Geologic and Biotic Perspectives on Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River Region: Conference Abstracts

April 12–15, 2005
Desert Studies Center, Zzyzx, California

By Marith C. Reheis, Editor

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Open-File Report 2005–1404

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Preface

The late Cenozoic history of surface waters in the southwestern Great Basin and lower Colorado River region has been a subject of intensive study for more than 200 years. Prior models of regional drainage history have been undergoing major revision in the past decade as a result of more refined studies of the lacustrine and fluvial rock records and improved dating methods. At the same time, a substantial body of pertinent evidence has been rapidly accumulating in the form of biogeographic inquiries of diverse aquatic organisms that are based on detailed examination of the fossil record, phylogenetic analysis, phylogeography, and other modern analytical tools. The abstracts in this volume represent presentations from a workshop held in April 2005 at the Desert Studies Center in Zzyzx, California, in which these geologic and biotic perspectives were summarized and integrated to provide a current synthesis of the aquatic history of this fascinating western North American region. Abstracts by U.S. Geological Survey authors were reviewed and approved prior to presentation, whereas abstracts by authors outside the U.S. Geological Survey were reviewed and in some cases slightly revised following the workshop.

Key issues addressed in the workshop include the following:

(1) The configuration, areal extent, and temporal development of the chain of interconnected lakes which emptied into Death Valley during periods of the Pleistocene.

(2) The development of Mojave River drainage in conjunction with uplift of the Transverse Ranges and downstream integration of progressively lower basins.

(3) The late Cenozoic history of drainage in the lower Colorado River region prior to the incision of Grand Canyon, including the possible existence of an inland estuarine embayment of the ancestral Gulf of California.

(4) Comparison of the biogeographic histories of regional aquatic organisms. Reconciling differences in patterns with factors such as ecological deployment, modes of dispersal, and biogeographic origin. Correlating patterns with current interpretations of drainage history based on the physical record and seeking explanations for major discrepancies.

The workshop, sponsored by the U.S. Geological Survey Earth Surface Dynamics Program and National Cooperative Geologic Mapping Program and by the Smithsonian Institution, was open to all scientists interested in the hydrographic history of the southwestern Great Basin and lower Colorado River regions. Participants included research scientists in geology, paleontology, and biology from the U.S. Geological Survey, Smithsonian Institution, California State Parks and Fish and Game Departments, the Desert Research Institute, Arizona Geological Survey, Nevada Bureau of Mines and Geology, 17 universities throughout the United States and one in Canada, and private consultants. The meeting also was attended by managers from the Mojave National Preserve. The workshop included a series of presentations that reviewed major ideas concerning regional hydrographic history and summarized past and present studies from the geologic and biotic perspectives, followed by presentations of new and provocative ideas and research thrusts. The meeting encouraged geologists and biologists to interact to develop a broader perspective on the types of research that are being conducted to address issues of regional drainage history. The convenors hope that these new opportunities of interaction among scientists of different disciplines will lead to future proposals for collaborative studies.

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The Use of Clock-Like Divergence in Fish DNA to Time Hydrological Events in Great Basin and Colorado River Drainages

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Small fishes with well-constrained habitat requirements are hypothesized to have some predictable responses to hydrographic and climatic changes. Paleontological dates are used here to calibrate mitochondrial DNA sequence divergence (*seq div*) rates in 20 populations of minnows (Cyprinidae) and pupfish (Cyprinodontidae). These rates are then used to back-calculate timing of hydrographic connections in the Great Basin and the Paleo-Colorado River System.

Estimation of rates with this method must mitigate: (1) heterogeneity of rates caused by mass-specific variability in metabolic rate (small, warm water fishes evolve faster than large or cold-water fishes); (2) an incomplete fossil record, causing underestimation of time in the denominator of the rate equation (Rate = pairwise DNA *seq div* / m.y.); (3) possible stasis in an ancestral species' history, causing over-estimation of elapsed time of evolution in the denominator of the rate equation; (4) difficulty assigning age when repeated episodes of either isolation or genetic mixing are equally probable.

Assuming these uncertainties are small, the estimated rate of molecular evolution (rate = 1.3% / m.y.) allows several conclusions: (1) Populations of *Rhinichthys* in the Los Angeles basin, which differ from the Lower Colorado River drainage populations by an average of 9.2% *seq div*, originated about 7 Ma. Little Colorado River and Gila River populations also began diverging from the Los Angeles basin and other Lower Colorado populations 7.7–6.2 Ma. (2) Death Valley populations of *Rhinichthys* (*seq div* = 4.8%) were derived from populations of the Lahontan basin 3.7 Ma. (3) Owens Valley and Death Valley *Cyprinodon* (rate = 1.3% / m.y.) were derived from the Colorado drainage (*seq div* = 7.8% and 9.5%, respectively) about 7.3–6 Ma. Several Death Valley *Cyprinodon* species (*seq div* = 0.5%–1.3%) diverged over the time span 0.38–1 Ma and the subspecies (*seq div* = 0.2%) originated 0.15 Ma. (4) *Rhinichthys* were connected across the Sevier River-Virgin R. drainage divide (*seq div* 1.5%) 1.2 Ma; The eastern Sevier River sub-populations (*seq div* = 0.4–1.3) were connected to each other 1–0.3 Ma., but there was also a 4 m.y. old split between eastern and western populations of the southern Bonneville basin.

(5) Many local populations of White River, Meadow Valley Wash, and Virgin River *Rhinichthys* have been diverging from each other over the past 0.77–0.08 m.y., although there is also a 3.6 m.y. split within the Virgin River populations. Plagopterin minnows of Meadow Valley Wash and the Sevier River drainages split 3.8 m.y. ago. These episodes of connection and isolation sometimes coincide with known climatic shifts. To attribute the most recent of the above divergence estimates to the end of the most recent pluvial period in the Great Basin would require unrealistically high rates.

Hydrologic History of the Paleo-Owens River Drainage, from Mono Lake to Panamint Valley

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The paleo-Owens River is a particularly interesting locality for the study of climatic and hydrologic fluctuations during the Quaternary because it consists of a string of presently-closed hydrologic basins that were progressively interconnected as the climate became more pluvial. The principal basin, the present Owens River, heads in high mountain areas with abundant precipitation. In the past, as climate grew wetter, this basin overflowed into a series of arid basins that extend into the Mojave Desert. This is valuable for paleohydrologic reconstruction because the downstream position of the terminal lake is a direct indicator of the degree of wetness in the headwaters. However, reconstruction of this record is laborious because hydrologic histories of a number of basins must be separately investigated and correlated.

Evidence for the extent and chronology of lacustrine interconnection becomes weaker with increasing age. Marine Isotope Stage (MIS) 6 was clearly a pluvial episode, but the extent of the lacustrine system is unclear. The critical evidence is extensive shoreline deposits in Panamint Valley near the overflow-sill elevation. These record the maximum degree of wetness during at least the past several hundred thousand years. The shoreline deposits have proved difficult to date, but the most likely ages are during MIS 6 or MIS 4, or possibly both. The timing of overflow of Mono Basin into the Owens River has likewise been difficult to establish, but certainly predates the Last Glacial Maximum (LGM). MIS 4 appears the most likely age of the last overflow, but Mono certainly could have overflowed during MIS 6 as well.

MIS 5 appears to have been generally dry and Owens Lake was apparently the terminus, although there may have been one or two brief overflow episodes. There is evidence, although equivocal, of a major pluvial episode during MIS 4. During MIS 3 the terminus of the system fluctuated, apparently in concert with quasi-global Dansgaard/Oeschgar cycles, between Owens Lake and Searles Lake. Wetness increased at the beginning of MIS 2 and Searles Lake was the usual terminus. At ~20 to ~16 ka, during the LGM, Searles apparently episodically overflowed to form a shallow lake in Panamint Valley. This general pluvial condition was abruptly interrupted by a brief dry event sometime during the interval between 19 and 17 ka that may have brought the terminus as far upstream as Owens Lake. At about 16 ka the system returned to almost its previous degree of wetness, then receded again shortly after 15 ka. A relatively low level in the Searles basin appears to have been the terminal condition through the late-glacial global oscillations (15 to 10 ka). At the end of the Younger Dryas the Searles basin was permanently abandoned, and Owens Lake has remained the terminus throughout the Holocene.

Late Pleistocene Climate and Tectonic Impacts on the Owens River Cascade

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The Eastern California Lake Cascade comprises a series of lakes along three rivers, the Owens, Mojave, and Amargosa, which developed frequently during the wetter stages of Pliocene and Pleistocene times, only to atrophy during drier interludes, most recently during the Holocene. A cascading system of lakes and rivers has existed on and off east of the Sierra Nevada since at least late Pliocene time, as reflected in deformed lake beds in the Waucobi Hills and Coso Range. Whereas hydroclimatic changes during Pleistocene time are reflected in sediment cores retrieved from Owens Lake and Searles Lake, tectonic and volcanic activity hinder the precise interpretation of physical linkages within the system.

