13.160	-115	34.753	S
C13	33	13.160	-115	34.828	S
C14	33	13.166	-115	34.629	S
C15	33	13.174	-115	34.349	
C16	33	13.177	-115	34.807	S
C17	33	13.269	-115	34.854	S
C18	33	13.383	-115	34.840	S
C19	33	13.559	-115	34.693	S
C20	33	13.857	-115	35.042	
C21	33	13.947	-115	35.457	
C22	33	13.967	-115	35.097	
C23	33	13.980	-115	35.324	
C24	33	14.017	-115	35.098	
C25	33	14.019	-115	35.125	
C26	33	14.022	-115	35.381	
C27	33	14.046	-115	35.292	
C28	33	14.070	-115	35.529	
C29	33	14.121	-115	36.134	S
C30	33	14.128	-115	35.993	S
C31	33	14.149	-115	35.832	S
C32	33	14.158	-115	35.933	S
C33	33	14.179	-115	35.696	S
C34	33	14.194	-115	36.052	S
C35	33	14.198	-115	35.058	
C36	33	14.209	-115	36.250	S
C37	33	14.214	-115	35.635	S
C38	33	14.241	-115	35.472	
C39	33	14.272	-115	35.283	
C40	33	14.275	-115	36.159	S
C41	33	14.310	-115	35.478	
C42	33	14.372	-115	35.482	
C43	33	14.385	-115	35.416	
C44	33	14.400	-115	35.094	
C45	33	14.427	-115	35.399	
C46	33	14.460	-115	35.458	
C47	33	14.489	-115	35.504	
C48	33	14.503	-115	35.621	S
C49	33	14.503	-115	36.004	S
C50	33	14.510	-115	36.168	S
C51	33	14.557	-115	35.898	S
C52	33	14.621	-115	35.956	S
C53	33	14.641	-115	35.866	S
C54	33	14.657	-115	35.867	S
C55	33	14.750	-115	35.970	S
C56	33	14.848	-115	35.981	S
C57	33	14.856	-115	36.288	S

name	latitude		longitude	
A1	33	13.013	-115	34.757
A2	33	13.054	-115	34.688
A3	33	13.080	-115	34.810
A4	33	13.110	-115	34.810
A5	33	13.124	-115	34.649
A6	33	13.129	-115	34.811
A7	33	13.133	-115	34.759
A8	33	13.171	-115	34.698
A9	33	13.145	-115	34.827
A10	33	13.157	-115	34.632
A11	33	13.174	-115	34.884
A12	33	13.179	-115	34.649
A13	33	13.277	-115	34.860
A14	33	13.555	-115	34.702

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The Salton Sea geothermal brines

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The sediment-hosted Salton Sea geothermal system (SSGS) contains some of the most saline, metal-rich hydrothermal fluids known from an active system (White et al., 1963; Skinner et al., 1967; Helgeson, 1968). Recent extensive scientific and commercial drilling into this system has provided a wealth of new samples and data relevant to understanding this unique hydrothermal system and its metalliferous brines (Elders and Sass, 1988; McKibben et al., 1988a, 1988b; Williams, 1988; McKibben and Eldridge, 1989; McKibben and Williams, 1989; Williams and McKibben, 1989; McKibben et al., 1990). Only a brief overview of the SSGS is presented here.

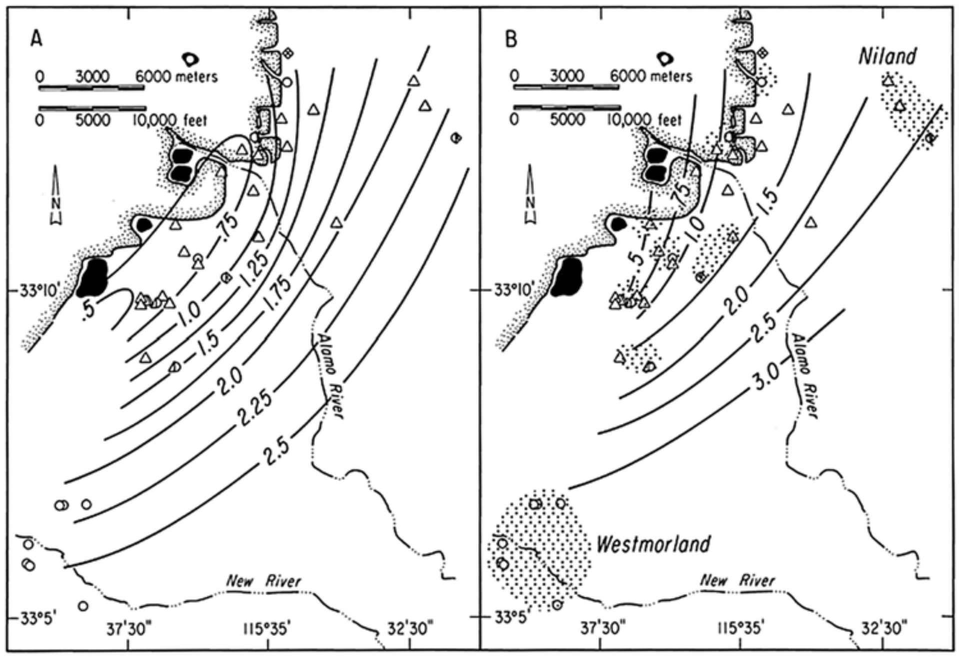


Figure 1. (a) Contour map of the SSGS showing depth (km) to the 250°C isotherm as compiled from geothermal well temperature measurements from more than 30 wells. (b) Contour map of the SSGS showing depth (km) to the fluid interface constrained by salinity differences between closely spaced production zones. Stippled areas indicate locations of constraints on countours. From Williams and McKibben (1989, Figure 7).

Reservoir topology

The saline brine reservoir of the SSGS appears to have a domal upper surface defined by both the 260⁰C isotherm and a sharp fluid interface where salinities increase rapidly with depth from <12% TDS to >15% TDS (Figure 1). This interface occurs at a depth of only 500 m in the central part of the field (Figure 2) and appears to be density-stabilized (non-convecting) due to a balance between salinity and temperature (Williams, 1988; Williams and McKibben, 1989). The underlying reservoir of hypersaline brine has a temperature-salinity gradient that permits convection, and the brine's stable isotopic homogeneity supports this possibility. The lower limits to the brine reservoir, if any, are not known; saline brine has been encountered at depths greater than 4 km in many locations in the northern trough (Figure 3). Currently there is no economic incentive for the geothermal companies to drill to produce brine from depths greater than 2–3 km.

A model for the brine reservoir and its evolution has been proposed (Williams and McKibben, 1989). In this model, rift basinal brines that have accumulated in the closed Salton Sea basin have been magmatically heated above spreading center fragments to generate an internally-convecting brine diapir that has advected to within 0.5 km of the trough surface. According to this model, the geothermal companies are currently drilling into the top of this brine diapir.

Brine chemistry

The hot (up to 365⁰C), hypersaline Na–Ca–K–Cl brines contain up to 26 TDS and are rich in Fe, Mn, Zn, Pb, and other metals (Table 1). On a molal rather than weight basis, the dominant constituents in these brines are Na, Ca, K, CI, B and NH_3. Interestingly, there are only 5 water molecules per ion in these brines, so that if each ion is even partially hydrated there is effectively no free solvent left! Undoubtedly a large fraction of the ionic constituents are chloride-complexed or ion-paired rather than hydrated, but in effect the brines behave more like molten salts or molecular fluids than dilute aqueous solutions. These brines, therefore, are quite viscous and are very slow to convect and mix with shallower, more dilute fluids. U-Th decay chain measurements imply that the hypersaline brines have long residence times in the SSGS, on the order of 10^4 years (Zukin et al., 1987). For this reason their apparent existence as a buoyant, discrete diapir within the Salton Trough is not surprising. Their closest chemical analogs in fossil deposits

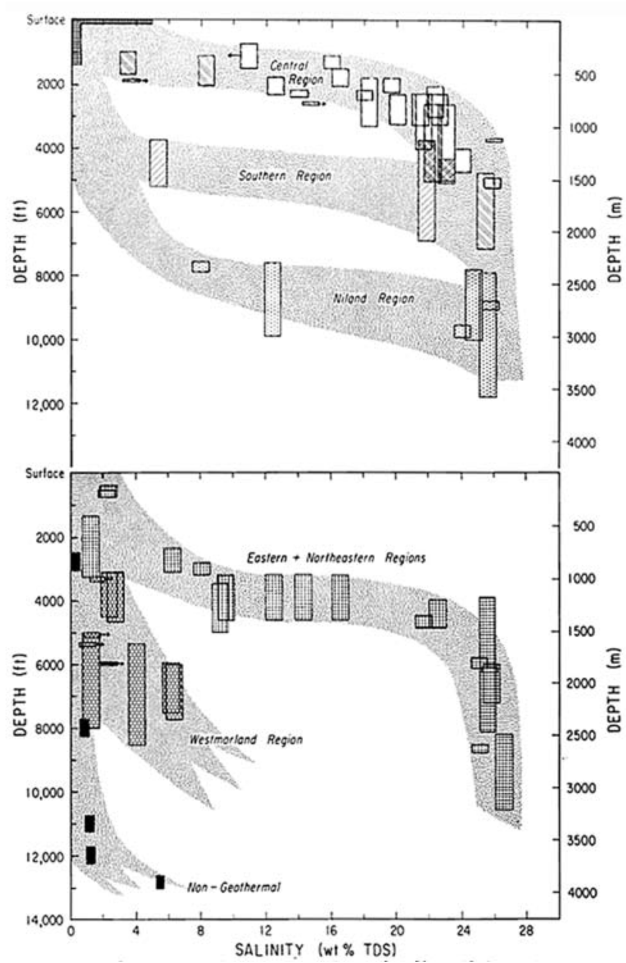


Figure 2. Plots of production depth versus salinity (wt % TDS) for SSGS geothermal fluids and for reference non-geothermal fluids from different geographic parts of the geothermal field, Stippled patterns represent inferred trends of fluid salinity with depth in each region of the field. Note that the fluid interface (the rapid rise in salinity) occurs at depths as shallow as 0.5 km in the central part of the geothermal field. From Williams and McKibben (1989, Figure 6).

are the brines of Mississippi Valley-type deposits.

Stable isotopic studies of the brines (Figure 4) indicate that their water originated as Colorado River water that has undergone substantial near-surface evaporation and subsequent water-rock interaction at elevated temperatures (Williams and McKibben, 1989, and references therein). The hypersaline brines are oxygen-isotope equilibrated with the host metasediments and have a hydrogen isotopic composition that is distinct from the less equilibrated, less saline overlying fluids. This implies that they may represent older (Plio-Pleistocene?) fluids that accumulated under different climatic or recharge conditions than more recent surface waters.

Patterns of metamorphic mineral zonation with depth (Figure 5) reflect the diapiric topology of the heated brine reservoir, and record greenschist and amphibolite facies assemblages at depths of less than 4 km (Muffler and White, 1969; McDowell and Elders, 1980; Cho et al., 1988).

Shales in the host metasediments of the SSGS show a progressive, nearly complete depletion in their base metal contents with increasing depth (McDowell, 1987), implying that the hot brines have effectively stripped the

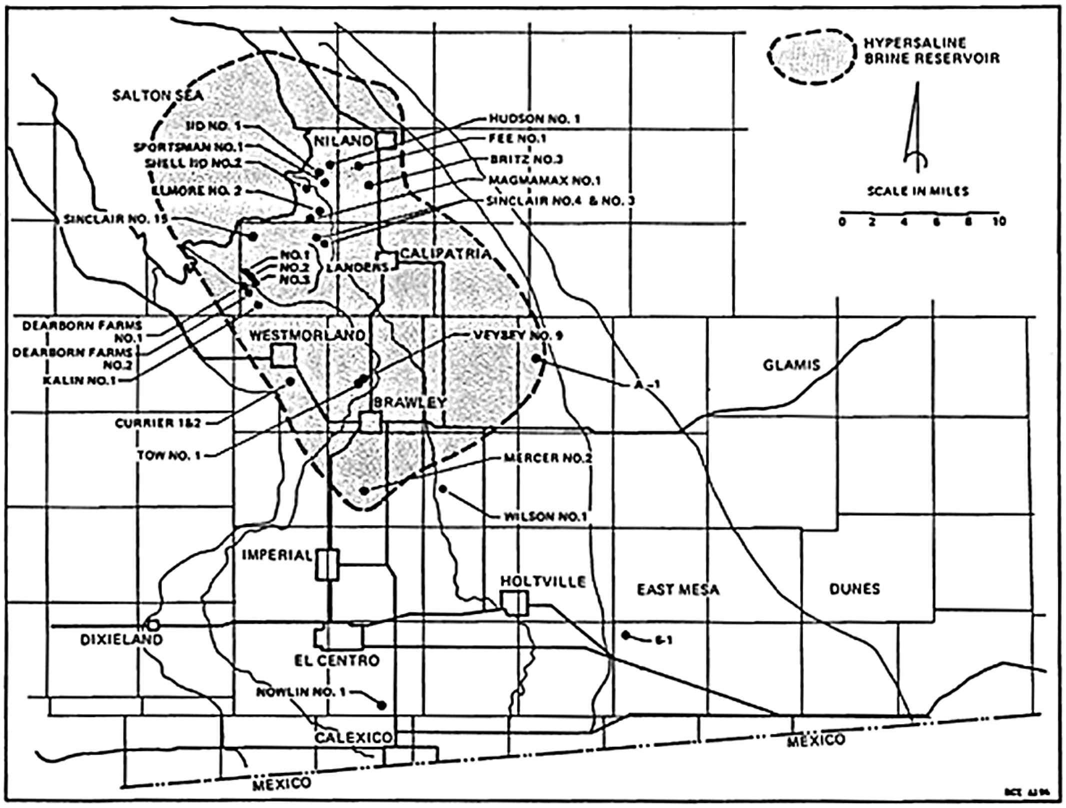
TABLE 1

Representative
Flash Corrected Brine Analyses

	HYPERSALINE					LOW T.D.S.(h)			
	SSSDP(i) Well, State 2-14								
	12-1985	3-1986(d)	6-1988(e)	Commercial Well #11b	Commercial Well #10	Woolsey(f) Well #1	Commercial Well #B1	I.I.D.(g) Well #3	Commercial Well #113
Temp (°C)	305	330	320	300	295	240	230	190	200
pH	5.4	5.1	5.3	5.2	5.3	?	6.9	?	7.6
Depth (m)	1,850 - 1,890	2,500 - 3,220	1,830 - 2,200	660-1,070	700-1,070	570-720	710-940	?-520	410-990
Na	53,000 ppm	54,800	53,700	46,200	41,400	25,000	15,000	10,600	4,800
Ca	27,400	28,500	26,300	22,800	20,900	11,000	2,520	1,130	117
K	16,700	17,700	17,100	12,500	11,800	5,000	2,480	1,250	297
Fe	1,560	1,710	1,620	582	969	65	86	0.7	25
Mn	1,450	1,500	1,470	801	855	NA	60	6.4	ND
SiO_2(c)	>461	>588	>840	>336	>404	NA	>255	>120	102
Zn	518	507	510	321	323	NA	11	NA	ND
Sr	411	421	410	376	345	513	112	85	10
B	257	271	380	204	197	NA	92	100	32
Ba	203	353(b)	218	183	156	NA	45	3	0.7
Li	194	209	215	157	152	93	55	40	9
Mg	33	49	43	19	33	NA	54	74	24
Pb	100	102	107	69	67	NA	2.6	NA	ND
Cu	5.9	6.8	5.8	NA	2	NA	ND	NA	ND
Cd	2.2	2.3	2.2	1.0	1.4	NA	ND	NA	ND
Cs	NA	NA	23	NA	NA	NA	NA	NA	NA
NH_4^+	333	330	356	339	341	NA	103	321	NA
Cl^-	151,000	157,500	152,000	128,000	116,000	85,000	31,000	19,700	6,900
Br^-	99	111	111	95	78	NA	24	15	10
CO_2(a)	1,600	1,580	1,950	1,100	5,500	NA	10,000	NA	NA
H_2S	15	10	NA	15	20	NA	NA	NA	NA
$SO_4^=$	65	53	~123	~100	53	NA	53	621	440
TDS	~25.6%	~26.5	~25.6	~21.4	~20.0	~12.7	~6.2	~3.5	~1.3

(a) Volumetric measurement of total non-condensible gas.
(b) Probable contamination from drilling fluid.
(c) Silica values low due to precipitation prior to and during sampling.
(d) Concentrations corrected for ~5% dilution by drilling fluid.
(e) Short clean-out flow probably some contamination
(f) Needham et al. 1980
(g) Muffler and White, 1969
(h) Total dissolved solids
(i) Salton Sea Scientific Drilling Project

Figure 3. Distribution of hypersaline geothermal brine in the northern Salton Trough based on well production information, from Rex (1985, Figure 5).



sediments of their detrital metal content as the brine diapir advected upwards through the sedimentary section. Mass balance calculations by McDowell indicate that the content of most of the metals in the brines can be accounted for by leaching of the host sediments. There appears to be no need to invoke magmatic or other external sources for the base metals.

Ore mineralization

In contrast to the spectacular metal contents of the brines, ore mineralization within the system is presently rather feeble (McKibben and Elders, 1985; McKibben et al., 1988a). The metals apparently precipitate only infrequently, when tectonic movements generate vertical fractures that transgress the fluid interface and allow shallow, more oxidized dilute fluids to mix with the metalliferous hypersaline brines (McKibben et al., 1988a). The most common ore minerals in these open veins are pyrite, hematite, chalcopyrite, sphalerite, and galena. Common gangue minerals are calcite, quartz, epidote, and chlorite. Fluid inclusion salinities are intermediate between those of the endmember fluids, further supporting a fluid mixing model.

The sampled brines have a relatively high oxidation state, corresponding to the hematite–pyrite and SO_4–H_2S redox couples (McKibben and Elders, 1985). Most of the brine samples come from production zones just below the

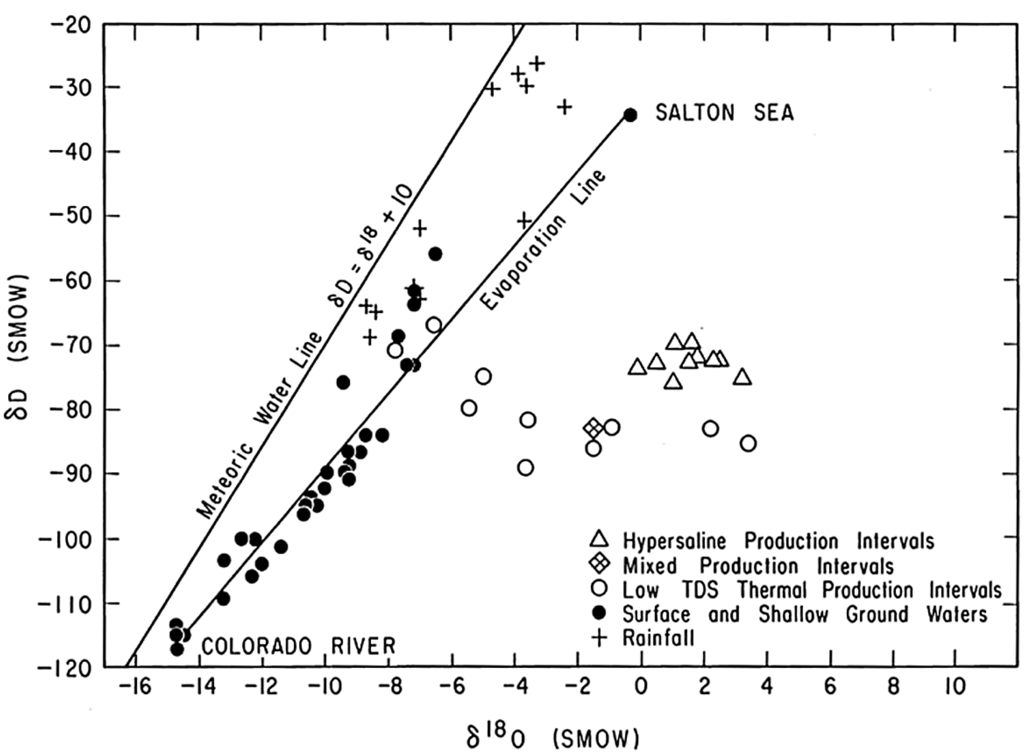


Figure 4. Plot of δD versus δ18O for fluids in the SSGS and northern Salton Trough. Modified from Wiliams and McKibben (1989, Figure 5).

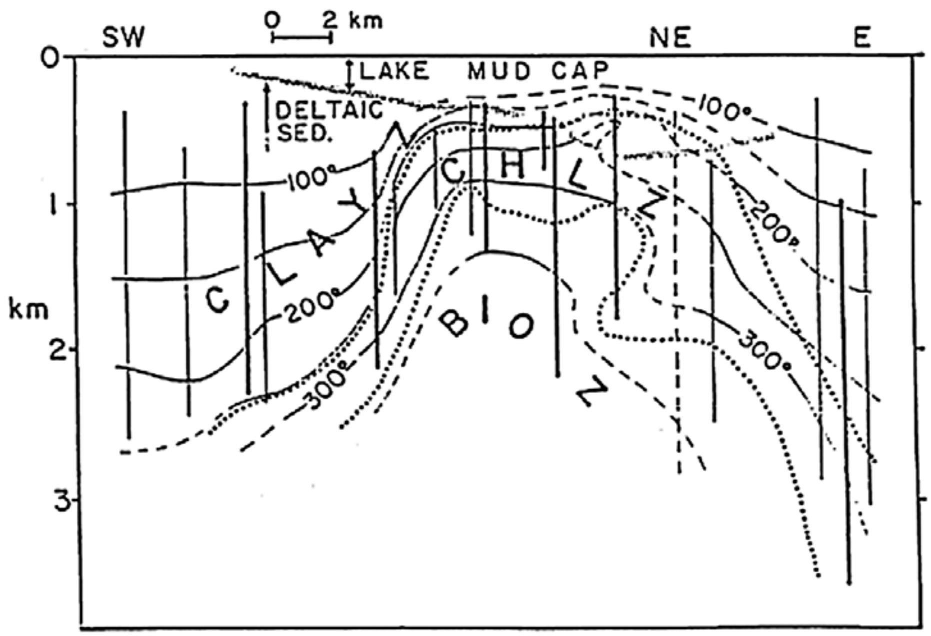


Figure 5. Cross section of Salton Sea geothermal system showing the three major authigenic alteration zones (denoted by dotted lines) within the fluvial–deltaic–lacustrine sedimentary section. CHL Z = chlorite zone, BIO Z = biotite zone. Isotherms (solid lines) in degrees Centigrade. Vert5ical lines indicate well intervals on which alteration zonation and temperature are based. Lower boundary of shallow unconsolidated lake sediments shown by stippled pattern. Section runs NE from Westmorland area through central part of field and then E to Niland area. From McDowell (1987, Figure 1B).

fluid interface, so it is not known if the brines may become more reduced at depth. However, sulfur isotopic data imply that the brine redox state may be buffered at this high value by metamorphic redox reactions between Fe^{2+} in the brines and abundant evaporitic anhydrite in the host metasediments (McKibben and Eldridge, 1989; Osborn et al., 1988). The sulfur isotopic composition of H_2S in the brines can be accounted for by this hydrothermal sulfate reduction mechanism, and no major magmatic sulfur component is required.

The high oxidation state and high Ca^{2+} content of the brines thus keep the dissolved H_2S and SO_4 contents quite low («10^{-3} each). The low activity of reduced sulfur coupled with high chloride activity permit the spectacular metal contents of the brines, while at the same time inhibiting the amount of metal sulfide precipitation. The persistent saline lake environment generated in the northern Salton Trough for the past 4 Ma by the growth of the Colorado River delta has therefore significantly influenced the ore-forming capacity of these brines, providing a sedimentary section rich in metalliferous shales and lacustrine sulfate.

