

Chronology, sedimentology, and microfauna of groundwater discharge deposits in the central Mojave Desert, Valley Wells, California

Jeffrey S. Pigati^{1,†}, David M. Miller², Jordon E. Bright^{3,§}, Shannon A. Mahan⁴, Jeffrey C. Nekola⁵, and James B. Paces⁶

¹U.S. Geological Survey, Denver Federal Center, Box 25046, MS-980, Denver, Colorado 80225, USA

²U.S. Geological Survey, 345 Middlefield Road, MS-973, Menlo Park, California 94025, USA

³School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, Arizona 86011, USA

⁴U.S. Geological Survey, Denver Federal Center, Box 25046, MS-974, Denver, Colorado 80225, USA

⁵Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131, USA

⁶U.S. Geological Survey, Denver Federal Center, Box 25046, MS-963, Denver, Colorado 80225, USA

ABSTRACT

During the late Pleistocene, emergent groundwater supported persistent and long-lived desert wetlands in many broad valleys and basins in the American Southwest. When active, these systems provided important food and water sources for local fauna, supported hydrophilic and phreatophytic vegetation, and acted as catchments for eolian and alluvial sediments. Desert wetlands are represented in the geologic record by groundwater discharge deposits, which are also called spring or wetland deposits. Groundwater discharge deposits contain information on the timing and magnitude of past changes in water-table levels and, thus, are a source of paleohydrologic and paleoclimatic information. Here, we present the results of an investigation of extensive groundwater discharge deposits in the central Mojave Desert at Valley Wells, California. We used geologic mapping and stratigraphic relations to identify two distinct wetland sequences at Valley Wells, which we dated using radiocarbon, luminescence, and uranium-series techniques. We also analyzed the sediments and microfauna (ostracodes and gastropods) to reconstruct the specific environments in which they formed. Our results suggest that the earliest episode of high water-table conditions at Valley Wells began ca. 60 ka (thousands of calendar yr B.P.), and culminated in peak discharge between ca. 40 and 35 ka. During this time, cold (4–12 °C) emergent groundwater supported extensive

wetlands that likely were composed of a wet, sedge-rush-tussock meadow mixed with mesic riparian forest. After ca. 35 ka, the water table dropped below the ground surface but was still shallow enough to support dense stands of phreatophytes through the Last Glacial Maximum (LGM). The water table dropped further after the LGM, and xeric conditions prevailed until modest wetlands returned briefly during the Younger Dryas cold event (13.0–11.6 ka). We did not observe any evidence of wet conditions during the Holocene at Valley Wells. The timing of these fluctuations is consistent with changes in other paleowetland systems in the Mojave Desert, the nearby Great Basin Desert, and in southeastern Arizona, near the border of the Sonoran and Chihuahuan Deserts. The similarities in hydrologic conditions between these disparate locations suggest that changes in groundwater levels during the late Pleistocene in desert wetlands scattered throughout the American Southwest were likely driven by synoptic-scale climate processes.

INTRODUCTION

The Mojave Desert is the smallest of the four major deserts of North America, and it occupies a transitional zone between the hot Sonoran Desert to the south and the cool Great Basin Desert to the north. Like the adjacent deserts, valley floors and basins of the Mojave are largely dry today because water tables lie far below the ground surface (even in low-lying areas), and runoff from melting snowpack, rainfall, and high-elevation springs is limited. Ephemeral streams, small arroyos, and dry playas occasionally become active after unusu-

ally large or prolonged rain events, but these are rarely wet for more than a few weeks.

Conditions in the recent geologic past were substantially different. Large lakes were present in many areas of the Mojave Desert during the late Pleistocene (Jefferson, 2003; Wells et al., 2003; Orme, 2007; Phillips, 2007; Reheis and Redwine, 2007). In the northern Mojave, thousands of square kilometers of broad valleys and basins along the Owens River drainage system were occupied by the Owens-China-Searles-Panamint-Manly lake chain. Similar settings along the Mojave River drainage system to the south were occupied by Lake Manix and its successor, Lake Mojave. In other areas, emergent groundwater supported numerous low-elevation springs and wetlands that were persistent and long-lived (Paces et al., 1997; Nelson et al., 2001; Mahan et al., 2007; Jayko et al., 2008; Miller et al., 2010).

Traditionally, geologists have relied heavily on lake sediments and lacustrine landforms (shorelines, wave-cut benches, spits, etc.) to reconstruct the magnitude and timing of late Quaternary climatic and hydrologic changes in the American Southwest. Paleohydrologic information is also present in desert wetland settings, which include seeps, springs, marshes, and wet meadows. When active, desert wetlands provide important food and water sources for local fauna, support hydrophilic and phreatophytic vegetation, and act as catchments for eolian and alluvial sediments. The interplay among emergent water tables, ecological and biological systems, and eolian and alluvial processes results in complex depositional environments that are represented in the fossil record by groundwater discharge deposits, which are also referred to as spring or wetland deposits (Forester et al., 2003).

[†]E-mail: jpigati@usgs.gov

[§]Current address: Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA.

Groundwater discharge deposits are typically composed of a combination of groundwater precipitates (often carbonate), fine-grained alluvial and eolian sediments, and/or organic material. They are relatively common in arid environments and have been identified in all four deserts of the American Southwest. In the Mojave Desert alone, there are more than 130 different localities that exhibit some evidence of past discharge (e.g., Amoroso and Miller, 2006; Bedford et al., 2006; Schmidt and McMackin, 2006). Although several have been dated to the Younger Dryas cold event (e.g., Mahan et al., 2007; Miller et al., 2010), many deposits in the Mojave remain undated, and, for most, little is known about the spe-

cific environments in which they formed or their duration.

Groundwater discharge deposits contain information on the timing and magnitude of past changes in local or regional hydrologic budgets, and they clearly mark the position of past groundwater “highstands” on the landscape. Thus, they are a potential source of paleohydrologic and paleoclimatic information. Previous studies have established stratigraphic and chronologic frameworks for groundwater discharge deposits in the southern Great Basin (Haynes, 1967; Quade, 1986; Quade and Pratt, 1989; Quade et al., 1995, 2003). Here, we extend and expand upon these studies through an investigation of groundwater discharge deposits

at Valley Wells, California, located in Shadow Valley in the central Mojave Desert (Fig. 1). The deposits at Valley Wells are among the most extensive groundwater discharge deposits identified in the Mojave, and they contain evidence for multiple episodes of high water-table conditions. We used three independent dating techniques (radiocarbon, luminescence, and uranium-series) to establish the ages of the different units, and we analyzed the stratigraphy, sedimentology, and microfauna (ostracodes and gastropods) to reconstruct the specific environments in which they formed. We then compared the timing of water-table fluctuations at Valley Wells to other groundwater discharge deposits in the American Southwest in an attempt

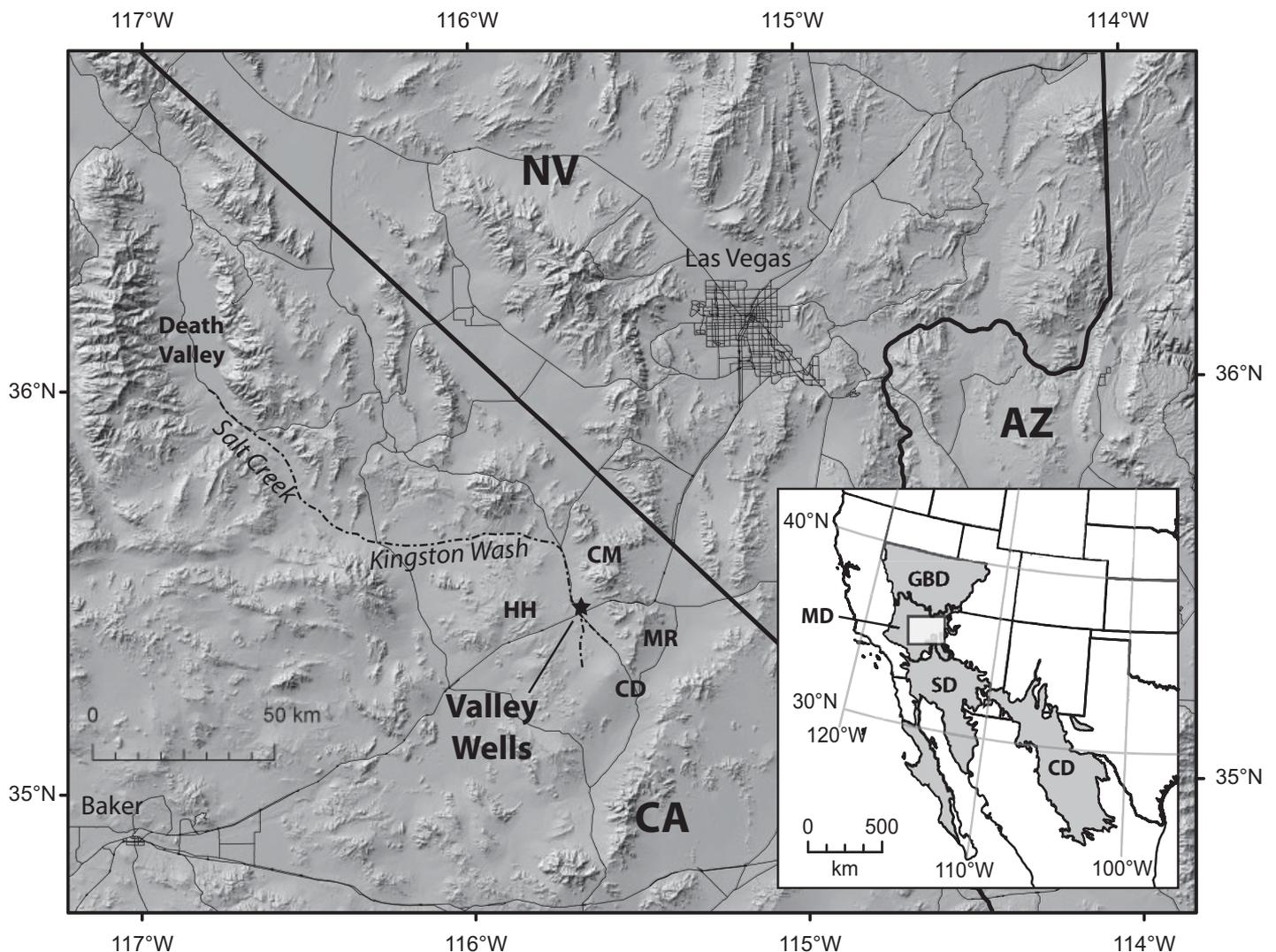


Figure 1. Location of Valley Wells in the Mojave Desert of southeastern California. Surrounding ranges, clockwise from north: CM—Clark Mountains, MR—Mescal Range, CD—Cima Dome, HH—Halloran Hills. Kingston Wash drains to the north through Shadow Valley, including the Valley Wells basin, before meeting Salt Creek and ultimately terminating in Death Valley. AZ—Arizona, CA—California, NV—Nevada. Inset: Deserts of the American Southwest (shaded) include the Great Basin Desert (GBD), Mojave Desert (MD), Sonoran Desert (SD), and the Chihuahuan Desert (CD). The lightly shaded box in the inset shows the extent of the area covered in the main panel of this figure.

to better understand the driving forces behind changes in hydrologic conditions in the central Mojave Desert during the late Pleistocene.

GEOLOGIC SETTING

Shadow Valley is located in the central Mojave Desert between the Clark Mountains and Mescal Range to the east and the Halloran Hills to the west, ~40 km northeast of Baker, California (Fig. 1). Most of the valley lowlands are covered by alluvial fans 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 valley floor has a gentle gradient down to the north and drains into Salt Creek via Kingston Wash and eventually into Death Valley.