The Owens River Cascade last flourished during the terminal Pleistocene but desiccated rapidly south of Owens Lake early in Holocene time. High late Pleistocene lake levels, subsequent lake oscillations, and eventual regression are revealed at intervals around Owens Lake and raise issues regarding both climate change and tectonic deformation [in 1872, prior to water removal from the Owens River, the lake surface lay 1096 m above sea level]. Dated shoreline sequences around its northeast margins show that the lake reached its highest late Pleistocene level of 1140 m around 20,000 ^{14}C years BP, at which time it spilled southwards beyond the modern Haiwee Reservoir towards Searles Lake. Following regression, the lake again rose to form a massive beach ridge cresting at 1128 m around 12,000–13,000 ^{14}C years BP. The outer face of this beach ridge was later reworked by fluvial and lake processes during modest lake regressions and transgressions between 12,000 and 9,500 ^{14}C years BP. These oscillations probably reflect climatic forcing of changes in the hydrologic regime similar to those recognized for the terminal Pleistocene elsewhere, notably during the Younger Dryas interlude.

Fragments of the main (1128 m) beach ridge may be traced southwards above the east shore of Owens Lake and then westwards along the south shore, interspersed with bluffs that may be either fault scarps or shorelines, or both. The ridge crests at 1157 m southeast of the lake and then rises westward over 6 km to 1167 m above the south-central shore. A similar shoreline sequence, at lower elevations, occurs southwest of the lake between Olancha, where the main beach ridge reaches 1139 m, and the Haiwee spillway to the south. The maximum elevation of this spillway, beneath the Haiwee reservoir, is now 1146 m, but this also reflects tectonic activity and alluviation since the last overflow.

These data suggest that terminal Pleistocene shorelines have been significantly deformed during Holocene time, perhaps most recently during the 1872 Lone Pine earthquake. Further, both uplift of the Coso Range magmatic complex, and subsidence and faulting within the Owens Lake basin, must be incorporated into models that seek to interpret the capacity and geochemistry of Owens Lake, and the elevation and timing of its spillage southward to Searles Lake. Theoretically, if the Haiwee spillway was lower and/or the lake basin had reduced capacity during late Pleistocene time, then freshwater would have spilled more frequently to Searles Lake, with implications for sedimentation, geochemistry, and ecology in both lakes. Such changes would be superimposed upon those attributable solely to climate.

Late Pleistocene lakes, Panamint Valley, California

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Late Pleistocene to recent lacustrine and wetland deposits in Panamint Valley record times of Owens River flow into the basin in contrast to times when the discharge from deep regional aquifers dominated. Surficial deposits, a shallow auger hole, and DH-1 core contain fauna including the ostracode *Limnocythere sappaensis*, which indicates at least a 200 m deep saline lake occupied the northern and southern basins where playas are present today at 470 and 317 m elevation, respectively. The presence of *Limnocythere sappaensis* in an auger sample and several inset shoreline deposits requires a high alk/Ca Owens River water, indicating that the Owens River flowed into Panamint Valley during the last glacial period supporting a lake until at least 12,575 ^{14}C BP. The saline lake was succeeded in the upper playa with a fresh, groundwater-discharge supported wetland until around 10,500 ^{14}C, when the record changes to dry-playa sedimentation in the upper basin and salt-laden wet playa sediments in the lower playa.

Most of the ostracodes from a ~100 m deep core (DH-1) drilled in the 1950's (Smith and Pratt, 1957) require low alk/Ca waters indicative of both local meteoric and deep regional groundwater sources rather than flow from the Owens River. Ostracodes, including *Cyprideis beaconensis,* occur between about –34 and –78 m depth in the core, which yielded ^{14}C dates of 24,880 ± 160 at 30.2 m depth and a finite date of 40,720 ± 670 at 40.4 m depth. Foraminifera *Elphidium sp* are abundant at 40–41 m depth and *Ruppia* seeds at 55–60 m. The fauna indicate a saline wetland or very shallow lake environment fed predominantly by regional groundwater discharge. The presence of *C. beaconensis,* which is a west coast estuarine ostracode, indicates Pacific flyway migrants used the area. Comparison of DH-1 and DH-3 cores with the Owens Lake core (Smith and Bischoff, 1997) suggests the fossiliferous interval at 34 to 78 m depth in the DH-1 core may span all or much of OIS-4 time.

Highstand surficial deposits at ~ 610 to 580 m contain two environmentally exclusive ostracode assemblages indicating waters from both the Owens River system and the regional aquifer. Paleodischarge of the regional aquifer near the highstand elevations appears to be structurally controlled by Quaternary and active faults nearby. Amino acid racemization (AAR) ratios on ostracodes and snails suggest the shoreline and groundwater discharge features that lie between 610 and 550 m (spillway elevation presently lies at ~603 m) elevation formed during one event, likely OIS-6. The ostracode *Cyprideis salebrosa* in the highest elevation deposits suggests bird migrants from the Gulf of Mexico used the lake during this period. Lakes that formed during the LGM and OIS-6 time were deep and supported by Owens River flow, and during the intervening period, shallow lakes or wetlands were supported by discharge from the regional aquifer or were absent.

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Where was the Southern End of Lake Manly during the Blackwelder Stand?

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During oxygen isotope stage 6 (OIS-6), Lake Manly rose to the Blackwelder high stand and carved the well-known prominent strandlines at ~90 m above sea level on Shoreline Butte, Mormon Point, and elsewhere in Death Valley. The southern limit of the Blackwelder stand is not well defined, however. This is probably because most evidence has been obliterated by subsequent erosion and deposition. Near Mesquite Spring at the southern end of the Soda Lake basin there is a well-defined strandline at an elevation of 340 m. Near the Salt Spring and Saddle Peak hills, there are also a distinct strandline and several gravel deposits of possible lacustrine origin at ~180 m above sea level. Between these two localities and Death Valley there are no sills that would impound a lake at these elevations; lake surfaces at either 180 or 340 m today would extend to the northern end of the valley. There is also a ~40 m-thick bed of bluish clay, suggestive of a perennial lake, in Soda Lake basin (Burnham, 1955). This bed is overlain by ~45 m of younger lacustrine sediments. Its depth is consistent with an OIS-6 age.

The strandlines and possible lacustrine gravels at elevations of ~180 and ~340 m may well have been formed during the Blackwelder stand and subsequently displaced vertically with respect to one another by tectonic warping (Hooke, 1999). The regional deformation pattern is one that would result in subsidence of Death Valley and the Salt Spring Hills relative to Mesquite Spring. The rate of differential subsidence (or uplift) implied by the strandline displacement is only ~2 mm/yr, which is quite reasonable in a tectonically active setting. Enzel *et al.* (2002), however, have reported that there is no displacement of "latest Pleistocene" strandlines over a distance of ~40 km in the vicinity of Baker. If correct, this implies that the vertical component of the deformation has essentially ceased, at least in this area.

A reconstruction of the topography at the time of the Blackwelder stand suggests that a sill may have existed at the entrance to Cronese Basin, and that another sill may have existed in the Salt Spring Hills, ~20 m below the level of the high stand. The latter would correspond to the next most prominent Blackwelder-stand strandline in Death Valley. Expansion of the lake over these sills would have increased evaporation, and may have been responsible for stabilizing the lake at these levels.

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Fish Fossil Evidence for an Aquatic Connection between the Death Valley System and the Colorado River?

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The Death Valley aquatic system includes the Mono Lake basin, Owens River, Owens River-Death Valley connection, Amargosa River, and Mohave River. These are all streams that, provided with enough rain, could potentially flow into Death Valley. The current presence of speckled dace *Rhinichthys osculus*, pupfishes *Cyprinodon* spp., and suckers *Catostomus* spp. in both the Colorado River and Death Valley systems suggests a prehistoric aquatic connection. On the other hand, razorback sucker *Xyrauchen texanus* and distinctive members of the *Gila robusta* complex are endemic to the Colorado River below Lee's Ferry. The Owens sucker *C. fumeiventris* and tui chub *Siphateles bicolor* from the Owens and Mohave rivers have affinities with the Lahontan system of northern Nevada. Middle Pleistocene connections of the ancestral Mono Lake (Lake Russell) to the Lahontan system to the north followed by outflow to the Owens River to the south would account for the presence of tui chub, Owens sucker, speckled dace, and scales of trout *Oncorhynchus* sp. and whitefish *Prosopium* sp. (identified by G. R. Smith from Pleistocene cores of Owens Lake) in the Owens and Mohave Rivers. The extensive volcanism of the Long Valley Caldera postdating the shifting drainage outflows, however, suggests a more recent connection with the Lahontan system.

Pliocene fossil fishes diagnosed from the Mono Lake Basin include a new species, the Mono tui chub *Siphateles davidgainesi,* a pikeminnow *Ptychocheilus*, and suckers of the genera *Catostomus* and *Chasmistes.* These have affinities with the Pliocene Lahontan system to the north where in the Carson Valley fossils of Mono tui chub, pikeminnow, trout *Oncorhynchus* sp., *Catostomus, Chasmistes*, and possibly *Lavinia* have been found. Pliocene fossils of tui chub and the two sucker genera have been identified from China Lake in the Death Valley System.