The low content of Cu relative to other base metals in these brines may be caused by the high Fe content, which stabilizes chalcopyrite as a vein mineral phase and keeps Cu solubility low.

A future ore deposit?

The SSGS will not likely form a major concentrated base metal ore deposit in its present configuration, unless precipitation by episodic mixing at the fluid interface is allowed to continue for a protracted length of time. Given the tectonically dynamic nature of the trough, this seems unlikely. The quantitative precipitation of the brines' contained metals will instead require some catastrophic event, such as sudden magmatic heating and advective expulsion of the fluids onto the floor of the Salton Sea.

The modern Salton Sea is quite shallow and well-mixed, so that such an expulsive event would likely generate a stratiform Fe–Mn oxide deposit. However, some of the Pleistocene lakes that were present in the northern trough were considerably larger and deeper (Waters, 1983) and could have had anoxic, H_2S-rich bottom waters. In this case lake-floor expulsion of the brines could generate a massive stratiform base metal sulfide deposit.

The ore-forming capacity of the SSGS brines can be estimated by calculating the total mass of metals that the brines contain (McKibben et al., 1990). This can be estimated very conservatively by taking the volume between the domal upper surface of the hypersaline brine diapir and the maximum commercially exploited depth of 2 km. This volume excludes portions of the explored field containing lower-salinity fluids, and yields about 55 km^3 of total reservoir. With a 20% fracture and granular porosity, the resulting hypersaline brine volume is about 11 km^3 (Elders, 1989). At a brine density of 1.0 at 300^0C, this volume contains about 10^{13} kg of brine. Using typical metal contents from Table 1 and McKibben et al. (1990), the following amounts are calculated for a few selected metals:

Fe	1600 mg/kg	18 million metric tons
Zn	500 mg/kg	6 million metric tons
Ag	1 mg/kg	350 million ounces
Pd	1 ug/kg	350,000 ounces

These estimates are approximate, because they consider only the currently exploited hypersaline geothermal system and assume a uniform metals content. Hypersaline brines are found at depths below 2 km, both within and outside of the exploited Salton Sea field (Figure 3). It has been proposed that the total hypersaline brine volume is at least 10 times that which is presently exploited in the SSGS (Rex, 1983; Williams and McKibben, 1989). If the metal content of these brines is uniform, then the entire hydrothermal system could contain ten times the amounts of dissolved metals calculated above.

The tonnage estimates above compare favorably with those for several major types of stratiform sediment-hosted base metal ore deposits (e.g., Cox and Singer, 1986). The SSGS therefore may be a reasonable and useful analog for modeling the accumulation and eventual subaqueous expulsion of metalliferous brines to form stratiform ores in continental rift environments.

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The Lake Cahuilla high shoreline and a stable overflow path elevation, southeastern California and northeastern Baja California

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Lake Cahuilla exhibits a distinctive high shoreline indicative of an elevationally stable overflow geomorphic sill for the Salton Basin (Figure 1). Did relatively young dacitic flows of the Cerro Prieto volcanic field, located at the lowest point on the basin rim and on the overflow path, stabilize basin sill level and act as erosion-resistant armor on the Colorado River unconsolidated distal delta deposits?

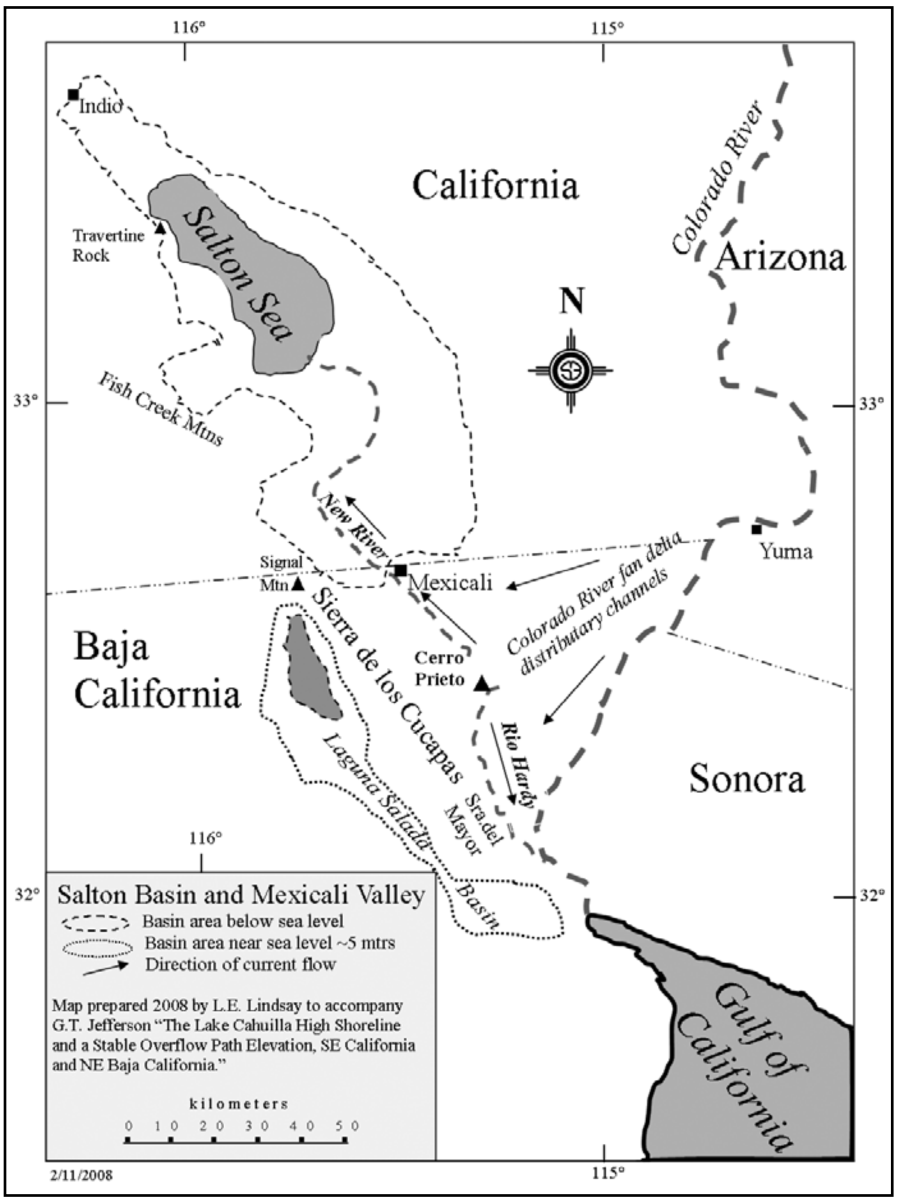

Figure 1. Regional map of the Salton Trough Basin.

The average 12.5 m (40.5 feet) above mean sea level (msl) shore line of Lake Cahuilla apparently was repeatedly occupied at high lake stands during the latest Wisconsinan and Holocene (Waters 1983, Larson 1990, Gurrola and Rockwell 1996, Buckles et al. 2002, Luttrell et al. 2007), which indicates that the Salton Basin had a relatively stable overflow sill at this elevation. This distinctive shoreline was first described by Blake (1854), and is well exposed at Travertine Rock (Point) on the west side of the Salton Sea and on the northeast and east Fish Creek Mountains. The last high stand, about 300 yr ago, reached the 12.5 m elevation, and it has been assumed that earlier Holocene levels were approximately the same (Wilke 1978, Waters 1983, Li 2003, Luttrell et al. 2007). However, radiometric dates on oncoid tufa, lacustrine algal $CaCO_3$ deposits at Travertine Rock are below the highest lake level (at 24 m and ≈ 30 m below msl) (Turner and Reynolds 1977, Li 2003, Reynolds pers. comm. 2008). The dates range from 17.5 to 1.3 kyr BP (Turner and Reynolds 1977, Li 2003). Nevertheless, these data imply relatively long duration stability in the elevation of the Salton Basin sill at about 12.5 m (average of 32 data points from Larson 1990, Buckles et al. 2002, and Luttrell et al. 2007). Presently, the Salton Basin is largely open to the south towards the Gulf of California, and has a minimum rim or sill elevation of about 10 m msl near the Cerro Prieto volcano (Luttrell et al. 2007) on the Colorado River delta 35 km (22 miles) SE of Mexicali, BC.

Overflow from Lake Cahuilla, a significant portion of the Colorado River flow and local drainage input, at high lake stands simply could not have crossed the distal por-

Figure 2. Cerro Prieto volcanic dome and cone, view is to the WNW (photograph from Global Volcanism Program 2007).

tion of the Colorado River fan delta into the northern Gulf of California without eroding the unconsolidated fluvial deltaic deposits. It is suggested here that these alluvial sediments could not have supported a stable sill level. It is also unreasonable to propose that deposition on the delta kept exact pace with overflow channel erosion, lake loading and rebound, and/or regional tectonic subsidence, as the repeatedly occupied high shore line would require. What geological features or processes maintained the overflow sill elevation near the 12.5 m-high stands throughout at least Holocene time?

The filling and overflow of the Salton Basin by the Colorado River and/or other sources depends on a number of conditions. During interglacial/interstadial and Holocene times, the Colorado River periodically switched across its fan delta between the Salton Basin and the Gulf of California (Waters 1983). This was driven by changes in delta gradient as Lake Cahuilla reached overflow level and as distributary channels filled with sediment (see Howard et al. this volume). However, during glacial periods, when sea level in the Gulf of California was about 100 m below modern msl, the River would have entrenched itself on the south side of the delta preventing any shifts to the NW (Spaulding pers. comm. 2006, Armstrong 2008). Although the Colorado River likely did not enter the Salton Basin at these times, under late Wisconsinan climatic conditions, Lake Cahuilla apparently received sufficient local runoff to periodically occupy the 12.5 m level (Li 2003). Lake filling time is estimated at 20 yrs, and 60 yrs for evaporation under present climatic conditions (Wilke 1978, Luttrell et al. 2007).

An examination of the topography of the delta region reveals the NW-SE trending Mexicali Valley depression where the alluvial bajada from the Sierra de los Cucapas and Sierra del Mayor on the west meets the deltaic apron of the Colorado River flowing from the NE. This sub-linear depression, although lower in elevation at the north and south ends, parallels the Cerro Prieto and Imperial faults that underlie this part of the Colorado River delta, and extends from SW of Mexicali to the present Colorado River channel east of the Sierra del Mayor. This structurally controlled depression presently confines any overflow from the Salton Basin to a single linear path.

The Cerro Prieto volcanic field (Figure 2), centrally located in the Mexicali Valley and east of the Sierra de los Cucapas, occupies a critical place on the distal edge of the Colorado River fan delta (Figure 1). Here, deltaic drainages split into northern and southern sections, and a drainage divide extends from Cerro Prieto NE to the apex of the fan near Yuma, AZ. The volcano sits on the rim of the Salton Basin drainage catchment at the west end of a narrow 2 km-wide strip of land that is ~10 m above msl (Luttrell et al. 2007). The Rio Hardy flows south from Cerro Prieto along the distal margin of the Sierra de los Cucapas and Sierra del Mayor bajadas. It is joined from the east by a number of distributary branches of the modern Colorado River before reaching the Gulf of California. To the north of Cerro Prieto, drainages collect into the New River and flow NW into the Salton Basin.

Did buried latest Pleistocene igneous dikes and sills and/or surficial Holocene flows and ejecta from the Cerro Prieto volcano act as an erosion-resistant armor in the overflow path for the Salton Basin? The small Cerro Prieto volcanic dome is over 1 km (0.6 mile) in diameter and the NE cone stands 223 m (725 feet) above msl with a 200 m-wide crater. Although wide-spread volcanic flows are not evident at the surface, the dacitic dome consists of intrusives and lava flows (Reed 1984, Global Volcanism Program 2007). Also, buried flows are depicted east of the dome within the upper-most "poorly or non-consolidated" sedimentary deposits (Lithologic Unit A) in the Cerro Prieto geothermal field (Lindsay and Hample 1998).

A short spreading zone lies between the Imperial and Cerro Prieto transform faults. Here, the Mexicali Valley region has been down dropped (Silver and Silver 1987, Alles 2007) and is presently subsiding within the Cerro Prieto geothermal field (Glowacka et al. 2000). The elevation of the field is ~ 2.5 m below the average Lake Cahuilla high shoreline. Measurements, taken there from 1970 through 1997, record a 1.74 m-displacement. However, Glowacka et al. (2005) estimate that only about 4% of this total measured displacement (a subsidence velocity of about 2.6 mm/yr) is the result natural tectonic processes (the rest is due to resource extraction methods). Apparently, Cerro Prieto has subsided a little over 1/2 m from natural causes over the past 300 yrs, or at a rate of about 1.6 mm/yr, which is comparable to regional subsidence rates elsewhere in the Salton Basin that are on the order of 1.5 to 3 mm/yr.

However, other dynamic processes also changed the elevation of the Lake Cahuilla shore line and the Cerro Prieto rim. Recently, Luttrell et al. (2007) described a maximum of about 1 m depression and rebound in Salton Basin elevations due to lake mass loading and unloading. The velocity of these changes is not precisely known but it is something less that about 5 mm/yr. This effect decreases outward from the deepest, northern part of the basin under the Salton Sea. The Luttrell et al. (2007) model predicts that Cerro Prieto would experience much less overall elevation displacement than Travertine Rock, for example. Such basin-wide changes should form an upward migrating lake shore "zone" (rather than a shore line) at locations proximal to the basin depocenter when elevations there, relative to Cerro Prieto, dropped ~ 1 m as Lake Cahuilla filled.

The Cerro Prieto volcanics may well have served as an erosion-resistant geomorphic sill, possibly armoring the surface of the deltaic deposits. The volcanics are at the correct location within the linear overflow path, and were at the proper elevation to sustain at least the latest high stands of Lake Cahuilla. Also, if native Cucupah legends are considered, Cerro Prieto volcano was active during the Holocene (Global Volcanism Program 2007), and first erupted prior to about 0.75 Ma (Reed 1984). Early-Holocene occupation of the 12.5 m-high shoreline argues for little, if any, unidirectional changes in overflow sill elevation. However, a less than thorough understanding of regional tectonics and subsidence velocities, lake mass loading and rebound, the magnitude and timing of volcanic activity, and the magnitude and timing of alluviation across this portion of the Colorado River fan delta, preclude correlation of the Cerro Prieto volcanics with a possible geomorphic sill for the oldest high stands of Lake Cahuilla.

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Proceedings of the 2008 Desert Symposium: abstracts and short papers

Are physiological responses in desert holly (*Atriplex hymenelytra*) gender specific?

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Desert holly (*Atriplex hymenelytra*) is broadly distributed throughout desert areas of southwestern North America. An evergreen perennial, desert holly is classified as a dioecious species in which male and female flowers are produced by separate individuals. However, on occasion, monoecious individuals that retain the potential to produce both male and female flowers occur. An earlier study of resource allocation among different gender types indicated that there is a cost associated with generalization (monoecy) compared to single sex expression (either being a male or female). Consequently, I chose to focus my study on determining whether physiological responses to environmental conditions might show a similar pattern. Currently, physiological parameters related to water and gas exchange including water potential, stomatal conductance, relative water content of leaves, photosynthetic capacity, CO_2 uptake and transpiration rates are being measured for male, female, and monoecious individuals quarterly. Although preliminary results of measurements taken during the summer of 2007 indicate a high level of similarity among individuals, these will be compared to subsequent measures taken during fall 2007 and winter 2008 to determine if physiological responses vary seasonally among gender types.

Marine vertebrates from the Yuha member of the Deguynos Formation, Anza-Borrego Desert State Park®

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The paleontologic history of the Anza-Borrego Desert spans a critical 25 million year period of the earth's history (Miocene to Pleistocene), and the fossils preserved there represent an unparalleled North American paleoenvironmental resource (Jefferson and Lindsay 2006). An unusual assemblage of new marine invertebrate and vertebrate fossils, as well as terrestrial mammalian fossils, recently have been discovered in the marine part of the ancestral Colorado River delta deposits of Anza-Borrego Desert State Park. The specimens were recovered from the Yuha member of the Deguynos Formation, Imperial Group (Winker and Kidwell 1996), located in the southern part of the Park near Fish Creek. This mid-Pliocene formation, which records the terminal marine to terrestrial transition, approximately 4.4 to 4.1 Ma, will be more precisely bracketed by further paleomagnetic work in the area (Dorsey et al. 2007). Local sediments include delta front and delta plain lens-shaped sandstone beds, sandstone coquinas, and massively bedded silty fine sandstones that interfinger with fossil wood-bearing sandstones of the overlying Camels Head member and Arroyo Diablo Formation of the Palm Spring Group (Cassiliano 2002).

Exposures of the Deguynos Formation crop out in a region of the park previously unexplored for fossils, and many of the specimens thus far recovered are representative of very rare or new taxa for the local record, including members of Istiophoridae (bill fish), Chelonidae (sea turtle), Crocodilia (crocodile), Dugongidae (dugong), Odontoceti (toothed whales), and Pinnipedia (seal and/or sea lion). Of particular interest is a potentially new species of *Valenictus* (walrus), based on nearly complete, curiously small humerus, femur and tibia (Deméré 1993, Deméré et al. 2003). In addition, several *Odontaspis* (sand shark) teeth have been identified, indicative of warm, shallow waters, and *Squalus* (dogfish), a deeper water form (Roeder pers. comm. 2006).

Along with the marine invertebrate fossils which support paleoenvironmental reconstructions (Deméré 2006), the role of this study aids the reconstruction of the local paleonenvironments, and is thus crucial to understanding the paleontologic history of the ancestral Colorado River and the Salton Trough rift valley.

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Sources of groundwater recharge to Mojave Chub Spring

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On the east side of Limestone Hill at the Zzyzx Desert Studies Center, Mojave Chub Spring is home to the endangered Mohave tui chub. The water level in the spring is constant year-round. By studying the groundwater and surface water in the Zzyzx area, a hydrogeologic model was prepared to identify sources of groundwater recharge to Mojave Chub Spring. Water table elevations, water quality in the groundwater and surface water, and vegetation patters suggest that fractures in Limestone Hill provide a path for recharge of Mojave Chub Spring from groundwater in the alluvial aquifer.

Dispersal agents of desert fan palm (*Washingtonia filifera*) seeds

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The Late Quaternary arrival of the desert fan palm (*Washingtonia filifera*) in the Mojave and Sonoran desert regions can be explained by the dispersal of its seeds by mammalian and avian frugivores. Only highly mobile vertebrates have the capacity to reach the widely scattered desert seeps, springs, and streams where palms exist.

During the fall of 2007, approximately 200 hours were spent observing vertebrates visit clusters of palm fruits hanging from trees as well as individual palm fruits that had fallen to the ground. Based upon these observations, each animal species was classified as either a possible short-, intermediate-, or long-range dispersal agent of desert fan palm seeds. The classification was dependent upon the maximum estimated distance that a vertebrate might travel with viable seed.

Short-range dispersal agents were those species observed to disseminate seeds but unlikely to distribute them more than 1 kilometer from the parent fan palm. Such species included Gambel's quail (*Callipepla gambelii*), verdin (*Auriparus flaviceps*), western bluebird (*Sialia mexicana*), yellow-rumped warbler (*Dendroica coronata*), house finch (*Carpodacus mexicanus*) and white-crowned sparrow (*Zonotrichia leucophrys*). Each of these species was regularly observed to consume the flesh (epicarp, mesocarp, and endocarp) of palm fruits. An individual bird would peck at the fruit while it hung from a tree or lay on the ground, or pick up an entire fruit in its bill and fly a short distance to a perch where it would then remove the flesh. None of these species were ever observed to consume the seeds, though in western bluebirds the entire fruit might disappear in their mouths only to be regurgitated. This behavior was first observed by Bullock (1980). Seed dispersal occurred when the birds knocked the fruits from the tree while feeding or when carrying the fruit to a perch.

The dispersal agent for desert fan palms seeds best described as intermediate (between 1 and 50 km) was the coyote (*Canis latrans*). Coyote scats filled with undigested palm seeds were common along oasis trails. As the maximum range of the coyote before defecation is approximately 20 km, coyote dispersal of palm seeds could explain most, but not all of the present locations of the desert fan palm (Cornett, 2008). The northern mockingbird (*Mimus polyglottos*) and European starling (*Sturnus vulgaris*) may also be considered intermediate dispersal agents as they have been observed engulfing entire fruits without disgorging the seeds. Both species are considered residents where they are observed and would not normally be expected to travel more than 50 km from where seeds were consumed.

The northern flicker (*Colaptes auratus*), American robin (*Turdus migratorius*), hermit thrush (*Catharus guttatus*) and cedar waxwing (*Bombycilla cedrorum*) are migratory birds that were observed to consume the entire fruit. As these species are known to migrate distances well in excess of 50 km, they may be considered potential long-distance dispersal agents, assuming none digest the seeds. Human dispersal of desert fan palm seeds in excess of 50 km in historical times has been well documented (Cornett, 1988; 1989). Evidence also exists that Native Americans transported desert fan palm seeds over long distances (Patencio, 1943). The existence of the most isolated desert fan palm oases is best explained by human long-distance dispersal.

This research was made possible by financial support from the Joshua Tree National Park Association.

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The fish of the Mojave Valley: current research and recent findings

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Mohave tui chub (*Siphateles bicolor mohavensis*) is an endangered fish species native to the Mohave River drainage in southern California. Present populations of Mohave tui chub are restricted to four highly modified habitats: Lake Tuendae and MC Spring in the Mojave National Preserve, the Camp Cady Wildlife Area, and a seep system at China Lake Naval Air Weapons Station. The Mohave tui chub is listed as an endangered species mainly due to restricted range and small population size. Potential threats to Mohave tui chub include algal blooms in Lake Tuendae and introduced non-native mosquitofish (*Gambusia affinis*) which occupy two of the habitats, Lake Tuendae and China Lake. The effects of mosquitofish and barley straw (for algal growth control) on population dynamics of Mohave tui chub were evaluated using a mesocosm experiment in spring 2007. This preliminary study showed that mosquitofish could prevent the recruitment of Mohave tui chub, possibly by feeding on eggs, fry, and juveniles. There was no effect of barley straw as a controlling agent of algal blooms. Additionally, a recent population estimate suggested that the Lake Tuendae Mohave chub population has declined nearly by 50% from the 2005 estimate. This may indicate a possible impact of mosquitofish on Mohave tui chub. Additional research is focused on describing the life history and the ecology of the species.

Boulders deposited by Pliocene and Pleistocene floods on the lower Colorado River

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Boulders are present in several parts of the stratigraphic record of the lower Colorado River below Grand Canyon, which coursed alternately through canyon and broad valley reaches. The boulder deposits are unlike the bed of the modern river, which coarsened upstream from sand to fine gravel. Most but not all of the boulder deposits are in the canyon reaches where high discharge velocities could be expected from confined flood flows of the river. Some boulders have distant provenance. Others, including most of the largest examples, are locally derived from older fanglomerate, limestone, and fluvial conglomerate. Some of these likely entered the river in debris flows from local tributaries before being carried as river bedload, although House et al. (2005) suggested that two locally derived boulder deposits near Laughlin, Nevada record breakout floods that eroded through bedrock, one flood at river inception 4–5 Ma and another in the Pleistocene.