The southeastern part of Shadow Valley includes the Valley Wells basin, which contains a distinct set of light-colored sediments that are situated near the valley floor and cover an area of ~4.5 km² (Fig. 2). We used field mapping, sedimentological properties, and stratigraphic relations to identify at least two distinct geologic units within the light-colored sediments. Our unit terminology follows that of Haynes (1967), with particular reference to Units D (late Pleistocene) and E₂ (latest Pleistocene to early Holocene) (Table 1). In the southern Great Basin, Unit D represents extensive groundwater discharge deposits that are widespread and well exposed. In the Corn Creek badlands of the Las Vegas Valley, for example, Unit D dominates the landscape; whitish outcrops of carbonate-rich silty clay interbedded with pale-green mudstones cover much of the valley floor and form bluffs that are ~4–8 m high (Quade, 1986). Unit D has a similar appearance elsewhere in the southern Great Basin, and it consistently yields radiometric ages (mostly ¹⁴C) that correspond to full-glacial times (e.g., Quade and Pratt, 1989; Quade et al., 1995; Paces et al., 1996, 1997).

Unit E₂ is generally more subdued and restricted in spatial extent (Quade et al., 1998). Where preserved, it typically consists of spring and channel depressions that are filled with alluvium, organic-rich mats, and green clays, and it dates to the Younger Dryas cold event (13.0–11.6 ka; Alley et al., 1993) or early Holocene. The units that we identified at Valley Wells are similar to these in terms of their physical appearance and extent, relative stratigraphic positions, sedimentology, microfauna, and chronology.

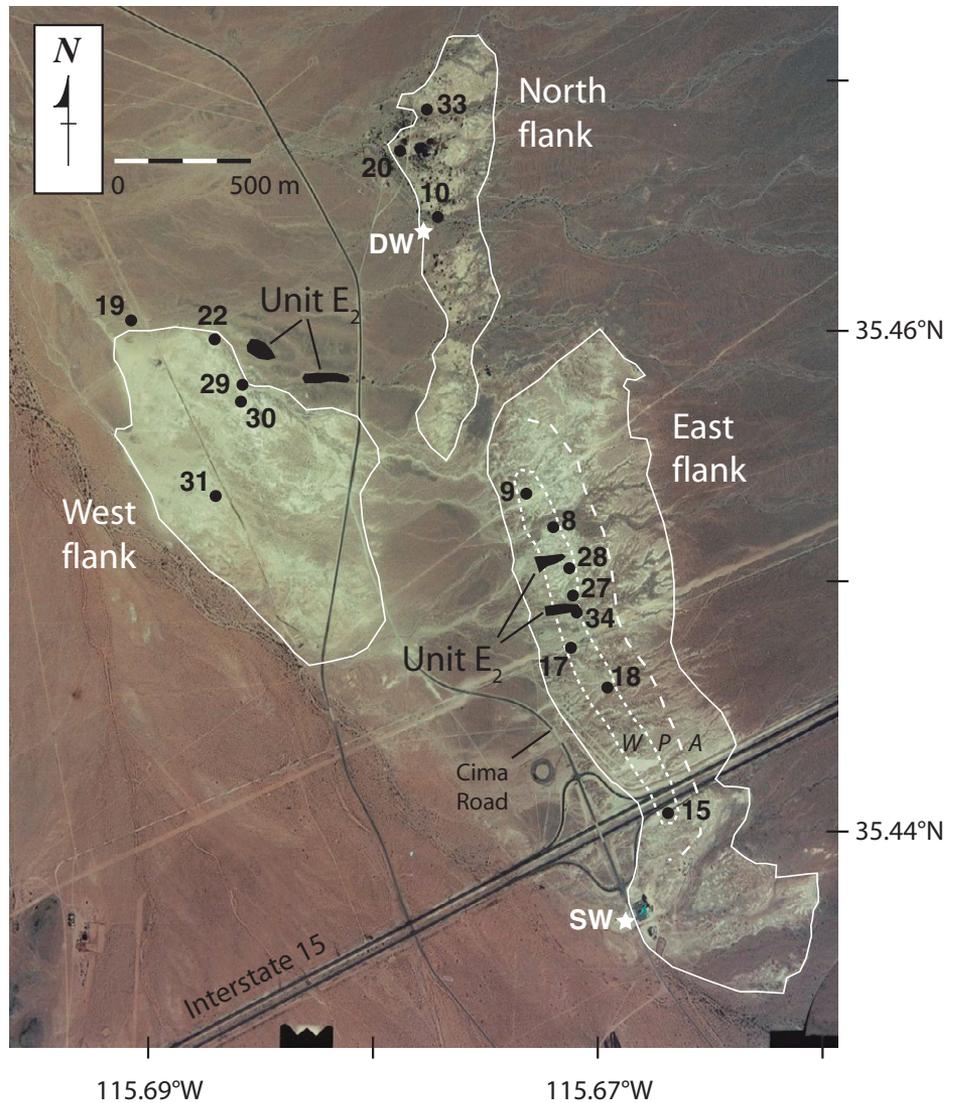


Figure 2. Map of groundwater discharge deposits at Valley Wells. Unit D is separated into three areas, called the north, east, and west flanks, based on differences in sedimentology, preservation, and position on the landscape. Sedimentological facies in the east flank are based on the Quade et al. (1995) model as follows: W—wetland or marsh, P—phreatophyte flat, A—alluvial setting. Areas that were not assigned a specific facies were either degraded or poorly exposed. Unit E₂ is exposed in two places within the east flank, where it is inset within the older, more extensive deposits of Unit D. Unit E₂ is also present in a small arroyo between Cima Road and the west flank, where it is capped by Holocene alluvium. Numbered dots denote stations (exposures) that are referred to in the text and supplemental information (latitudes and longitudes are listed in the supplemental information [see text footnote 1]). White stars denote location of groundwater samples: DW—dug well, SW—station well. Aerial photograph taken 8 June 1974, photo 8:32, U.S. Bureau of Land Management 32–27.

TABLE 1. WETLAND UNITS IN GREAT BASIN

Unit	Marine isotope stage	Approximate age range* (¹⁴ C ka)	Environment
A	>6	—	Fluvial
B	6?	—	Extensive (?) wetlands
C	3–4?	—	Fluvial/alluvial
D	2	14–30	Extensive wetlands
E ₁	Late 2	11.8–13.5	Modest wetlands
E ₂	Early 1, late 2	7.2–11.2	Waning wetlands
F	1	4.0–7.0	Desiccation

*Defined by Haynes (1967) and Quade (1986).

Stratigraphic Units at Valley Wells

Unit D

Unit D constitutes nearly all of the light-colored sediments at Valley Wells and is present in three separate locations in the basin, which we refer to as the north, east, and west flanks (Fig. 2). Within the north and east flanks, the surface of Unit D was probably continuous upon formation, but it is now dissected by a series of arroyos. Resistant capping sediments in these areas form quasi-continuous bluffs that are up to 5–6 m high, and the surface dips $\sim 0.8^\circ$ to the west in the north flank and $\sim 0.6^\circ$ in the same direction in the east flank. In the west flank, Unit D is heavily eroded. The original surface is preserved only in a few discontinuous outcrops in this area, and it dips slightly (0.3°) to the north or northwest. Based on the morphology and distribution of the light-colored sediments (they are absent near Cima Road; Fig. 2), it appears that the west flank has always been separate from the north and east flanks.

The composition of Unit D varies depending on location because there are several sedimentary facies that represent strata that formed in different wetland environments (Fig. 2; discussed in detail in the following). The basal sediments of Unit D are not exposed. Near the western margin of the east flank, the lowest exposed sediments of the unit range from a pale-reddish-brown, well-sorted silty clay to light-brown fine sands and silts. These sediments are overlain by a thin (~ 30 cm), pale-green sandy silt that includes numerous small root voids filled with secondary Fe-oxides (stratum D_{gss}).¹ Above this, a thin (20–40 cm), well-sorted green silty clay (stratum D_{gsc}) is present that contains abundant ostracodes and gastropod shells; it, in turn, is overlain by 30–50 cm of light-brown silty clay (Fig. 3A). In many places, this series of fine-grained sediments is capped by a thick (up to ~ 1 m), extremely hard and well-cemented, light-gray stratum that is composed almost entirely of calcium carbonate (stratum D_{carb} ; Fig. 4A). Where exposed, the surface of stratum D_{carb} is usually shattered, probably by a combination of freeze-thaw, salt accumulation, and bioturbation processes, and is expressed in many places as desert pavement composed of carbonate rubble.

¹Names are assigned to strata within Unit D that are traceable from one station (or exposure) to another; subscripts refer to their defining characteristic: gss—green sandy silt, gsc—green silty clay, carb—carbonate, and gyp—gypsum. These names are restricted to groundwater discharge deposits at Valley Wells and do not correlate with deposits elsewhere in the Mojave or southern Great Basin. Strata that cannot be traced from station to station at Valley Wells were not assigned names.

In general, these fine-grained strata grade progressively to the east into coarser-grained sediments, ranging from moderately well-sorted silt and very fine sand (Fig. 3B) to poorly sorted, coarse sand and gravel (Fig. 3C). Stratum D_{carb} also changes character to the east, grading into softer (less cemented) carbonate-rich silty clay that is interbedded with alluvial sand and gravel near the eastern margin. In the eastern half of the east flank, Unit D is topped by a thin (30–50 cm), soft stratum that is composed almost entirely of gypsum (stratum D_{gyp} ; Fig. 4B).

Unit D deposits in the north flank are similar to those in the east flank except that strata D_{gss} and D_{gsc} are absent in the north. Deposits in the north flank range from well-sorted silty clay to poorly sorted, medium- and coarse-grained sand and gravel. In some places, carbonate nodules are present in the lower part of the unit (e.g., at station 10; Fig. 2). Much of the northern half of the north flank is composed of carbonate-rich silty clay that is capped by stratum D_{carb} , whereas the southern half of the north flank is either capped by stratum D_{gyp} or has been significantly eroded.

Finally, in the west flank, the lowest exposed part of Unit D is composed of carbonate-rich silty clay that is ~ 1 m thick and is overlain by stratum D_{carb} . In some outcrops, the hard carbonate is covered by an additional ~ 1 m of silty clay, which, in turn, is capped by stratum D_{gyp} . We did not find ostracodes or gastropod shells in either the north or west flanks.

Unit E₂

Unit E₂ at Valley Wells consists of (from bottom to top) at least 40–50 cm of olive-green clay (stratum E_{2a}), 20–40 cm of dark-brown, organic-rich clay (stratum E_{2b}), and 20–30 cm of soft, light-brown silt (stratum E_{2c}) (Fig. 3D). We did not observe any lateral changes in facies within this unit. In all, Unit E₂ is typically 1–2 m thick, relatively soft, and easily eroded, and it exhibits a badland appearance where exposed at the surface. In the east flank, Unit E₂ is inset into the underlying Unit D deposits in at least two places, where the top of Unit E₂ is ~ 4 –5 m lower than the top of Unit D. It is also present in two small areas between Cima Road and the west flank deposits, where it is covered by Holocene alluvium (Fig. 2). Unit E₂ was not found in either the north or west flanks.

CHRONOLOGY

Unit D

We used three independent dating techniques (radiocarbon, luminescence, and uranium series) to constrain the age of Unit D. Methodologi-

cal details of each technique are included in the supplemental information.² To determine the minimum age for the base of the unit, we used infrared-stimulated luminescence (IRSL) on feldspars recovered from fine-grained sediments in the east flank (stations 9 and 17), coarser-grained sediments in the north flank (station 10), and carbonate-rich sediments in the west flank (station 29). The systematics of IRSL techniques are well known (Auclair et al., 2003; Preusser, 2003; Steffen et al., 2009), and, in general, IRSL ages derived from feldspars have proved to be more reliable than optically stimulated luminescence (OSL) ages on quartz in wetland settings elsewhere in the Desert Southwest (Pigati et al., 2009).