A Pliocene or earlier aquatic connection can account for some of the genera common to the Death Valley system, Lahontan system, and Colorado River. Miocene fossils of *Ptychocheilus*, early Pliocene fossils of *Xyrauchen texanus* (that shares a common ancestor with *Chasmistes*) in the current drainage of the Colorado River and Miocene/Pliocene *Fundulus* and *Cyprinodon* fossils in Death Valley support such an early connection. A Pleistocene aquatic connection between the Lahontan and Death Valley systems accounts for the presence of tui chub and Owens sucker in the Owens River, and tui chub in the Mohave River. No fossils of speckled dace contribute to these proposed connections.

Lake Manly – A Brief Review

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Geologic evidence of Lake Manly, the intermittent pluvial lake of Death Valley, has progressively grown from sparse outcrops of a single (?) lake to many outcrops and lake stands spanning Pliocene to Holocene time. Blair and McPherson (1999) called the lacustrine facies of the Furnace Creek Formation Lake Zabriskie. Elsewhere, these facies have been dated at ~3.35 Ma (Knott and Sarna-Wojcicki, 2001; Machette, 2001) and <3.7 and >0.77 Ma (Klinger and Sarna-Wojcicki, 2001). At Mormon Point, the Kit Fox Hills and Ubehebe-Rogers basin, 0.6 to 1.0 Ma tephra layers are intercalated with lake deposits equivalent to OIS 16 & 18; however, the sparse outcrops do not strongly indicate a valley-filling lake (Knott et al., 1999; Klinger, 2001).

Drill cores show evidence of lakes at 186–120 ka and 35–11 ka (Hooke, 1972; Lowenstein et al., 1999; Anderson and Wells, 2003) correlative with pluvial lakes elsewhere and marine oxygen isotope stages (OIS) 6 and 2, respectively. Outcrops have yielded definitive evidence of only the OIS 6 lake along both the Black Mountains (Ku et al., 1998) and western piedmont (Machette et al., 2003).

A possible connection between the Owens, Amargosa and Mojave rivers and Lake Manly has piqued biological and geological interests for years. Amargosa River-Death Valley integration occurred after 140 ka (Morrison, 1991). A deep Lake Manly may have included pluvial Lake Mojave during OIS 6; however, core sediment shows no lakes in Soda Lake playa during OIS 18, 16, or 6 (Knott et al., in prep.). Stratigraphic studies in Panamint Valley, the first valley upstream from Death Valley along the pluvial Owens River, show no overspilling lake during OIS 18 or 16 (Larsen et al., 2003) or during OIS 2 (Jayko et al., 2002), whereas Jayko et al. (2003) inferred an Owens River-Death Valley connection during OIS-6.

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Molecular Evidence Suggests a Complex Biogeographic History of Springsnails in the Death Valley Region, California-Nevada

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Hydrobiid gastropods of the genus *Pyrgulopsis*, commonly known as springsnails, are one of the most ubiquitous and diverse groups of aquatic organisms in the Death Valley region. These tiny, gill-breathing animals are tightly linked with their aquatic habitats and have been a popular subject for biogeographic inquiries in which their distributions were used to infer regional drainage history (e.g., Taylor, 1985; Hershler and Pratt, 1990). We are currently using DNA sequence data to provide a new perspective on the biogeographic history of this fauna. Phylogenetic reconstructions based on two genes suggest that, as is the case in other western areas (Liu and Hershler, 2004), the springsnail fauna of the Death Valley region is a composite of unrelated lineages. Those lineages whose relationships are well resolved apparently originated prior to the development of the modern regional landscape – e.g., two lineages in the Owens Valley region are sister to western California springsnails and two lineages in the Amargosa River basin are sister to Gila River (Arizona) species. Most of the lineages are narrowly distributed and provide no evidence of prior spread within the well integrated late Quaternary drainage of the Death Valley region. However, two lineages range across modern drainage divides and have a shallow phylogeographic structure consistent with geologically recent dispersal. One of these consists of populations of *P. wongi* that are spread among the Walker River basin, pluvial Owens River drainage, and several endorheic basins adjacent to (and east of) Owens Valley. The other consists of populations of *P. micrococcus* and *P. turbatrix* whose broad range includes Death Valley, Panamint Valley, the lower Colorado River basin, and the San Bernardino Mountains (Liu et al., 2003). The distribution of both of these lineages suggests either previously unrecognized late Quaternary drainage integration or a surprising ability of springsnails to disperse across terrestrial barriers.

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Death Valley Pupfishes, mtDNA Divergence Times and Drainage History

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The four pupfish species (*C. radiosus, C. diabolis, C. nevadensis,* and *C. salinus*) in the Death Valley System {DVS) are members of the "western" clade of the genus, a group of 9 extant species in a region extending from the Guzman Basin of NW Chihuahua, Mexico, to Owens River in California. Phylogenetic analysis of allozymes indicated that the DVS pupfishes are monophyletic, whereas for mtDNA the group is paraphyletic (fig. 1): the mtDNA of *C. radiosus* of Owens River is basal and those of the three species of Ash Meadows and Death Valley form the sister group to the mtDNA of *C. fontinalis* of the Guzman Basin. The latter relationship is problematic because of the geographically intervening, and

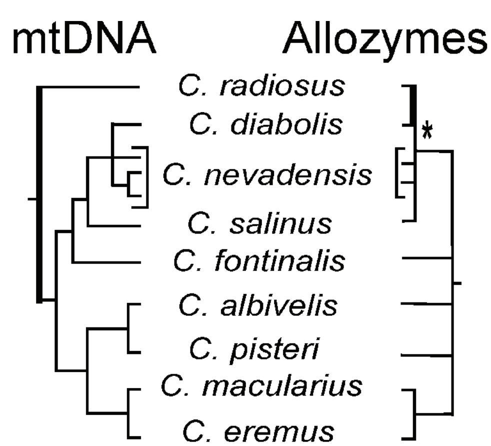

Figure 1. Phylogenetic inferences from mtDNA and allozymes for the western pubfish clade.

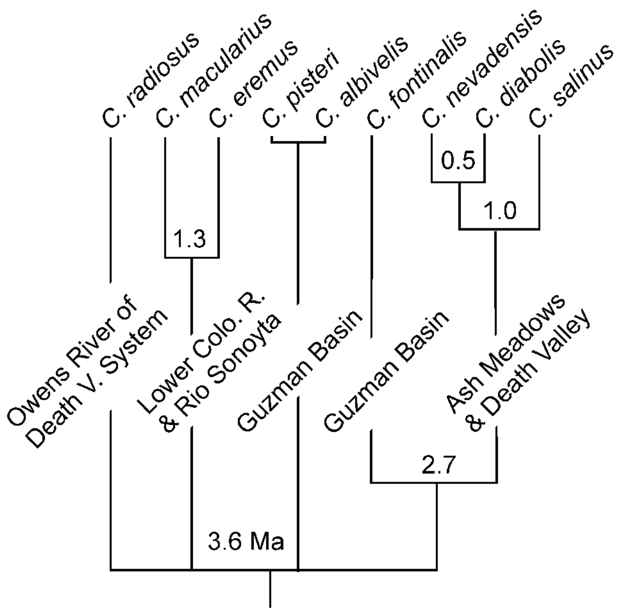

Figure 2. Mitochondrial DNA tree and chronology for the western pupfish clade (Echelle et al., 2005).

seemingly less closely related, clade in the Lower Colorado River and Rio Sonoyta area (fig. 2). For pupfish mtDNA, there is close agreement in estimated divergence times from two different approaches, a Bayesian approach allowing rate variation in different parts of the tree, and a constant molecular clock developed from the cyprinodontid genus *Aphanius*.

The results suggest that there were surface-water connections between the Guzman, Lower Colorado River, and Death Valley systems before ~3.6 Ma. The geography of the five deeper mtDNA clades suggests (1) rapid speciation in the late Pliocene and (2) lineage sorting from a polymorphic common ancestor in the region.

Similarly, the distribution of mtDNA haplotypes in the Ash Meadows/Death Valley area may reflect lineage sorting from an ancestral Death Valley pupfish that carried divergent mtDNA haplotypes. For example, the mtDNA divergence time for *C. diabolis* (0.5 Ma) appears to be an order of magnitude greater than the age of the isolation event (opening of Devils Hole to the surface) inferred from geologic and paleoclimatic data. Random lineage sorting makes it difficult to use mtDNA to infer temporal patterns of surface-water connection. Other aspects of genetic structure indicate a further problem: secondary contact and genetic introgression might have been more frequent than generally appreciated, despite the formidable geographic barriers to dispersal presently in place.