A thick Pliocene sequence of coarse-grained fluvial gravel and sand contains boulders in many places. The sequence includes unit B of Metzger et al. (1973), the alluvium of Bullhead City of House et al (2005), and deformed conglomerate in the Lake Mead area (Longwell, 1936) interbedded with 4.4-Ma basalt (Faulds et al., 2001). This sequence represents the coarsest of four major aggradation sequences known from the river's history, and contains far-traveled quartzite boulders and larger locally derived boulders. In the Lake Mead area, some large boulders at the base of the section likely were derived nearby from the substrate of the river bed; others likely entered and mixed with the main stream from tributary debris flows. Boulders in channel thalwegs are as large as 5 m in the upper Lake Mead area. They are as large as 1m near in lower Mohave Valley and the head of Topock Gorge 275 km downstream, where they are preserved over a downstream extent > 4 km, a lateral extent of hundreds of meters in a valley up to >2 km wide, and a fining-upward stratigraphic thickness >20 m. Boulders in this sequence indicate high Pliocene stream power at least as far as 300 km downstream from the Grand Canyon.

Pleistocene boulder conglomerate at the base of an aggradational sequence of fluvial sand and mud, the Chemehuevi Formation of Longwell (1963), hosted a mammoth tooth found by J. S. Newberry (1862). Late Pleistocene terrace gravels that formed when the river re-incised into the Chemehuevi Formation contain boulders in Topock Gorge as large as 1 m, transported by the river after being derived at least in part from the nearby Pliocene conglomerate. Valley widths range 0.5–1 km at the levels where these bouldery terraces occur. Discovery of boulders at >2 levels in the young terrace gravels suggests late Pleistocene floods of high discharge through valleys 0.5–1 km wide.

Wyatt Berry Stapp Earp's Trona Experience

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The Searles Lake Basin is synomous with the history of the west. The map of the basin is replete with names that emblazon the mining history of the Mojave Desert: Eagle Crags, Robbers Mountain, Bandit Springs, Indian Springs, Hidden Springs, Wingate Pass, the Epsom Salt Monorail Line, Panamint Valley, Pilot Knob, Lead Pipe Springs, the Slate Mountain Range, Randsburg Wash, and Shady Myrick's Bloodstone Mine, to name a few. Names of pioneers that embolden the history of the Trona area include George Hearst, owner of the Wall Street Mine and the New York Mines; and Ronald Reagan as the "Old Ranger" host of Death Valley Days and its stories of the Twenty Mule Team Borax Route, of which 34 miles crosses the South Range of China Lake Naval Air Weapons Station. Tiburcio Vasquez, Shady Myrick, T. H. Wright, Death Valley Scotty, Dennis and John Searles, S. Wallace Austin (husband of author Mary Austin), Seldom Seen Slim Ferge, Shorty Harris, and George Pipkin are among those who at one time or another left their mark on the history of the Trona area.

This story focuses on an interesting discovery as a part of research that I was able to do with the assistance of the Searles Valley Historical Society. The research was done to fulfill requirements of the National Historic Preservation Act and is part of a program for which the Friends of China Lake Archaeology, a volunteer group, is vital and crucial, and without whom we would lose much of the history we have been able to save.

Shortly after the Death Valley Forty-niners made their sojourn in 1849–1850 across the Panamint Mountains, Slate Range, and the Argus Mountains, southern California was agog in stories of gold and silver leaping out at miners in the California desert. John and Dennis Searles first sought the precious minerals and developed a mill on the east side of then Slate Range Lake (becoming Borax Lake and finally Searles Lake). By 1872 they had abandoned gold and silver for borax and potash. Some historians say they invented the Twenty Mule Team later made famous by Coleman and his association with Death Valley. They had two mining districts: Borax Lake on the east side of Searles Lake, much of which is now on the South Range of China Lake Naval Air Weapons Station, and the Brier Mining District near present-day Trona.

Because of world market conditions, local economics, the death of John W. Searles in 1896, and other factors, the operations at Searles Lake were closed down. In the early 1900s, some think as a preparation for World War I, there was much interest in the potash, borax, and salts in Searles Lake. S. "Wallace" Austin was appointed as receiver for the Trona Company. He had been the General Land Office Recorder in Independence. The General Land Office was the predecessor of the Bureau of Land Management. Austin's job was to take the company into a world market. He got it financed and built roads, oversaw plants to develop the minerals at Searles Lake, and made certain that the mining claims were patented. He oversaw the development of the community of Trona and finally the Trona Railroad.

Much of the land was on what is now the South Range of China Lake, across the lake from present day Trona, including a mining community by the name of Slate Range City. Slate Range City was close to Layton Canyon adjacent to Dean's Mill near the Wall Street Mine owned by George Hearst. Slate Range City had been known to the outside world in 1875 because the bar there was robbed by Octavio Chavez, one of Tiburcio Vazquez's soldiers, in an attempt to terrorize the local area into requesting that Mr. Vazquez be pardoned and not hanged for his mayhem. It was also a stage stop of the Myerstein Stage Route that brought miners from San Bernardino to Panamint (City).

During 1900–1901 a post office called Slaterange, California graced the community. Its postmaster was a Mr. Dean. The Dean family lived in a large home surrounded with trees on the east side of Searles Lake. The post office quickly moved to Searles but a small community of miners continued to work the gold and silver ledges of the Slate Range. During 1910, as Wallace Austin was trying to perfect the mining claims and get the industrialization of Searles Lake established, one of the legendary occurrences of western history happened—claim jumpers showed up. From Austin's diaries and as related by articles in the Trona Potash (one by Wallace Austin dated January 26, 1929), both on file at the Searles Valley Historical Society, we learned what happened.

> *The recent death of Wyatt Earp [Wyatt died January 13, 1929] recalls to mind the part he played in the claim jumping expedition to Searles Lake in October 1910. At the time I was Acting Receiver for the California Trona Company and was in charge of a group of placer mining claims covering some 40,000 acres. The party had been organized at Los Angeles by Henry E. Lee, an Oakland attorney and probably was the best-equipped gang of claim jumpers ever assembled in the west. It consisted of three complete crews of surveyors, the necessary helpers and laborers and about 20 armed guards or gunmen under the command of Wyatt Stapp.*
>
> *The party of 44 in number, arrived at Searles Lake in seven touring cars and established a camp at the abandoned town of "Slate Range City" about eight miles south east of the company's headquarters. On the morning following their arrival we saw some of the surveyors across the lake and our foreman rode over and ordered them off the property but they paid no attention to his protest and proceeded to do a very thorough job of surveying and staking.*
>
> *As I considered it necessary to make some show of force in protecting our claims, I visited the enemy's camp at sunrise the next day with our whole force of five men who were armed with all the weapons they could collect. It was a very critical moment when we jumped from our wagon and walked up in front of the mess house where the raiders were assembled for breakfast. I stood in the center with my boys on either side of me. There was a shout and men came running from all directions and fearing there might be trouble. I started right off to explain to the surveyors present that I had only come over to give notice that I was officially and legally in possession of the claims and that they were trespassers. Before I got very far a tall man with iron grey hair and a mustache pushed his way to the front and in a loud voice demanded why I had come into their camp with armed men. At the same time he grabbed hold of my shotgun held by the boy on my left and attempted to take it away from him. At this attack upon us I drew an automatic and ordered him to let go. He did so and then ran to a building nearby saying "I'll fix you." Before he could secure a rifle, however, the cooler headed members of the party surrounded him and*

calmed him down. Also, you may be sure every effort was made to prevent a fight, as, in spite of our bold being, we were pretty badly scared.

Just as things seemed to have quieted down one of the excited jumpers accidentally discharged a gun. No one was hurt but, it was a very tense moment for all of us. Having failed to dislodge the enemy the following day I called for a US Marshall and when he arrived the claim jumpers were all arrested and sent home including 'Wyatt Berry Stapp,' none other than the famous Marshall Wyatt Stapp Earp."

Wyatt Earp was arrested on the east side of Searles Lake by federal marshals. I am still attempting to find the actual records of his arrest. The following year he was arrested again, this time in Los Angeles for being involved in an illegal Faro gambling house with none other than Walter (Death Valley Scotty) Scott. Wyatt and his wife Josephine "Sadie" had many mining claims in the Mojave Desert, living a part of the year near Vidal, now Earp, California. He had mining interest in the Darwin area, and perhaps in the Coso Mountains. This talk will focus on Wyatt's involvement with Trona and the history of the formative years of the industrialization of the Searles Valley, San Bernardino County, California.

Effects of fire on rodents in a sagebrush–juniper community of the Mojave Desert

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Fire can have severe effects on rodent communities directly through mortality, and indirectly, by eliminating and altering habitat and food resources. Very few studies have examined changes in rodent communities following fires in North American dry deserts because fires tend to be infrequent. We investigated the effects of the 2005 Hackberry Complex Fire on rodents in sagebrush–juniper and Joshua tree woodland habitats at high elevations in the Mojave Desert. We live-trapped rodents across the boundary between burned and unburned areas to determine how different species responded to fire, and examined foraging in artificial seed trays across the transition to determine the potential effects of fire on rates of granivory, which could affect plant recovery. Trapping and foraging trials were conducted during full and new moon phases for two summers after the fire. Rodent communities in the unburned areas were more speciose (S = 6-7 species) than burned areas (S = 5-6 species) in sagebrush-juniper habitats, but not in Joshua tree woodland (S = 5 unburned, 6 burned). Kangaroo rats (Dipodomys spp.) represented more unique individuals in burned (88–98%) than unburned (47–63%) areas in both years. In 2006, seed removal rates in burned sagebrush-juniper were much higher on dark than on full moon nights, and decreased with distance from the unburned edge, suggesting that rodents were sensitive to predation risk in the open. However, this difference disappeared in 2007, when rates of seed removal were high (>75-95% of seeds) regardless of distance from the edge, and on both full and new moon nights. We speculate that rodents foraged more on risky, full moon nights in 2007 because fewer natural seeds were available as a result of a persistent drought. These results demonstrate the large effect of fire on rodent communities, and suggest how granivorous rodents may affect plant recovery via their foraging activity.

The geology and history of southeastern San Diego County, California

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Each year the San Diego Association of Geologists (SDAG) mounts a field trip for its members and interested parties that highlights some aspect of San Diego County, California and its environs. An extensive guidebook is published to accompany each field trip which is meant to be useful for people working in the area, and at the same time be of interest to and educational for the general reader. The book contains road logs and associated papers pertinent to the area. Various authors contribute these papers. Normally, the person who is leading the field trip is also the one responsible for producing the guidebook. Over the last few years, these guidebooks have become well-recognized in the community and have even been sought after by people in other countries who are interested in the San Diego area. With each year the guidebooks have become more sophisticated and now require the use of field trip editors (David M. Bloom and Philip T. Garquharson), a managing editor (Carole L. Ziegler), copy editors, technical map editors, and book designers. Due to the proximity of the areas covered by the 2005 and 2006 SDAG field trips, the last guidebook covered two years of field trips which includes geologic information on the desert areas of southeastern San Diego County. The guidebook includes new works as well as some earlier works pertinent to the area. There are also some articles on the history of the railroad, an old feldspar mine and other historical sights in San Diego County.

Plotting the Bradshaw Road

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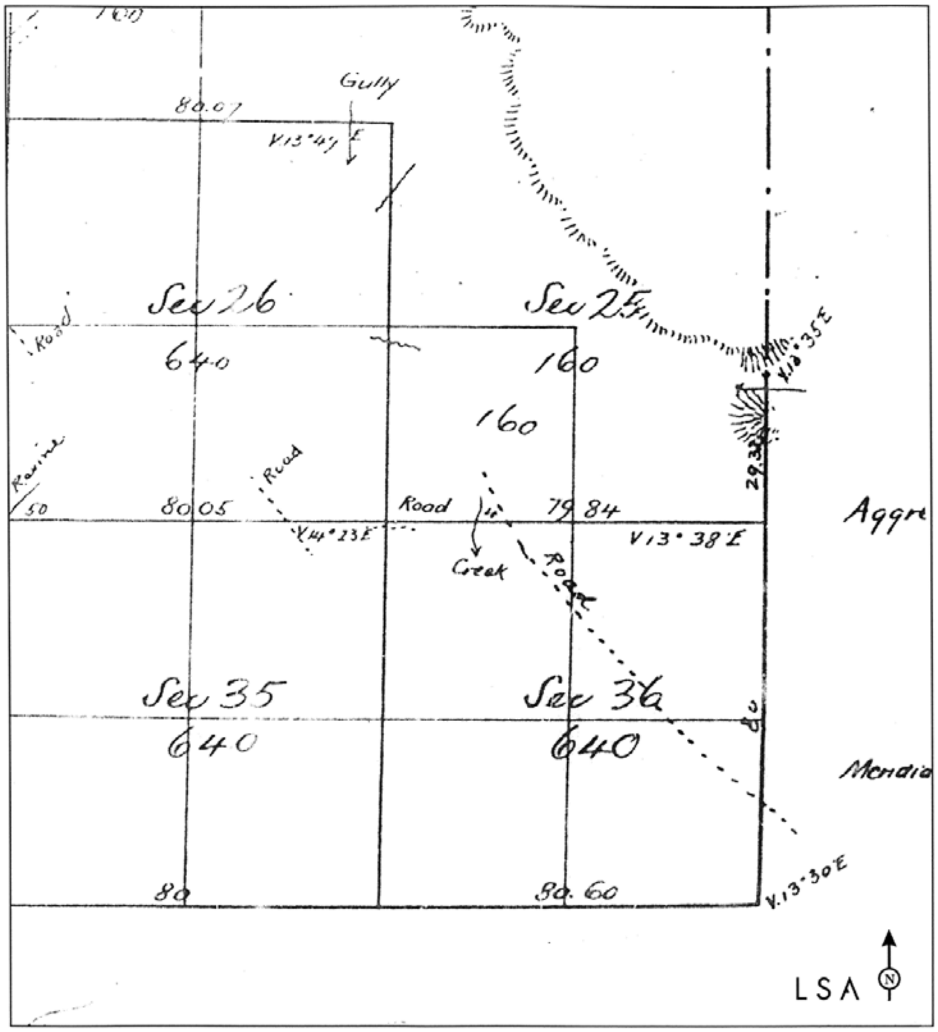

Figure 1. Bradshaw Road shown on 1875 topographic map.

The Bradshaw Road connected Santa Fe, New Mexico by way of Ehrenburg, through the Chuckwalla and Chocolate Mountains to Indian Wells, to Los Angeles, California. It is well known as a pre-railroad artery used for transporting eastern populations and commodities across the Southwest to California. This study was conceptualized while completing a cultural resources assessment near Banning, Riverside County, California. Map research had revealed that a small segment of the Bradshaw Road crossed the property in 1857 (Brunzell 2006; Government Land Office 1857). An earlier survey (see Brown and Selig 1972) identified and recorded the historic Highland Springs Resort (CA-RIV-90H) approximately one-quarter mile west of the assessment area's northwest corner. The resort, which continues to operate, was originally part of the Isaac Smith Ranch. The Smith Ranch consisted of land bought from Paulino Weaver in 1853, a Victorian house erected in 1854, and a stage stop on the Bradshaw Road known as Smith's Station (Robinson 2005: 106-107). A prehistoric component of the site consisting of several bedrock mortars was also recorded near the original house. The ranch was preceded by the so-called Rancho San Gorgonio (unconfirmed by Mexico), parsed out of former San Gabriel Mission holdings in 1843 (Robinson 2005). Although no physical trace of the actual route was observed, an extremely rusty leaf spring from a wagon seat was discovered within the assessment boundaries along the approximate alignment of the road. Although a solitary artifact has little data and can scarcely be unequivocally attributed to the road, it did encourage further research.

The road's general footprint is well documented and in places remains intact and accurately plotted, but much has been lost beneath modern development or destroyed by a combination of neglect, erosion, and overgrowth. It is this study's intention to transfer historic map data of the Bradshaw Trail between Needles and Los Angeles into Geographic Information Systems (GIS) format for easy and accurate reference. We have been able to reconstruct much of the route by connecting the dots between known stations and accurately plotted segments gleaned from historic maps (as in Figure 1 within the assessment boundaries), as well as recently plotted general route locations (see Figure 2). In addition to plotting the route more accurately, this study elucidates early road engineering and construction strategies across the western frontier, including but not limited to areas preferred or avoided due to instances of flooding or ambush.

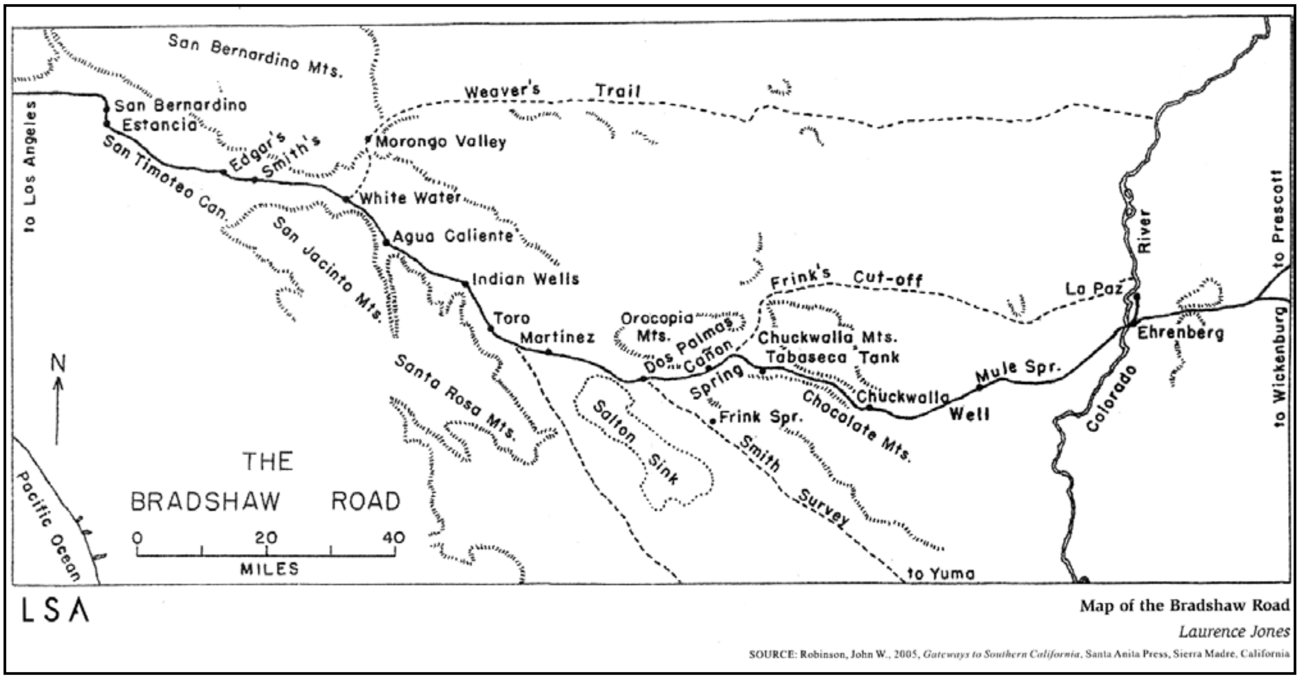

Figure 2. Map of the Bradshaw Road.

Acknowledgements

Thanks to Bill Bell, Historic Researcher, LSA Associates, Inc. for help with research and brainstorming, and to Margaret Gooding, M.A., Geographic Information Systems (GIS) Specialist for developing maps and showing me how GIS works.

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Recovering the endangered Mohave tui chub (*Siphatales bicolor mohavensis*)

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The Mohave tui chub (*Siphateles bicolor mohavensis*) of the minnow (Cyprinidae) family, the only native fish of the Mojave river system (Hubbs & Miller 1943), was listed as endangered October 13, 1970. A Recovery Plan, published Sept. 17, 1984, explained the extirpation of Mohave tui chub from the Mojave River as a result of hybridization with the arroyo chub (*Gila orcutti*). The Recovery Plan states, "[t]he exotic species of *Gila* invaded the Mohave River and subsequently hybridized with the Mohave tui chub. By 1970 genetically pure Mohave tui chubs had been eliminated from the river by hybridization and subsequent introgression." This assessment (Hubbs and Miller 1943, Miller 1969) was based on anatomical characters. More recent genetic analyses (Chen et al. 2006), however, found only genetically pure arroyo chub in the Mojave River, and genetically pure Mohave tui chub in the four extant populations at Zzyzx, the Naval Air Weapons Station at China Lake, and Camp Cady State Wildlife Area. Our present best estimate of the adult population size is approximately 1300 in Lake Tuendae (a man-made facility) and about 600 in MC Spring at Zzyzx, California. A recent estimate of 3,600 adult Mohave tui chub was determined for the population at Camp Cady (a man-made pond) near Newberry Springs. There may be 6000 Mohave tui chub at China Lake Naval Air Weapons Station at Ridgecrest, California but the confidence interval is large.

Abiotic factors may have contributed to the extirpation of Mohave tui chub from the Mojave River. Castleberry and Cech (1986) argue that physiological responses to high temperatures, rapidly fluctuating temperatures, and high flow velocities give arroyo chub a competitive advantage over Mohave tui chub in predator avoidance, feeding, and escaping stressful environmental conditions. Mohave tui chub, on the other hand, may have a competitive advantage in low temperature hypoxic conditions that typically occur in stratified lake environments, particularly during a winter freeze. Arroyo chub is a better swimmer than Mohave tui chub and thus less likely to be swept downstream and out on to the Soda Lake playa. In the flood-prone Mojave River the Mohave tui chub may have been frequently washed downstream to expire on the exposed terminal basin. A combination of hybrid infertility and greater tolerance of existing environmental conditions may explain the present existence of pure arroyo chub in the Mojave River drainage.

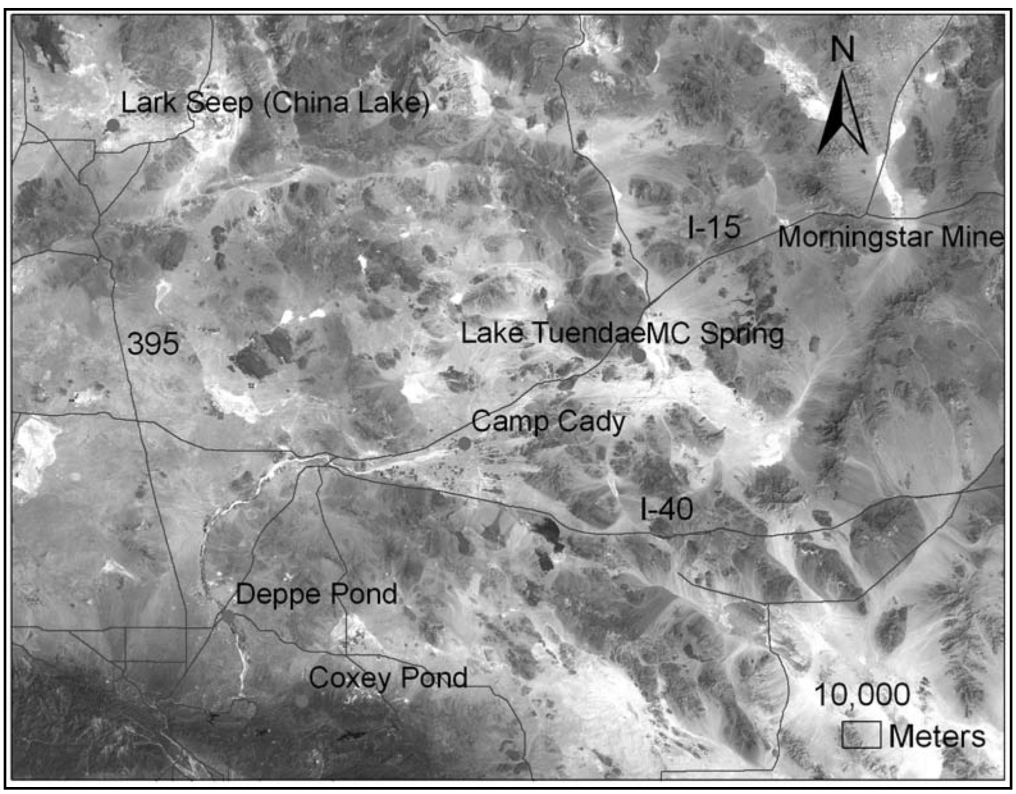

Figure 1. Populations of the Mohave tui chub.