IRSL ages from the lowest exposed sediments of Unit D in the north and east flanks ranged from 48.5 ± 5.2 to 53.5 ± 8.2 ka (ka = thousands of calendar yr B.P.; uncertainties for all dating techniques are given at the 95%, or 2σ , confidence level; Table 2). Duplicate IRSL measurements of a sample taken from the lowest exposed sediments in the west flank yielded ages of 54.8 ± 8.6 and 61.4 ± 6.4 ka, which are slightly older than the IRSL ages from the north and east flanks. It is unclear if the lowest exposed sediments in the west flank are indeed older than those to the north and east, or if the sampled sediments in the west flank were simply positioned lower in the unit relative to those sampled elsewhere (Fig. 5).

We used radiocarbon dating of gastropod shells and IRSL dating of feldspars to determine the age of sediments near the middle of Unit D. Radiocarbon ages obtained from terrestrial gastropod shells are often considered to be suspect because many taxa consume limestone or other carbonate rocks and incorporate the “dead” carbon from the rocks in their shells. This can cause ¹⁴C ages of terrestrial gastropod shells to be as much as 3000 ¹⁴C yr too old (e.g., Goodfriend and Stipp, 1983). Recent studies, however, have demonstrated that some small (<1 cm in maximum dimension) terrestrial gastropods appear to avoid this “limestone problem,” even when living in terrain dominated by carbonate rocks (Pigati et al., 2004, 2010). Small terrestrial gastropod shells, including several taxa that are present in the Valley Wells deposits, have yielded reliable ¹⁴C ages in similar settings elsewhere in the Desert Southwest (Brennan and Quade, 1997; Pedone and Rivera, 2003; Pigati et al., 2009).

We obtained ¹⁴C ages for stratum D_{gsc} using terrestrial gastropods, including Succineidae

²GSA Data Repository item 2011197, Methodology, is available at <http://www.geosociety.org/pubs/ft2011.htm> or by request to editing@geosociety.org.

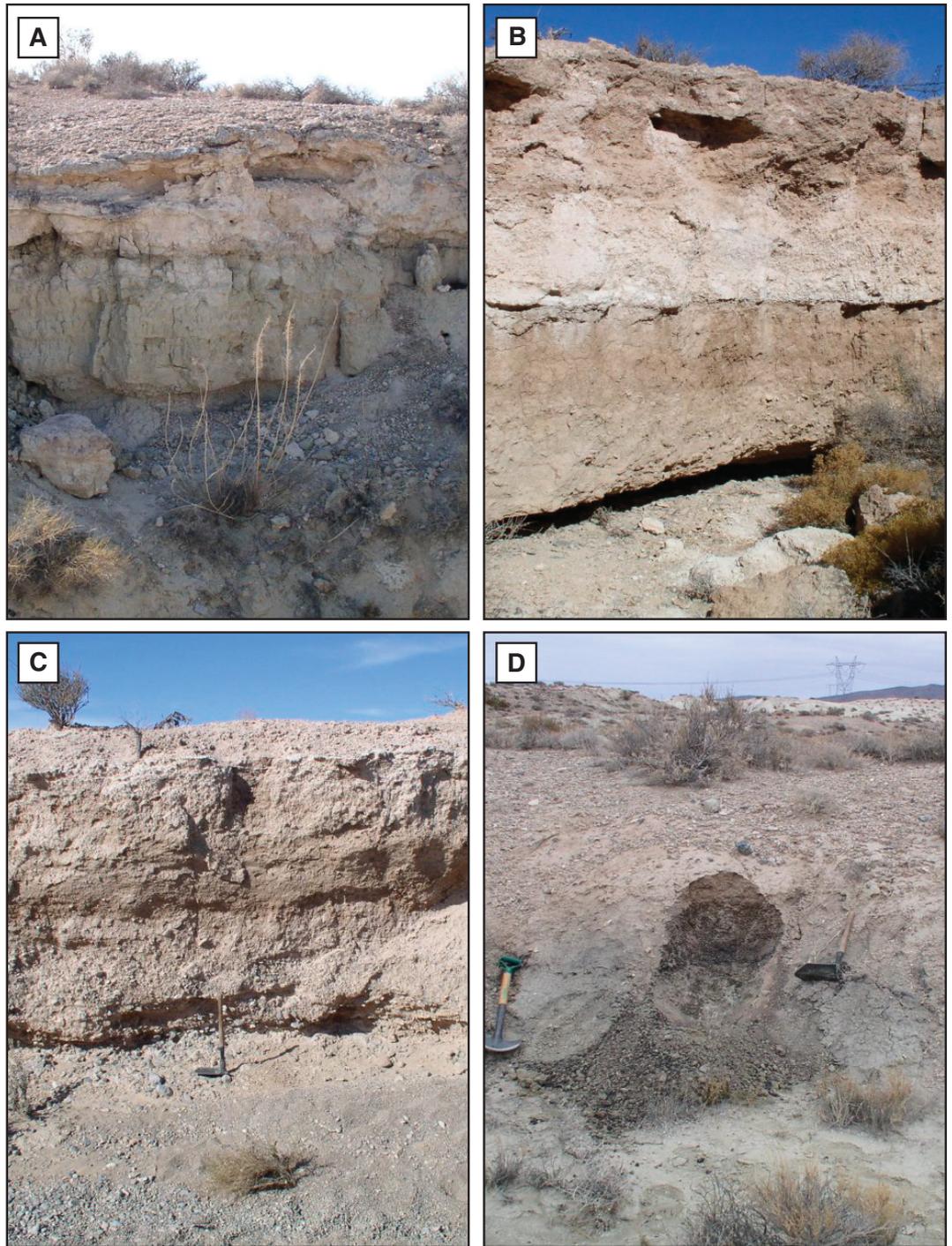


Figure 3. Photographs of Unit D deposits in the east flank that represent (A) wetland facies, (B) phreatophyte flat facies, and (C) alluvial facies. Deposits shown in each of these photographs are ~4–5 m thick. (D) Typical strata that comprise Unit E₂. Total thickness of the unit shown here is 1.5 m.

($n = 4$) and *Pupilla muscorum* ($n = 1$), as well as the aquatic gastropod *Gyraulus* sp. ($n = 2$). We did not find any difference in the ages between the terrestrial and aquatic taxa, which suggests that carbon-reservoir (or hard-water) effects in the emergent groundwater at Valley Wells were negligible during the late Pleistocene. In all, the ^{14}C ages of the gastropod shells ranged from 30.26 ± 0.42 to 33.74 ± 0.44 ^{14}C ka (Table 3). After calibration to calendar years using the

IntCal09 calibration curve (Calib 6.0.0; Stuiver and Reimer, 1993; Reimer et al., 2009), the shell ages range from 34.85 ± 0.29 to 38.39 ± 0.76 ka. These calendar-year ages are indistinguishable from IRSL ages obtained from stratum D_{gsc} in the east flank (35.4 ± 4.1 ka, station 9; 38.4 ± 5.1 and 38.6 ± 4.8 ka, station 17) and strata positioned at similar depths within Unit D in the north flank (34.8 ± 4.3 ka, station 10) (Table 2; Fig. 5).

The uppermost age of Unit D proved more elusive to constrain. We obtained IRSL ages of 25.4 ± 2.6 ka (station 9) and 27.5 ± 4.6 ka (station 17) on feldspars that were collected at depths of ~60 cm below the top of the unit (Fig. 5). Above this, however, stratum D_{carb} at stations 9 and 17 proved to be too indurated to sample for luminescence dating, and stratum D_{gyp} at station 10 was not suitable for dating because it had been significantly bioturbated.

Figure 4. Photographs of capping units of Unit D: (A) stratum D_{carb} at station 17 and (B) stratum D_{gyp} at station 30. For scale, the lengths of the shovel and hammer are ~55 and 30 cm, respectively.

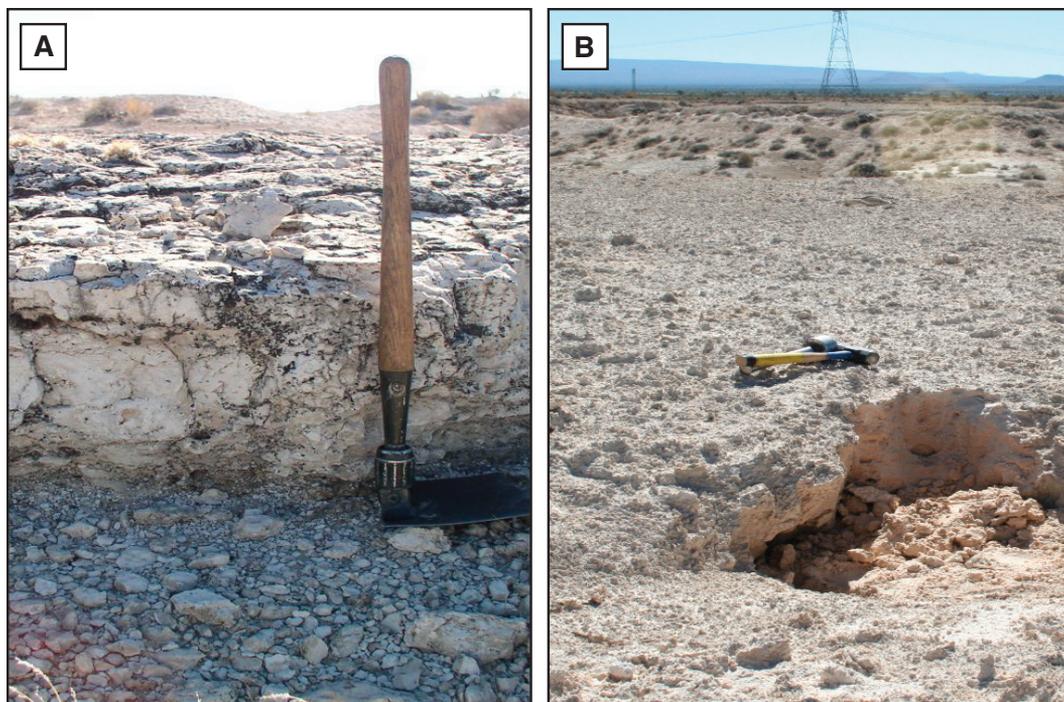


TABLE 2. SUMMARY OF INFRARED STIMULATED LUMINESCENCE (IRSL) RESULTS

Sample ID*	Water content (%) [†]	K (%)	U (ppm)	Th (ppm)	Cosmic dose addition (Gy/ka) [§]	Total dose rate (Gy/ka) [§]	Equivalent dose (Gy) [#]	IRSL age (ka)**
VW9-120	0 (16)	0.55 ± 0.03	2.64 ± 0.01	2.62 ± 0.01	0.24 ± 0.04	2.48 ± 0.12	53.1 ± 1.7	25.4 ± 2.6
VW9-119	12 (40)	2.29 ± 0.02	3.11 ± 0.02	12.70 ± 0.01	0.23 ± 0.04	5.52 ± 0.28	164.0 ± 11.1	35.4 ± 4.1
VW9-118-1	3 (12)	2.07 ± 0.02	2.78 ± 0.02	12.30 ± 0.01	0.22 ± 0.02	5.88 ± 0.32	218.0 ± 6.5	48.5 ± 5.2
VW9-118-2	3 (12)	2.07 ± 0.02	2.78 ± 0.02	12.30 ± 0.01	0.22 ± 0.02	5.88 ± 0.32	256.0 ± 7.2	52.7 ± 6.1
VW10-122	1 (18)	1.50 ± 0.02	2.00 ± 0.02	7.50 ± 0.01	0.33 ± 0.04	3.59 ± 0.16	93.1 ± 7.4	34.8 ± 4.3
VW10-121	2 (37)	1.91 ± 0.01	2.06 ± 0.02	10.10 ± 0.01	0.21 ± 0.02	4.07 ± 0.22	178.0 ± 11.0	51.4 ± 6.0
VW17-115	17 (50)	0.77 ± 0.03	1.26 ± 0.03	4.41 ± 0.04	0.24 ± 0.04	1.98 ± 0.10	47.5 ± 6.4	27.5 ± 4.6
VW17-114-2	3 (24)	2.51 ± 0.06	2.52 ± 0.05	13.50 ± 0.11	0.22 ± 0.02	5.68 ± 0.28	190.0 ± 16.4	38.4 ± 5.1
VW17-114-1	3 (24)	2.51 ± 0.06	2.52 ± 0.05	13.50 ± 0.11	0.22 ± 0.02	5.68 ± 0.28	191.0 ± 13.7	38.6 ± 4.8
VW17-113	7 (26)	1.47 ± 0.12	2.18 ± 0.26	8.05 ± 0.35	0.18 ± 0.02	3.38 ± 0.24	148.0 ± 8.0	53.5 ± 8.2
VW29-125-1	12 (52)	1.32 ± 0.09	1.62 ± 0.15	7.59 ± 0.24	0.23 ± 0.04	3.00 ± 0.18	148.0 ± 18.4	54.8 ± 8.6
VW29-125-2	12 (52)	1.32 ± 0.09	1.62 ± 0.15	7.59 ± 0.24	0.23 ± 0.04	3.00 ± 0.18	150.0 ± 6.0	61.4 ± 6.4
VW34-175	3 (36)	1.96 ± 0.06	8.87 ± 0.09	1.66 ± 0.05	0.23 ± 0.04	3.96 ± 0.20	99.8 ± 12.8	29.4 ± 4.8

Note: Uncertainties for all dose parameters and ages are given at the 2σ (95%) confidence level.