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Evolutionary Insights From the Disjunct Distribution of the Salt Flat Endemic Spider Saltonia incerta Banks (Araneae: Dictynidae) in Southwestern North America

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The Mojave and lower Colorado deserts of California comprise numerous geologic features attributable to a recent and complex history. Previous biogeographic studies have yielded a great deal of information about the timing and formation of California deserts and their features, as well as the organisms inhabiting them, but there are still insights to be gained from further examination of this system. Many desert features, such as dune systems and dry lakes, provide a unique habitat type found nowhere else in the world, and subsequently harbor organisms also found nowhere else in the world. These endemic organisms are not only of interest for conservation purposes, but are potentially important indicators of environmental changes which have occurred throughout history in this region.

One such endemic organism that may provide significant clues to past environments is the monotypic spider species *Saltonia incerta*. This species is apparently restricted to salt-crust habitats of dry or intermittent lakes and rivers. Previously known from only two localities, it has now been found at several salt flats in southern California and northern México. This extreme habitat restriction allows for the testing of an explicit hypothesis. We hypothesize that paleoriver drainage pathways should have played an important role in the current distribution of *S. incerta* and should thus be reflected in the biogeographic history of the group. More specifically, if vicariance has been more important than dispersal in the history of this group, we hypothesize that spiders from three drainages (Amargosa, Mojave, Colorado) will be more closely related to others within rather than between drainages, and that spiders within salt flats will be more closely related within these habitats than between different salt flats. This scenario assumes that the spiders could disperse from one salt lake to the next through riverine corridors that would have connected these lakes during the Pleistocene, and that now there is little to no gene flow as the salt flats now are rarely connected, and the harsh desert habitat separating these salt flats is unsuitable for *S. incerta*. If this is the case, we would expect populations within lake beds to be monophyletic with respect to populations from other lake beds. Alternatively, there could be gene flow occurring between salt flats and drainage basins via active dispersal in juveniles and small adults through aerial ballooning on silk threads. *Saltonia* has not been observed to balloon, and as they reside under the salt crust and there are few high points on these salt flats for them to ascend in order to initiate the activity, ballooning as a means of dispersal seems unlikely. Moreover, most of the salt flats are in valleys surrounded by mountains. However, dispersal by ballooning can not be ruled out without the use of molecular genetic data. If the spiders are dispersing by ballooning, data analyses would be expected to reveal a much greater degree of mixing of haplotypes (unique DNA sequences) from different localities, and perhaps this would not be totally random mixing as the wind blows more often from one particular direction than others.

So far, we have obtained and analyzed mitochondrial DNA sequences (~1000 bp; CO1) from 10 populations. These data indicate that spiders within each of the three drainage basins are indeed more closely related to each other than to spiders from other drainage basins, indicating an important role for vicariance in shaping the population structure of this group. Additionally, there appears to be some mixing within each of these drainages, i.e., each salt flat is not monophyletic with respect to other salt flats in the same drainage. There is also occasional mixing between drainages. There are three explanations for this pattern within drainages. One is that the spiders are ballooning successfully between localities and gene flow is occurring. The second is that gene flow occurs occasionally due to intermittent connections of salt flats during wetter years. The third explanation is that not enough time has passed since the increasing aridity has caused the salt flats to become largely disconnected from each other and we are seeing a pattern of incomplete lineage sorting. We are currently elucidating which of these alternatives can be rejected using faster-evolving loci (microsatellites).

Late Cenozoic Drainage History of the Amargosa River, Southwestern Nevada and Eastern California

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The Amargosa River is a 275-km long, mostly ephemeral river system, straddling the border between southwestern Nevada and eastern California. This river system drains generally southward from headwaters in the Timber Mountain volcanic highlands (2200 m altitude) to its terminus in central Death Valley (-90 m altitude). The river occupies a large drainage basin (15,540 km^2) with a range of modern climatic regimes varying from subhumid in its headwaters to hyperarid, hyperthermic at the terminus.

The river traverses a physiographically complex drainage basin containing a series of four distinct sub-basins (valley lowlands) each comprising 3-4 component reaches with different fluvial and channel characteristics. From north to south these sub-basin-scale sections consist of the following: (1) an upper section deeply incised into mostly Tertiary sediments and volcanic rocks between the headwater region of Pahute Mesa-Timber Mountain and bedrock narrows to southeast of Beatty, Nevada; (2) a mostly low-gradient section, characterized by fluvial transport and aggradation, within the Amargosa Desert valley between the Beatty narrows and the Franklin Playa-Eagle Mountain area; (3) a section, extending southward from a narrows reach near the southwest side of Eagle Mountain through the Amargosa Canyon south of Tecopa, where the river has incised through a sequence of Pliocene and Quaternary alluvial, lacustrine, and paleogroundwater discharge sediments best exposed within Tecopa Basin; and (4) a west- to northwest-oriented lower section of the river flowing down the axis of southern and central Death Valley. This final section is characterized mostly by fluvial transport and aggradation, except where the channel is locally incised across active tectonic uplifts associated with the southern Death Valley fault zone.

These four sections of the river are hydrologically interconnected on their southern margins by three narrow canyon reaches of the river variably incised (30-275 m) into significant exposures of pre-Quaternary bedrock. These include: (1) the Beatty narrows between the upper and Amargosa Desert sections where the river has incised into Tertiary bedrock during a poorly constrained latest Miocene-early Pliocene to mid(?) Pleistocene interval; (2) a low, primarily alluvial paleodivide to the south of the Amargosa Desert section only recently breached by incision along the Eagle Mountain narrows in middle to late Pleistocene (150-100 ka) time; and (3) several reaches in the Amargosa Canyon that, beginning in mid Pleistocene (145-195 ka) time, have deeply incised through an actively uplifting arch of Tertiary bedrock that forms the breached paleodivide between Tecopa basin and southeastern Death Valley. These patterns collectively suggest relatively recent establishment of the full modern course of the Amargosa River via a succession of discrete diachronous integration events that began near Beatty sometime after 7-4 Ma and did not end near Eagle Mountain until sometime in early late Pleistocene (150-100 ka) time. The mechanism for the linkages across these pre-integration topographic paleodivides includes headward erosion and knickpoint migration from below and (or) spillover from above. These processes were largely driven by fluvial responses to factors such as climatic change, local base-level differences across divides, and (or) tectonic activity (only recognized in Amargosa Canyon).

Age and Paleoenvironments (Paleomagnetism, Tephra, and Ostracodes) of the Pliocene and Pleistocene Tecopa Beds, Southeastern California

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Well-exposed sediments (~100 m) in Tecopa basin reveal a 2-million-year record of climate change, spring activity, and landscape evolution of the southwestern Great Basin. Age control of the lower Tecopa beds is determined by: Huckleberry Ridge ash bed (2.1 Ma), Olduvai normal subchron (1.77 – 1.95 Ma), Jaramillo normal subchron (0.99 – 1.05 Ma), Glass Mountain ash beds (0.8 -1.2 Ma), Matuyama-Brunhes polarity transition (0.78 Ma), Bishop ash bed (0.76 Ma), and Lava Creek B ash bed (0.64 Ma). Except near basin margins, the lower Tecopa beds are dominantly fine-grained and include lacustrine, playa, stream, and spring deposits. Above the level of the Lava Creek B ash, the beds are mainly coarse alluvial deposits, sparse mudstone facies, and spring-related carbonate deposits. We infer paleohydrologic conditions in the Tecopa basin from a small collection of ostracode samples at key horizons, which indicate a diversity of environments and complex water chemistry. Near Tecopa, green clay between the Bishop and Lava Creek B ashes (~465 m) yielded ground-water species; surface water species are absent. Just below the Lava Creek B ash, silty sand and an inferred beach deposit yielded a smooth-shelled ostracode associated with a very saline, shallow lake or wetland. Fine sand 5 m above the Lava Creek B ash contained ground-water species and spring-related carbonate residue. East of Shoshone, muds and sands one meter above the Lava Creek ash (~500 m) yielded estuarine ostracodes that thrive in permanent springs and less commonly in wetlands with very low alkali/carbonate ratios. Two meters higher in the section, the smooth-shelled species is again present, indicating the occurrence of shallow lake or wetland conditions. Ostracode species indicate a flowing wetland complex or low-gradient stream six meters above the Lava Creek B ash. Thus, the ostracode data are consistent with, but do not prove, the presence of a perennial, alkaline lake at about 640 ka.
The youngest volcanic ash bed known in the Tecopa area is approximately 200 ka, as inferred from stratigraphy, chemistry, and argon dating at Pringle Falls and Summer Lake, Oregon. This tephra was also found in cores from Walker Lake, Nevada, and in diatomite on Paoha Island, Mono Lake, California, but does not match the Wadsworth bed of the Eetza Formation, Nevada. Morrison (1999) interpreted this uppermost ash and the related sediments, beaches, and benches as marking the strandline of the last and highest lake (543 m elevation). Near Chappo Spring, green sand beneath a tufa deposit (dates of 159 and 204 ka) has species associated with flowing spring water and seasonal surface water. No ostracodes were found in beds enclosing the uppermost tuff in the Tecopa basin, so our data do not add support for a deep lake at 200 ka.