Following a workshop at Zzyzx in 2003 (Hughson and Woo 2004), agencies and organizations including the National Park Service, California Department of Fish and Game, the U.S. Fish and Wildlife Service, the Desert Studies Center, and the Lewis Center for Educational Research began a major effort to improve the status of the species. Research was conducted on population status (Garron 2006), effects of the exotic Asian tapeworm (*Bothriocephalus acheilognathi*) (Archdeacon and Bonar 2006, Archdeacon 2007), and genetics (Chen et al. 2006). Research projects underway include a study of lake ecology and interactions with an introduced non-native mosquitofish (*Gambusia affinis*) (Henkanaththegedara, this volume) and a study to evaluate whether Mohave tui chub and arroyo chub produce viable hybrids and whether the first generation hybrids are morphologically similar to the presumptive hybrids identified by Hubbs and Miller (1943).

The Recovery Plan establishes thresholds for downlisting to threatened (establishment of six self-sustaining populations of at least 500 fish each) and delisting (establishment of viable populations in a majority of the species' historic habitat in the Mojave River drainage). Three new sites have been proposed for additional refuges: an existing pond (Deppe Pond) and a newly constructed pond at the Lewis Center for Educational Research in Apple Valley, the Morningstar Mine pit lake in Mojave National Preserve, and a pond created by a small dam on Coxey Creek in the San Bernardino National Forest. Reintroduction in an oxbow lake on the Upper Narrows of the Mojave River at the Lewis Center has also been proposed and may begin to move the species towards full recovery. Results of the lake ecology study (Henkanaththegedara, this volume) regarding competition with mosquitofish and a hybridization experiment at the Desert Discovery Center in Barstow will provide essential information to guide the reintroduction strategy. If Mojave tui chub and arroyo chub do not produce viable hybrids, then the consequences of hybridization can be discounted, potentially allowing for experimental introductions into the Mojave River.

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An archaeological and geological view of cupule production in an area of western Riverside County, California

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Abstract. An initial summary of cupule-associated sites and locations in southern California was published by Smith and Lerch (1984). There has been no serious update in the more than 20 years since then. Recent archaeological and geological research by LSA Associates, Inc. in western Riverside County has led to a new perspective on the processes that resulted in the formation of cupule-like depressions in the project area, and may have implications for academic research and cultural resources management in the rest of the Inland Empire, and beyond. Robert E. Reynolds's geological interpretation is that all cupule-sized depressions examined at three western Riverside County locations are natural—a result of subaerial erosion by percolation of acidic ground water at a pre-late Pleistocene time when granitic boulder outcrops of the Perris Block were buried under granitic gruss and colluvium. None of the purported cupules at these locations could be demonstrated to be cultural in origin, since the grains of quartz and feldspar in the cupule-sized depressions did not exhibit marks of abrasion. A quick review of other previously recorded "cupule" sites indicated that in some cases the depressions were in fact cultural, while in others they had resulted from the same or similar processes to those that operated in the three locations discussed here. This paper explores the questions: (1) can we define the processes by which cupule-like natural depressions were formed, (2) can we distinguish between natural depressions and cultural depressions, and (3) in the case of bona fide cultural cupules, have we added to our knowledge of who made the cupules and what were they used for?

Introduction

Small, shallow depressions referred to as "cupules" are often found on the "wave-shaped" faces of tonalite boulders throughout southern California, usually in relative association with prehistoric milling or habitation sites but occasionally in apparent isolation from other cultural traces. Similar shallow depressions that may be referred to as cupules are found throughout the world (Rau 1882).

The initial summary of cupule-associated sites and locations in southern California was published by Smith and Lerch (1984). They summarized, "All of the various ethnographic accounts in this region and around the world which relate to cupule rocks have in common the idea that there is some power embodies in the rock which can be tapped by making cupules." They also noted that "With one exception, Native American consultants contacted for this study had no specific knowledge of cupule features or their function, but all considered them significant and related them to the mythic past when 'the rocks were still soft,' and considered them to have been made by various culture heroes."

No further ethnographic evidence has been uncovered since 1984 and there has been no serious reassessment of the largely unfounded ceremonial assumptions since then. Recent archaeological and geological research by LSA Associates, Inc. at three possible cupule locations in western Riverside County, however, has led to a new perspective on the natural processes that resulted in the formation of cupule-like depressions in the study region. Our understanding of these processes, long understood by geologists but not previously applied to possible archaeological contexts, may have implications for cultural resources management in the rest of the Inland Empire, and beyond. The following paper explores the questions: (1) Can we explain the geological processes that created cupule-like depressions?, (2) Can We Distinguish Between Natural Depressions and Cultural Depressions?, and, (3) In the case of bona fide cultural cupules, who made the cupules and what were they used for?

1. Can we explain the geological processes that created cupule-like depressions?

Robert Reynolds's geological interpretation is that all cupule-like depressions examined at the project location were natural—the result of subaerial erosion by percolation of acidic ground water at a pre-late Pleistocene time when granitic boulder outcrops of the Perris Block were buried under granitic gruss and colluvium.

Reynolds's interpretation is that all depressions below the boulder lip (overhang) at the three locations were caused by the interaction of acidic ground water loosening mineral grains in the boulders while the now exposed faces *were buried underground* thousands of years ago. The approximate original ground level that covered the

Wave-shaped boulder in western Riverside County. Dashed line indicates former grade level.

now exposed face is calculated as being at the boulder lip. Reddish-brown iron and manganese oxides exposed below the lip suggest subaerial "armoring" of the boulder surface by ground water percolation while buried. After exposure of faces below the lip by erosion, exfoliation of the dark, armored surface produced "fresh" surfaces whose light color contrasts with the dark oxide coloration. None of the cupule-sized depressions at these three points were apparently made, used, or altered by cultural activity.

2. Can we distinguish between natural depressions and cultural depressions?

None of the purported cupules at these locations could be demonstrated to be cultural in origin, since the grains of quartz and feldspar in the cupule-sized depressions did not exhibit marks of abrasion. One cupule at Outcrop 7 had previously been proposed as "good" based on tactile exploration ("…hey, this one feels really smooth, it must be cultural") by a group of archaeologists. However, when examined with a 10x hand lens, the depression failed to show abrasion on exposed grains that would demonstrate cultural grinding or pecking.

In contrast, culturally produced smoothing on milling slicks near Outcrop 7 in the same study region show abrasion and fracturing of mineral grains (often referred to by ground stone specialists as "shearing"), and produce a surface orders-of-magnitude smoother than that inside the cupule-sized depressions. Furthermore, all of the cupules located at two other sites in the general area of the three locations mentioned above, one with approximately 200 cupules total and a second with approximately 10 cupules, do demonstrate trace evidence of grinding that are notable to the touch, the ground surfaces within the cupules are visible without magnification, and under magnification show that the mineral crystals have been sheared from the act of grinding: that is, they are the result of cultural grinding. In contrast, other sites rechecked by LSA since the development of the subsurface water filtration model explanation of the cupule-like depressions at Outcrop 7 present similar details of natural processes and not cultural behavior.

Most, if not all, of the cupule sites inventoried by Smith and Lerch (1984:11-15) and those identified since then by other researchers should be re-examined. The cupule-formation model presented here has significant implications for protecting Native American belief systems and the managing of southern California's prehistoric and protohistoric cultural resources.

3. In the case of bona fide cultural cupules, who made the cupules and what were they used for?

The ethnographic record for southern California cupules is extremely limited and at times misleading. For example, in Smith and Lerch's original publication (1984:6) there is an example of a young boy manufacturing a cupule as part of a puberty ceremony. The example is enticing until the reader realizes that the youth is using a jade adze (not part of the usual cultural inventory in southern California) and that the description was taken from Native American behavior in British Columbia (Teit 1900) some 1,500 miles away. There are no direct descriptions of cupule manufacture from southern California. Although there are more than two dozen published speculations regarding what they might have been used for, all are based on observations in other culture and culture areas.

Detailed descriptions of young girls' ceremonies in southern California appear to be extrapolated from the same two or three original observations and they deal with painting on bodies and rocks, not on the manufacture of cupules.

Summary

Why the apparent discrepancy between the lack of ethnographic description of cupule manufacture or use, and the number of reported cupule or cupule-like sites? The response to this query is a separate investigation and analysis, but in the current presentation we can summarize briefly in the following manner:

1. Many of the reported cupule-like sites probably are the result of natural rather than cultural processes;
2. Cupules have not been noted as being manufactured or used in southern California from the time of the first European visits in the 16th century to the present;
3. As mentioned earlier by True and Baumhoff (1981), there was a scarcity or absence of reliable ethnographic testimony regarding cupules. Our literature review

confirms that none of the early anthropologists and ethnologists (Rau 1881; Kroeber 1908, 1925; DuBois 1908; Sparkman 1908; Hooper 1920; Strong 1929; Harrington 1933; White 1963; Bean 1978; Oxendine 1979, 1983) or slightly later ethnographies (Cline 1984, Shipek 1991) mention cupule manufacture or use.

4. All analogies of cupule manufacture and use have been misapplied from non-southern California tribes to southern California tribes. As Robert Ascher noted (1961:317), analogy in its most general sense involves interpreting non-observed behavior through the medium of behavior that is considered comparable. Various limitations, such as selecting ethnographic groups within similar levels of ecological and social adjustment, have been attached to the technique to add rigidity to the comparative method, but utilization of observed behavior is still often ill-considered or unsophisticated. Such is the case with the vast majority of cupule analogies applied to southern California archaeological sites.

5. Anthropologists and archaeologists have contributed to the confusion by erroneously applying inappropriate ethnographic analogies to non-cultural tonalite boulder landscapes and by failing to involve geologists in the investigation of what are clearly multi-disciplinary investigations.

6. Based on lack of pertinent historic or ethnographic references, the legitimate cultural cupules almost certainly precede the European invasion of California. In such cases the ethnographic chain of evidence has been broken and it is not possible to determine if such sites had a secular or sacred function in the past.

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Charcoal sketches at El Pakiva, Mitchell Caverns State Recreation Area, Providence Mountains, California

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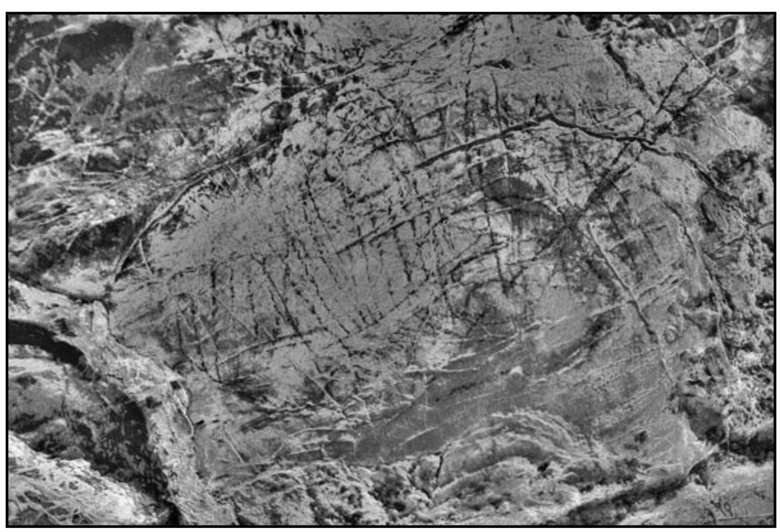
Of the various rock art production techniques, pigment stick application has not received sufficient attention. However, many sites have elements applied with a pigment stick and frequently the pigment is charcoal. Sticks and fires go together, yet charcoal drawings at rock art sites are not as common as one might presume, particularly at sites where this is the only application technique. As more and more sites are recorded, there is a larger basis for comparison. Now a newly recorded site at Mitchell Caverns State Recreation Area (Providence Mountains, Eastern Mojave Desert, California) offers an opportunity to shed some light and attention on this type of rock art.

In the smoke-blackened shelter of the entrance to El Pakiva, one of the four caverns located in the park, is a rock art site consisting solely of the pigment stick application of black charcoal lines. The motifs are abstract and mainly rectilinear, consisting of thin lines, cross-hatching, and grids. They are difficult to distinguish from the blackened ceiling and superimposed historic names, but they are indeed there and have yet to be described as part of the archaeological complex. The caverns were visited by Native Americans beginning as early as 500 AD and continued to be visited by Chemehuevi Indians through historic times. A hard-packed sterile floor separates two layers of midden for an indeterminate amount of time (Pinto, 1981). The layers of midden have yielded many well preserved artifacts due to the aridity of the caves. These artifacts, along with ethnography (Pinto, 1986), have led researchers to conclude that El Pakiva was considered by the Chemehuevi Indians to be a sacred and powerful place. The charcoal sketching may support this theory.

Examples of charcoal sketching have been described globally, from Brazil to France, Australia, Malaysia, (Guimaraes, 1992; Rouzaud, et al. 1994; David, et al. 1994; Faulstich, 1991), and the United States, among others. In the United States charcoal sketching can be found in the dark zones of caves in Tennessee and Kentucky (Faulkner, 1988; DiBlassi, 1987), in Navajo lands, where the Ute Raid Panel is well known as a depiction of a battle that occurred in 1858 (Grant, 1978), in the Great Basin (Thomas, 1983), and in California (Hyder, 1987; Hedges, 1989; Breschini, et al. 2004). Two ethnographic references to charcoal sketching have been reported in the literature. In one, a Navajo boy was observed “making a charcoal drawing on a rock,” leading these observers to question whether all or most Navajo rock art might be the work of children (Kidder, 1919). Another citation from northern New Mexico states that “the author was told that charcoal cross motifs on the cave ceiling were placed there as a prayer to keep the cave from collapsing” (Brugge, 1986).

A comparison of pigment stick sites found in California, Nevada, and Arizona shows little regional stylistic variation. Most pigment stick sketching is linear and abstract, including fine lines, crosshatching, grids, and zigzags. Many of these sites are attributed to recent times because when representational motifs do occur, they often include historic elements: figures on horseback, figures wearing western hats or dresses, and in one case, a clock. Other representational motifs include plant forms. The charcoal sketches from El Pakiva do not have any representational elements, but do resemble the style of drawings from the Paiute and the Havasupai from Arizona (Christensen and Dickey, 1998 and 2006). To the southwest of the Providence Mountains, the Kumeyaay and the Cahuilla territories both exhibit sites with similar charcoal sketching, and similar stylistic examples extend up the California coast, and throughout the Great Basin. Although the Providence Mountains are Chemehuevi territory in recent times, this area is said to be a central meeting place where tribes could meet and talk, not fight, and ideas could have been brought



The most noticeable pigment stick panel at El Pakiva.

The natural entrance to El Pakiva is on the left, and the pictographs cover the ceiling of the shelter on the right, now the current entrance to the cave tours offered at Providence Mountains State Recreation Area.

in (Felton Bricker, personal communication, 2008).

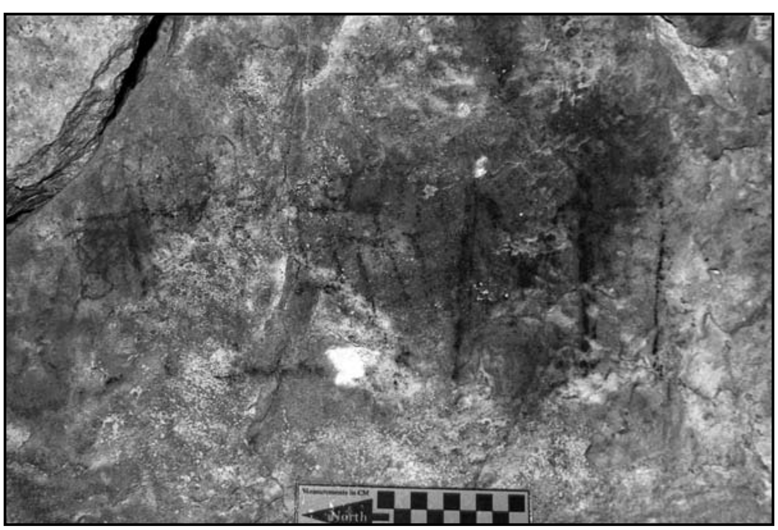
An ongoing rock art site documentation effort conducted by Don Christensen et al. lists approximately 89 painted sites in the East Mojave; 16.9% include pigment stick application along with other painted elements. Very rarely is pigment stick the only medium at a site (1.78%). (Near the south rim of the Grand Canyon, this number is 1%.) The overwhelming trend is that charcoal sketching is superimposed over other paintings. Where another style is well established and the pigment stick is superimposed over those elements, a later time frame is inferred.

Just how much later is not precisely known at this time. Accelerated mass spectrometry (AMS) is a process of dating charcoal in rock art panels and could one day give us an answer. Following the first publication of AMS dating (Van der Merwe, et al. 1987) several researchers have tested rock art panels from around the world (Clottes, 1996; David, 1992; Valladas et al. 1992) and in the United States (Armitage, 1997; Chaffee, 1994, Hyman and Rowe, 1997; Steelman, et al. 2004). "For charcoal pigments with the plasma-chemical oxidation sample pretreatment and then AMS, (results are) fairly reliable, within the limitations of calibration and sampling" (Armitage, personal communication, 2008). A benefit of AMS is that it requires a small sample size (approximately 2-4 mm) which can be procured from some panels fairly unobtrusively.

Several charcoal samples from the southwestern United Sates have been tested. A charcoal anthropomorphic figure from southeastern Arizona yielded a date of 2370 ±150 years BP when it was dated by plasma-chemical extraction and AMS radiocarbon dating (Steelman, et al. 2004). A black charcoal sample from a shield in Red Cliffs, Arizona, dates to 1080±100 years BP (Armitage, et al. 2000). An uncalibrated date for the All-American Man in Canyonlands came back 675±50 BP (Chaffee, 1994). Unfortunately, none of the sites tested match the style of the sketched charcoal lines discussed here. Until a sample is tested from charcoal sketching, the dates remain relative.

Why is this technique used and why is it used so late in the Mojave's rock art record? Pigment stick sketching is an easily accessible medium, and it could be used universally through time. Cave entrances provide reliable shelter and have been used by people throughout time. However, pigment stick sketching is not so common as to be considered simply gestural. It seems purposeful and definite, but not overly common. Christensen observes that Paiute panels that follow in this tradition lack compositional conception and motifs often seem to be random and superimposed over each other, possibly because "designs were added periodically over time." He notes that there is "a tendency to replicate rock art of earlier groups" and "earlier images are outlined or repainted." He concludes that pigment stick sketching seems to be more about image production than appearance (Christensen, 2007). Hedges also notes that "these lines often enclose or link elements in a panel" in Andreas Canyon and "most of the fine charcoal lines and drawings appear to be fully integrated into the rock art panels" made by other techniques (Hedges, 1989).

Native Americans have subsisted in the East Mojave Desert for millennia. In the 1540s Europeans began to explore the western region of the United States, introducing diseases that caused a drastic drop in native population. In 1776 Father Francisco Garces arrived, the first European to travel through the Mojave. He was the beginning of a wave of explorers and settlers to come through the area. The influx of foreigners created intense conflict between the native inhabitants whose livelihoods were dis-



Charcoal pigment stick sketchings appear behind larger letters at another site in the Providence Mountains. Photo enhanced.

turbed and the Europeans who had stepped in, also trying to utilize the land. Ultimately, the fighting greatly diminished by the 1870s and Native Americans began to work for mines and ranches. Profound decreases in indigenous population disrupting lifestyle, culture, and traditions that had been effective for so long. It is possible that earlier tradition surrounding rock art production was lost, and the knowledgeable people who fulfilled central roles were gone and the process had to be redeveloped in a world that did not welcome such practices. Given the geographic span and distinguishing characteristics of the charcoal sketching style, it was most likely in use for generations and developed into a tradition. Perhaps pigment stick sketching could be done properly in the confines of a new life and the Chemehuevi and other historic tribes adopted this technique, developing it into a new rock art tradition.

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Acknowledgements

I owe a depth of gratitude to the staff at Mitchell Caverns State Recreation Park for their cooperation in allowing me to record the pictographs at the entrance of El Pakiva. I am also indebted to David Lee for leading the recording project. Don Christensen was invaluable in providing me with unpublished reports and assistance along the way. This paper also could not have been completed without valuable comments from Felton Bricker and Ruth Ann Armitage. Many of my citations were found in the Rock Art Studies database published on-line at http://bancroft.berkeley.edu/collections/rockart/search.html. I cannot go without mentioning Leigh Marymor for lending me publications and for his patient editing.

A brief introduction to the intaglios of the Mojave Desert

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Intaglios, also known as geoglyphs or earthen figures, occur throughout the Mojave Desert from southern Nevada and Arizona to the Gulf of California, on both sides of the Colorado River. The most impressive figures surround the Lower Colorado River and have captured world-wide attention.

The Mojave Desert is the only place where figures of this type exist in North America. Other famous intaglios are found in Chile and Peru, and rock alignments are found in Australia. Intaglios are made on flat terraces by displacing the dark desert pavement to expose the lighter desert sand beneath. The pebbles pushed aside form a slight ridge on the outline of the figure. Native Americans tramped some of the designs in ritual dancing (Von Werlhof, 1987). The surface then hardened, hampering plant growth and animal burrowing, leaving the figures we see today. Other forms of earthen art include rock alignments, or lines of rocks, and cairns, piles of rocks. As of 1986, the count for intaglios was over 200 (Johnson, 1986).

The Blythe intaglios were the first to be rediscovered. In 1932 on a flight from Las Vegas, Nevada to Blythe, California George Palmer noticed the outline of a human figure that was over 100 feet long. The full figures are best viewed from the air, but still difficult to see. Malcolm Rogers of the San Diego Museum of Man began studying and recording earthen art soon after this and several other researchers followed him. In the 1940s National Geographic became interested and ultimately published an article about the Blythe intaglios in 1952. In the process of doing field work for this article, another cluster of more than ten intaglios was discovered, called the Ripley Group. In the 1960s several other people began to actively search for and record intaglios. In the forefront were Arda Haenszel of the San Bernardino County Museum and Julian Hayden from University of Arizona, Tuscon. In the 1970s, a farmer from Imperial County, Harry Casey, began a systematic search and study of intaglios and rock alignments. He later teamed up with Jay von Werlhof who published part of their systematic work on intaglios and rock alignments in the southwest, *Spirits of the Earth: A Study of Earthen Art in the North American Deserts*. Boma Johnson met von Werlhof and Casey, and in 1986 published an excellent summary that concentrates on the bigger, more figurative intaglios and their possible meanings, *Earth Figures of the Lower Colorado and Gila River Deserts: A Functional Analysis*.

The Blythe Intaglios are the most well-known and are found north of Blythe, California west of the Colorado River. Since National Geographic magazine first featured these figures in 1952, people began to visit these and other giant figures despite their remote location. In visiting, people began driving over the figures leaving tire track marks and threatening to obliterate the figures. The Bureau of Land Management subsequently built post and cable fencing to protect the Blythe Intaglios and Ripley Group images in 1974, and maintains a management program. To ensure public awareness and continued protection, a cooperative group consisting of the BLM, Imperial Valley College Museum, and Dorothy Gray of the California Native American Heritage Commission nominated intaglio sites to the National Register of Historic Places in 1982. This is an open-ended list so that when new sites are found they may qualify for the same protection (Johnson, 1986).

Figurative intaglios take the shape of huge anthropomorphic figures, mountain lions, birds, and rattlesnakes.

