Earth-Science Reviews 132 (2014) 67–81

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Review

Desert wetlands in the geologic record

Jeffrey S. Pigati [a,*], Jason A. Rech [b], Jay Quade [c], Jordon Bright [c]

[a] U.S. Geological Survey, Denver Federal Center, Box 25046, MS-980, Denver, CO 80225, United States
[b] Department of Geology and Environmental Earth Science, Miami University, Oxford, OH 45056, United States
[c] Department of Geosciences, University of Arizona, Tucson, AZ 85721, United States

ARTICLE INFO

Article history:
Received 22 January 2013
Accepted 3 February 2014
Available online 14 February 2014

Keywords:
Ground water
Wetland
Paleohydrology
Ostracodes
Desert
Paleoclimate

ABSTRACT

Desert wetlands support flora and fauna in a variety of hydrologic settings, including seeps, springs, marshes, wet meadows, ponds, and spring pools. Over time, eolian, alluvial, and fluvial sediments become trapped in these settings by a combination of wet ground conditions and dense plant cover. The result is a unique combination of clastic sediments, chemical precipitates, and organic matter that is preserved in the geologic record as ground-water discharge (GWD) deposits. GWD deposits contain information on the timing and magnitude of past changes in water-table levels and, therefore, are a potential source of paleohydrologic and paleoclimatic information. In addition, they can be important archeological and paleontological archives because desert wetlands provide reliable sources of fresh water, and thus act as focal points for human and faunal activities, in some of the world's harshest and driest lands. Here, we review some of the physical, sedimentological, and geochemical characteristics common to GWD deposits, and provide a contextual framework that researchers can use to identify and interpret geologic deposits associated with desert wetlands. We discuss several lines of evidence used to differentiate GWD deposits from lake deposits (they are commonly confused), and examine how various types of microbiota and depositional facies aid in reconstructing past environmental and hydrologic conditions. We also review how late Quaternary GWD deposits are dated, as well as methods used to investigate desert wetlands deeper in geologic time. We end by evaluating the strengths and limitations of hydrologic and climatic records derived from GWD deposits, and suggest several avenues of potential future research to further develop and utilize these unique and complex systems.

Published by Elsevier B.V.

Contents

1. Introduction . . . 68
2. Desert wetlands . . . 68
3. Physical characteristics and sedimentology of GWD deposits . . . 69
   3.1. Clastic sediments . . . 69
   3.2. Ground-water precipitates . . . 70
   3.3. Organic matter . . . 71
4. Biota in GWD deposits . . . 71
   4.1. Ostracodes . . . 72
   4.2. Gastropods . . . 73
5. Depositional facies in wetland settings . . . 73
   5.1. Dry alluvial fan environments . . . 73
   5.2. Phreatophyte flats . . . 74
   5.3. Wet meadow . . . 74
   5.4. Marshes. . . . 75
   5.5. Spring orifices . . . 75
6. Differentiation of GWD and lake deposits . . . 75
7. Chronologic considerations . . . 76
   7.1. Radiocarbon dating of GWD deposits. . . . 76

* Corresponding author. Tel.: +1 303 236 7870; fax: +1 303 236 5349.
E-mail address: jpigati@usgs.gov (J.S. Pigati).

http://dx.doi.org/10.1016/j.earscirev.2014.02.001
0012-8252/Published by Elsevier B.V.

7.2. Luminescence dating of GWD deposits . . . 78
8. Strengths and limitations of GWD deposits . . . 78
9. GWD deposits in deep geologic time . . . 78
10. Summary . . . 79
Acknowledgments . . . 79
References . . . 79

1. Introduction

Desert wetlands form in arid environments where water tables approach or breach the ground surface. When active, they serve as watering holes for local fauna, support vegetation that depends on access to ground water for survival, and act as catchments for eolian, alluvial, and fluvial sediments. Active wetlands and springs also serve as a focus of human activity in arid lands, and thus archeological materials are frequently found in association with fossil wetland deposits (Nicholas, 1998; Ashley, 2001).