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Spectacular Diversity, Enigmatic Relationships and Accelerated Molecular Diversification among Hyalellid Lineages in the Southern Great Basin

by Jonathan Witt[1] and Doug Threloff[2]

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Molecular genetic methodologies can be powerful tools for probing the historical events that have shaped relationships within specific taxa, as well as the dynamic factors that have shaped contemporary taxonomic composition within communities. In this study, we apply phylogenetic and population genetic methods to mitochondrial cytochrome *c* oxidase subunit I (COI) DNA sequence data derived from 53 populations of the amphipod crustacean genus *Hyalella* in the North American Great Basin. Emphasis is placed on desert springs in the Amargosa, Mojave, Owens, and White River drainages. The sequence data revealed extraordinary levels of morphologically cryptic endemic diversity, with potentially 36 undescribed taxa occurring in the study area. Nucleotide sequence divergences were as high as 29% between lineages, but divergences within lineages (populations) were invariably less than 1%. Phylogenetic relationships among lineages inhabiting Ash Meadows and the Moapa Warm Springs provide evidence for an historical connection between the White and Amargosa River drainages. The relationships among the remaining lineages are complex, and they exhibit sequence divergences that are superficially inconsistent with Pleistocene events. When Great Basin lineages are analyzed in conjunction with all other known hyalellid lineages, there is strong evidence for marked

rate heterogeneity among lineages, and lineages from two springs, Travertine and Nevares in Death Valley (Amargosa), exhibit clear phylogenetic and population genetic signatures of accelerated molecular evolution. This result suggests that a Pleistocene origin for some lineages cannot be discounted, and that particular care should be taken when applying molecular clocks in a regional context.

Ecological Implications for Great Basin Springsnail Biogeography

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Most springsnails in the western U.S. inhabit only springs and many species occupy comparatively few isolated and relictual habitats. Morphological and genetic evidence from springsnails of the Intermountain Region suggests their distribution and biogeography are attributable to ancient aquatic linkages that have been disrupted by geologic events and the onset of drier climates. It is also possible that springsnails are translocated by waterfowl, humans, or other vectors. Ecological studies provide insight into mechanisms of distribution by examining two hypotheses: 1) Species with distributions representing ancient aquatic linkages prefer specific microhabitats, occupy relatively few habitats, exhibit specific physiochemical adaptations, and are intolerant of translocation; 2) Species representing translocation by birds or other vectors are widely distributed, tolerant of a broad spectrum of physiochemical conditions, have broad microhabitat preferences, and tolerate translocation. Quantitative ecological studies of nine species (*Pyrgulopsis notidicola, P. limaria, P. carinifera, P. avernalis, P. owensensis, P. perturbata, P. bacchus, Tryonia clathrata,* and *Ipnobius robustus*) suggest that 1) each species occupies a microhabitat defined by specific aspects of the aquatic environment (e.g., current velocity, substrate size, water temperature, water depth, etc.); 2) sympatric species partition habitat use; 3) most species are intolerant of artificial translocation, and 4) many species occupy springs with unique physiochemical characteristics. Although springsnail translocation via waterfowl, humans, or other vectors may occur, ecological characteristics of many species suggest that this has been relatively uncommon, and that colonization is largely attributable to ancient aquatic connections among basins.

Summary of the Evolution of the Mojave River

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Mojave River and its ancestors span about 3.5 Ma. The depositional record indicates episodic downstream lengthening of the fluvial system by successive overtopping of terminal lakes and downcutting through sills to integrate river segments. The Mojave River connected with Death Valley from ~19 to 9 ka, and may have connected as early as OIS 6 or so, but probably did not before ~500 ka. Many authors have contributed to the current understanding of the river system, with four recent papers by Cox et al., Jefferson et al., Enzel et al., and Wells et al., in *Geological Society of America Special Paper* **368** providing the bulk of information for this short summary. Our studies underway are sharpening some aspects of the river evolution. Mojave River history can be divided into early and late time periods, roughly divided by 500-750 ka time, before which geomorphic and depositional records are extremely scarce and interpretations depend on drill-hole data.

Early history. Near Victorville, sediments in bluff exposures and drill cores are interpreted to represent a change from south-flowing drainages to marsh and lake environments to northeast-flowing drainages. These changes were evidently driven by the uplift of the San Bernardino Mountains, which blocked southward flowing streams and created a new source for the ancestral Mojave River. The ancestral Mojave River progressed northeastward by filling small basins, cutting through sills, and expanding toward the Harper Lake and then Barstow areas from ~ 2 to 0.7 Ma.

Late history. Beginning about 500 ka, the Mojave River flowed beyond the position of Barstow, where several small basins probably existed, but the details of when and where flow occurred are meager. The present configuration of the Coyote, Troy, and Afton basins probably represents initial basin geometry, although more basins may have existed between Barstow and the Afton basin. The Mojave River episodically filled these proximal basins during pluvial periods, forming Lake Manix during its highest stands when all basins were joined into a single lake. Lake Manix deposits apparently span ~500 ka to 19 ka (radiocarbon years). The lake occupied a single high-stand position several times, suggesting that a sill controlled maximum lake level. Periodic overflow took place to the sites of present Cronese and Soda Lakes. Lake Manix eventually cut through its sill to form Afton Canyon about 19 ka, draining the Afton arm of the lake, but the Mojave River episodically filled the Coyote and Troy sub-lakes until about 13 ka.

Lake Mojave formed in the Soda-Silver lakes basin by the greater influx of Mojave River water after the Afton basin sill was breached. Lake Mojave overflowed at hills on the north side of Silver Lake, cascading down a narrow channel and thence to Death Valley. Full Lake Mojave and associated overflow to Death Valley occurred between about 19 and 17 ka, and episodically from 14 to 9 ka. Since that time, there has been no fluvial communication between the Mojave River and points lower than Silver Lake, but episodic flow of the Mojave River from the San Bernardino Mountains to Silver Lake occurs regularly, including winter 2005!

Old Shorelines of Lake Manix: Implications for Afton Canyon Incision

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Lake Manix was the terminal basin of the Mojave River until the late Pleistocene. The lake reached a highstand at an altitude of 543 m one or more times between about 31 and 18 ka and eventually overtopped a sill, discharging eastward to fill Lake Mojave and initiating the incision of Afton Canyon (Meek, 1999). Estimates of time required to cut the canyon have ranged from a few years or decades in the upper part of the canyon (equivalent to lake depth at that time; Meek, 1999) to several thousand years (Enzel et al., 2003). Based on new field observations, we propose modifications to these previous hypotheses of the history of Lake Manix and incision of Afton Canyon.

Several beach barriers and wave-cut scarps indicate that one or more highstands of Lake Manix prior to 18 ka reached altitudes of 558-547 m (differentially corrected GPS data). Meek (1990) thought that one site represented uplift near the Manix Fault, but several newly discovered sites are distant from each other and from faults with late Pleistocene displacement. Properties of surface soils suggest that a barrier at ~547 m (profile development index (PDI)=0.19) is more than twice as old as barriers at the 543-m highstand (PDI=0.04). Comparisons with soils from Silver Lake (Reheis et al., 1989) to the east suggest that the 547-m barrier is also at least as old as fans thought to be ≥35 ka. *Anodonta* shells in barrier deposits of the 543-m shoreline yielded ^{14}C ages from 22-25 ka, and ages as young as ~18 ka in previous reports (Meek, 1990, 1999); ages younger than 18 ka have been obtained only from the Coyote subbasin. These ages support Meek's (1990) hypothesis that the Mojave River in western Manix Basin was diverted episodically into the Coyote subbasin after dissection had begun in Afton Canyon.

Evidence from two alluvial remnants (altitude 538 m) downstream of the Lake Manix sill suggests discharge prior to cutting of modern Afton Canyon. Locally derived fan deposits are interbedded with fluvial fine gravel and sand that contain reworked lacustrine ostracodes. The surface soil and five paleosols overlying the fluvial deposit have a cumulative PDI of 0.25, suggesting an age similar to the soil on the 547-m barrier. These observations of shoreline altitudes and soils suggest (1) overflow of Lake Manix toward Soda Lake basin well prior to ~30-18 ka, and (2) progressive erosion of a sill that may once have been as high as about 558 m during one or more highstands prior to ~30 ka.

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Stratigraphic Evidence for the Inception and Evolution of the Lower Colorado River Near the Conjunction of Arizona, California, and Nevada

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Recently completed and ongoing mapping of late Neogene stratigraphy in Cottonwood Valley and Mohave Valley provides strong evidence for the mode, timing, and regional geologic consequences of the inception of this reach of the Lower Colorado River (LCR).

A section in Mohave Valley immediately downstream from Pyramid Canyon contains a diverse sequence of deposits that record a transition from alluvial fan and axial valley deposition to rapid scour and deposition by a catastrophic divide-breaching flood through the canyon. The flood deposit is a monomictic boulder conglomerate composed almost entirely of Proterozoic megacrystic granite from Pyramid Canyon that is immediately overlain by the basal marl, mud, and sand of the Bouse Formation. A tephra bed in fanglomerate below the Bouse marl in Mohave Valley places the maximum age of this event at 5.51 Ma[1].