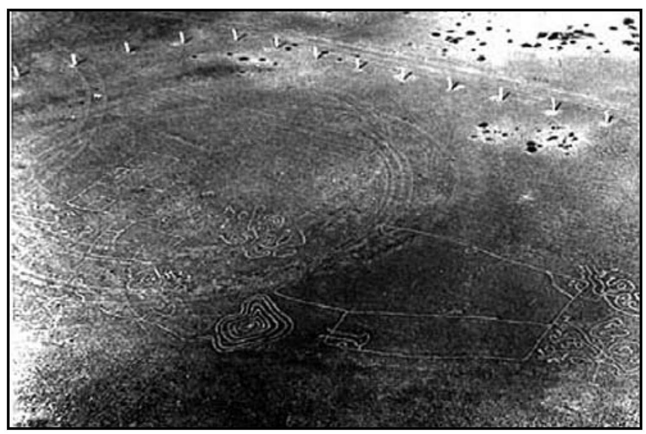

Figure 1. Yuha Plain. An example of a geometric intaglio. Image courtesy San Bernardino County Museum, Arda Haenszel Rock Art Photo/Slide Collection, SBCM A84-322.

Figure 2. A view of Topock Maze near Highway 40. Image courtesy San Bernardino County Museum, Arda Haenszel Rock Art Photo/Slide Collection, SBCM A84-322.

Figure 3. Fort Mojave. A pair of human figures, or "twins." Image courtesy San Bernardino County Museum, Arda Haenszel Rock Art Photo/Slide Collection, SBCM A84-322.

Others are more vague in shape, but are described with interpretive names that describe the shapes they resemble like spider, "serpent-like," lizard, or quail. Geometric patterns exist, too—stars, spirals, and patterns with long, curved and circular lines. A more involved one is called the "Maltese Cross." Intaglios may be alone at a site, or there may be a cluster of designs. Often trails intersect or pass by. Other features such as cleared circles, dance patterns, circles, rock alignments, or cairns are also associated with intaglios.

Many times two human figures are associated together, one incomplete, usually missing a head and an arm. These figures are referred to as twins. Johnson cites 16 sets of twins (Johnson, 1986). Ethnography collected by von Werlhof suggests that many intaglios are connected to the creation stories of surrounding tribes. In *That They May Know and Remember*, von Werlhof explains that the Yuman creation story takes four days to tell and few remain who are able to retell it. The twins could represent two original creative forms. The first, a creator named Kumat, warned his companion not to open his eyes underwater. The other believed Kumat was trying to trick him, opened his eyes, and was blinded. He is named Blind Old Man and his creations had webbed hands and feet. Another character named Kumastamho is one of the first babies conceived and born; his father was Kumat. Kumastamho also had creative powers. Together father and son created the Mohave, Quechan, Maricopa, Cocopa, and Kumeyaay people, and the four Pai societies (Havasupai, Walapai, Yavapai, and Pai Pai) (von Werlhof, 2004). Other twin sets may represent an evil giant named Haak Vaak, who was fond of eating children. Elder Brother steps in a kills Haak Vaak. This story is told by the Pima/Papago Indians of the Gila River Reservation in Arizona, but similar stories are told along both the Colorado and Gila Rivers (Johnson, 1986).

Intaglios may depict parts of the creation myth, but the act of creating them not only tells the story, it also renews it. Yuman groups retell creation stories through songs and the many dance patterns and dance circles near intaglios imply an interaction at the sites. Rocks are a permanent part of the world and figure into the origin myths of many people (von Werlhof, 2004). Johnson reminds us that modern Native Americans hold these places special and both the living and the dead use these sites in the spiritual world. In protecting them we protect spiritual balance.

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Distribution of native turtles in the arid southwestern United States with comments on *Kinosternon sonoriense*: a species presumed to be lost from California's herpetofauna

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Abstract. The United States has a rich diversity of 55 turtle species, rivaling that of virtually any country. Because of the aridity characterizing the Mojave Desert, Sonoran Desert, northern Baja California, and the Colorado Plateau regions of Arizona, California, and Mexico, only seven native species occur there. Three families are represented including the **Emydidae** or semi-aquatic pond and marsh turtles (Pacific Pond Turtle, *Actinemys marmorata*; Painted Turtle, *Chrysemys picta*; Ornate Box Turtle, *Terrapene ornata*), the **Kinosternidae** or mud turtles (Arizona Mud Turtle, *Kinosternon arizonense*; Yellow Mud Turtle, *K. flavescens*; Sonora Mud Turtle, *K. sonoriense*), and the **Testudinidae** or tortoises (Desert Tortoise, *Gopherus agassizii*). Over half of these species have broad ranges that just enter the area of interest but the Desert Tortoise, Arizona Mud Turtle, and Sonora Mud Turtle have ranges centered on the southwest. The Pacific Pond Turtle has a range focused along the Pacific versant, while the other species have ranges centered more in the humid central and eastern United States. The Sonora Mud Turtle disappeared from the fauna of California sometime after 1960, perhaps due to competition with the introduced Softshell Turtle (*Apalone spinifera*), predation by introduced fish, or because of changes in hydrology due to dam building in the Colorado River Basin. Turtles in the southwest include some of the best-studied species (e.g., Desert Tortoise And Painted Turtle), as well as some of the least-studied (especially the Arizona Mud Turtle).

Introduction

There are about 300 species of turtles in the world (Bickham et al., 2007). They occur on all continents and in all oceans except for in and around Antarctica. From oceans, rivers, and ponds to rugged mountains, humid jungles, and hot deserts, turtles have found a home in all but the coldest and most arid of climates (Hecnar, 1999).

The United States has one of the richest turtle faunas of any country with 55 native species (Ernst and Lovich, in press) and at least two well-established exotic species (Ernst et al., 1994). The greatest turtle diversity in the United States occurs in the Southeast (Buhlmann et al., 2008) with comparatively few species in the Southwest, especially in the Great Basin (Iverson, 1992a), a reflection of the aridity of the region. Despite the relatively low diversity and subsequent reduced research focus on turtles in the southwestern United States, several species are of interest and conservation concern. Our main purpose in this paper is to provide a brief review of the distribution of turtles in the Mojave and Sonoran Deserts in Arizona, California, and northern Mexico to increase awareness of a largely neglected element of biodiversity. We include turtle records from northern Baja California and the Colorado Plateau due to the arid nature of those adjacent regions. We also discuss the apparent disappearance of the Sonora Mud Turtle (*Kinosternon sonoriense*) from California's fauna, the only turtle species extirpated from a range state in our focus area during historical times. We do not attempt to present and synthesize all of the available literature on southwestern turtles but provide a general overview of their current distributions in the region. The reader is referred to Ernst et al. (1994) and Ernst and Lovich (in press) for the most recent synopses of the ecology, conservation, and fossil records of turtles in the United States.

Materials and methods

We compiled the list of species in the region from distribution maps presented in Iverson (1992b). We compiled museum records using HerpNET (http://www.herpnet.org), an online resource with 53 participating natural history museums listing over 5.5 million specimens. Since the Ornate Box Turtle (*Terrapene ornata*), Sonoran Mud Turtle (*K. sonoriense*), and the Desert Tortoise (*Gopherus agassizii*) are well represented in collections, we include museum records for only the other, more poorly represented species. Exact locality data for museum specimens are not included in this paper, and the following tables use the output as generated by HerpNet. We searched all museums currently listed under HerpNet and collection acronyms follow those posted on HerpNet: CAS—California Academy of Sciences; LACM—Natural History Museum of Los Angeles County; MPM—Milwaukee Public Museum; SDNHM—San Diego Natural History Museum; TCWC—Texas Cooperative Wildlife Collection, Texas A & M University; UAZ—Amphibian and Reptile Collection, University of Arizona; USNM—United States National Museum (Smithsonian). Taxonomy follows Crother (2000) and updates (Crother et al., 2003) as does common name usage.

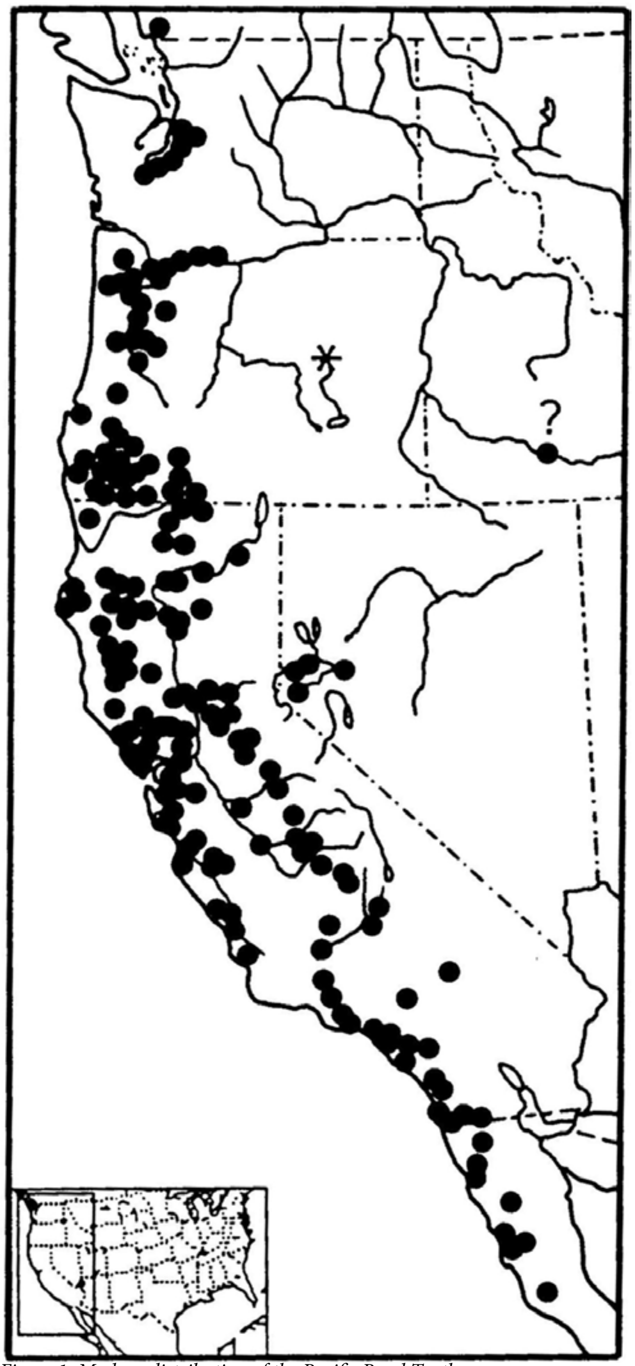

Figure 1. Modern distribution of the Pacific Pond Turtle.

Results

Seven species of turtles representing three families (Emydidae, Kinosternidae, and Testudinidae), and five genera are found in the region of treatment. One species, the Painted Turtle (*Chrysemys picta*), has a distribution in the United States that is primarily eastern with a narrow western extension. The Ornate Box Turtle (*Terrapene ornata*) and Yellow Mud Turtle (*Kinosternon flavescens*) are primarily midwestern species and the Pacific Pond Turtle (*Actinemys marmorata*) is primarily far western. The remainder, including the Desert Tortoise (*Gopherus agassizii*), Arizona Mud Turtle, (*Kinosternon arizonense*) and Sonora Mud Turtle (*K. sonoriense*) are primarily southwestern in their distribution.

FAMILY EMYDIDAE

Actinemys marmorata (Pacific Pond Turtle, formerly *Clemmys marmorata*)

The Pacific Pond Turtle has a long but narrow modern distribution in freshwater (and occasionally brackish) wetlands between the Pacific coastline and the Sierra-Cascade Crest, from northern Baja California, Mexico to Puget Sound, Washington and, formerly, southern British Columbia (Figure 1). Despite this largely Pacific versant distribution, the species ranges into the dry interior of the Great Basin and Mojave deserts in a few locations, including records in the Truckee, Carson, and possibly Humboldt rivers in Nevada, the Columbia Gorge of Washington, and the Mojave River in San Bernardino County, California (Ernst et al., 1994; Ernst and Lovich, in press). In Baja California, the species occurs as far south as Arroyo Grande (Grismer, 2002). The peripheral range of the species may reflect use and translocation by Native Americans due to the presence of pond turtle remains in archaeological sites (Schneider and Everson, 1989).

Fossil remains of *A. marmorata* have been identified from Pliocene (Blancan) and Pleistocene (Irvingtonian, Rancholabrean) deposits in California (Ernst et al., 1994), including the Mojave Desert for the latter (Jefferson, 1968).

Lovich and Meyer (2002) studied the ecology of Pacific Pond Turtles at Camp Cady and Afton Canyon along the Mojave River and reported that these populations exhibit few adaptations that differentiate them from populations occurring in more mesic coastal environments. A notable exception was the fact that terrestrial estivation and hibernation, commonly observed in coastal populations, were not observed in the desert, an obvious response to hyperaridity. A single specimen from Montezuma Well, Yavapai County, Arizona in 2007 (Lovich, unpublished) is likely a result of human introduction, as non-native Red-eared Slider Turtles (*Trachemys scripta elegans*) are also found at the site.

Table 1 contains a partial list of museum records for *A. marmorata* from the area of study. All of the California records are from the Mojave River downstream from Barstow.

Table 1. Selected museum records of *Actinemys marmorata* from the Mojave Desert of California and Baja California.

Institution	Catalog number	Country	State/Province	County	Year collected
LACM	7997	USA	California	San Bernardino	1937
SDNHM	17135	USA	California	San Bernardino	1937
SDNHM	17136	USA	California	San Bernardino	1937
SDNHM	19222	Mexico	Baja California Norte		1957
SDNHM	43635	Mexico	Baja California Norte		1958
SDNHM	46798	Mexico	Baja California Norte		1966
LACM	105322	Mexico	Baja California		
LACM	105323	Mexico	Baja California		1960
UAZ	UAZ 22057	Mexico	Baja California Norte		1952

Chrysemys picta (Painted Turtle)

The Painted Turtle is the only native species of turtle in the United States whose natural distribution is transcontinental, extending from the Atlantic to the Pacific coasts. Their range extends west of the northern Rocky Mountains through Montana, Idaho and into Washington, Oregon and southern British Columbia. Farther south, relict populations and records are reported from restricted portions of southern Utah, Arizona, New Mexico, and Colorado (Figure 2), all of which are represented by the Western Painted Turtle, *C. p. bellii*. The southernmost distribution of the taxon is in northern Chihuahua in the lower portion of the internally draining Rio Santa Maria (Smith and Smith, 1979), and possibly the Rio Grande (Smith and Smith, 1979; Iverson, 1992b).

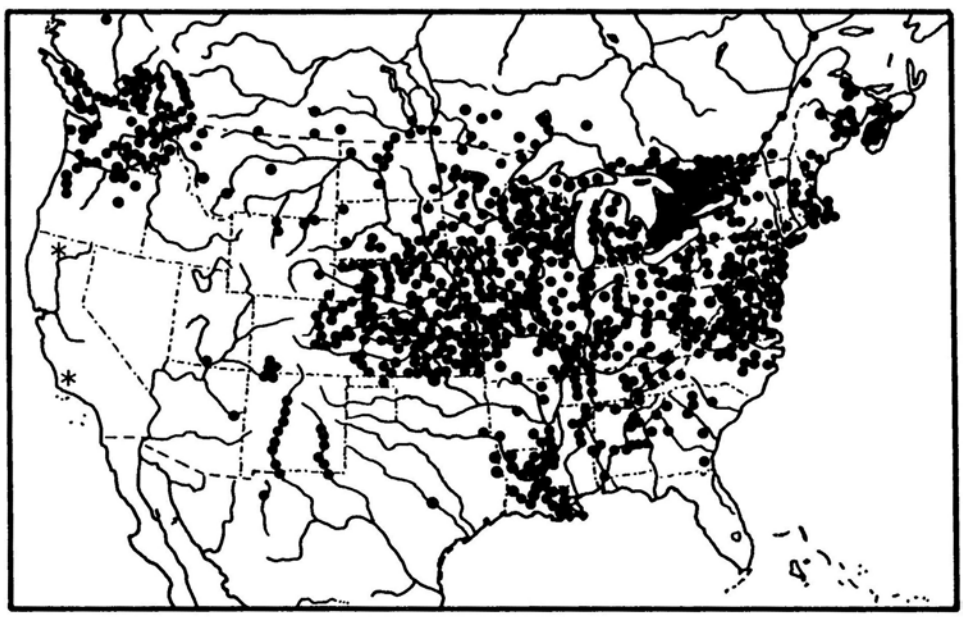

Figure 2. Modern distribution of the Painted Turtle.

Brennan and Holycross (2006) state: “Populations in Apache County [Arizona] near St. Johns and Concho might be native” without providing additional details. As recently as 2007, Charles Drost (USGS, pers. comm.) found the shells of two individuals near Lyman Lake, Apache County, Arizona. Given the existence of other populations at various locations throughout the arid western United States and Mexico, it is likely that Painted Turtles are native to Arizona. Early records of *Kinosternon* from southern Utah that were likely Painted Turtles (Iverson, 1978) support this hypothesis. Individuals occurring in and around Phoenix and Tucson, Arizona (including the photographic record from the Tucson area in Table 2–UAZ 55305) are considered released pets. The presence of native Painted Turtles in the San Juan River Basin of northwestern New Mexico (Degenhardt et al., 1996) and southeastern Utah (Iverson, 1978) may explain the occasional reports of this species on the Colorado Plateau in the Lake Powell region. Drost et al. (in press) summarized literature records (primarily from Woodbury, 1959) for the Lake Powell region including Labyrinth, Face, and Rock Creek canyons. The former two canyons straddle the Arizona/Utah state line with their mouths only 1–2 miles north of Arizona. The latter is contained fully in Utah. Drost et al. concluded that painted turtles occurred in the Colorado River in Glen Canyon prior to the construction of Glen Canyon Dam (the dam that impounds Lake Powell) with none documented since completion of the dam in 1963. Table 2 lists museum records for Arizona.

Nothing is known of the ecology of this species in Arizona where it occurs primarily in the vicinity of the White

Table 2. Selected museum records of *Chrysemys picta* from Arizona.

Institution	Catalog number	Country	State/Province	County	Year collected
UAZ	UAZ 55305-PSV	USA	Arizona	Pima	2002
CAS	188541	USA	Arizona	Apache	1988
CAS	188542	USA	Arizona	Apache	1988

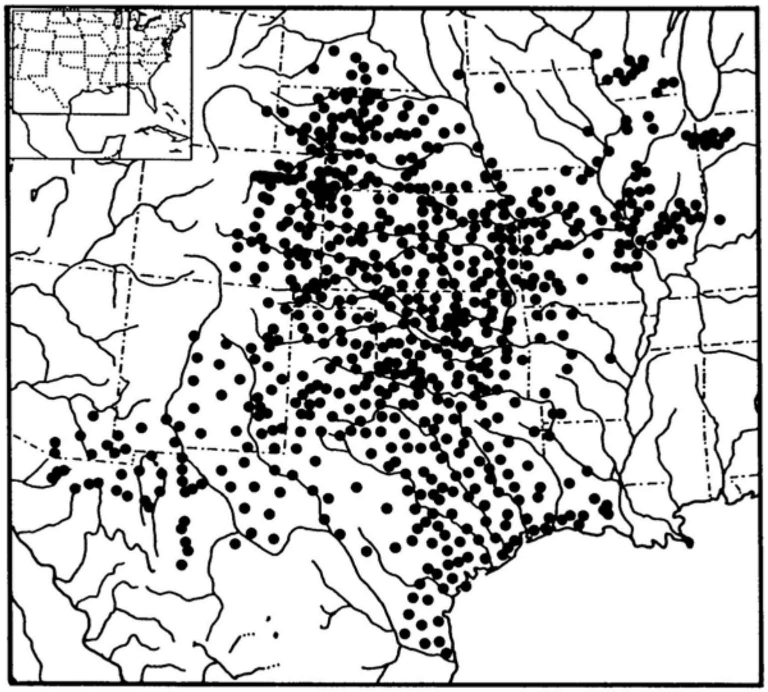

Figure 3. Modern distribution of the Ornate Box Turtle.

Terrapene ornata (Ornate Box Turtle)
Desert Box Turtles (*T. ornata luteola*) reach their westernmost distribution in southeastern Arizona and northern Mexico (Figure 3), mostly in semidesert grasslands, Chihuahuan desertscrub, lower Madrean evergreen woodland, and rarely in sky island mountain ranges (Brennan and Holycross, 2006) to about 2,200 m elevation (Brennan and Feldner, 2003). Arizona records exist for Cochise, Gila, Pima, Pinal, Santa Cruz, and Graham counties. The records from Navajo County (Petrified Forest) and Maricopa County probably represent released captives.

Pleistocene fossil material and recent archaeological material is known from Arizona (Ernst et al., 1994). The Ornate Box Turtle is well studied and several recent publications document the ecology and behavior of this species in Arizona (Plummer, 2003, 2004; Plummer et al., 2003).

Mountains at the periphery of the arid region covered in our paper (except for the Lake Powell records). Although represented by fossil material throughout the eastern United States, we know of no records closer to the Southwest than Texas (Ernst et al., 1994).

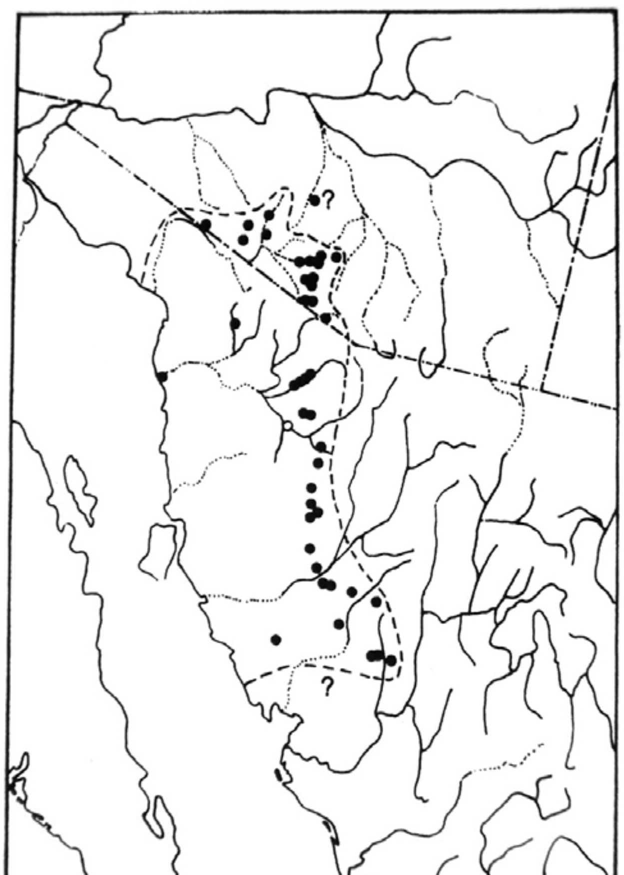

Figure 4. Modern distribution of the Arizona Mud Turtle.

FAMILY KINOSTERNIDAE

Kinosternon arizonense (Arizona Mud Turtle)
The majority of the range of the Arizona Mud Turtle is in Mexico with the northern limit barely extending into southern Arizona (Figure 4). It occurs from Pima County southward into Sonora, where it is confined to the watersheds of the Rio Sonoyta, Rio Magdalena, Rio Sonora, and northern portions of the Rio Matape and Rio Yaqui (Houseal et al., 1982; Iverson, 1978, 1989). *K. arizonense* occurs mostly at elevations of 200–800 m, but occasionally ranges to 1,050 m in Pima County, Arizona. Formerly considered to be a subspecies of the more wide-ranging Yellow Mud Turtle (*Kinosternon flavescens stejnegeri* and later *K. f. arizonense*), Iverson (1989) demonstrated that *K. arizonense* was a distinct species first described from fossils (see below). Subsequent analysis of mtDNA control region sequences provided additional support for the recognition of *K. arizonense* as a distinct species (Serb et al., 2001).