*Sample ID key: Valley Wells (VW), station number (refer to Fig. 2), sample number, and replicate number (if applicable).

[†]Field moisture (complete sample saturation). Ages were calculated using ~40% of saturation values.

[§]Cosmic doses and attenuation with depth were calculated following Prescott and Hutton (1994). See text for details.

[#]Dose rate and equivalent doses for fine silt (4–11 mm) polymineral IRSL. Exponential fit used for equivalent dose.

**Ages were calculated using fade corrections of $g = 6\%–9\%$ per decade.

We attempted to improve upon our constraints of the uppermost part of Unit D by radiocarbon dating the hard carbonate of stratum D_{carb} . Unlike gastropod shells, which are composed of aragonite, X-ray diffraction techniques cannot be used to identify secondary calcite precipitation because the primary material in this stratum is also calcite. We had hoped that the ^{14}C ages of the carbonate would cluster tightly, which could be taken as an indication that secondary processes, such as addition or exchange of carbon with the local environment, had not taken place to a significant degree. However, the four ^{14}C ages that we obtained from the carbonate cap exhibited a large range,

from 12.27 ± 0.10 to 23.08 ± 0.18 ^{14}C ka, or 14.24 ± 0.32 to 28.01 ± 0.39 cal ka (Table 3). The large variability in our ^{14}C ages indicates that either stratum D_{carb} was formed between ca. 28 and 14 ka or, more likely, that the hard carbonate has not behaved as a closed system with respect to carbon since deposition.

We also attempted to use uranium-series dating to constrain the age of stratum D_{carb} . Uranium-series ages obtained for this stratum are significantly older than both the IRSL and ^{14}C ages that we obtained for strata lower in Unit D, and results ranged from 41.6 ± 1.4 to 56.0 ± 4.9 ka in the east flank, 60 ± 13 to 76 ± 14 ka in the north flank, and 47.5 ± 7.7 to 49.3 ± 6.7 ka

in the west flank (Table 4). Initial $^{234}U/^{238}U$ activity ratio (AR) values also show a wide range, from 3.31 ± 0.07 to 4.17 ± 1.09 , which is uncharacteristic of groundwater discharging over a relatively limited area, such as Valley Wells. At least some of the variation in age and initial $^{234}U/^{238}U$ AR values can be attributed to large uncertainties associated with samples requiring significant detrital ^{230}Th corrections. However, results for two samples (VW9–168 and VW17–170) that required only minor corrections define a horizontal trend, which implies that initial $^{234}U/^{238}U$ AR values increase with age on a U-series isotope evolution plot (Fig. 6). This behavior is commonly observed

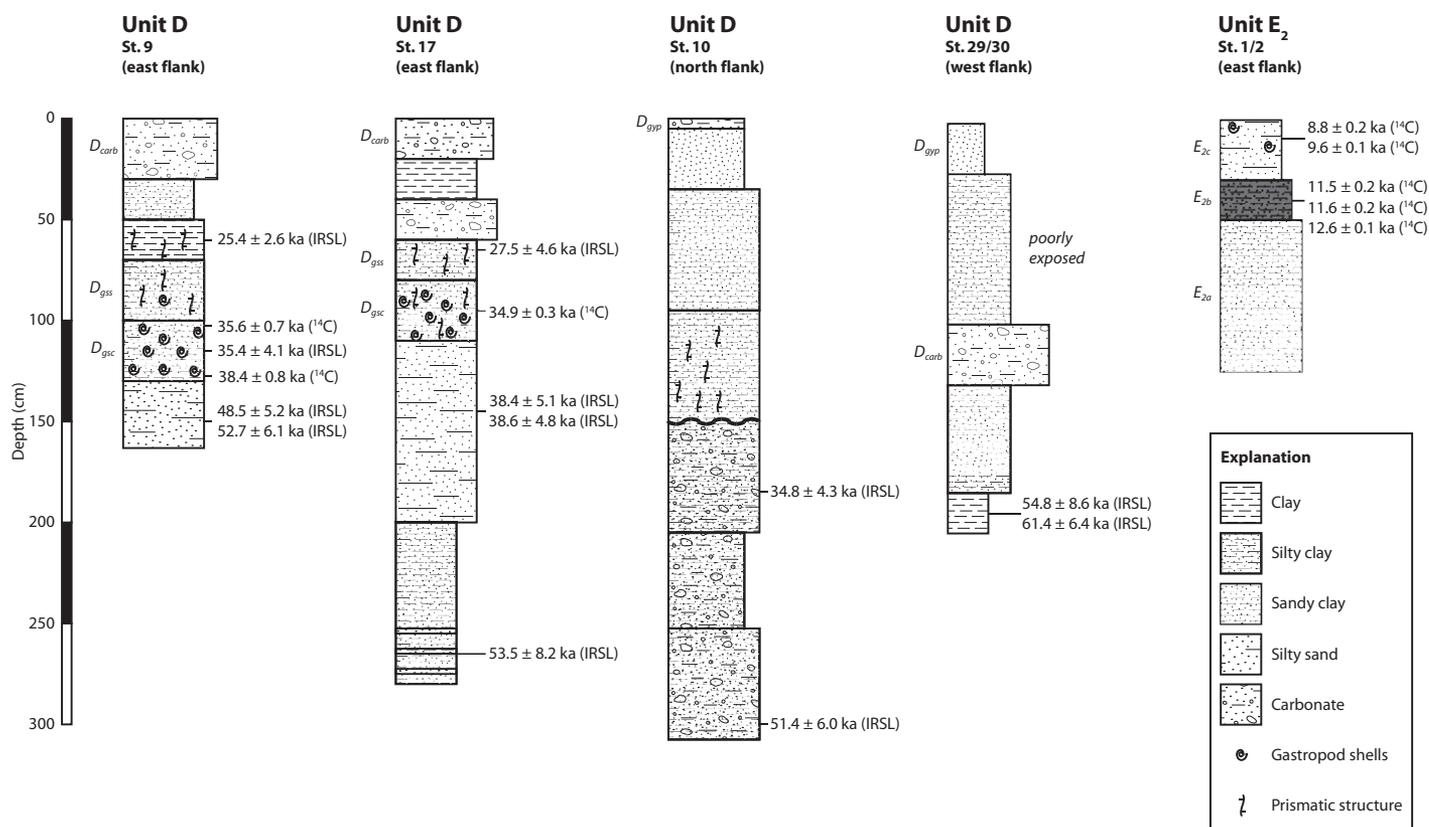


Figure 5. Stratigraphic sections for selected stations in the wetland facies (stations 9 and 17) and phreatophyte flat facies (station 10) of Unit D, a representative section of Unit D in the west flank (stations 29 and 30), and a representative section of Unit E₂ in the east flank (stations 1 and 2). Calendar-year ages are shown for ages derived from ^{14}C and infrared stimulated luminescence (IRSL) techniques.

for samples subject to recent open-system behavior where U is preferentially mobilized with respect to Th, resulting in artificially high $^{230}Th/^{238}U$ AR values and erroneously old ages (e.g., Gallup et al., 1994).

All of our samples that yielded permissible ages have a narrow range of measured $^{234}U/^{238}U$ AR values, which varied between 3.026 and 3.054. These values can be used to calculate model $^{234}U/^{238}U$ ages if the $^{234}U/^{238}U$ AR value in the original groundwater is known. Samples of modern groundwater from two nearby wells (see Fig. 2 for locations) had nearly identical measured $^{234}U/^{238}U$ AR values of 3.205 ± 0.008 and 3.197 ± 0.007 , respectively. If we can assume that this was the same U isotopic composition of emergent groundwater at the time stratum D_{carb} was formed, then model $^{234}U/^{238}U$ ages ranging from 24 to 29 ka can be calculated for samples VW9–168 and VW17–170 (Table 4; Fig. 6). Although estimates of the uncertainties associated with these model ages are large, the model ages are consistent with existing ^{14}C and IRSL ages for stratum D_{carb} and the underlying sediments. Therefore, despite the evidence for open-system behavior of the carbonate cap

with respect to both carbon and uranium, the ^{14}C and U-series ages of stratum D_{carb} suggest that these carbonate cements formed from discharging groundwater between ca. 29 and 24 ka (or possibly even 14 ka).

Unit E₂

Greatly divergent age estimates have been made previously for Unit E₂. Reynolds and Jefferson (1971) and, later, Reynolds et al. (1991) recovered vertebrate fossils of several different fauna from stratum E_{2a} (the basal olive-green clay of Unit E₂) in the east flank, including *Symmetrodontomys* n. sp. (cricket rodent) and *Onychomys* n. sp. (grasshopper mouse). The presence of these taxa suggests that stratum E_{2a} has a land mammal age of late Blancan (2.6–1.8 Ma; Savage and Russell, 1983). During the course of this study, we attempted to verify the identification of these taxa but were unsuccessful in locating the original specimens (R.E. Reynolds, 2008, personal commun.). If the faunal identifications are correct, they imply that Unit E₂ was deposited in the early Pleistocene. In contrast, Quade et al. (1995, 1998) ob-

tained radiocarbon dates of 10.25 ± 0.32 ^{14}C ka and 11.60 ± 0.24 ^{14}C ka from stratum E_{2b} (the organic-rich clay of Unit E₂) at Valley Wells (Table 3).

We collected one sample from stratum E_{2a} at station 34 for luminescence dating that yielded an age of 29.4 ± 4.8 ka (Table 2). We also collected samples of stratum E_{2b} from the east flank and the area between Cima Road and the west flank for radiocarbon dating. We ^{14}C -dated both the base-insoluble (A fraction) and base-soluble (B fraction) components of the organic matter to determine if one would yield more reliable ages than the other, as well as to evaluate possible effects of contamination from either young rootlets (which would affect the A fraction ages) or young humic acids in the environment (which would affect the B fraction ages).