In Cottonwood Valley, upstream of Pyramid Canyon, a fining-upward sequence of flat-lying conglomerate, sandstone, and mudstone overlies a series of interbedded fanglomerates from the valley-flanking mountains. Mudstone in the upper part of this sequence contains the same 5.51 Ma tephra bed found below the Bouse in Mohave Valley. Erosional clefts in the top of the mudstone are filled with Bouse marl. The Cottonwood Valley sequence indicates a latest Miocene transition from fanglomerate to axial-valley fluvial deposition to lacustrine deposition. Combined, the Mohave Valley and Cottonwood Valley sequences document two lakes: one in Cottonwood Valley that failed through Pyramid Canyon, and a subsequent, deeper lake that submerged both valleys. The first lake in Cottonwood Valley may have been a brief inundation of an evolving axial fluvial system. Shore deposits from the second lake can be found at the same elevation in both valleys over an axial distance of ~32 km.

The arrival of the LCR into dry, post-Bouse valleys is indicated by a distinctive fluvial deposit that cuts through the transitional sequence to near the pre-transition valley axis. The base of this large-scale fluvial deposit contains an abundance of locally derived sediment peppered with far-traveled, well-rounded chert pebbles. The LCR ultimately aggraded ~250 m in CV and Mohave Valley and the lithologic diversity of its fill increases upsection. A tephra bed near the top of the fill indicates fluvial aggradation continued to at least 3.9 Ma. Additionally, a 3.3 Ma tephra bed is found in alluvial fan deposits that just bevel the top of the fill. This indicates that the river remained at high levels in the valley for at least ~600 ka before cutting through its own fill to near the pre-river valley axis by the early(?) Pleistocene.

The major transitions in depositional conditions and fluvial processes along this reach of the LCR parallel the development of through-going drainage upstream, including significant enlargement of Grand Canyon. This suggests a linkage of drainage integration and canyon excavation upstream with thick valley aggradation downstream. The central position of Cottonwood Valley and Mohave Valley in the LCR system and their newly described stratigraphic records have important implications for the evolution of river reaches both upstream and downstream. The new chronostratigraphic framework provides a fresh basis for investigating the river's evolution from source to sink.

(Footnotes)

[1] The identification of tephra beds described in this abstract were performed by M. Perkins, Univ. Utah, with supporting data from A.M. Sarna-Wojcicki, U.S. Geological Survey.

The Changing Paths of the Lower Colorado River

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The lower Colorado River downstream of the Grand Canyon has a 5-m.y. history of incision punctuated by aggradational interludes, during which it has changed the course of its channel many times. Diversions stranded numerous paleochannels around bedrock obstacles. Diversions likely happened by avulsion when aggradational fills buried or breached local divides.

Where the river enters the Basin and Range province from Grand Canyon in the Lake Mead area, the distribution of Pliocene(?) river-gravel remnants indicate that the early river flowed through a series of wide basins floored by the upper Miocene Hualapai Limestone and underlying basin fills. Remnants of high-level river gravels on the rims of broad basins suggest that a succession of broad fluvial (braid?) plains occupied the valleys during pauses or aggradational reversals in the river's incision history. The oldest channel gravels in Temple basin and Detrital Valley are incised a few meters to tens of meters below the highest Hualapai Limestone. Younger river gravels occupy channels eroded deeper into the Hualapai Limestone and underlying detritus, and record as much as 500 m of progressive incision. The first major bedrock range downstream from the Grand Canyon is crossed by parallel abandoned gravel-bed river channels up to 11 km apart, separated by bedrock hills >400 m higher and by the site of the historic river in Virgin Canyon, up to 350 m deeper. At a lower level downstream, an old abandoned channel perched high above Hoover Dam was stranded when the river diverted around the other side of Sugarloaf Hill, now >100 m higher, to its present course 275 m deeper in Black Canyon. Farther downstream reaches of the river exhibit several still-lower and likely younger abandoned channels around bedrock obstacles (recognized a century ago in Topock Gorge). Their abandonment and diversion into the modern course ~1 km away may have happened during stages in the river's history when thick aggradational sequences covered the intervening bedrock hills.

Before the 20th century dams, the historic river's paths through its floodplains and delta were as dynamic as any river system, as it periodically modified its course during annual spring floods. As described in 1913 (C.K. Clarke *in* H.T. Cory, Am. Soc. Civil Engin. Trans. 76, 1204–1571): "The lower Colorado has no fixed channel, because of the character of the soil, which is a deposit of silt, easily eroded. The current swings back and forth, cutting the banks and changing the meander line…."

The dynamic fan delta has distributed and alternated its flows S toward the Gulf of California, which received most of the historic pre-dam discharge, and N toward the sub-sea-level basin now occupied by the Salton Sea, which received Colorado River discharge at least 7 times in the 19th and early 20th centuries. In line with evidence that in the late Holocene the huge Salton basin filled several times to overflowing (ancestral Lake Cahuilla), an automatic delta-switching mechanism governed by changing base levels is here proposed. In this model, incised N-directed channels graded to below sea level would tend to capture the river's flow from other delta distributaries until Lake Cahuilla filled to above sea level. When the flow then switched back toward the Gulf, the lake would evaporate and the cycle would renew.

Pliocene Evolution of the Lower Colorado River in the Salton Trough: Tectonic Controls on Paleogeography and the Regional Borrego Lake

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The San Felipe-Borrego basin (SFBB) is a large sub-basin in the western Salton Trough that has evolved independently of the Fish Creek-Vallecito sub-basin since Pliocene time. The Pliocene Diablo Formation (Fm..) accumulated in the Lower Colorado River and delta system, which covered the full width of the Salton Trough before the SFBB and Fish Creek-Vallecito sub-basin became separate basins. The Diablo Fm.. in the SFBB is overlain by the Plio-Pleistocene Borrego Fm.., which records the transgression of a large regional lake over the Lower Colorado River and delta during initiation and early growth of the SFBB. The age of the Diablo-Borrego contact is poorly known and will be dated with magnetostratigraphy (B. Housen and Dorsey, in progress). The Diablo-Borrego transition is interbedded and gradational, and shows large variations in thickness and complexity around the SFBB. Lithofacies range from sand-rich (Diablo) to clay-rich (Borrego) end members and include: very thick cross-bedded sandstone (Colorado River channel); tabular bedded sandstone and mudstone (delta plain and lake-margin bays); and claystone, marlstone and siltstone (Borrego Lake). These facies record a transgressive lacustrine-delta setting during the Diablo-Borrego transition. Mudstone and claystone units in the Diablo Fm. yield benthic foraminifers *(Ammonia beccarii)*, green algae *(Chara)*, and smooth-shelled ostracodes, suggesting lagoon or estuary environments with a possible connection to the Gulf of California. Microfossils in the Borrego Fm. include *Chara*, ostracodes, micromollusks, diatoms, and rare benthic foraminifers, suggesting possible migration of marine faunas into the Borrego Lake through channels of the lower Colorado River. Lithofacies of the Borrego Fm. are more consistent with a perennial lake (not lagoonal) depositional environment. Paleocurrent data in the Diablo Fm. show overall transport to the SW in the NE San Felipe Hills, and toward the SE in the Borrego Sink area. Restoring paleocurrents for younger faults, we infer that the Colorado River entered the Salton Trough northeast of what is now Salton City during Diablo deposition. This implies approximately 125 km of right-lateral slip on the San Andreas fault since Diablo time, as suggested by Winker and Kidwell (1986). The significance of this slip amount will not be known until the age of the top of the Diablo Formation is determined.

During younger Borrego deposition, the Colorado Delta probably formed a low topographic barrier that separated the Borrego Lake in the NW from the Gulf of California in the SE, similar to the modern setting. The older Diablo-Borrego transition, however, is poorly understood. We believe climate was not the main control on lake formation because regional climate records indicate cooling and drying in the SW U.S. at ~3.0-2.5 Ma (e.g., Forester, 1991; Smith, et al., 1993). If the Colorado River entered the Salton Trough NE of present-day Salton City, it could not have also created a topographic barrier to the SE. This suggests that multiple delta lobes and/or a structural barrier may have been present SE of the lake to isolate it from the gulf. Also, a tectonic barrier would likely be required to isolate the Fish Creek-Vallecito sub-basin from Colorado River input starting ~2.8 Ma (Winker, 1987) and initiate lake transgression in the SFBB. Two possible structural controls on basin segmentation are: (1) initiation of the Fish Creek Mountains fault on the NE flank of the Fish Creek and Vallecito Mountains; or (2) syn-depositional growth of a large NW trending anticline. Ongoing research will allow us to test these hypotheses.