Kinosternon arizonense was originally described from Pliocene (Blancan) fossils found in Cochise County, Arizona (Gilmore, 1922). This distinction makes it the only living turtle species in the United States that was known from fossil material and type specimens first, a coelocanth among turtles! A Pleistocene (Rancholabrean) record of *K. arizonense* was also reported from Sonora, Mexico (Van Devender et al., 1985).

Based on a paucity of published papers, this is the most poorly known turtle species in the United States (Ernst and Lovich, in press). Table 3 presents a compilation of museum records (the record from Maricopa County is likely a *K. sonoriense*). Prior to 1981, *K. arizonense* was known from only seven localities in southern Arizona and 14 localities in Sonora, Mexico. Forty-four new localities are listed by Iverson (1989).

Table 3. Selected museum records of *Kinosternon arizonense* from Arizona.

Institution	Catalog number	Country	State/Province	County	Year collected
UAZ	UAZ 27949	USA	Arizona	Pima	1961
UAZ	UAZ 27950	USA	Arizona	Pima	1959
UAZ	UAZ 27954	USA	Arizona	Pima	1958
UAZ	UAZ 27955	USA	Arizona	Pima	1960
UAZ	UAZ 27964	USA	Arizona	Pima	
UAZ	UAZ 31739	Mexico	Sonora		1969
UAZ	UAZ 31740	Mexico	Sonora		1969
UAZ	UAZ 33581	USA	Arizona	Pima	1965
UAZ	UAZ 35394	USA	Arizona	Pima	1961
UAZ	UAZ 35395	USA	Arizona	Pima	1961
UAZ	UAZ 43037	Mexico	Sonora		1979
UAZ	UAZ 44250	USA	Arizona	Pima	1980
UAZ	UAZ 49433	USA	Arizona	Pima	1992
UAZ	UAZ 51809	USA	Arizona	Pima	1997
UAZ	UAZ 56581-PSV	USA	Arizona	Maricopa	2006

Kinosternon flavescens (Yellow Mud Turtle)
The Yellow Mud Turtle exhibits a more southerly midwestern distribution in the United States, from Nebraska southward, and then extending eastward in relict populations within the Prairie Peninsula. South of Texas it extends into northeastern Mexico (Figure 5). Within this range, it has been reported to elevations of about 1,500 m. This species' range barely extends into the southeastern corner of Arizona. Brennan and Holycross (2006) depicted the distribution in Arizona to include Cochise and Graham Counties where the turtle lives in ponds and slow moving water in Chihuahuan desertscrub and semidesert grasslands. It is not found in either the Colorado or Gila River Basins of Arizona (Iverson, 1978) despite misidentifications (usually of *K. sonoriense*) in the literature suggesting so (e.g., Vitt and Ohmart, 1978). Because *K. arizonense* was formerly recognized as a subspecies of the wide-ranging *K. flavescens*, differentiating the two species in the literature in Arizona is difficult without examining specimens or obtaining exact locality data.

Within the area of treatment, Pleistocene (Rancholabrean) fossil material is known from Sonora, Mexico (Van Devender et al., 1985). This species is well studied in the Midwest (but not in the Southwest) and the reader is referred to Ernst et al. (1994) for further details on their biology.

Kinosternon sonoriense (Sonora Mud Turtle)
The Sonora Mud Turtle (Figure 6) occurs primarily in the Sonoran Desert, as its name suggests. The range of this turtle is shared almost equally by Arizona and Sonora, Mexico (Figure 7), with a slight extension into western Chihuahua. In the United States, records are known or reported from Arizona, extreme southeastern California, extreme southern Nevada, and New Mexico. The *K. flavescens* record mentioned by La Rivers (1942) from along the Colorado River in Clark County, Nevada is probably based on a specimen of *K. sonoriense* (Iverson, 1978). We are not aware of any later records of any species of *Kinosternon* from Nevada.

The Sonora Mud Turtle occupies a variety of habitat types in rocky streams, rivers, cattle tanks, and ponds from Lower Colorado River desertscrub to Petran montane conifer forest (Brennan and Holycross, 2006), especially along the Mogollon Rim of Arizona. The reported elevational range is 43–2,040 m (Jennings and Hayes, 1994). Ongoing research at Montezuma Well in Yavapai County, Arizona demonstrates that *K. sonoriense* populations have the ability to thrive even in chemically challenging environments incapable of sustaining fish (Lovich, Drost, Casper, and Monatesti, unpublished). Springs arising out of limestone formations at this locality are heavily charged with calcium carbonate, producing water high in dissolved CO_2. An impoverished aquatic invertebrate fauna, with several

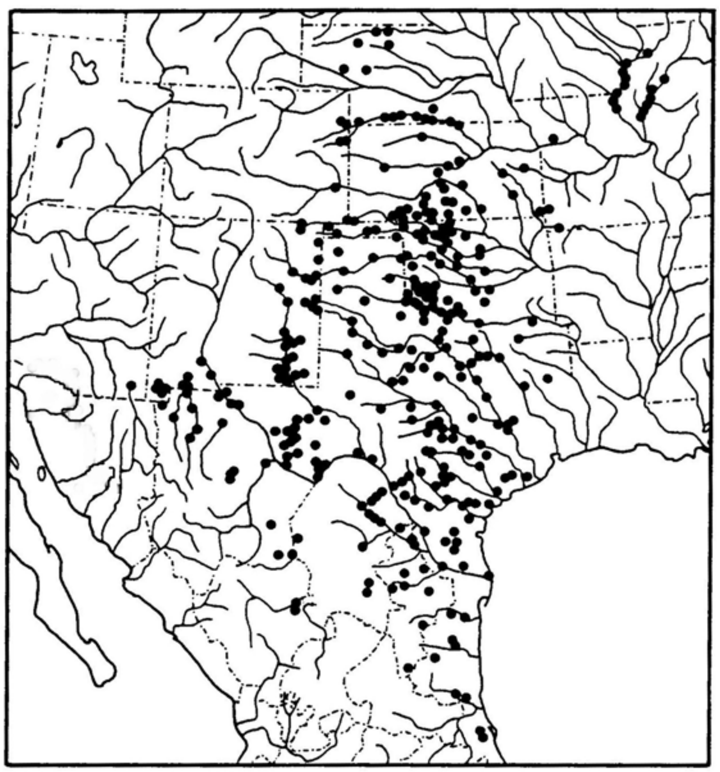

Figure 5. Modern distribution of the yellow mud turtle.

Table 4. Selected museum records of *Kinosternon flavescens* from the Arizona. Only records from Cochise and Graham Counties are included. Other county records in museums likely represent *K. sonoriense* or *K. arizonense*.

Institution	Catalog number	Country	State/Province	County	Year collected
UAZ	UAZ 27953	USA	Arizona	Cochise	1952
UAZ	UAZ 50637	USA	Arizona	Cochise	1994
UAZ	UAZ 50638	USA	Arizona	Cochise	1994
UAZ	UAZ 50639	USA	Arizona	Cochise	
TCWC	72419	USA	Arizona		1992
USNM	55627	United States	Arizona	Graham	1898
USNM	55628	United States	Arizona	Graham	1898

Figure 6. Sonora Mud Turtle.

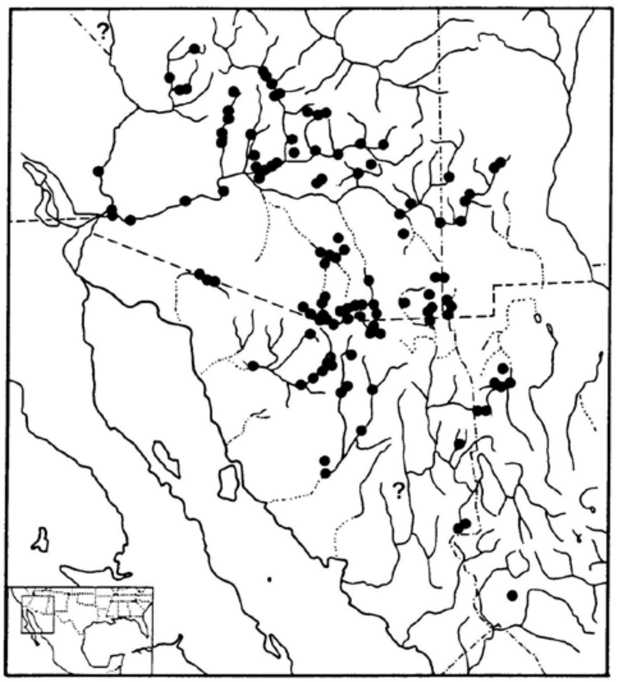

Figure 7. Modern distribution of the Sonora Mud Turtle.

endemic species, presents an unusual array of food items and diet studies are currently in progress at the site.

The available evidence suggests that Sonora mud turtles were never widespread in California. Sporadic records exist along the length of the Colorado River, mostly in Imperial County. Historical documentation of this species in California is summarized by Jennings and Hayes (1994). Records for *K. sonoriense* in California appeared in various publications from 1870 to the early 1900s. The earliest museum records we located were for two specimens collected in 1912 in Imperial County. Another was collected at Palo Verde in 1917. Subsequently, specimens were collected at Bard (1941) and Calexico (1942) according to data from museum specimens. According to Jennings and Hayes, the last two were collected along irrigation canals, implicating humans in the role of temporarily extending the range of this turtle away from the marshes and oxbows that likely constituted their natural habitat along the Colorado River. One of the last published records for this species in the extreme lower Colorado River was based on an observation 1.6 km southwest of Laguna Dam in a canal on the Arizona side of the river on 31 March, 1962 (Funk, 1974), as summarized by Jennings and Hayes (1994). This appears to be the same specimen reported by Vitt and Ohmart (1978) with locality data listed as "N Gila E main canal, 1.0 mile SW Laguna Dam" since it was in the collection of Richard S. Funk.

The Sonora Mud Turtle may be extirpated in California (Palermo, 1988). Efforts to sample this species with fyke nets during April and May, 1991 were unsuccessful, resulting in the capture of non-native Texas Spiny Softshell Turtles (*Apalone spinifera emoryi*) only, according to information summarized in Jennings and Hayes (1994). The authors concluded that the species was endangered. The exact reasons for the disappearance of *K. sonoriense* from California are unknown. Certainly, California occurs at the margin of this species' wide distribution, but habitats along the Colorado River prior to human modification likely provided good conditions for this species based on our knowledge of their requirements. Introduction of exotic species, especially predatory fish (Mueller and Marsh, 2002) and possibly softshell turtles (Jennings and Hayes, 1994), may have been a factor. Jennings and Hayes suggest that widespread riparian habitat changes along the Colorado River were responsible. Certainly, the Colorado River is considered to be one of the most regulated rivers in the world (Blinn and Poff, 2005; Gloss et al., 2005; Mueller and Marsh, 2002), and completion of Hoover Dam in 1936 and Glen Canyon Dam in 1963 resulted in major changes to hydrology and subsequently riparian habitat, possibly to the detriment of this species (Iverson, 1978).

Pleistocene (Rancholabrean) fossils are known from Arizona and Sonora, Mexico (Moodie and Van Devender, 1974, Van Devender et al., 1985). Although several excellent studies have been published for this species (Hulse 1974; 1976a, b; 1982), it remains poorly studied and more research is needed both the United States and Mexico.

Since this species is represented by hundreds of museum specimens, a complete list is beyond the scope of our paper.

FAMILY TESTUDINIDAE

Gopherus agassizii (Desert Tortoise)

This is the quintessential turtle of the southwestern United States. The Desert Tortoise is widely distributed throughout most of the Mojave and Sonoran Deserts of California, Arizona, and northern Mexico, ranging northward into southern Nevada and southwestern Utah (Figure 8). In California, the Desert Tortoise typically occurs in valleys and on bajadas, while those in Arizona tend to occupy rocky hill slopes in Sonoran upland habitat. Populations on either side of the Colorado River usually exhibit significant behavioral, ecological, morphological and genetic differences (but see McLuckie et al., 1999 for an exception in the Black

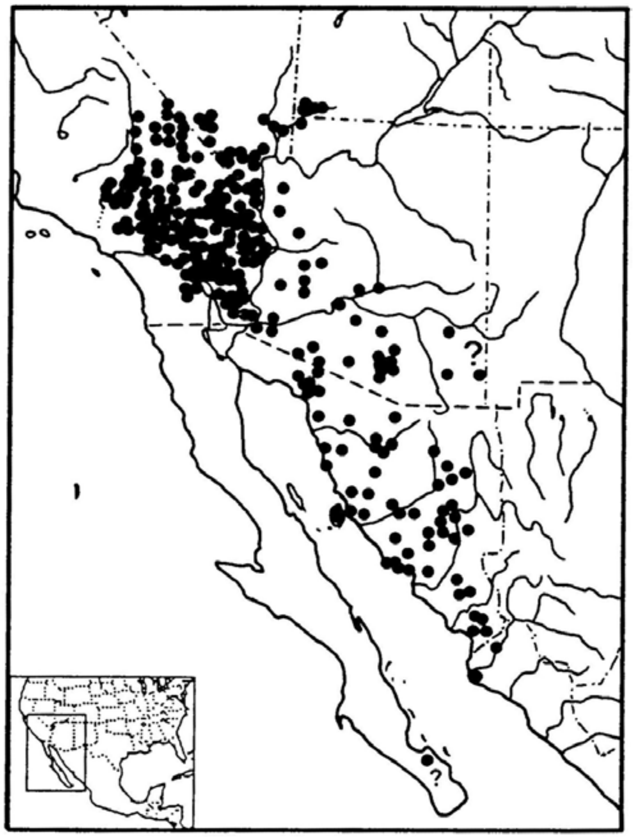

Figure 8. Modern distribution of the Desert Tortoise.

Mountains of Arizona). Throughout their broad latitudinal distribution (about 1,000 km from north to south—fully half of the latitudes occupied by turtles in North America: Hecnar, 1999), Desert Tortoises occupy an extensive array of habitats including tropical deciduous forest, thornscrub, desertscrub, and occasionally desert grasslands. They rarely occur above elevations of 1,600 m. Populations west and north of the Colorado River are protected as Threatened under the Endangered Species Act.

Pliocene (Blancan) and Pleistocene (Irvingtonian and Rancholabrean) remains have been recovered in California and Arizona along with more recent remains at archaeological sites (Ernst et al., 1994; Schneider and Everson, 1989). McCord (2002) provides a review of fossil history and evolution of *G. agassizii*.

This is the second best-studied turtle in the United States, as measured by the number of scientific publications, and the reader is referred to Ernst et al. (1994) and Ernst and Lovich (in press) for a review of their voluminous literature. This turtle is well represented in museum collections (but not necessarily from the lower Colorado River region according to Vitt and Ohmart, 1978) and for that reason, a list of specimens is not provided. Details on the range and habitats of the desert tortoise are provided by Germano et al. (1994.).

Discussion

The depauperate turtle fauna of the desert southwestern United States is not unexpected due to the aridity of the region. Semi-aquatic and aquatic organisms are obviously limited by the availability of wetlands and this is mirrored by similarly reduced fish and amphibian biodiversity in the Southwest, relative to the humid east. In an analysis of global correlates of species richness in turtles involving 12 environmental variables (including latitude, temperatures and basin area and discharge), only annual rainfall was highly significant (Iverson, 1992c).

Although rivers and other wetlands in the region have been altered, depleted, or eliminated by human activities, others have been created through construction of impoundments from the scale of cattle tanks to huge impoundments like Lakes Mead and Powell. Anthropogenic water sources do not appear to have contributed to an increase in the range or population size of native turtles in the Southwest with the possible exception noted above for Sonora Mud Turtles utilizing irrigation canals and possibly cattle tanks. In contrast, several non-native species appear to flourish in anthropogenic waters, especially the Red-Eared Slider now found in most artificial wetlands in the Phoenix and Tucson metropolitan areas (Lovich, pers. obs.), and the Texas Spiny Softshell Turtle, introduced into the Gila River of Arizona or New Mexico in the early 1900s (Linsdale and Gressitt, 1937), probably before 1904 (Miller, 1946).

We still have much to learn regarding some of the turtle species in the Southwest. A recent review of the literature of turtles in the United States and Canada (Ernst and Lovich, in press) provides an assessment of our knowledge of the 55 species currently recognized. The number of references in one of the authors' bibliographic database (Lovich, unpublished) provides a rough metric for assessing the status of our knowledge based on the number of citations for each species (shown in brackets). Accordingly, *Gopherus agassizii* [373] and *Chrysemys picta* [363] are the second- and third- best-studied turtles in the United States (first place goes to *Trachemys scripta* [418]). *Kinosternon arizonense* [3] is the least-studied, followed by *K. sonoriense* [25], and the other turtles in our area of treatment (*Actinemys marmorata* [89], *K. flavescens* [54], and *Terrapene ornata* [82]) are moderately to well-studied. The southwestern United States and northern Mexico still hold numerous opportunities for researchers and graduate students interested in turtle ecology and systematics.

Acknowledgements

Special thanks to Carol Spencer, acting curator of herpetology at the Museum of Vertebrate Zoology, University of California, Berkeley and HerpNET coordinator, for assistance with the HerpNet searches. Rick Feeney of the Natural History Museum, Los Angeles County also assisted with museum record retrieval. Earlier versions of the manuscript benefitted from the insightful reviews of Charles Drost, Mark Sogge, and Whit Gibbons.

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New pterosaur tracksites from the Upper Jurassic of central Utah: a regional *Pteraichnus* facies in marginal marine and non-marine shoreline environments

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Abstract. Recently identified pterosaur tracks (cf. *Pteraichnus*) from the Summerville, Stump, and Morrison formations (Fig. 1) of central Utah add to the growing record of *Pteraichnus* tracksites in the Late Jurassic of North America. Rocks deposited during the Late Jurassic throughout much of Utah record the final retreat of the Sundance Seaway. Pterosaur tracks in these rocks are distributed around the margins of the broadly defined Sundance Seaway in units deposited in shallow-marine through continental environments. It is interpreted here that *Pteraichnus*-dominated assemblages in western North America are concentrated in shoreline environments, and that the presence of *Pteraichnus* is a good indicator of a shoreline depositional setting.

Purpose

The purpose of this study is to provide an overview of Upper Jurassic marginal-marine shoreline pterosaur tracks from an ichnofacies perspective. Pterosaur tracks in marginal marine and continental settings are concentrated in lithofacies that are interpreted to have been deposited in shoreline environments. Previous studies have identified, with a high degree of certainty, the types of depositional environments represented by the rocks at various locations. Because the depositional environments of these rocks are well understood, information about the presence or absence of different types of trace fossils in different lithofacies can be used to identify specific trace fossils that are strongly correlated with the depositional environment. In this study, the consistent association of *Pteraichnus* with rocks deposited in shoreline environments, and the absence of pterosaur traces in rocks deposited in other environments, is interpreted to indicate that the presence of *Pteraichnus* can be used as an indicator of shoreline settings.

Descriptions

Three new localities described as part of this study can be used to document the characteristics of an extensive and complex *Pteraichnus* ichnofacies. Analysis and interpretation of the field data rests on one fundamental concept and two definitions of terms in ichnology, all of which are relevant to ichnofacies studies. As stated by Bromley and Asgaard (1991), Lockley and Hunt (1995), Bromley (1996), McIlroy (2004), and Hunt and Lucas (2007), the paleoenvironment of marginal marine and non-marine sediments can be interpreted by investigating lithology, primary sedimentary structures, and faunal elements. Trace fossils and associations of trace fossils, owing to their autochthonous nature, are particularly useful in paleogeographic investigations because many trace fossils are good facies indicators. Associations of trace fossils may be particularly helpful in paleoenvironmental reconstruction, and any assemblage of ichnofossils conceptually equivalent to an assemblage of body fossils is referred to as an ichnoassemblage. A trace fossil assemblage produced by a biological community that can be characterized by morphological criteria is often referred to as an ichnocoenosis.

The Late Jurassic Summerville and Stump Formations and Tidwell Member of the Morrison Formation were deposited in a wide variety of environments. Based on current research, the Summerville and Stump formations are temporally equivalent strata (Early to Late Oxfordian in age, 161–155 Ma) (Wilcox and Currie, 2006) in western North America. The Tidwell Member of the lower Morrison Formation is slightly younger in age (approximately latest Oxfordian to Early Kimmeridgian, ~156 Ma) (Kowallis et al., 1996). Deposition of these units occurred during a marine transgression/regression into the northern part of the study area (Kreisa and Moiola, 1986; Caputo, 1988; Doeling, 2001; Wilcox and Currie, 2006). Marine transgression is represented by deposition of shallow marine sandstone beds of the Summerville and Stump formations. Regression resulted in the development of evaporitic basins and deposition of the limestone and gypsum beds that are locally present at the base of the Tidwell Member (Peterson, 1990; O'Sullivan, 1992, p. 14; Turner and Peterson, 2004; Bernier and Chan, 2006). Subsequent deposition in fully continental settings is reflected by the occurrence of strata interpreted to represent mudflats, overbank floodplains, isolated streams, scattered small eolian sand fields,

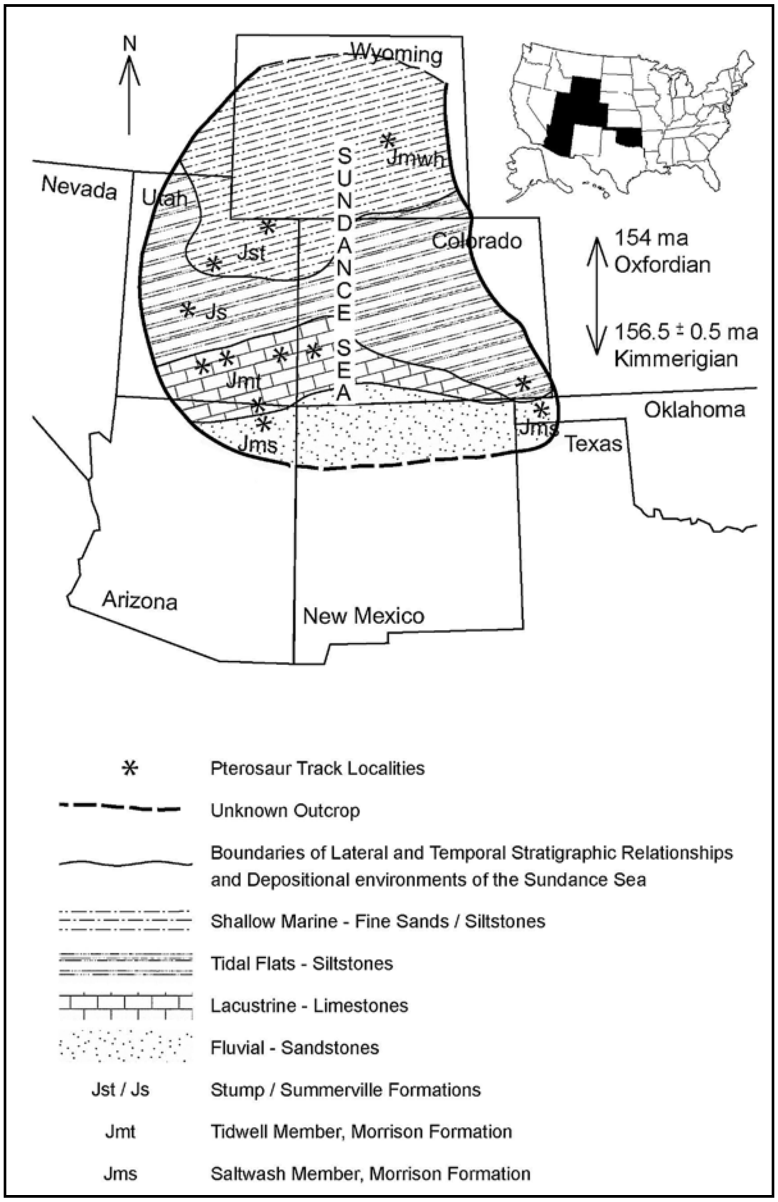

Figure 1. Paleogeographic map of the western U.S., showing the lateral extent of the pterosaur track localities during the Upper Jurassic. Both marginal marine and non-marine shorelines are represented. In ascending stratigraphic order (oldest to youngest beds): Stump Formation (Jst); Summerville Formation (Js); Windy Hill Member, Morrison Formation (Jmwh); Tidwell Member, Morrison Formation (Jmt); and Salt Wash Member, Morrison Formation (Jms). Latest Oxfordian and earliest Kimmerigian in age.

and small lakes and ponds. All of these environments (Fig. 2) are represented within the Tidwell Member of the Morrison Formation, which was deposited during the final retreat of the Sundance Seaway from Utah. The Late Jurassic rocks preserve the most extensive pterosaur (*Pteraichnus)* track-bearing unit in the world. Rare footprints attest to the co-existence of dinosaurs with pterosaurs at many sites.