Radiocarbon ages derived from the base-insoluble (A) fraction of the organic material ranged from 9.99 ± 0.08 to 11.19 ± 0.08 ^{14}C ka or, after calibration, 11.45 ± 0.18 to 13.07 ± 0.17 ka (Table 3). The ^{14}C ages derived from the base-soluble (B) fraction of the organic material ranged from 9.65 ± 0.10 to 10.32 ± 0.08 ^{14}C ka, or 11.01 ± 0.12 to 12.21 ± 0.15 ka after

TABLE 3. SUMMARY OF ¹⁴C RESULTS

Sample ID*	Lab ID	AMS	Source	Material†	δ ¹³ C (‰, VPDB)	¹⁴ C age (ka)	Calendar age (ka) [§]	P [#]
Unit E2a								
VW1-21	DL-383	AA75183	This study	Succineidae (4)	-5.5	7.93 ± 0.10	8.81 ± 0.18	0.99
VW3-9	DL-382	AA75182	This study	Succineidae (7)	-2.5	8.63 ± 0.12	9.62 ± 0.13	1.00
Unit E2b								
VW7-19	DL-401	AA75197	This study	Organics (b)	-25.0	9.65 ± 0.10	10.88 ± 0.10 11.01 ± 0.03 11.13 ± 0.07	0.47 0.06 0.47
VW2-7	DL-427	AA76585	This study	Organics (a)	-22.2	9.99 ± 0.08	11.45 ± 0.18	0.98
VW1-3	DL-399	AA75195	This study	Organics (b)	-25.3	10.08 ± 0.10	11.61 ± 0.22 11.92 ± 0.05	0.92 0.07
VW26-69	DL-430	AA76588	This study	Organics (a)	-22.2	10.15 ± 0.08	11.65 ± 0.03 11.84 ± 0.16	0.07 0.93
VWF87-1b	—	AA4898	Quade et al. (1995)	Organics (b)	-25.0	10.25 ± 0.32	11.92 ± 0.53	0.96
VW23-67	DL-429	AA76587	This study	Organics (b)	-25.0	10.32 ± 0.08	12.11 ± 0.12 12.32 ± 0.06	0.76 0.24
VW23-67	DL-428	AA76586	This study	Organics (a)	-25.2	10.47 ± 0.08	12.26 ± 0.04 12.33 ± 0.03 12.47 ± 0.10	0.15 0.06 0.76
VW1-3	DL-398	AA75194	This study	Organics (a)	-25.5	10.67 ± 0.12	12.63 ± 0.10	0.98
VW7-19	DL-400	AA75196	This study	Organics (a)	-23.4	10.78 ± 0.08	12.68 ± 0.11	1.00
VW24-68	DL-433	AA76591	This study	Organics (a)	-23.9	11.19 ± 0.08	13.07 ± 0.17	1.00
VWC87-3b	—	AA5879	Quade et al. (1998)	Organics (b)	-25.9	11.60 ± 0.24	13.49 ± 0.25	1.00
Carbonate cap								
VW17-44	DL-419	AA76577	This study	Carbonate	-3.6	12.27 ± 0.10	14.24 ± 0.32	0.97
VW27-71	DL-420	AA76578	This study	Carbonate	-5.0	17.97 ± 0.18	21.46 ± 0.32	1.00
VW22-76	DL-422	AA76580	This study	Carbonate	-3.9	18.40 ± 0.14	21.92 ± 0.36	1.00
VW28-74	DL-421	AA76579	This study	Carbonate	-1.9	23.08 ± 0.18	28.01 ± 0.39	1.00
Unit D								
VW17-41	DL-384	AA75184	This study	Succineidae (5)	-4.6	30.26 ± 0.42	34.85 ± 0.29	1.00
VW8-22	DL-386	AA75186	This study	Succineidae (1)	-6.4	30.63 ± 0.44	35.09 ± 0.42 36.05 ± 0.15	0.89 0.11
VW9-27	DL-389	AA75189	This study	Succineidae (4)	-5.4	30.96 ± 0.38	35.32 ± 0.38 36.02 ± 0.26	0.62 0.38
VW8-23	DL-391	AA75191	This study	<i>Gyraulus</i> sp. (6)	-7.6	31.21 ± 0.48	35.74 ± 0.65	1.00
VW18-45	DL-385	AA75185	This study	<i>Gyraulus</i> sp. (13)	-8.1	31.36 ± 0.56	35.82 ± 0.68	1.00
VW8-23	DL-390	AA75190	This study	<i>Pupilla muscorum</i> (4)	-5.8	31.78 ± 0.36	35.74 ± 0.23 36.45 ± 0.28	0.29 0.71
VW9-26	DL-387	AA75187	This study	Succineidae (4)	-6.0	33.74 ± 0.44	38.39 ± 0.76	1.00

Note: Uncertainties for the ¹⁴C and calibrated ages are given at the 2σ (95%) confidence level.

*Sample ID key: Valley Wells (VW), station number (refer to Fig. 2), sample number, and replicate number (if applicable).

†In parentheses: a—base-insoluble fraction; b—base-soluble fraction; n—number of shells used for dating.

§CALIB version 6.0.0, IntCal09.¹⁴C data set; limit 50.0 calendar k.y. B.P. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are reported as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater. Multiple ages are reported when the probability of a calibrated age range exceeded 0.05.

#P—probability of the calibrated age falling within the reported range as calculated by CALIB.

calibration. Finally, we obtained ¹⁴C ages from terrestrial gastropod shells (Succineidae) that were recovered from the uppermost few centimeters of stratum E_{2c} (the soft brown silt that caps Unit E₂) in the east flank. These shells yielded ¹⁴C ages of 7.93 ± 0.10 and 8.63 ± 0.12 ¹⁴C ka, or 8.81 ± 0.18 and 9.62 ± 0.13 ka after calibration, respectively. We have no explanation for the discrepancy between the faunal age estimates and the ¹⁴C ages for Unit E₂; however, our ages and those of Quade et al. (1995, 1998) indicate that Unit E₂ is likely late Pleistocene to early Holocene.

HABITAT RECONSTRUCTION

The light-colored sediments at Valley Wells were first interpreted as Pleistocene lake deposits by Hewett (1956) and later mapped as such by Evans (1971). Subsequent paleontological investigations recovered the remains of

a number of terrestrial fauna, including small invertebrates, rodents, ungulates, and proboscideans, as well as a mix of terrestrial and freshwater gastropod shells (Reynolds and Jefferson, 1971; Reynolds et al., 1991). Despite the prevalence of terrestrial fauna, these studies held to the lacustrine interpretation, which persisted until Quade et al. (1995) suggested the deposits at Valley Wells likely were related to groundwater discharge processes. Scott (1996) and Reynolds et al. (2003) later concurred with this interpretation.

Groundwater discharge deposits are often mistaken for lake deposits for several reasons: (1) they occupy essentially the same positions on the landscape, specifically the floors of broad valleys and basins, (2) they are both typically composed of fine-grained, light-colored sediments that often exhibit badland landscapes (e.g., highly dissected but smooth, undulating erosional surfaces), and (3) microfauna from

both settings can include freshwater aquatic taxa that can be difficult to differentiate. These similarities have caused confusion in analogous settings in the nearby southern Great Basin (Quade, 1986; Quade and Pratt, 1989) and elsewhere in the Desert Southwest (Forester et al., 2003; Pigati et al., 2009).

We support the idea that the Valley Wells sediments were, in fact, formed in a wetland setting, rather than a lake. One line of evidence is that lakes require topographic or hydrologic closure, whereas wetlands do not. The presence of a lake in the Valley Wells basin would require a topographic barrier in either the northern part of Shadow Valley or somewhere along Kingston Wash before it drains into Salt Creek and ultimately Death Valley (see Fig. 2). To our knowledge, there is no evidence of such a barrier anywhere in this drainage system.

The morphology of the light-colored deposits at Valley Wells also does not support a lacustrine

TABLE 4. SUMMARY OF URANIUM-SERIES DATING RESULTS

Sample ID*	Mass		U (mg/g)	Th (mg/g)	Measured activity ratios ^{1,5}			Detritus-corrected activity ratios ^{1,5}			Ages and initial ratios ⁶			Model ²³⁴ U/ ²³⁸ U age (ka) ^{7,8}
	(g)	(g)			²³² Th/ ²³⁸ U	²³⁰ Th/ ²³⁸ U	²³⁴ U/ ²³⁸ U	²³⁰ Th/ ²³⁸ U	²³⁴ U/ ²³⁸ U	²³⁰ Th/ ²³⁸ U	²³⁴ U/ ²³⁸ U	²³⁰ Th/ ²³⁸ U	²³⁴ U/ ²³⁸ U	
VW22-167-U1	0.0319	1.543	1.724	0.368134 ± 0.002158	1.180 ± 0.0266	2.706 ± 0.0125	3.2	1.253 ± 0.120	3.398 ± 0.488	0.42751	47.5 ± 7.7	3.74 ± 0.51	-0.725	Negative age
VW22-167-U2	0.0380	0.899	0.900	0.330070 ± 0.002036	1.191 ± 0.0106	2.708 ± 0.0073	3.6	1.257 ± 0.099	3.304 ± 0.404	0.45078	49.3 ± 6.7	3.65 ± 0.43	-0.737	Negative age
VW9-168-U2	0.0273	1.092	0.252	0.075930 ± 0.000809	1.005 ± 0.0068	2.932 ± 0.0109	13.2	1.005 ± 0.017	3.054 ± 0.066	0.00954	41.6 ± 1.4	3.31 ± 0.07	-0.733	24 ± 13
VW33-169-U1	0.0335	0.936	1.522	0.535742 ± 0.003240	1.334 ± 0.0099	2.467 ± 0.0077	2.5	1.576 ± 0.277	3.529 ± 0.918	0.75125	60 ± 13	4.00 ± 1.01	-0.707	Negative age
VW33-169-U2	0.0470	0.818	1.347	0.542339 ± 0.003312	1.525 ± 0.0119	2.471 ± 0.0078	2.8	1.912 ± 0.385	3.559 ± 0.949	0.87294	76 ± 14	4.17 ± 1.09	-0.646	Negative age
VW17-170-U1	0.0300	0.822	0.596	0.239244 ± 0.001684	1.226 ± 0.0100	2.648 ± 0.0088	5.1	1.278 ± 0.067	3.029 ± 0.235	0.47437	56.0 ± 4.9	3.38 ± 0.25	-0.706	29 +45/-40
VW17-170-U2	0.0121	0.987	0.315	0.107338 ± 0.001906	1.176 ± 0.0118	2.872 ± 0.0096	11.0	1.193 ± 0.028	3.044 ± 0.095	0.31557	51.2 ± 2.0	3.36 ± 0.10	-0.679	26 ± 18
VW17-170-U3	0.0281	0.877	0.509	0.191402 ± 0.001272	1.139 ± 0.0080	2.722 ± 0.0079	6.0	1.163 ± 0.047	3.026 ± 0.180	0.30264	50.1 ± 3.7	3.33 ± 0.19	-0.727	29 +35/-32

Note: Uncertainties for all activity ratios and ages are given at the 2σ (95%) confidence level.

*Sample ID key: Valley Wells (VW), station number (refer to Fig. 2), sample number, and replicate number (if applicable).

¹Measured isotope ratios are corrected for mass fractionation, spike contributions, and procedural blank, and normalized relative to a standard value for NIST SRM 4321b.

²Assumed Th-bearing detrital component has an atomic Th/U ratio of 4 with the following activity ratios and 2σ errors: ²³²Th/²³⁸U = 1.276 ± 0.64, ²³⁴U/²³⁸U = 1.0 ± 0.1, and ²³⁰Th/²³⁸U = 1.0 ± 0.25.

³²³⁰Th/U ages, initial ²³⁴U/²³⁸U ratios, and associated errors were calculated using detritus-corrected activity ratios.

⁴Model ²³⁴U/²³⁸U ages were calculated using measured ²³⁴U/²³⁸U activity ratios (AR) and an assumed initial ²³⁴U/²³⁸U AR of 3.20 ± 0.01 derived from analyses of modern groundwater sampled from Valley Wells dug well (²³⁴U/²³⁸U AR = 3.205 ± 0.008) and station well (²³⁴U/²³⁸U AR = 3.197 ± 0.007).