Wetlands are relatively common features in arid environments, and encompass a variety of hydrologic settings, including seeps, springs, marshes, wet meadows, ponds, and spring pools. Ground water feeding these settings can originate from a number of different sources, ranging from deep-seated bedrock aquifers to shallow alluvial aquifers. Hot springs fed by deeply-circulating ground water are widespread and have been the topic of a number of recent studies (e.g., Hancock et al., 1999; Fouke et al., 2000; Jones and Renaut, 2003; Crossey et al., 2006; Costa et al., 2009). In this paper, however, we focus on low-temperature ground-water discharge systems found in arid and semi-arid environments. Similarly, we have chosen to focus on the freshwater springs that we are most familiar with and do not address saline springs such as those found on the floor of Death Valley (Forester et al., 2005). A final caveat, the springs and wetlands we describe herein are not necessarily related to nearby lakes or rivers as reviewed by Tooth and McCarthy (2007), but rather are stand-alone systems fed by ground water.

Geologic deposits associated with desert wetlands, called ground-water discharge (or GWD) deposits, are also common in arid environments. Since they were first described systematically in the 1980's (Quade, 1986; Quade and Pratt, 1989), GWD deposits have been identified in all four deserts of the American Southwest (Chihuahuan, Great Basin, Mojave, and Sonoran), the Atacama Desert of northern Chile, the Middle East, North Africa, Australia, and Tibet (Paces et al., 1996, 1997; Deocampo et al., 2002; Rech et al., 2002; Liutkus and Ashley, 2003; Smith and Giegengack, 2003; Ashley et al., 2004; Owen et al., 2004; Smith et al., 2004a, 2004b; Quade et al., 2008; Pigati et al., 2009; Winer, 2010). In the Mojave Desert of southern California, detailed mapping of surficial deposits has identified GWD deposits at more than 130 different locations in this small desert alone (Schmidt and McMackin, 2006; Bedford et al., 2010; Miller, 2010; Amoroso and Miller, 2012; Phelps et al., 2012). To our knowledge, comprehensive geologic mapping that includes these features has not been conducted in other deserts, but we contend that, by extension, GWD deposits are likely as common, but underrecognized, elsewhere in the world's arid lands.

Ground-water discharge deposits, which are also called spring or wetland deposits, record past climatic and hydrologic conditions (Mensing et al., 2008, 2013). For example, the average temperature of emergent ground water in isolated, low-temperature wetlands typically approaches the mean annual air temperature at the point of discharge (Quade et al., 2003). Thus, geologic deposits that are associated with desert wetlands can be used to reconstruct past air and water temperatures on a variety of spatial and temporal scales. Similarly, GWD deposits contain information on the timing and magnitude of episodes of high water-table conditions related to moister and/or cooler conditions in the past.

Importantly, researchers must be able to discern between GWD and lake deposits (they are commonly confused) as conditions required to support the two systems can be markedly different. In arid lands, for example, low precipitation and high evaporation rates can make it difficult to maintain perennial lakes, whereas wetland systems can survive periods of relatively low effective precipitation because aquifers that feed wetlands are largely shielded from evaporation. Misidentifying the different deposits, therefore, may lead to erroneous interpretations of past climate regimes. By improving our ability to recognize and interpret GWD deposits, we can more accurately estimate the magnitude of past climate and hydrologic changes, better address what drove the changes, and place constraints on what it might mean for the future of freshwater springs.

In this paper, we review a number of topics related to low-temperature springs and wetlands that are preserved in the geologic record. We begin with a general discussion of how and where desert wetlands and GWD deposits are formed, their physical attributes and chemical composition, and the microfauna (specifically ostracodes and gastropods) that are preserved within the sediments. We then discuss how microfauna and different sedimentary facies can be used to reconstruct specific environments within paleowetlands, and review some approaches that can be used to differentiate GWD and lake deposits. We end with a discussion of chronologic techniques that can be used to establish the age of GWD deposits, an evaluation of the strengths and limitations of hydrologic and climatic records derived from GWD deposits, and suggest further avenues of research related to desert wetlands. In the discussions that follow, we rely heavily on our experience working with GWD deposits in the deserts of the American Southwest and the Atacama Desert of northern Chile. However, the lessons learned should be applicable throughout the world's arid lands.