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Evidence for a Lacustrine Origin for the Lower Pliocene Bouse Formation, Lower Colorado River Valley

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The lower Pliocene Bouse Formation in the lower Colorado River valley consists of basal marl and overlying siltstone with sparse sandstone and bedrock-coating tufa (e.g., Metzger et al., 1973; Buising, 1990). An estuarine origin for the Bouse Formation has been supported in paleontologic literature because of its mix of marine, brackish, and fresh water fauna (Smith, 1970; Todd, 1976; Lucchitta et al., 2001). However, at least three lines of evidence support a lacustrine origin: (1) The concentration of strontium in sea water is many times that in river water and the isotopic signature of sea water is readily detected in materials derived from mixed waters. $^{87}Sr/^{86}Sr$ of Bouse marl, tufa, and calcareous shells are similar to Colorado River water but unlike sea water (Spencer and Patchett, 1997). This is especially problematic for an estuarine interpretation because $^{87}Sr/^{86}Sr$ from southern exposures near the mouth of the presumed Bouse estuary shows no marine influence; (2) Numerical simulations of first arrival of Colorado River water to a sequence of closed basins along what is now the lower Colorado River valley indicate that salinity will increase due to evaporation as outflow incision lowers lake levels. For slow incision the lowest basin, centered on the town of Blythe, will reach salinities comparable to sea water and would in theory become hospitable to marine organisms introduced by birds; (3) In the Parker area, deposition of the Bouse Formation was associated with a transition from locally derived gravels to far traveled, quartz-rich sands that resemble Colorado River sediments (Buising, 1990). In Mohave Valley, this transition was marked by flood deposits derived from the north that probably record abrupt arrival of Colorado River water (House et al., 2002).

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Late Neogene Marine Incursions and the Ancestral Gulf of California

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Microfossil evidence in the Salton Trough, lower Colorado River, southwestern Arizona, and Gulf of California region suggest that there were three marine incursions from the middle Miocene to the Pliocene to Pleistocene (McDougall and others, 1999). The middle Miocene incursion (11-14 Ma) extended at least as far north as the Isla Tiburon in the Gulf of California and although microfossils have been found farther north, none are *in situ*. Thus the northern limit of this incursion has not been determined. Middle Miocene microfaunas suggest deposition occurred during warm climatic conditions and high sea level. The late Miocene incursion (6-7 Ma) extends as far north as San Gorgonio Pass, California, and as far east as Yuma, Arizona. This incursion appears to be the most extensive, and microfossils suggest a wide variety of environments in a warm climatic interval. During the Pliocene to Pleistocene incursion (post 5.2 Ma), marine waters covered most of the Salton Trough and lower Colorado River area. The marine section was strongly affected by the Colorado River, which rapidly filled the area with fresh water and sediment, reducing the marine influence. These late Neogene marine incursions indicate that a Proto-Gulf of California opened during the middle and late Miocene during extension and that the present Gulf of California opened during the Pliocene following rifting of Baja California away from the North American plate (Stock and Hodges, 1989).

The late Neogene section in the Salton Trough, California, along the lower Colorado River, and in southwestern Arizona, is composed of a marine unit bracketed by nonmarine units. The marine section, which is generally referred to as the Imperial Formation in California and the Bouse Formation in Arizona, occurs in discontinuous outcrops throughout the area. Fossiliferous coeval strata also occur around the Gulf of California in Mexico; however, the stratigraphic sequence is not as simple as in the U.S. Microfossil data available from the marine sections throughout the region have been used to determine age, environment, and correlation of the marine strata (McDougall, 1998; McDougall and others, 1999). Paleogeographic reconstructions show the extent of the region covered by marine waters as well as the timing and the effect of the influx of Colorado River water.

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POSTERS

Geologic and Geomorphic Record of Late Pleistocene and Holocene Lake Levels of Owens Lake,eastern California

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Newly described fluvio-deltaic and lacustrine sediments exposed in stream cuts, quarry walls, and deep trenches in southern Owens Valley near Lone Pine and Keeler are dated by 22 radiocarbon (^{14}C) dates and 3 tephra horizons. These near-surface stratigraphic data provide new age constraints on late Pleistocene and Holocene oscillations in the level of Owens Lake. These oscillations occurred between the elevations of 1,110-1,135 m in the time from ~25,000 to 7,750 cal yr (calendar years) B.P., well below the present sill elevation of 1,145 m. On the basis of compilation of this new stratigraphic analysis with published near-surface stratigraphic data and subsurface core data, we have constructed a lake-level elevation curve for the time interval ~27,000 cal yr B.P. to present.

Between ~27,000 and ~15,300 cal yr B.P., pluvial Owens Lake regressed from its late Pleistocene highstands at ~1,158 and 1,145 m, respectively, as recorded by ~13 m of down cutting of the sill (Lubetkin and Clark, 1988; Orme and Orme, 1993, 2000). By ~11,600 cal yr B.P., the lake had dropped ~45 m from the sill. This lowstand was followed by an early Holocene transgression that attained a highstand near 1,135 m before dropping to 1,120 m at ~7,750 cal yr B.P. The elevation and age of this early Holocene transgression and associated highstand were previously unrecognized and are chronologically well constrained by ^{14}C ages from tufa and charcoal, and tephra correlation. The lake then lowered another ~30 m to near desiccation levels from ~6,500 to 4,200 cal yr B.P. (Benson et al., 1997; Smith et al., 1997). From fluvial cut-and-fill relations north of Lone Pine in the Owens River meander belt and shoreline features at ~1,108 m in the south-southeastern basin, we hypothesize a minor lake-level rise after 4,200 cal yr B.P. that was followed by alkaline and shallow conditions during the late Holocene.

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Similarity of Mono Lake, CA, and Big Soda Lake, NV, Tufa: Are They Typical of Tufa Found in the Southwest of the United States?

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Tufa mounds and other forms of microbial carbonates are found in lake and river systems throughout the world. Tufa mounds have been used as evidence for paleoclimate changes, as well as evidence of shoreline positions and ground-water input to a basin. In the Western United States, the most spectacular actively forming tufa is found at Mono Lake, Calif. Recent work in Big Soda Lake (BSL), Nevada, has found fast growing recent tufa mounds that have many attributes that are similar to the Mono Lake tufas. This discovery leads to the question of whether this type of tufa formation is regionally typical.

BSL formed in a volcanic explosion crater created sometime in the last 10,000 years. There are no surface-water inputs to the lake and lake level is maintained by ground-water seepage. In BSL and Mono Lake, tufa forms where ground water, high in dissolved calcium, discharges into the lake. When the Newlands Irrigation Project began in 1907, irrigation of farmlands surrounding the lake raised the water table, which caused the lake level to rise by 18 m between 1907 and 1930. This led to the rapid growth of tufa over the last 100 years. The tufa at BSL is similar in mineral composition and morphology to the tufa found in Mono Lake. The chemical composition of the lake waters also is similar. Thin sections of BSL tufa show that calcite pseudomorphs of a presumably monoclinic mineral are prevalent. This pseudomorph may have originally been ikaite. X-ray diffraction analysis of BSL tufas indicates that monohydrocalcite ($CaCO_3 \cdot H_2O$) is an abundant tufa-forming mineral. Although ikaite ($CaCO_3 \cdot 6H_2O$), which is present in Mono Lake, has not been found at BSL, it is possible that the monohydrocalcite is a transformation product of ikaite.

The geology and hydrology of BSL and Mono Lake basins are similar: both basins are dominated by volcanic activity, both basins have some geothermal-fluid input within the basin, and both are terminal basins. Tufa towers are texturally and chemically similar, as is the water precipitating the carbonate minerals. Although these two basins have the same unusual combination of geological and hydrological characteristics, other Pleistocene tufa-forming basins in the Western United States (e.g., Pyramid, Searles, Panamint, Death Valley Lakes) lack these geological characteristics and therefore are probably only similar hydrologically. The main unifying factor to tufa formation in this region (other than possible biological factors) is the contribution of ground water, rich in dissolved Ca, mixing with lake waters high in carbonate and bicarbonate needed to reach calcium carbonate saturation. The similarity of BSL and Mono Lake tufa is remarkable, but is probably unique in the desert southwest of the United States.

Late Pleistocene Fluvial Fish Flushing Introduces Stickleback (Gasterosteus sp.) to Western Mojave Desert Drainages

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Two species of fish are known from the late Pleistocene rivers and lakes of the Mojave Desert, California. The Mojave tui chub (*Siphateles mohavensis*) was widespread; Pleistocene fossils of threespine stickleback (*Gasterosteus aculeatus*) are known from Rosamond and Coyote lakes and from pond sediments at Daggett. The Daggett locality dates between 12,000 and 9,000 years; the others may date to the Wisconsinan glacial maximum (20,000 years) or later. *Gasterosteus* occurs at these localities with floaters (*Anodonta* sp. bivalves) and anurans, but the only co-occurrence with *Siphateles* is at Daggett. *Siphateles* is unrecorded and apparently absent from the Rosamond Lake record. At Coyote Lake, stickleback are abundant low in the section, but are replaced by the Mojave tui chub higher in the section. Miocene occurrences of stickleback are known from Yermo, California ($\geq$17 Ma) and Hazen, northwestern Nevada (9.8 Ma). Pliocene occurrences are from sediments of the Ridge Basin (4 Ma) near Gorman, California, and from Bautista (2 Ma) east of Hemet, California. Stickleback are unrecorded and apparently absent from middle Miocene through late Pliocene lacustrine sediments of the Mojave Desert.