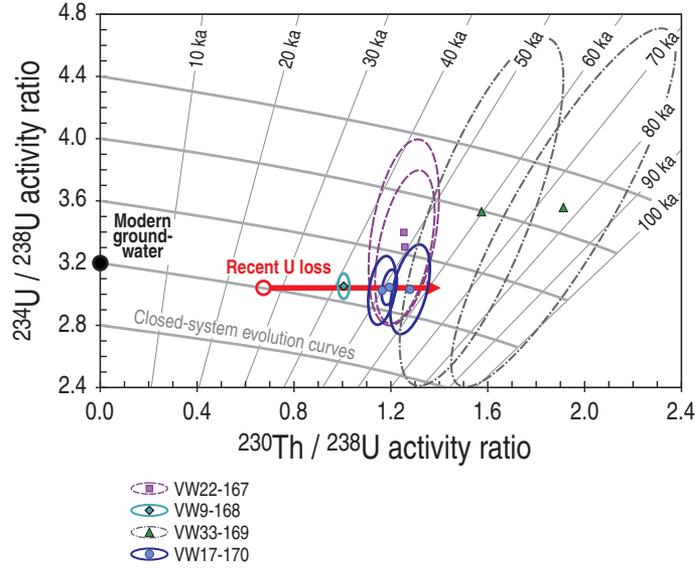


Figure 6. Uranium-series isotope evolution plot showing analytical results for samples of dense carbonate from stratum D_{carb}. Shallowly dipping lines represent the evolution of isotopic compositions of material formed with different initial ²³⁴U/²³⁸U activity ratios. Steeply dipping lines represent isochrons. Detritus-corrected isotope ratios from Table 4 are plotted as symbols along with associated 2σ error ellipses.

origin interpretation. The north flank is positioned between 1125 and 1130 m above sea level (asl) and dips slightly to the west, the east flank is positioned between 1130 and 1140 m asl and dips slightly in the same direction, and the west flank is positioned ~20 m lower, between 1108 and 1115 m asl, and dips slightly to the north or northwest. Thus, rather than forming a “bathtub ring” of deposits around the valley at a constant elevation, as they would if the deposits were lacustrine, the surface of the deposits mimics the local topography, which is common in groundwater discharge settings (Quade, 1986). Deformation associated with tectonic activity could be invoked to explain the complex morphology of Unit D, assuming it was originally flat. However, we are not aware of any geologic evidence for substantial tectonism in the central Mojave Desert during the Holocene that could be used to argue this point, although historic earthquakes certainly have occurred (e.g., Hauksson et al., 1993).

The assemblages of ostracodes and gastropod shells recovered from Units D and E₂ also indicate that the sediments were deposited in a wetland setting. Ostracodes present in stratum D_{gsc} include several species of *Candona*, *Cypridopsis*, and *Limnocythere* that are common today in springs and wetlands throughout the Desert Southwest (Forester, 1991; Forester et al., 2005). Gastropods present in the same stratum

include multiple terrestrial taxa, *Deroceras* sp., *Gastrocopta tappaniana*, *Pupilla muscorum*, *Succineidae*, *Vallonia cyclophorella*, and *Vertigo berryi*, as well as some freshwater aquatic taxa, including *Gyraulus* sp. Like the ostracodes, these gastropod taxa are common in extant wetland settings in the U.S. Southwest (Bequaert and Miller, 1973).

Finally, isotopic evidence for a wetland setting is indicated by the initial ²³⁴U/²³⁸U AR values of stratum D_{carb} at Valley Wells. Surface waters in the northern Mojave Desert (tributaries to Fortymile Wash in the Amargosa Desert, Nevada) have ²³⁴U/²³⁸U AR values of less than 1.7 (table 2 of Paces et al., 2002). Similar values have been noted elsewhere in the Mojave, including a sample of Mojave River water collected in 2008 at Oro Grande, California, by one of us (Paces), as well as multiple rivers sampled worldwide (mean value of 1.171 for 35 analyses reported by Chabaux et al., 2003). In contrast, the distinctly higher ²³⁴U/²³⁸U AR values obtained for stratum D_{carb}, which ranged from 3.31 to 4.17, require a groundwater source that was preferentially enriched in ²³⁴U, possibly via recoil processes occurring within the host aquifer (Table 4).

Taken together, the evidence from geomorphology, microfaunal assemblages, and isotopic content of the deposits at Valley Wells suggests that they were not formed in a lake, but rather in

wetlands or “ciénegas” that formed at the distal ends of alluvial fans emanating from the Clark Mountains and Mescal Range to the east.

Sedimentology

In modern groundwater discharge systems, Quade et al. (1995) found clear relations among the hydrologic regime, floral assemblages, and the types of sediments in the geologic record. For example, areas of active discharge that support dense stands of hydrophilic plants are represented in the geologic record by well-sorted, pale-green to white mudstones and dark-colored organic-rich clays. The fine-grained nature of groundwater discharge deposits is explained by the favored sediment-trapping environment (wet ground, dense plants) where groundwater discharge deposits are formed. Pale-green sediments indicate the presence of minerals that are stable in the reducing environment of desert wetlands, including some clays (illite, montmorillonite) and reduced iron species (Keller, 1953), and dark-colored sediments represent the remains of plants living in and around the wetland.

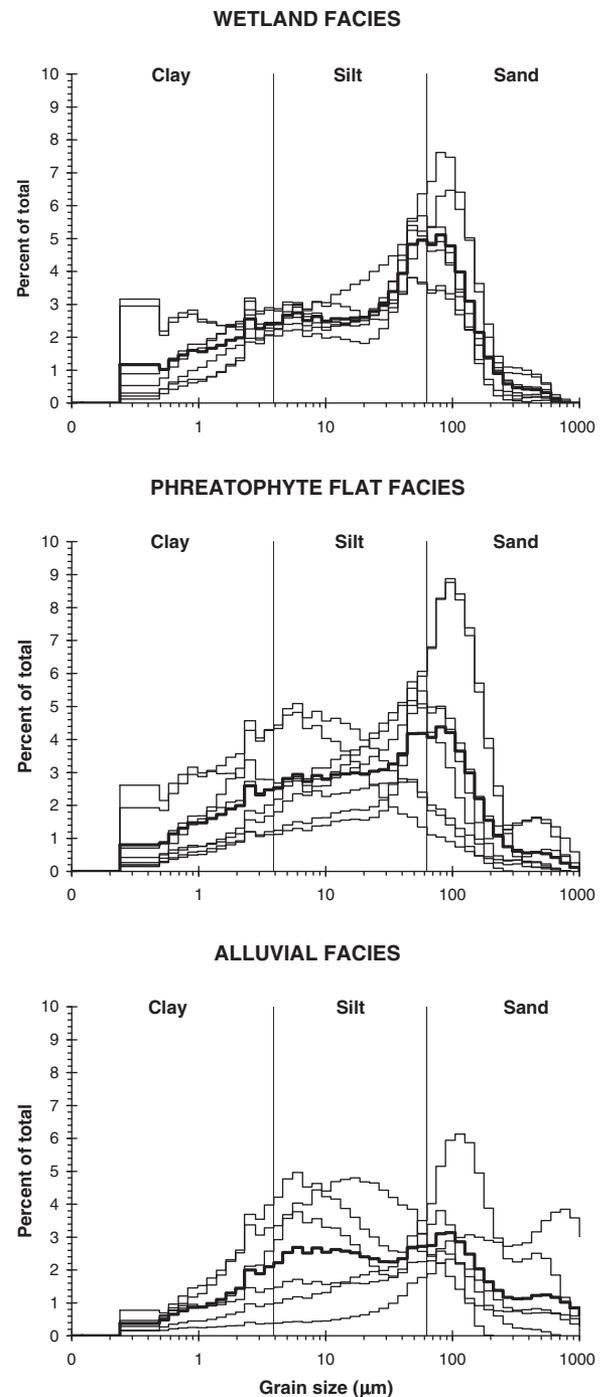
Phreatophytic plants often dominate the landscape in areas adjacent to active discharge because water tables are shallow enough to be tapped by plants. These plants efficiently capture fine-grained, wind-blown sediments, and, as a result, the “phreatophyte flat” zone is represented in the geologic record by well-sorted, eolian sediments (primarily silts and very fine sands) mixed with occasional alluvial sands and gravels. (Note that the most common grain sizes of eolian sediment outside of dune settings in the Mojave Desert today are also silt and very fine sand; Reheis et al., 1996; Muhs et al., 2007.) If water tables fluctuate near the ground surface in this zone, sediments in phreatophyte flats may contain secondary carbonate, gypsum, or other minerals related to capillary movement of water through the unsaturated zone (Forester et al., 2003), which we consider to be part of the phreatophyte flat facies.

Alluvial-fan environments that are just outside the influence of wetland systems typically support only xerophytic plants and are represented in the geologic record by rocky, poorly sorted, and vaguely bedded alluvial deposits. We identified all three of these facies in the sediments of Unit D in the east flank at Valley Wells.

Unit D (East Flank)—Wetland Facies

Based on the presence of microfauna, green sediments, and a fairly strong peak in the silt and very fine sand grain sizes (Fig. 7), we interpret stratum D_{gsc} as representing a period during which the water table breached the ground sur-

Figure 7. Results of particle-size analysis for sediments in the three facies of Unit D in the east flank. The thick black line in each panel represents the average size composition of each facies. We interpret the peaks in the silt and very fine sand fractions to represent eolian input.



face at Valley Wells. Stratum D_{gsc} is confined to an approximately linear area that is parallel to the western margin of the east flank at an elevation of ~1130 m (marked “W” in Fig. 2). Between ca. 40 and 35 ka, discharging groundwater supported wetlands that were probably fairly continuous along this lineament, based on the lateral continuity of the silty clay stratum. The sediments above and below stratum D_{gsc} suggest that the water table did not breach the

ground surface at any other time during deposition of Unit D, but groundwater was shallow enough near the western margin of the east flank to support phreatophytic vegetation both before and after the active wetland period.

Unit D (East Flank)—Phreatophyte Flat Facies

Upgradient to the east, strata near the middle of Unit D also are dominated by silt and very fine sand (Fig. 7) but lack green sediments and

microfauna, which support the idea that dense stands of phreatophytic plants were present in this area when wetlands were active downslope (marked “P” in Fig. 2). We attempted to analyze pollen in Unit D to characterize the specific types of vegetation that were present, but pollen was not preserved in any of the sediments that we submitted for analysis (D. Wahl, 2007, personal commun.).

Unit D (East Flank)—Alluvial Facies

Alluvial sands and gravels in Unit D increase in abundance to the east, which we interpret as representing areas of progressively deeper groundwater dominated by xerophytic plants and alluvial processes (marked “A” in Fig. 2). Sediments in this area tend to be dominated by poorly sorted, subangular coarse sand and gravel. Particle-size analysis shows a wide distribution of grain sizes, including abundant gravels, that includes only subdued peaks in the silt and very fine sand ranges (Fig. 7).

Unit D—North and West Flanks

Based on the sedimentology of Unit D in the north flank, a fairly large phreatophyte flat occupied much of this area during the late Pleistocene. Sediments in the northern part of this flank are generally fine grained and often rich in carbonate. Stratum D_{carb} covers the deposits in much of this area, and carbonate nodules are abundant in fine-grained sediments that date to between 40 and 35 ka at station 10, when wetlands were active in the east flank. Sediments in the west flank are similar in that they do not exhibit any evidence of active groundwater discharge, but they do contain abundant capillary fringe deposits, including strata D_{carb} and D_{gyp} . We did not find any evidence of the wetland or alluvial facies of Unit D in either the north or west flanks.