2. Desert wetlands

Wetlands constitute ~0.3% of the total land cover in the deserts of the American Southwest (Cowardin et al., 1979). In many settings, ground water in shallow alluvial aquifers originates as precipitation and snowmelt in the uplands of nearby mountain ranges and flows under unconfined or semi-confined conditions into valley-fill sediments (Mifflin, 1968). The topography of the water table in these systems generally mimics the local land topography, and ground-water flow continues through the aquifer until the water table intersects the ground surface, often near the distal toe of an alluvial fan or where shallow faults or bedrock force ground water to the surface. Ground-water discharge systems that are not associated with faults or bedrock can be either localized or fairly widespread, ranging up to a few km^2 or more in the American Southwest depending on the local topography (Quade, 1986). Where ground water encounters shallow faults or bedrock, however, discharge is generally more restricted in spatial extent and is often expressed on the landscape as one or more point sources or as a linear feature across an area of near-constant elevation (Quade et al., 1995). Desert wetlands can also act as discharge areas for confined regional aquifers by similar processes, although usually on a larger scale.

Extant springs and wetlands have been subject to a multitude of classification schemes based on characteristics such as water temperature (thermal, non-thermal, hot, warm, cold), water chemistry (sulfurous, saline, calcareous/lime, gypsum, borax, etc.), water persistence (perennial, permanent, intermittent, temporary), volume of discharge

(1st magnitude, 2nd magnitude, etc.), depth and type of aquifer (deep-seated, shallow, confined, semi-confined, unconfined), and geologic structure (bedrock, alluvium, mounds, knolls, pools, etc.) (Bryan, 1919; Meinzer, 1927; Alfaro and Wallace, 1994). In the discussion that follows, we attempt to keep our interpretations and environmental reconstructions as simple as possible as we often lack direct evidence of many of these parameters and have found that using terms such as seeps, marshes, wet meadows, and spring pools are usually sufficient. Following Bryan (1919), we use the term "seep" to refer to a type of spring where ground water emanates from numerous pore spaces over a small area (up to a few m^2 or tens of m^2) rather than coming from a single discharge point (Fig. 1a). "Marshes" are similar but typically larger in scale (hundreds of m^2 to a few km^2) and contain standing water throughout the year (Fig. 1b). "Wet meadows" are also essentially large seeps, but do not have standing water except seasonally or for brief periods after heavy precipitation events (Fig. 1c). Finally, "spring pools" are ground-water fed systems in which the surface water is largely free of vegetation, at least in some areas, often because of higher discharge rates (Fig. 1d). Making these distinctions is not always possible because of the gradual transitions between different features and the complexity of many extant and fossil wetland systems. In general, therefore, we tend to lump them all together as "wetlands" or "springs" unless clear information is present to discern specific hydrologic facies (see Section 5).

3. Physical characteristics and sedimentology of GWD deposits

The interaction between hydrologic systems (emergent ground water and surface water), biologic systems (plants and animals), and geologic systems (eolian, alluvial, and fluvial sediments) in desert wetlands creates unique and complex depositional environments that are preserved in the geologic record as ground-water discharge (GWD) deposits. The physical appearance and geochemistry of GWD deposits vary widely from place to place because of differences in ground-water chemistry, the density and types of plants living in and around the wetland system, the availability and mobility of surface waters, and diagenetic processes. They often appear as light-colored badlands, characterized by highly dissected, undulating surfaces positioned at or near the valley bottoms (Fig. 2).

At the outcrop scale, GWD deposits are generally composed of fine-grained sediments that include up to three distinct components: clastic sediments, ground-water precipitates, and organic matter.