Extant threespine stickleback populations are both anadromous and occupants of low gradient streams. They spawn in fresh water and their tolerance for low salinity waters allows them to migrate upstream in shallow gradient rivers in southern California, such as the Santa Clara, Los Angeles, Santa Ana, and San Jacinto. Their weak swimming ability prevents either their passage or colonization of steep gradient, swift reaches of stream. Isolated native populations currently occupy streams with shallow gradients and lakes and ponds in the San Bernardino Mountains at elevations between 1900 m (6250 ft) and 2000 m (6800 ft). One population inhabits the low gradient headwaters of Holcomb Creek, a tributary of the Mojave River. Another population occupies intermittent ponds around Baldwin Lake and its tributary, Shay Creek. Topography prevents the Baldwin Lake drainage system from connecting with Holcomb Creek or other drainages into the Mojave Desert.

If stickleback were extirpated from drainages in the Mojave Desert after 17 Ma, why are they found in late Pleistocene lacustrine deposits of the central and western Mojave Desert? The Transverse Ranges that bound the southwestern side of the Mojave Desert started rising around 3 Ma and reached elevations above 10,000 feet around 0.5 Ma. The occupation of extant stickleback populations in low gradient, high elevation streams suggests that populations could have survived the Plio-Pleistocene uplift of the Transverse Ranges. The presence of late Pleistocene *Gasterosteus* populations in lakes of the west and central Mojave Desert support a model wherein stickleback in mountain refugia were flushed downstream during heavy pluvial periods such as glacial maxima. This would account for the post-20,000 year records in sediments at Rosamond Lake, Coyote Lake, and pond sediments at Daggett.

Transition from Basins to Through-Flowing Drainage of the Colorado River, Lower Lake Mead Region, Nevada and Arizona

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The upper Miocene Muddy Creek Formation and overlying Hualapai Limestone mark the end of basin deposition in the Lake Mead region prior to integration of the lower Colorado River from Grand Canyon to the Gulf of California. The top of the Hualapai (average current elevation of 700 m) formed the surface on which the river must have originally flowed (Howard and Bohannon, 2000). Isolated outcrops of Colorado River gravels inset at various levels below the top of the Hualapai in the Temple Basin and Detrital Wash area are locally tilted and faulted. Inception of the river in this area is bracketed between a 6.0 Ma tuff (Spencer and others, 1998) near the top of the Hualapai and the 4.4 Ma basalt at Sandy Point that overlies Colorado River gravels (Faulds and others, 2000).

In the Lake Mohave area to the south, remnants of a pre-5.6 Ma axial stream to possible lacustrine deposit are unconformably overlain by the post-5.6 Ma Bouse Formation (House and others, 2004), consisting mostly of fine-grained quiet-water to deltaic sediments. Erosion of the Muddy Creek and Hualapai in the Lake Mead area may have supplied the fine-grained sediments of the Bouse and possibly of the underlying sequence, indicating a hydrologic connection between the two areas sometime after 5.6 Ma. Sediments of the Bouse occur as far north as Cottonwood Valley where they occur at a maximum elevation of 550 m (Lucchitta and others, 2000). Near Davis Dam the first far-traveled pebbles of probable lower Colorado River origin are inset into the Bouse near the present river level, where they form the base of a thick aggradational event that deposited at least 250 m of medium sands and gravels by 3.9 Ma (House and others, 2004).

The erosional interval between deposition of fine-grained sediments of the Bouse and the inset coarser grained Colorado River deposits suggests that either a local drainage was developed between the two basins prior to rapid integration of the Colorado River or that sand and gravel river deposits were ponded in the Lake Mead area for a while before the river broke through to lower reaches. A widespread topographic scarp or bench at between 550 and 580 m elevation in the Lake Mead area may be the result of this possible ponding at about 5 Ma.

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A 1.07 Ma Change from Persistent Lakes to Intermittent Flooding and Desiccation in the San Felipe Hills, Salton Trough, Southern California

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Sedimentary rocks of Pliocene to Pleistocene age in the San Felipe Hills (SFH), Salton Trough, record an abrupt change from the older, perennial lake beds of the Borrego Formation to cyclic alluvial and marginal lacustrine deposits at 1.07 Ma. The ~1680-m-thick lacustrine claystone, mudstone and sandstone of the Borrego Formation exhibit few marginal lacustrine facies in the San Felipe Hills, and formed in a large perennial lake. A regional disconformity and laterally equivalent angular unconformity at the crest of a bedrock-cored anticline separate the Borrego Formation from the overlying conglomeratic Ocotillo Formation and its fine-grained equivalent, the Brawley Formation. The disconformity is dated paleomagnetically at 1.07 Ma and records a permanent drop in base level as alluvial to eolian deposition replaced open lacustrine deposition. The Brawley Formation shows evidence for repeated drying of intermittent lakes (> 30 times). It consists of 3 interbedded lithofacies: (1) fluvial to deltaic sandstone with cross-bedding and weak calcic paleosols; (2) lacustrine mudstone, claystone, and marlstone with 0.5 to 1.5 m deep desiccation cracks, rare evaporite minerals, and locally abundant microfossils; and (3) eolian sandstone with large scale (~ 3-4 m high) high-angle cross stratification. Microfossils include marine to lagoonal forams, ostracods, micromollusks, and charophytes. Sandstones include ~60% arkose derived from local tonalite sources.and ~40% sublitharenite derived from the Colorado Plateau. Sediment transport was to the E to NNE. Sedimentation rates range from 1.1 mm/yr to 1.8 mm/yr.

The disconformity between the Borrego and Brawley Formations, at 1.07 Ma, indicates that the lake margin shifted ~25 km to the NE, the lake was reduced in size, and near modern depositional environments were established across a large area. This abrupt change reflects reorganization of the basin due to initiation or reorganization of the San Jacinto fault zone in the SFH. Brawley Formation sediments accumulated in an ephemeral stream and delta system on the western margin of the Salton Trough while evaporites accumulated offshore. Flooding of the basin occurred when channel switching in the Colorado River delta delivered water N into the Brawley basin. Although water in the Brawley lake was derived from the Colorado River to the SE, sand was derived from local sources in the W and SW. Colorado River derived sand was recycled from uplifted Pliocene Diablo Formation, which consists of older delta-plain deposits of the Colorado River. Folding and uplift in the SFH began after the end of deposition of the Brawley Formation (0.61 $\pm$ 0.02 to 0.52 Ma $\pm$ 0.03 Ma) and shifted the depocenter farther to the east. This latter transition records the initiation of the Clark strand of the San Jacinto fault SE of the Santa Rosa Mountains.

A Preliminary Hypothesis about the Origin of Late Pleistocene Deposits along the Lower Colorado River

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A conspicuous subset of fluvial deposits along the Colorado River downstream of Grand Canyon records at least one major period of river aggradation followed by incision, yet the cause and timing of these events remain unclear. The deposits are preserved discontinuously along the modern river course and major tributary valleys over more than 500 kilometers between Grand Canyon and the head of the Colorado River delta near Yuma, Arizona. The remnants of the deposit typically consist of a lower unit of reddish-brown, layered fine sand and mud overlain by an upper unit of unconsolidated, well-sorted, cross-bedded sand. Sparse data suggest the deposits are late Pleistocene in age. Longwell (1936) named the sequence the Chemehuevi Formation and interpreted it as lacustrine. This explanation is unlikely given that the tops of the remnants delineate a surface steeper than that of the historic (pre-dam) river (Lundstrom and others, 2004), and the deposits are probably too young to have been tilted enough to account for their gradient. The formation has also been associated with the excavation of the Grand Canyon (Faulds, 1995) and with the passage of very large floods (Lundstrom and others, 1998). Metzger and others (1973) assumed the formation must represent a period of river aggradation (lower unit) followed by temporary deposition during an interrupted sequence of downcutting (upper unit), although they did not provide a mechanistic explanation of the peculiar stratigraphy.

We suggest an elaboration of Metzger's hypothesis, in which the entire sequence (fine and coarse) resulted from a temporary oversupply of sediment derived from portions of the watershed underlain by red-colored sedimentary rocks with abundant fines. According to our hypothesis, fine-grained sediment accumulated in floodplains within the basins now drowned by Lake Mead, burying the pre-existing topography with over 100 m of sediment and possibly steepening the river gradient. Base level rise in the mainstem Colorado River would have contributed to sand and gravel deposition upstream (possibly into Grand Canyon) and in tributary valleys. As the sediment supply decreased, the river gradually incised its channel towards a grade adjusted to the reduced sediment load. The coarse sediment stored upstream of the original locus of deposition was consequently remobilized, transported downstream, and deposited on top of the fine-grained unit at multiple elevations. This interpretation explains all of the physical characteristics of the Chemehuevi remnants observed to date. The hypothesis implies a temporary increase in the supply of fine-grained sediment due to widespread landscape erosion and/or valley trenching in late Pleistocene time, perhaps caused by aridification of portions of the Colorado River watershed.

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