The terrestrial pterosaur tracks from the Summerville, Stump and Morrison formations described here are characterized by a suite of terrestrial walking traces, in addition to elongate scrape marks and incomplete trailways. The tracks indicate that pterosaurs could swim and float in water as well as walk on land. Traces resulting from aquatic activity occur in rocks that are laterally equivalent to strata in close geographic proximity that contain terrestrial walking traces. The occurrence of pterosaur tracks in both terrestrial and nearby shallow subaqueous environments is interpreted here to indicate that the pterosaurs were concentrated in shoreline settings. This interpretation is supported by the fact that pterosaur bones and tracks have been found in rocks deposited adjacent to shorelines (Lockley and Mickelson, 1997; Mickelson et al., 2004; Bilbey et al., 2005). Late Jurassic pterosaurs from the western U.S. were small, with wingspans on the order of 2–6 ft (0.6–1.8m). Where pterosaur footprints are preserved, there is evidence that a mixed "flock" was present. Tracks interpreted as having been made by both adults and juveniles are common. The occurrence of juveniles suggests that the pterosaurs nested and raised their young along shorelines.

A set of invertebrate traces is common wherever pterosaur tracks occur in marginal marine and non-marine shoreline environments. *Arenicolites*, *Fuersichnus*, and *Skolithos* are the dominant forms, and the organisms that produced these ichnofossils were probably a source of food for the pterosaurs. Preserved claw marks and beak probe marks are consistent with feeding/foraging behavior. Pterosaurs were apparently the "shorebirds" of the Late Jurassic in North America, as these animals occupied the same niche as modern shorebirds.

Conclusion

Previously documented Early to Late Jurassic tetrapod footprint assemblages were almost exclusively attributed to dinosaurs. The ichnological transition from marginal marine to terrestrial shoreline environments during the upper Jurassic, however, maintain that pterosaur footprints *Pteraichnus* are the dominant ichnofaunal forms. Prior to this study, bird skeletal material and/or tracks of birds have not been documented in Upper Jurassic marine or continental rocks in North America. The occurrence of *Pteraichnus* with *Arenicolites*, *Fuersichnus*, and *Skolithos* documented here has similarly not been reported previously. We interpret the occurrence of *Pteraichnus* with *Arenicolites*, *Fuersichnus*, and *Skolithos* as indicative of shoreline deposition during the Late Jurassic, and identify this ichnoassemblage as the *Pteraichnus* ichnocoenosis. Identification of the *Pteraichnus* ichnocoenosis should help to define the position of shorelines in Upper Jurassic rocks in the western U.S. and perhaps other areas. Future studies will determine whether or not this ichnocoenosis has the potential to delineate shoreline environments in rocks deposited elsewhere.

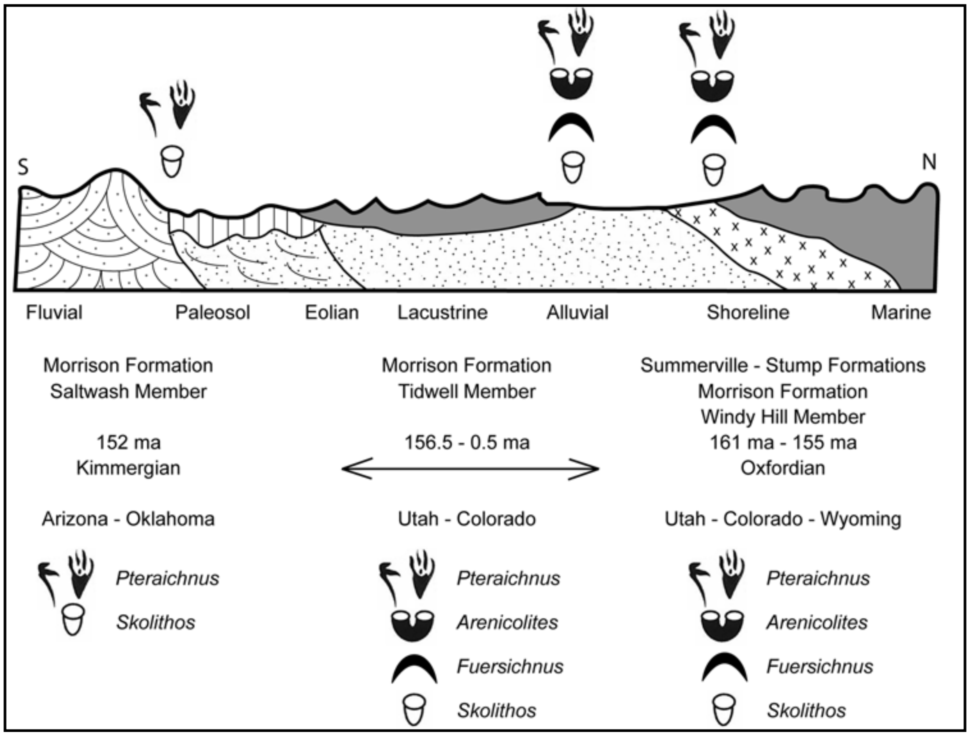

Figure 2. A north to south schematic cross-sectional diagram, depicting lateral and temporal facies relationships of marginal marine and non-marine shorelines during the time of Summerville throughout lower Morrison deposition. Pterosaur tracks and associated invertebrate trace fossils occur in these environments. The geologic age of these beds and facies relationships represent only a few million years of time.

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Late Pleistocene wetland deposits at Valley Wells, eastern Mojave Desert, California: initial results

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Introduction

Ground-water discharge (GWD) deposits form in arid environments when water tables approach or breach the ground surface during periods of enhanced effective precipitation. When active, desert springs and wetlands provide an important water source for local fauna, support hydrophilic vegetation, and act as a catchment system for eolian sediments. The interplay between emergent water tables, ecological and biological systems, and wind-blown sediments results in a complex depositional environment that contains information on the timing and magnitude of past changes in local or regional hydrologic budgets. GWD deposits, which are also called "spring" or "wetland" deposits, also clearly demarcate the position of past ground-water highstands and, therefore, can be used to constrain changes in climate for a given area.

GWD deposits are common in arid environments but are often misidentified as lake deposits because of their similar appearance and position on the landscape (Forester et al., 2003). They typically consist of fine-grained sediments that are commonly positioned at or near valley bottoms or other topographic lows. When eroded, they may exhibit a badland appearance similar to lake deposits, and may contain gastropod and bivalve shells that are similar to lacustrine taxa. GWD deposits have been identified in all four deserts of the American Southwest (Chihuahuan, Great Basin, Mojave, and Sonoran), but have been thoroughly investigated at only a handful of sites (Quade, 1986; Quade and Pratt, 1989; Haynes, 1991; Quade et al., 1995; Quade et al., 1998; Kaufman et al., 2002; Pedone and Rivera, 2003; Quade et al., 2003; Pigati et al., 2004; Mahan et al., 2007). Recent geologic mapping of surficial deposits in the Mojave Desert has identified more than 130 localities that exhibit evidence of past ground-water discharge (e.g., Bedford et al., 2006; Schmidt and McMackin, 2006). Of these, GWD deposits identified at Valley Wells, located in Shadow Valley in the eastern Mojave Desert (Fig. 1), are among the most spatially and stratigraphically extensive and contain evidence for multiple episodes of high water-table conditions that can be dated using several chronometric techniques. Our preliminary results suggest that there were at least two distinct ground-water highstands at Valley Wells that supported complex spring and wetland systems during the late Pleistocene.

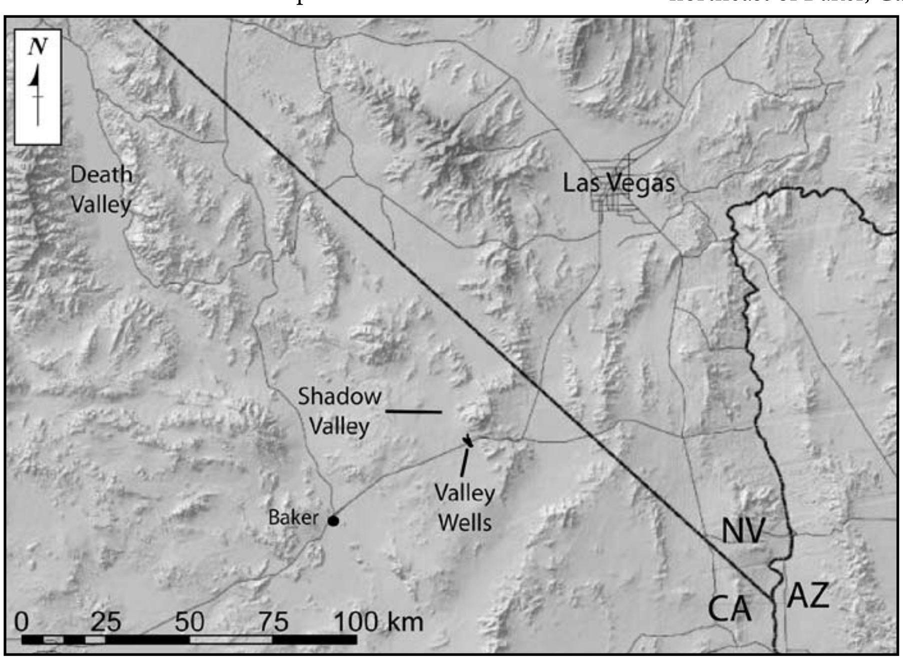

Figure 1. Locations of Shadow Valley and Valley Wells in the Mojave Desert of eastern California.

Valley Wells setting

Shadow Valley is located in the eastern Mojave Desert between the Clark Mountains and Mescal Range to the east and the Halloran Hills to the west, approximately 40 km northeast of Baker, California (Fig. 1). The valley lowlands are largely covered by alluvial fan deposits that consist of rocky detritus from a number of sources: Proterozoic quartzites and Paleozoic carbonates from the Clark Mountains and Mescal Range, arkosic sediments from granites underlying Cima Dome and Halloran Summit to the south and west, respectively, and a few local basalt flows (Hewett, 1956; Reynolds et al., 1991). The mountains east of the valley are higher than other nearby mountains, consist primarily of carbonate rocks, and thus are efficient at intercepting moisture and are highly permeable. The southeastern part of Shadow Valley includes the Valley Wells basin, which contains a distinct set of light-colored deposits that are

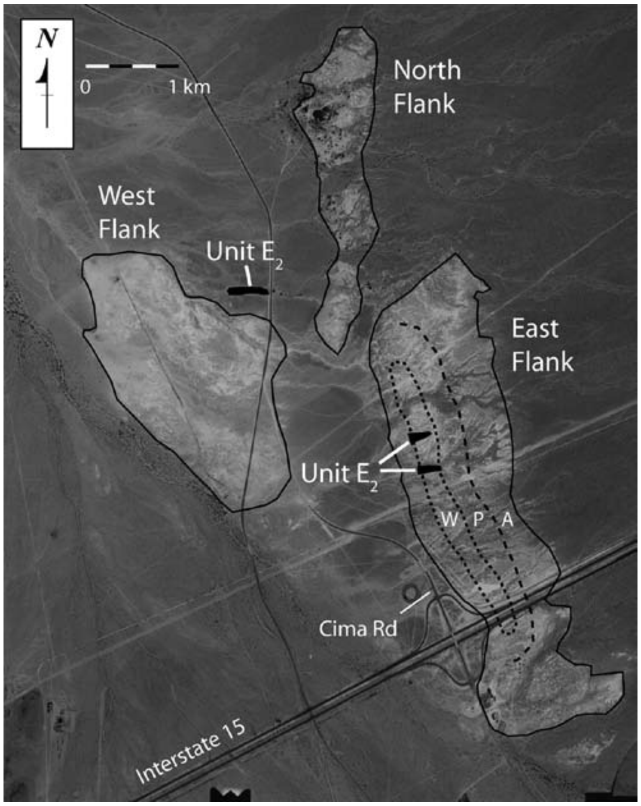

Figure 2. Map of GWD deposits at Valley Wells. Unit X deposits are separated into three areas, the east, north, and west flanks, respectively, based on differences in sedimentology, preservation, and position on the landscape. Wetland facies in the east flank are inferred using sedimentological properties and the presence/absence of microfauna (ostracodes, gastropods): W = wetland or marsh, P = phreatophyte flat, A = alluvial setting. Unit E_2 deposits are inset within the older, more extensive deposits of Unit X in at least two areas in the east flank and in a small arroyo between Cima Road and the west flank.

positioned near the valley floor and are bisected by Interstate 15 and Cima Road (Fig. 2). These sediments were first interpreted as Pleistocene lake deposits by Hewett (1956) and later mapped as such by Evans (1971). Additional investigations recovered a suite of terrestrial and freshwater gastropod shells, as well as a number of terrestrial fauna, including rodents, small invertebrates, ungulates, and megafauna (mammoth and mastodon), but the lacustrine interpretation for the origin of the sediments remained the same (Reynolds and Jefferson, 1971; Reynolds et al., 1991).

The light-colored deposits at Valley Wells are present in three separate locations in the basin, which we refer to as the east, north, and west flanks, respectively (Fig. 2). There are significant differences in the physical characteristics of the sediments between the three flanks that we suspect reflect differences in the mineralogical composition of the sediments, their ages, spatial relationship to past spring orifices, and position on the current landscape. In this paper, we concentrate our discussion on the sediments in the east flank for several reasons: (1) they are well preserved, (2) they contain abundant macrofossils (ostracodes and gastropods) that can be used to reconstruct past environmental conditions, (3) they contain material suitable for dating by radiocarbon, uranium series, and luminescence methods, and (4) they exhibit evidence of multiple ground-water highstands. Sediments in the west flank are largely deflated, and we have not found any ostracodes, gastropods (except for a few fragments), or material suitable for radiocarbon dating from either the north or west flank.

Stratigraphic units

We used field mapping, detailed sedimentological descriptions, and stratigraphic relations to identify at least two distinct sediment packages in the east flank of Valley Wells. Our unit terminology largely follows Haynes (1967), but we refer to the older, more extensive deposits at Valley Wells as Unit X because we cannot definitively correlate it with a specific unit in southern Nevada due to unresolved geochronologic questions. A brief summary of Haynes' unit terminology is given in Table 1.

Table 1: Summary of units in Southern Nevada

Unit	Oxygen Isotope Stage	Approximate age range (^{14}C yrs BP)	Environment
A	>6	--	fluvial
B	6?	--	extensive (?) wetlands
C	3-4?	--	fluvial/alluvial
D	2	14,000-30,000	extensive wetlands
E_1	late 2	11,800-13,500	modest wetlands
E_2	early 1, late 2	7,200-11,200	waning wetlands
F	1	4,000-7,000	dessication

[1] Age range as defined in Haynes (1967) and Quade (1986)

Unit X

Unit X is more than ~5–6 m thick (the base of the unit is not exposed) and comprises nearly all of the stratigraphic section in the east flank. The top of Unit X decreases in altitude ~6–8 meters from east to west and is essentially continuous except where it has been eroded either by headcutting or local slumping that occurred after spring discharge ceased. Near the western margin of the east flank, basal sediments of Unit X range from a light-purple silty clay to fine sands and silts. These sediments are overlain by light-brown silt that typically contains numerous root casts that are oxidized and easily identified. Above this silt, there is a thin (20–40 cm) olive-green clay containing abundant ostracodes and gastropod shells that is overlain by 30-50 cm of white silt to silty clay. This series of fine-grained units is capped by a thick (up to ~1 m), extremely hard and well-cemented, whitish-grey deposit that contains abundant calcium carbonate (hereafter referred to as the carbonate cap; shown at the top of the section in Fig. 3a). In a few places, the surface of the carbonate cap has been locally shattered by a combination of

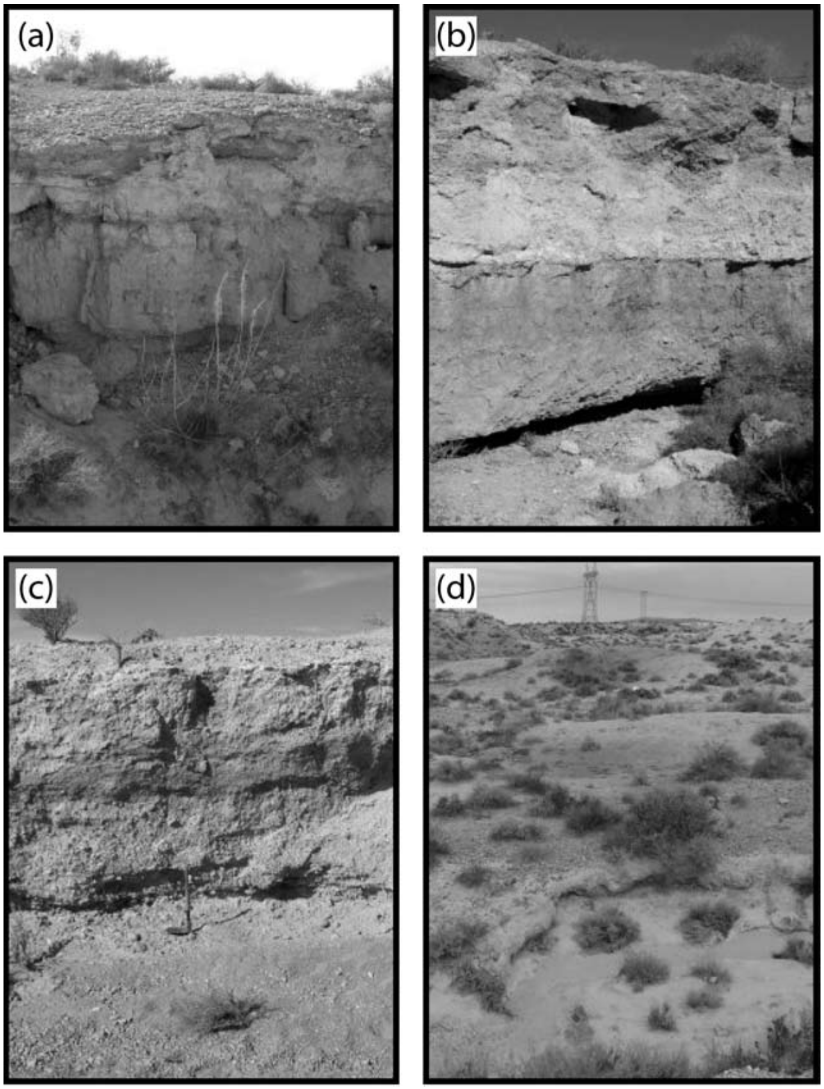

Figure 3. Photographs of Unit X deposits in the east flank that were likely associated with (a) areas of active ground-water discharge, (b) the adjacent phreatophyte flat, and (c) areas that were not influenced by the presence of active wetlands. Deposits shown in each of these photographs are ~4-5 m thick. Local badland topography exhibited by Unit E_2 deposits in the east flank is shown in (d).

freeze-thaw, salt accumulation, and bioturbation processes, and is exposed as small areas of desert pavement that are composed almost entirely of carbonate rubble. We did not find any evidence of microfauna, pollen, or plant macrofossils within the cap.

The fine-grained Unit X deposits progressively grade to the east into coarse-grained materials ranging from silt and sand (Fig. 3b) to gravel (Fig. 3c). The hard carbonate cap also changes character to the east, grading into a fairly soft unit that is interbedded with alluvial sand and gravel near the eastern margin. We did not find evidence of microfauna or plant macrofossils in any of the units in this area.

Unit E_2

Unit E_2 at Valley Wells consists of a package of olive-green clay overlain by a dark-brown to black, organic-rich clay, which is locally capped by a thin (20–30 cm) light-brown silt. Unit E_2 is typically 2–3 m thick, is inset into the older Unit X deposits in the east flank (the top of Unit E_2 is 4-6 m below the top of Unit X), and is relatively soft and easily eroded. Locally, Unit E_2 exhibits a badland appearance (Fig. 3d), but the unit is expressed as subdued topography elsewhere in the east flank. Unit E_2 deposits are also exposed in a small arroyo between Cima Road and the west flank deposits, where they are capped by Holocene alluvium (Fig. 2).

Habitat reconstruction

We used sedimentological data and the presence/absence of microfauna to reconstruct the paleoenvironmental conditions represented by Units X and E_2 at Valley Wells. First, we used the relations between hydrologic regime, plants, and sediments deposited within wetland systems established by Quade et al. (1995) to differentiate between areas of maximum ground-water discharge (wetland facies), areas that once supported phreatophytic plants (phreatophyte flat), and areas lacking shallow groundwater that were largely covered by xerophytic plants even when wetlands were present nearby. We then sampled sediments along several transects across the wetland facies to determine the presence/absence of ostracodes and gastropods to verify our interpretations based on the sedimentological evidence. We also attempted to verify our interpretation using pollen analysis, but pollen was not recovered in any of the Unit X deposits that we studied at Valley Wells (D. Wahl, pers. comm., 2007).

In modern wetland systems, Quade et al. (1995) found clear relations between the hydrologic regime, floral assemblages, and the types of sediments deposited. For example, areas of active ground-water discharge that support dense stands of hydrophilic plants are represented by fine-grained sediments that commonly exhibit a high organic content. In the geologic record, these areas are represented by pale-green to white mudstones and dark-colored organic mats. Phreatophytic plants dominate the landscape upslope of areas of active ground-water discharge where water tables do not reach the surface but are still close enough to be tapped by plants. These plants, which in southern Nevada include rabbitbrush, sagebrush, and greasewood, efficiently capture wind-blown material and, as a result, the "phreatophyte flat" zone is represented in both modern settings and the geologic record as eolian silt and fine sand interbedded with alluvial sediment. Alluvial fan depositional environments outside the influence of wetland systems are typically rocky, poorly sorted, and vaguely bedded deposits and are dominated by xerophytic plants.

Unit X

We mapped the spatial extent of the olive-green clay unit within Unit X at Valley Wells which, according to the Quade et al. model, represents the area of active discharge. The green clay deposits are largely confined to the western margins of the east flank, which we interpret as the likely home of active springs, seeps, wet meadows and marshes, or a mosaic of all of these (Fig. 2). Upgradient to the east, areas in Unit X that are dominated by brown silt and sand are interpreted as representing a phreatophyte flat when wetlands were active downslope. Alluvial sands and gravels in Unit X progressively increase in abundance to the east where they are overlain by the soft carbonate cap, which we interpret as representing areas of progressively deeper ground-water.

Terrestrial and semi-aquatic gastropod shells were abundant in the green clay unit, confirming our interpretation based on the sedimentology; that is, that this area once supported an active wetland system. Gastropods identified in the field included members of the semi-aquatic *Succineidae* family, several genera of the terrestrial *Pupillidae* family, and other taxa that we have not yet identified. We did not find gastropod shells in any other strata or locations within Unit X. Ongoing work with Jeff Nekola at the University of New Mexico in Albuquerque is aimed at identifying the suite of gastropods present in these deposits.