Unit E₂

The olive-green clay (stratum E_{2a}) and organic-rich clay (stratum E_{2b}) at the base and middle of Unit E₂, respectively, represent modest wetlands that were present at Valley Wells during the Younger Dryas cold event (13.0–11.6 ka). Based on the limited spatial extent of these deposits, discharge systems associated with this unit were not nearly as widespread as those represented by Unit D and were relatively short-lived. Stratum E_{2c} represents a small phreatophyte flat that persisted during the early Holocene after the water table dropped below the ground surface. We did not find sediments associated with xerophytic vegetation (i.e., the alluvial facies) in Unit E₂.

Microfauna. Groundwater discharge deposits commonly contain microfauna, specifically

ostracodes and gastropod shells, which can be used to interpret depositional conditions within paleowetland environments (Forester, 1991). At Valley Wells, we collected samples from all three facies (wetland, phreatophyte flat, and alluvial) of Unit D in the east flank, several strata of Unit D in the north and west flanks, and both the organic-rich clay and brown silt strata of Unit E₂. Stratum D_{gsc} in the east flank is the only stratum within Unit D that contained either ostracodes or gastropod shells (it had an abundance of both). Stratum E_{2c} was the only stratum within Unit E₂ that contained gastropod shells (it had only a few scattered shells and no ostracodes).

Ostracodes from stratum D_{gsc} at stations 8, 9, 15, 17, and 18 were analyzed to determine the assemblages present at each location. Stations 8, 9, and 15 contained the most abundant valves. The most common taxa identified at these three stations included *Cypridopsis vidua*, *Candona* aff. *patzcuaro*, *Limnocythere* aff. *paraornata*, and *Candona* sp. Each of these stations also contained unique ostracode occurrences. Less common taxa included *Candona acuminata* and *Candocyprinus ovatus* (station 8), *Cyprinus glaucus* and *Candona compressa* (station 9), *Potamocypris* sp. (stations 8 and 15), and *Cavernocypris wardi* (station 15). Stations 17 and 18 contained comparatively few ostracode valves, which were identified as juveniles of *Candona* aff. *patzcuaro* or unidentified fragments. Valves of *Limnocythere* aff. *paraornata* and *Cypridopsis vidua* were present at these two stations but were rare.

Collectively, the Valley Wells ostracode fauna is indicative of a freshwater wetland supported by cold (4–12 °C) spring discharge (Forester, 1991; Forester and Smith, 1994; Quade et al., 1998, 2003). Based on comparison with modern settings, the wetland likely had a total dissolved solids value of $\sim 600 \pm 200$ mg L⁻¹ and an alkalinity-to-calcium (Alk/Ca) ratio near 1 (Forester et al., 2005). The latter suggests a carbonate bedrock solute source (Forester, 1987). The ostracodes unique to each station probably reflect a complex, heterogeneous habitat. Organisms notably absent at Valley Wells are ostracode taxa typically associated with flowing water (e.g., *Ilyocypris bradyi*, *Candona caudata*), high-discharge springs (e.g., *Strandesia meadensis*), or seasonally warm water (e.g., *Physocypris*) (Curry, 1999; Quade et al., 2003).

Gastropod shells from stratum D_{gsc} at stations 8, 9, 17, and 18 were analyzed to determine the assemblages present at each location. Taxa identified at Valley Wells included *Deroceras* sp., *Gastrocopta tappaniana*, *Pupilla muscorum*, *Vallonia cyclophorella*, *Vertigo berryi*, Succineidae, and freshwater aquatic shells, in-

cluding *Gyraulus* sp. Aquatic taxa accounted for between <50% (stations 8 and 17) and >99% (station 18) of all recovered shells (Table 5).

We compared these gastropod assemblages to modern assemblages from 11 sites in California and Utah to interpret the ecological habitat that was present during deposition of stratum D_{gsc} . Twenty-five taxa were present in the 11 modern sites, including all of the Valley Wells taxa except for *Gastrocopta tappaniana* (Table 5). This species is present in extant wetlands in central Arizona, but no sites are currently known from within California or Utah (Pilsbry, 1948; NatureServe, 2010). *Deroceras* sp. was encountered from three of the modern sites, all representing areas with permanently wet soils from either groundwater or surface water. *Pupilla muscorum* was found at only a single modern site, a sandy riparian cottonwood forest. *Vallonia cyclophorella* was located at four modern sites, ranging from riparian alder and cottonwood forest to xeric desert limestone talus slopes. This taxon is commonly encountered in mid- to high-elevation forests across the Desert Southwest (Metcalf and Smartt, 1997). *Vertigo berryi* was located at two modern sites, both of which represent perennially wet sedge and rush meadows. Lastly, members of the Succineidae family were identified at three of the modern sites, all of which represented perennially wet sedge and rush meadows.

Collectively, the terrestrial gastropod taxa found in stratum D_{gsc} can only persist today in areas that possess standing water for at least part of the year. Comparison of the modern and fossil assemblages suggests that between 40 and 35 ka at Valley Wells, the western margin of the east flank was occupied by a wet sedge-rush-tussock meadow mixed with mesic riparian forest.

PALEOHYDROLOGY OF VALLEY WELLS

Local or Regional?

Today, the shallow groundwater table at Valley Wells is identified by subdued spring mounds that are characterized by the presence of salt grass and a thin crust of evaporite minerals. Spring mounds are present in at least three distinct locations, near stations 10 and 20 in the north flank and station 19 in the west flank (Fig. 2). Depth to groundwater at these locations is no more than 2–3 m, based on the depth to water in the well dug near station 10, and water probably approaches the surface periodically through capillary action.

In the past, groundwater discharge was far more extensive than today, which implies that there was significantly more recharge to the

TABLE 5. FOSSIL AND MODERN GASTROPOD ASSEMBLAGES

Taxa	Valley Wells stations				Modern sites										
	8	9	17	18	1	2	3	4	5	6	7	8	9	10	11
<i>Deroceras</i> sp.	X	X	X			X					X			X	
<i>Discus cronkhitei</i> (Newcomb, 1865)						X		X			X	X			
<i>Discus shimeki</i> (Pilsbry, 1890)									X						
<i>Euconulus alderi</i> (Gray, 1840)						X				X					
<i>Euconulus fulvus</i> (Müller, 1774)								X				X		X	X
<i>Gastrocopta pellucida</i> (Pfeiffer, 1841)							X								
<i>Gastrocopta tappaniana</i> (C.B. Adams, 1842)	X														
<i>Helminthoglypta tularensis</i> (Hemphill, 1892)											X				
<i>Nesovitrea electrina</i> (Gould, 1841)						X									
<i>Oreohelix eurekensis</i> (Henderson and Daniels, 1916)							X								
<i>Pristiloma gabrielinum</i> (Berry, 1924)									X		X		X	X	
<i>Pristiloma spelaeum</i> (Dall, 1877)									X					X	X
<i>Punctum californicum</i> (Pilsbry, 1898)									X		X			X	X
<i>Punctum conspectum</i> (Bland, 1865)													X		
<i>Pupilla hebes</i> (Ancy, 1881)										X					
<i>Pupilla</i> cf. <i>muscorum</i> (Linné, 1758)	X	X	X	X	X										
<i>Striatura pugetensis</i> (Dall, 1895)							X								
Succineidae	X	X	X	X			X			X		X			
<i>Vallonia cyclophorella</i> (Sterki, 1892)	X	X	X					X					X		X
<i>Vallonia gracilicosta</i> (Reinhardt, 1883)						X									
<i>Vertigo berryi</i> (Pilsbry, 1919)	X	X	X	X			X			X					
<i>Vertigo modesta castanea</i> (Sterki, 1892)								X						X	X
<i>Vertigo</i> UT 1							X								
<i>Vitrina alaskana</i> (Dall, 1905)						X	X	X	X			X	X		
<i>Zonitoides arboreus</i> (Say, 1816)							X	X							X
Aquatic	<50%	>75%	<50%	>99%			X					X			X

Key to modern sites							
Number	State	County	Name	Habitat	Latitude (°N)	Longitude (°W)	Elevation (m)
1	UT	Kane	Kanab North	Riparian cottonwood-willow forest	37.0999	112.5496	1546
2	UT	Kane	Mystic River	Open, calcareous seep	37.3743	112.5945	1093
3	UT	Millard	Skull Rock Pass	Xeric, N-facing limestone talus	39.0862	113.5678	1685
4	CA	El Dorado	Luther Pass Road	Wet-mesic aspen grove	38.7900	120.0093	2148
5	CA	Alpine	Loope West	Riparian cottonwood-aspen forest	38.6591	119.7222	1754
6	CA	Mono	Bridgeport	<i>Juncus-Carex-Geum</i> wet meadow	38.2255	119.2501	1982
7	CA	Tulare	Limestone Campground	Willow litter among boulders	35.9622	118.4768	1135
8	CA	San Bernardino	Ciénega Seca	<i>Juncus</i> tussock meadow	34.1749	116.7339	2363
9	CA	San Bernardino	Seven Oaks	Alder-nettle riparian forest	34.1865	116.9190	1597
10	CA	San Bernardino	Glass Road	Damp creekside with ferns and currants	34.1793	116.9058	1739
11	CA	San Bernardino	S. Fork Santa Ana River	Sedge-dominated bank with alder	34.1687	116.8316	1926

aquifer(s) that fed the Valley Wells basin during the late Pleistocene. The most likely recharge area for the north and east flanks would have been the adjacent Clark Mountains to the east. Reaching elevations in excess of 2400 m, the Clark Mountains are higher than other nearby mountain ranges and consist primarily of carbonate rocks with high secondary permeability (Hewett, 1956). Precipitation in the form of snow and rain likely fed shallow through-flow and/or unconfined groundwater flow through the alluvial fan that extends between the highlands and the Valley Wells basin.

Quade et al. (1995) speculated that at least two faults exist between the different flanks of Unit D at Valley Wells, with one running along the western margin of the north and east flanks and another between the north and east flanks trending to the northeast. If present, the faults may have served as barriers that impeded groundwater flow, forcing it toward the surface near the toe of the alluvial fan. The presence of faults may also explain the apparently disjointed nature of the shallow water table today, as well as the discrete areas of deposition for Units D and E₂ during the late Pleistocene. To our

knowledge, however, there have not been any seismic investigations at Valley Wells to verify the presence or absence of these faults, and we did not observe any expression of faulting in the nearby alluvial fans.

Regardless of whether faults exist at Valley Wells, we can envision a simple system in which groundwater originating in the Clark Mountains flowed through an unconfined alluvial aquifer and discharged in the north and east flanks where the water table intersected the ground surface. The linear appearance of the western edge of these flanks may signify the location of a shallow fault or the location at which groundwater emerged at a more or less constant elevation.

Potential sources of groundwater that supported wetlands in the west flank, however, may have been more complex. The west flank is positioned near the axis of Shadow Valley and sits ~20 m lower in elevation than either the north or east flanks. We suspect that at least two sources may have contributed groundwater to this area during the late Pleistocene: (1) the Clark Mountain alluvial aquifer, and (2) shallow, unconfined groundwater flowing from south to north along

the axis of Shadow Valley. The relative contributions of each source to groundwater flow at Valley Wells, both today and in the past, are unknown. Another potential contributing source to the west flank groundwater discharge deposits would have been the regional Paleozoic carbonate-rock aquifer system that underlies much of the Basin and Range Province, including a subregional flow system centered in Death Valley that may encompass Shadow Valley (Harrill et al., 1988; Harrill and Prudic, 1998; Hershey et al., 2010). If groundwater at Valley Wells is indeed fed by this regional aquifer, then part of our record, specifically the west flank deposits, may represent hydrologic processes that originated well outside of the Mojave Desert.