Similarly, we found a number of ground-water ostracode taxa (i.e., ostracodes that live near spring orifices or other wetland settings) in the green clay deposits in the western margin of the east flank, which lends further support to our paleoenvironmental interpretation. We did not find ostracodes in strata at any other location within Unit X. Ongoing work with Jordon Bright at Northern Arizona University in Flagstaff is aimed at identifying the full range of ostracodes present in the deposits and reconstructing local environmental habitats and chemical properties of the water that discharged at these locations.

Unit E_2

Exposures of Unit E_2 are limited to a few small areas in the east flank and in a small arroyo between Cima Road and the west flank deposits (Fig. 2). Based on the presence of the organic-rich clay and green clay deposits, we interpret Unit E_2 as representing relatively modest areas of past ground-water discharge. These systems were not as extensive as those represented by Unit X, and we did not find sedimentary units or macrofossils associated with either phreatophytic or xerophytic vegetation that may have been supported by high water table conditions in the past. We conclude that high-water table conditions represented by Unit E_2 were not extensive and/or pervasive enough to support a phreatophytic flat adjacent to the area of active ground-water discharge. We did find a few scattered gastropod shells (*Succineidae*, *Pupillidae*, etc.) in the thin brown silt near the top of Unit E_2, but ostracodes were not present in these sediments.

Chronology

Reynolds et al. (1971) recovered the remains of a number of mammals from Unit E_2 in the east flank, including *Symmetrodontomys* n. sp. (cricetid rodent) and *Onychomys* n. sp. (grasshopper mouse). The presence of these fauna suggests that the age of the base of Unit E_2 is late Blancan Land Mammal Age (2.6-1.8 Ma, Savage and Russell 1983). In contrast, Quade et al. obtained radiocarbon dates of 10,250±160 ^{14}C yrs (Quade et al., 1995) and 11,600±120 ^{14}C yrs (Quade et al., 1998) from organic-rich clay in Unit E_2. There have not been any reported ages for Unit X at Valley Wells.

We obtained preliminary radiocarbon dates from organic material and minute terrestrial gastropod shells recovered from Units E_2 and X to constrain the timing of ground-water highstands at Valley Wells. All samples were pretreated using standard procedures, which will be outlined in a forthcoming paper.

Preliminary ^{14}C ages for the organic-rich clay deposit in Unit E_2 range from 9,650±50 to 10,780±40 ^{14}C yrs, depending on the component of the material dated (e.g., base-soluble humic acids compared to base-insoluble humin residue). Additional ^{14}C ages on gastropod shell carbonate for shells recovered from the light brown silt unit that caps Unit E_2 ranged from 7,930±50 to 8,630±60 ^{14}C yrs. Unit E_2 deposits are common features of GWD in valleys in the southern Great Basin Desert and have been interpreted to represent a brief period of high water tables that peaked during the Younger Dryas (YD) cold event and continued into the early Holocene (Quade et al., 1998). Our dates are consistent with this interpretation.

Preliminary ^{14}C ages obtained from gastropod shells recovered from the green clay deposit in Unit X ranged from 30,280±210 to 33,770±220 ^{14}C yrs. For now, we assume that these ages should be taken at face value (i.e., they are not compromised by small amounts of contaminant carbon). If so, then Unit X at Valley Wells may correlate with Unit D deposits in southern Nevada (Table 2) (Haynes, 1967; Quade, 1986; Quade and Pratt, 1989) that are interpreted to represent an extensive resurgence in ground-water tables that occurred during oxygen isotope stage (OIS) 2. However, we cannot rule out the possibility that our preliminary ages for Unit X are the result of older shells that are slightly contaminated with younger carbon. If so, then Unit X at Valley Wells may correlate with Unit B deposits in southern Nevada, which are interpreted to represent an earlier discharge event that likely occurred during OIS 6. But we have not found evidence for a major unconformity, soil development, or other indications that a significant time break lies between Units E_2 and X. We are currently employing alternative methods, including uranium-series and luminescence dating techniques, to evaluate the veracity of our radiocarbon chronology for this unit.

Conclusions

We used sedimentological evidence, microfaunal assemblages (gastropods and ostracodes), and radiocarbon dating to define the spatial extent and timing of high water-table conditions at Valley Wells during the late Quaternary. Our initial results suggest that active springs and wetlands occupied the western margin of the east flank of deposits at least twice during the late Pleistocene. The most recent episode of high water-table conditions occurred during the YD cold event and continued into the early Holocene. The earlier and more extensive event occurred either during OIS 3-2 or perhaps prior to that, possibly during OIS 6.

Investigation of the GWD deposits at Valley Wells is ongoing. Future work will include additional dating of Unit X using uranium-series and luminescence methods to secure the timing of the deposits, the use of stable isotopes (oxygen, hydrogen, uranium and strontium) to define the composition of source waters that fed the Pleistocene wetland systems, and measurement of modern water tables to determine the magnitude of hydrologic change in the area. We are also investigating GWD deposits at other sites in the Mojave Desert to determine whether hydrologic systems represented by GWD deposits responded to climate change synchronously across the desert, or if their response was more fragmented and influenced by local or regional factors. The results of this work will have significance for rural populations and agricultural communities that depend on shallow aquifers for their water supply and agricultural needs, and will allow us to better understand the potential response of shallow hydrologic systems to future climate change.

Acknowledgements

We thank M. Reheis and R. Reynolds for constructive reviews of this manuscript. This project was funded by the U.S. Geological Survey's Mendenhall post-doctoral research program.

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New Pleistocene records of the Tiger Salamander (*Ambystoma tigrinum*) in Riverside County, California

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Abstract: A new middle Pleistocene occurrence of *Ambystoma tigrinum* is reported from the Irvingtonian NALMA Pauba Formation in Murrieta, southwestern Riverside County. A late Pleistocene occurrence is reported from a locality in Lake Cahuilla sediments in the Colorado Desert at La Quinta, central Riverside County. The La Quinta locality is below the +36 foot high-stand of Pleistocene Lake Cahuilla, and is probably associated with a freshening event by the Colorado River since Tiger Salamanders have little tolerance for saline waters. Both localities are outside the recorded Holocene range of this salamander. Pleistocene introduction of the Tiger Salamander to the Salton Trough may have occurred by way of the Colorado River drainage system or along San Gorgonio and the Whitewater rivers that drain the northern Peninsular Range and the southeastern Transverse Range geologic provinces.

Introduction

The Tiger Salamander (*Ambystoma tigrinum*) has distinctive trunk vertebrae (Figure 1) that facilitate identification (Olsen, 1968). Excavation monitoring by LSA Associates, Inc. for significant, nonrenewable paleontological resources has produced two new Pleistocene localities for the genus (Figure 2). The Murrieta locality in the Pauba Formation is from Irvingtonian North American Land Mammal Age (NALMA) sediments. The La Quinta locality in the Salton Trough of the Colorado Desert is late Pleistocene or possibly early Holocene. The localities are described below and faunal associations presented in Appendix A.

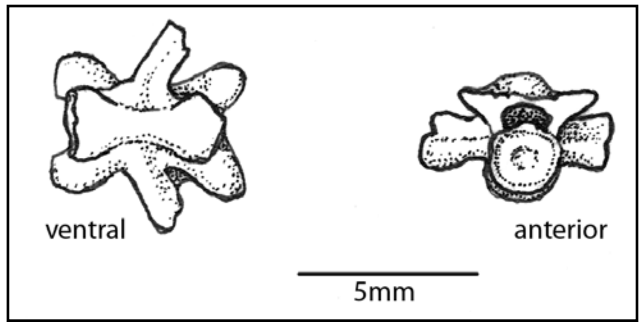

Figure 1. Tiger Salamander trunk vertebra. Illustration by Katura Reynolds.

Distribution

Large salamanders that range across the North American continent include *Necturus* sp. (Waterdogs and Mudpuppies), *Cryptobranchus* sp. (Hellbender), *Amphiuma* sp. (Amphiumas) *Siren* sp. and Pseudobranchus sp. *Sirens*), *Dicamptodon* sp. (Pacific Giant Salamanders) and *Rhyacotriton* sp. (Torrent Salamanders), and *Ambystoma* sp. (Mole Salamanders). Small salamanders are not reviewed in this report.

Today, the Giant and Torrent Salamanders *Dicamptodon* sp. and *Rhyacotriton* sp. are restricted to the Pacific margin of the northwest coast. Three species of True Mole Salamanders (*Ambystoma* sp.) occur west of the continental divide. *A. macrodactylum* (Long-Toed Salamander) is recorded from the Pacific Northwest in portions of California, Oregon and Washington (Smith, 1978). *Ambystoma gracile* (Northwestern Salamander) has a coastal northwestern distribution from northern California into British Columbia. The Tiger Salamander (*Ambystoma tigrinum*) inhabits both sides of the Rocky Mountains and the Colorado Plateau. Arid portions of Arizona and Nevada separate the extensive population from an isolated group in southern California. The California group ranges from Sonoma County, south along the California coast to Santa Barbara County, east to the Central Valley and into the Sierra Foothills from Tulare County to Sacramento County (Californiaherps, 2007). The break in range between populations of *A. tigrinum* in the arid areas along the Colorado River Trough suggests that populations might have been connected during the wetter Pleistocene period.

The fossil record of *Ambystoma* in California and Arizona is scant, and the genus is apparently absent in Nevada as a native species during historical times. Pleistocene records for Alameda County fall within its historic range (UCMP). Within its historic Arizona range, *Ambystoma* is recorded from the middle Wisconsin of southern Arizona (Jefferson, 2008a). The oldest Arizona record is from latest Blancan NALMA Pliocene age in south eastern Arizona. The genus *Ambystoma* is reported from Oligocene deposits east of the Rocky Mountains (Carroll, 1988).

Morphology

The Mole Salamanders (*A. macrodactylum)* reach six to eleven inches. The Tiger Salamander (*A. tigrinum*) is larger than *A. macrodactylum*, reaching thirteen inches.

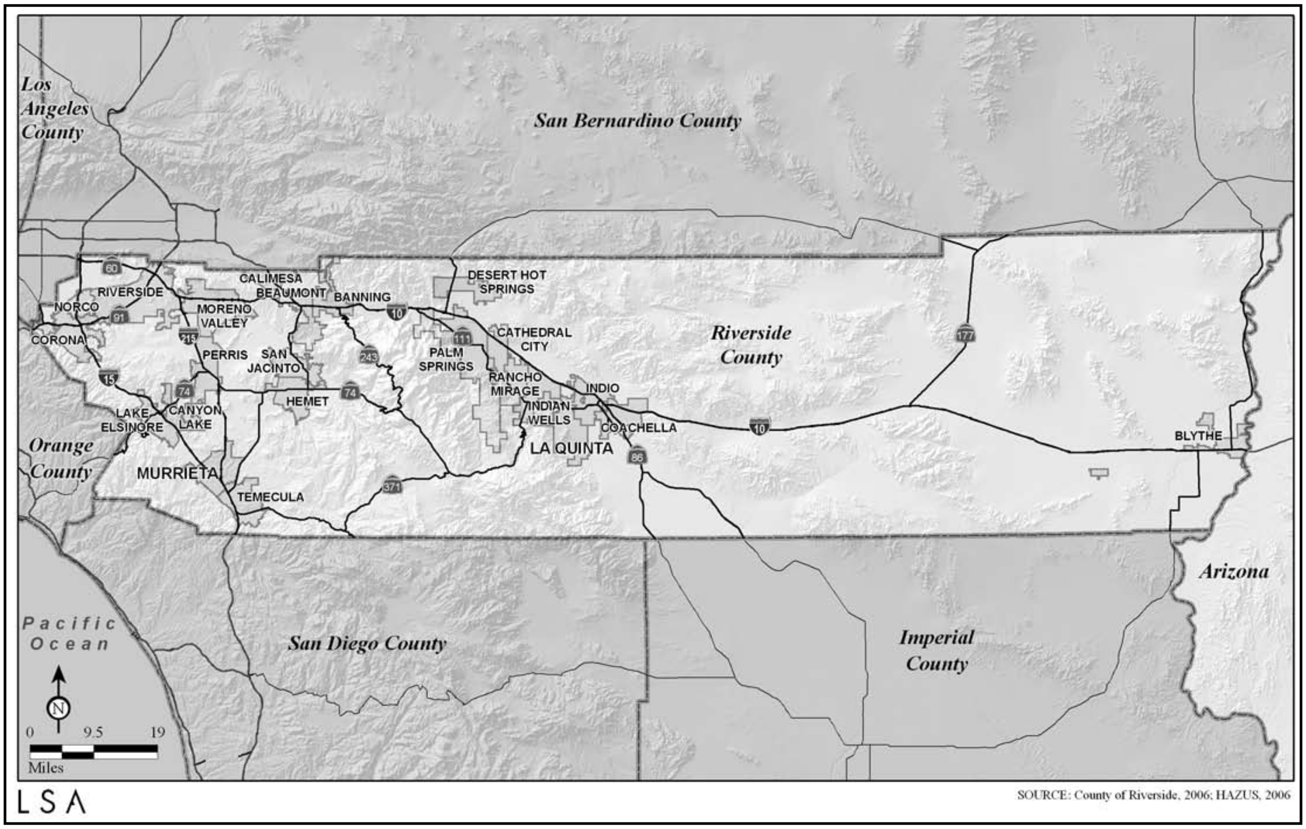

Figure 2. Vicinity map, new Pleistocene localities for Tiger Salamander at Murrieta and La Quinta, Riverside County, California.

Salamander vertebrae are distinct from frog and toad vertebrae. The length of salamander centra is equal or greater than the width of lateral processes, and processes have a slender base. Frogs and toads have short centra and broad transverse processes (see Fig. 55, Olsen, 1968). Figures compare A. *tigrinum* to *A. maculatum* (Fig. 55, Olsen, 1968). Morphology and large size are the basis for referring specimens from Murrieta and La Quinta to *A. tigrinum.*

New localities

Middle Pleistocene, Irvingtonian NALMA

Arboretum Development, Murrieta, Riverside County, CA (RMM TR02-08. 257 – 273, Pauba Formation)

The locality is within the Pauba Formation, which represents portions of the Irvingtonian NALMA based on the presence of *Mammuthus* sp. and the absence of *Bison* sp. (Reynolds and others, 1991). The Pauba Formation contains the Bishop Ash, dated around 760,000 ky (Kennedy, 1977), and therefore the Pauba Formation represents a period between 1 Ma and 200,000 years (Woodburne and Swisher, 1995; Bell and others, 2004) The location is within the southeast quarter of Section 23 (projected), T 7 S, R 3 W, SBBM, as shown on the *Murrieta, California* 7.5' USGS Quadrangle map (USGS 1953, photorevised 1973). Associated fossils are listed in Appendix A. The site is now covered by residences.

Excavation monitoring recovered large mammal fossils including giant ground sloth, mammoth, camel, pronghorn, deer, peccary, horse, and tapir. Small vertebrate taxa present included rodents, rabbits, birds, lizards, and snakes. Mesic and riparian species in the fauna that would be found in a habitat equitable to the Tiger Salamander include the meadow mouse (*Microtus* sp), Pacific pond turtle (*Actinemys marmorata*), small bony fish and frogs or toads.

Late Pleistocene, Rancholabrean NALMA

Mountain View Country Club, La Quinta, Riverside County, CA (RMM La Q LV-034, Lake Cahuilla sediments)

The locality is at elevation +20 feet, below the +40 foot (12m) maximum level for Pleistocene Lake Cahuilla that occurred during the Younger Dryas 12.3 kyr BP (Li, 2003). The location is within the southeast quarter of Section 4, T 6 S, R 7 E, SBBM, as shown on the *La Quinta, California* 7.5' USGS Quadrangle map (USGS 1953, photorevised 1973). Associated fossils are listed in Appendix A. The site is now covered by residences.

Excavation monitoring recovered large mammal fossils including antelope, coyote, and mustelids. The diverse rodent assemblage suggests that skeletal elements of rodents may have been introduced in owl pellets. Mesic and riparian species in the fauna that would be found in a habitat equitable to the Tiger Salamander include the meadow mouse (*Microtus* sp), muskrat (*Ondatra* sp.), ducks (*Anas* sp.) and frogs or toads. Frogs, toads, and salamanders live in and near fresh water sources, which are necessary for their reproduction. They can only tolerate water that is low in salinity. Exceptions are Tiger Salamander in lab experiments and populations entrenched in east coast saline habitats (Romspert and McClanahan, 1981). The ten species of aquatic snails present require aquatic vegetation and need relatively fresh, aerated water in rivers, lakes and ponds. Of importance are associated *Anodonta californica* (freshwater mussel) and *Pisidium compressum* (compressed clam). *Anodonta* live in fresh water with a sandy bottom while *Pisidium* prefers standing water. *Siphateles* sp. (chub fish) prefers slow-moving water full of vegetation. The large catostomid fish (humpback sucker) prefers open, moving water with a gravel bottom.

The fish, clams, and snails all suggest a habitat containing fresh water and associated aquatic and riparian vegetation. A series of fresh water influxes from the Colorado River entering Lake Cahuilla during the last twenty thousand years has been documented (Li, 2003), suggesting a major lake level rise around 12.3 kyr BP after the 18,000 kyr Wisconsin maximum (Li, 2003). Fresh water from the Peninsular and Transverse ranges also would have contributed to the freshening of Lake Cahuilla.

Discussion

Tiger Salamander (*Ambystoma tigrinum*) fossil occurrences are recorded from middle Pliocene deposits in Murrieta, California, and in late Pleistocene localities of southern Arizona (Jefferson 2007a, b) and from within its historic range in Alameda County (UCMP). There is no fossil record of large salamanders from southern Nevada, or along the Colorado River.

The presence of the Tiger Salamander in Lake Cahuilla sediments near the outflow of the Whitewater River suggest that the salamander could have been introduced to the Salton Trough during latest Pleistocene time by the San Gorgonio River drainage system that reached into the northern Transverse Range and San Bernardino Mountain Range. Another possibility is introduction to the Salton Basin by the Colorado River.

Acknowledgements

This article was improved by thoughtful review by Dr. Jeffrey Lovich and George Jefferson. I thank Margaret Gooding, LSA Associates, for preparing the vicinity map and Katura Reynolds for the illustration of the salamander vertebra.

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Appendix A

Table 1. Irvingtonian Fossils from the Arboretum Development, Murrieta, CA.

Invertebrates
- Mollusca
  - *Anodonta californica* (fresh water mussel)
  - *Physa* sp. (aquatic snail)
  - *Menetus* sp. (aquatic snail)
  - *Helisoma* sp. (aquatic ? snail)

Vertebrates
- Pisces
  - Osteichthyes (bony fish)
- Amphibia
  - Urodela (frog or toad)
  - *Ambystoma tigrinum* (tiger salamander)
- Reptilia
  - Colubridae (colubrid snakes)
  - Crotalidae (venomous snakes)
  - Lacertilia (iguanid lizards)
  - *Actinemys marmorata* (pond turtle)
- Aves
  - *Asio* sp. cf. *otus* (long-eared owl)
  - *Callipepla* sp. (quail)
  - Icteridae (oriole or blackbird)
  - Corvidae (crow)
  - Fringillidae (finch)
- Mammalia
  - Lagomorpha (rabbits)
    - *Sylvilagus* sp. (sm) (small cottontail)
    - *Sylvilagus* sp. (cottontail)

Lepus californicus (California jack rabbit)
Sciuridae (squirrels)
Sciuridae (small) (small squirrel)
Rodentia (rodents)
Heteromyidae
Perognathus sp. (pocket mouse)
Dipodomys sp. cf. *agilis* (Pacific kangaroo rat)
Dipodomys sp. (large) (large kangaroo rat)
Dipodomys sp. (small) (small kangaroo rat)
Geomyidae
Thomomys bottae (Botta's pocket gopher)
Cricetidae
Peromyscus sp. (large) (large deer mouse)
Peromyscus sp. (small) (small deer mouse)
Neotoma sp. (woodrat)
Neotoma sp. cf. *fuscipes* (dusky-footed woodrat)
Microtinae
Microtus sp. cf. *californicus* (California vole)
Edentata (giant ground sloth)
Megalonyx jeffersoni (Jefferson's ground sloth)
Paramylodon harlani (Harlan's ground sloth)
Proboscidea
Mammuthus sp. (mammoth)
Artiodactyla
Camelidae (camels)
Camelops sp. (large camel)
Antilocapridae (pronghorn)
Odocoileus hemionus (deer)
Platygonus sp. (peccary)
Perissodactyla
Equus sp. (large) (large horse)
Equus sp. (small) (small horse)
Tapirus sp. (tapir)

From: Reynolds, 2003. Ambystoma *curated into the Riverside Metropolitan Museum as TR02-08.257 – 275.*

Table B – Late Pleistocene Fossils from Mountain View Country Club, La Quinta, CA

PLANTAE
Branching plants with tufa brush /bushes
Taphaceae (water reeds/cattails)
INVERTEBRATES
Mollusks
Pelecypods
Anodonta sp. cf. *californica* (California freshwater mussel)
Pisidium cf. *compressum* (compressed clam)
Gastropods
Physa humerosa (aquatic snail)
Fluminicola sp. (aquatic snail)
Amnicola? sp. (aquatic snail)
Tyronia (*Elimia*) sp. (aquatic snail)
Tyronia protea (var. smooth) (aquatic snail)
Tyronia protea (var. cancellate) (aquatic snail)
Tyronia protea (var. ribbed cancellate) (aquatic snail)
Tyronia clatricata (var. shouldered) (aquatic snail)
Gyraulus parvus (aquatic planorbid snail)
Helisoma ammon (aquatic planorbid snail)
VERTEBRATES
Pisces (fish)
Gila sp. (chub fish)
Catostomid (humpback sucker)
Amphibia (amphibians)
cf. *Rana*/*Hyla* (toad or frog)
Ambystoma tigrinum (tiger salamander)
Reptilia (reptiles)
Lacertilia (iguanid lizards)
Sceloporus sp. (spiny lizard)
Phrynosoma sp. (horned lizard)
Sauromalus? (chuckwalla)
Serpentes (snakes)
Thamnophis sp. (garter snake)
Lampropeltis sp. (kingsnake)
Pituophis sp. (gopher snake)
Crotalus sp. (rattlesnake)
Aves (birds)
Fringillidae (finch?)
Otus sp. (screech owl)
cf. *Anas* (sm) (small duck)
Aves (lg) (large bird)
Mammalia (mammals)
Lagomorpha (rabbits)
Sylvilagus sp. cf. *auduboni* (Audubon's cottontail)
Sylvilagus sp. (sm) (small cottontail)
Lepus californicus (California jack rabbit)
Sciuridae (squirrels)
Ammospermophilus leucurus (antelope ground squirrel)
Citellus cf. *tereticaudus* (round-tailed ground squirrel)
Spermophilus sp. cf. *beechyi* (Beechy's ground squirrel)
Rodentia (rodents)
Heteromyidae
Perognathus sp. cf. *penicillatus* (desert pocket mouse)
Perognathus sp. (lg) (large pocket mouse)
Dipodomys sp. cf. *deserti* (desert kangaroo rat)
Dipodomys sp. cf. *merriami* (Merriam's kangaroo rat)
Geomyidae
Thomomys bottae (Botta's pocket gopher)
Cricetidae
Peromyscus sp. cf. *eremicus* (cactus mouse)
Neotoma sp. cf. *lepida* (desert woodrat)
Neotoma sp. cf. *fuscipes* (dusky-footed woodrat)
Microtinae
Microtus sp. cf. californicus (California vole)
Ondrata zibethica (muskrat)
Insectivora (insectivores)
Notiosorex crawfordi (desert shrew)
Carnivora (carnivores)
Mustelidae (skunk or weasel)
Taxidea sp. (badger)
Canis latrans (coyote)
Mammalia (lg) (artiodactyl?) (pronghorn? or deer?)

From: Reynolds, 2004. Ambystoma *curated into the RMM as La Q LV-034.*