Reconstruction of Water-Table Fluctuations

In many paleowetland systems, it is difficult to reconstruct water-table fluctuations through time because once water tables breach the ground surface, any additional discharge is lost via overland flow or evapotranspiration. The wetland systems at Valley Wells are somewhat unusual in that the water table rarely breached

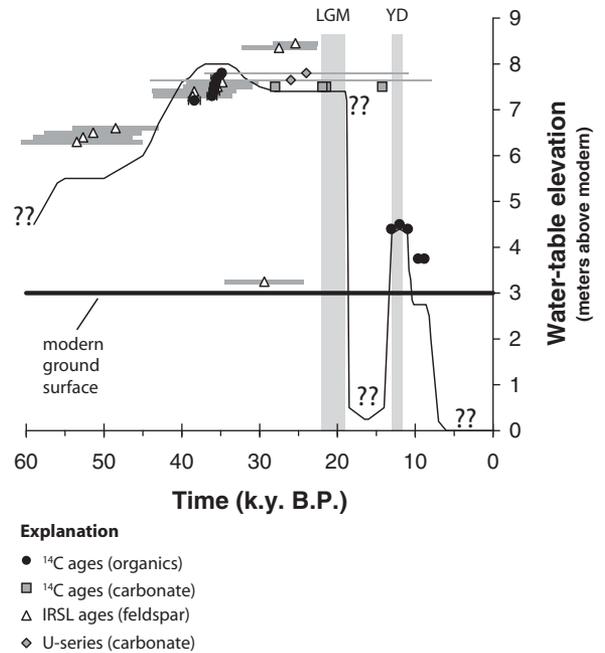
the ground surface but still left behind a nearly continuous record of its existence in the geologic record.

We used sedimentology and the presence/absence of microfauna in Units D and E₂ to reconstruct the approximate elevations of the water table at Valley Wells over the past ~60 k.y. Several assumptions were required for this: (1) the current depth to groundwater (3 m) in the north flank near station 10 is constant across the areas covered by Unit D; (2) constant average thicknesses of 6 and 1.5 m for all Unit D and E₂ deposits, respectively; (3) depths to groundwater were ~1 m during periods in which phreatophyte flat zones were present; and (4) groundwater levels during the past ~9 k.y. were similar to today. We recognize that these assumptions oversimplify the complex nature of the paleowetland systems at Valley Wells, but this exercise allows for a reasonable estimate of the timing and approximate magnitude of changes in the depths to groundwater during the late Pleistocene and early Holocene.

The water table at Valley Wells began rising some time before ca. 60 ka in response to an increase in effective precipitation (i.e., precipitation minus evaporation) and recharge (Fig. 8). Depths to groundwater were shallow enough to support a phreatophyte flat throughout much of the lowland between ca. 60 and 45 ka, as evidenced by the fine-grained nature of the sediments near the base of Unit D. The water table rose again shortly after ca. 45 ka and reached its maximum, ~8 m above the modern water table (or 5 m above the ground surface), between ca. 40 and 35 ka. At this time, active wetlands were present along the western margin of the east flank, and phreatophyte flat zones supported by the shallow water table were present up-gradient of this area in the east flank, as well as in the north and west flanks.

The water table dropped slightly after this period of active discharge but remained near the surface for the next ~10 k.y., again supporting a phreatophyte flat in the east flank. It is unclear exactly when the water table dropped after this, but it was likely sometime after the Last Glacial Maximum (LGM) based on the IRSL ages from the upper portion of Unit D. Dry conditions then prevailed, as evidenced by nondeposition and erosion of Unit D, until the water table rebounded briefly during deposition of Unit E₂ during the Younger Dryas cold event. Calibrated radiocarbon ages of the organic-rich clay of Unit E₂ suggest that the water table remained high for the duration of the Younger Dryas cold event, before dropping slightly at the onset of the Holocene. Shallow depths of water supported small areas of phreatophytic vegetation in discrete zones in the east flank and between Cima Road

Figure 8. Reconstruction of water-table levels at Valley Wells during the late Quaternary. Calendar-year ages are shown for ages derived from ¹⁴C, infrared stimulated luminescence (IRSL), and U-series techniques. Water-table levels were estimated using the current depth to groundwater (3 m) in the north flank near station 10, assuming constant average thicknesses of 6 and 1.5 m for all Unit D and E₂ deposits, respectively, and assigning groundwater depths of 1 m for periods in which phreatophyte plants were present (i.e., times of no active discharge). We did not find any evidence of groundwater discharge during the last ~9 k.y. and assumed that depths to groundwater during this period were similar to today. Vertical shaded bars represent the timing of the Last Glacial Maximum (LGM; Yokoyama et al., 2000) and Younger Dryas cold event (YD; Alley et al., 1993; Prescott and Hutton, 1994).



and the west flank until ca. 9 ka. After this time, the water table dropped far enough that phreatophytic vegetation was no longer supported, and probably approached the modern level.

One of the unknowns in this hydrologic reconstruction is the reliability of a single IRSL age (29.4 ± 4.8 ka; VW34-175) obtained from stratum E_{2a} in the east flank (Fig. 8; Table 2). For now, we choose not to rely on this date because it appears to be too old; it is essentially the same as IRSL ages from below the capping strata of Unit D. However, we acknowledge that if this age is replicated in future samples, then the timing of the drop in the water table following deposition of Unit D would become fixed earlier in time by several thousand years, to *before* the LGM. This would also mean that the ¹⁴C and uranium-series ages from stratum D_{carb} would have to be disregarded, which is not warranted at this time.

Groundwater Discharge Records in the American Southwest

Paleowetland sequences in the Mojave Desert and nearby southern Great Basin often contain older groundwater discharge deposits (Table 1) than those present at Valley Wells, such as Unit B, which represents wetlands that were supported by high-water-table conditions during the penultimate glaciation, or marine isotope stage (MIS) 6 (Haynes, 1967; Quade,

1986). Unit B has been dated by uranium-series and luminescence methods at several places in the Mojave and Great Basin Deserts (e.g., Paces et al., 1996, 1997; Nelson et al., 2001; Mahan et al., 2007) and has been identified, but not radiometrically dated, elsewhere in these deserts (Haynes, 1967; Quade, 1986). We did not find any evidence of Unit B at Valley Wells.

Unit D is generally more widespread than Unit B in the Desert Southwest and represents high-water-table conditions that persisted through the last glacial cycle (MIS 2). The timing of changes in water-table levels represented by Unit D at Valley Wells is similar to paleowetland sequences elsewhere in the Mojave Desert and southern Great Basin, as well as the distant San Pedro Valley of southeastern Arizona, near the border of the Sonoran and Chihuahuan Deserts (Quade, 1986; Quade and Pratt, 1989; Haynes, 1991; Quade et al., 1995, 2003; Paces et al., 1996, 1997; Kaufman et al., 2002; Pedone and Rivera, 2003; Pigati et al., 2004, 2009; Mahan et al., 2007). Water tables in these disparate locations generally began to rise prior to ca. 50 ka in response to an increase in effective precipitation, and remained high for the next ~30 k.y., supporting extensive, persistent wetlands during full glacial times.

Increased winter precipitation derived from westerly storms has long been championed as the driving force behind increased pluvial lake levels and, by extension, higher groundwater

tables throughout the American Southwest (Antevs, 1938). Expansion of continental ice sheets during full glacial times likely moved the position of the jet stream and associated winter storm tracks to the south, which would have led to a significant increase in high-elevation snow and rain (COHMAP, 1988). Such increases, in turn, would have supported both high lake levels and persistent, long-lived wetlands during the late Pleistocene.

It is possible that summer moisture associated with the North American monsoon also contributed to recharge of some valley-fill aquifers in the Desert Southwest during the last glacial period. However, the impact of enhanced summer rainfall was probably minimal based on several lines of reasoning. First, although there is evidence that the North American monsoon persisted through full glacial conditions in the Desert Southwest (Connin et al., 1998), there is no evidence that it increased either in strength or geographic extent during the last glacial period. Second, there is little difference between the timing of changes in high-water-table conditions in areas near the center of the monsoon influence (southeastern Arizona) and more distal regions (southeastern California, southern Nevada), where monsoonal influence is significantly less. Finally, increased summer precipitation in the form of brief, intense storms would have led to relatively more runoff and less infiltration compared to a similar increase in winter precipitation (Miller et al., 2010). What little infiltration that did occur in summer, particularly in the lowlands, would have had to pass through root zones in the unsaturated zone to recharge the aquifer.

The influence of cooler temperatures in sustaining high water-table levels in wetland settings in general and at Valley Wells in particular is unclear. Certainly, cooler temperatures during the last glacial period and Younger Dryas cold event would have led to increased effective precipitation across much of the Desert Southwest. However, we speculate that because groundwater flow is largely isolated from evaporation and transpiration processes, water levels in groundwater discharge systems may be less sensitive to changes in temperature than other sources of paleohydrologic information (i.e., lakes, speleothems). While speculative, supporting evidence comes from the San Pedro Valley in southeastern Arizona, where wetlands were sustained continuously through numerous cold/wet–warm/dry oscillations as recorded in nearby speleothems (Pigati et al., 2009; Wagner et al., 2010).

After ca. 15–16 ka, water tables at many locations in the Desert Southwest fell below the ground surface, and erosive conditions dominated the valley lowlands for ~1 k.y. or so. High-

water-table conditions returned briefly between ca. 13 and 11.6 ka, correlative with the Younger Dryas cold event (Haynes, 1967, 1987; Quade et al., 1998; Haynes, 2007; Jayko et al., 2008), before falling again at the onset of the Holocene. The timing of the rebound in water tables at the onset of the Younger Dryas was essentially synchronous in wetland settings across the Southwest (Haynes, 2008). The cause of the Younger Dryas itself and, by extension, the rise in water tables at this time has been the subject of much debate (e.g., Broecker et al., 1989; Carlson et al., 2007). Regardless of whether it was a result of climatologic changes or initiated by external forces (Firestone et al., 2007), evidence from groundwater discharge settings suggests that the processes responsible for the rise and fall of water tables in the central Mojave Desert during the late Pleistocene operated over relatively large areas of the American Southwest.

CONCLUSIONS

Emergent groundwater supported persistent and long-lived springs and wetlands in many places throughout the Desert Southwest during the late Pleistocene. These paleosprings and wetlands are represented in the geologic record by groundwater discharge deposits, which contain information on the timing and magnitude of past changes in local or regional hydrologic budgets. In this study, we investigated groundwater discharge deposits at Valley Wells, located in Shadow Valley in the central Mojave Desert. The deposits at Valley Wells are among the most extensive groundwater discharge deposits identified in the Mojave, and they are somewhat unusual in that while the water table rarely breached the ground surface, it left behind a nearly continuous record of its existence in the geologic record.

We identified two distinct periods of high water-table conditions at Valley Wells, which correlate to Units D and E₂ recognized earlier in the southern Great Basin. Unit D represents extensive wetlands that persisted through the last glacial period, whereas Unit E₂ represents a later, modest resurgence in wetland activity. We used multiple independent dating techniques (radiocarbon, luminescence, and uranium-series) to establish a chronologic framework for the units at Valley Wells, and sedimentology and microfaunal assemblages (gastropods and ostracodes) to reconstruct the specific environments in which they formed.

Our results suggest that the earliest episode of high-water-table conditions at Valley Wells began ca. 60 ka, and culminated in peak discharge between ca. 40 and 35 ka. During this time, cold (4–12 °C), dilute emergent ground-

water supported a wet sedge-rush-tussock meadow mixed with mesic riparian forest, as well as phreatophytic vegetation in the adjacent areas. After ca. 35 ka, the water table dropped slightly below the ground surface but was still shallow enough to support a phreatophyte flat that likely persisted through the Last Glacial Maximum. The water table dropped dramatically some time after the Last Glacial Maximum, and dry conditions prevailed until small discrete patches of wetlands returned briefly during the Younger Dryas cold event.

The timing of changes in water-table elevations at Valley Wells is similar to that of other paleowetland sequences in the Mojave Desert, southern Great Basin, and southeastern Arizona, near the border of the Sonoran and Chihuahuan Deserts. The similarities in hydrologic conditions between these disparate locations suggest that the driving forces behind changes in groundwater levels in the central Mojave Desert during the late Pleistocene operated over large areas of the American Southwest.

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