3.1. Clastic sediments

In most cases, clastic sediments comprise the bulk of GWD deposits (Pigati et al., 2011). The lithology, grain size, and geochemistry of clastic sediments found within GWD deposits depend on the surrounding rock types and local topography. Alluvial fan and, to a lesser extent, fluvial sediments, can be introduced to desert wetlands by overland flow and generally reflect source areas that are nearby. These sediments are usually concentrated near the wetland margins, and are rocky, poorly sorted, and massive to weakly bedded. Sediments in the wet meadows and wetlands themselves are mostly silt with variable amounts of fine to medium sand. They are typically well sorted and range from massive to weakly bedded. The fine-grained sediments that become trapped by wetland vegetation and incorporated into GWD deposits can originate from both local (alluvial fan) and extra-local (eolian) sources.

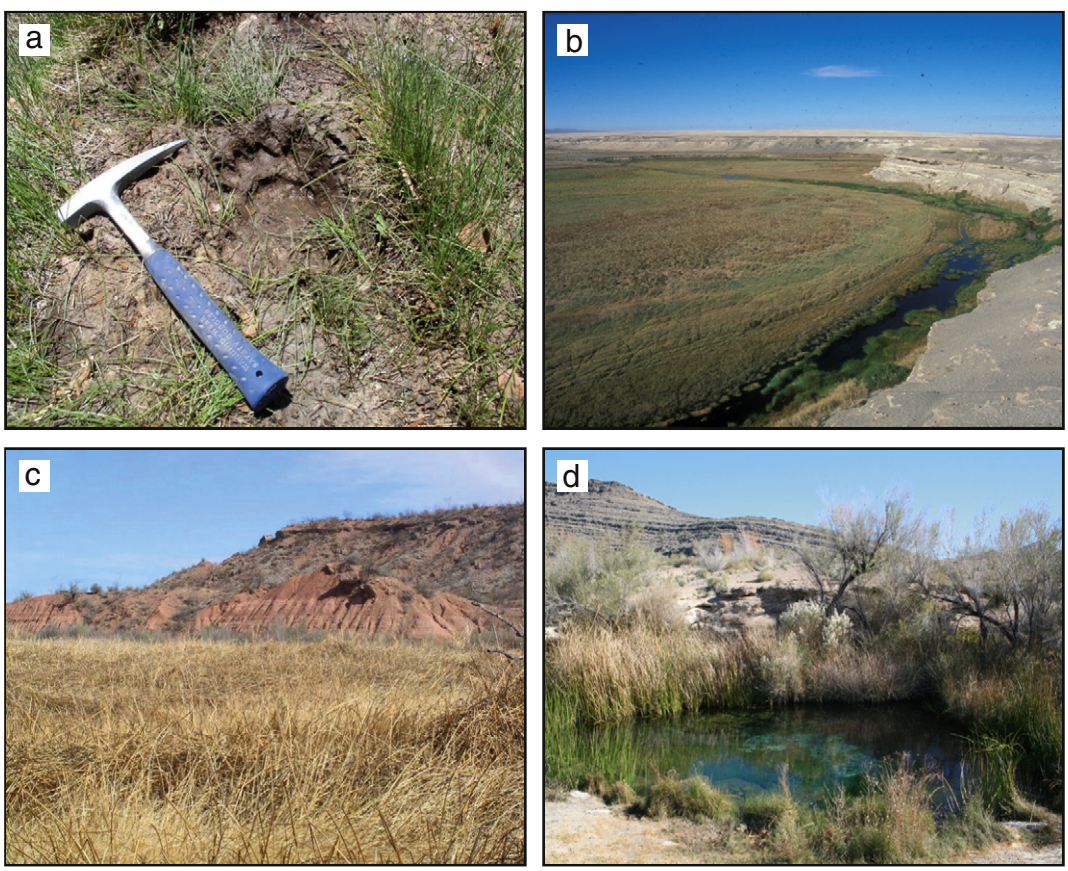

Fig. 1. Photographs of (a) a seep at Peterson Spring in southern Arizona, (b) a marsh at Rio Loa in the Atacama Desert of northern Chile, (c) a wet meadow in the San Pedro Valley Conservation Area in southeastern Arizona, and (d) a spring pool at Point of Rocks Spring in Ash Meadows National Wildlife Refuge in southern Nevada. Each of these hydrologic facies can be recognized in the fossil record based on a combination of their size, sedimentological characteristics, relative position on the landscape, and microfauna.

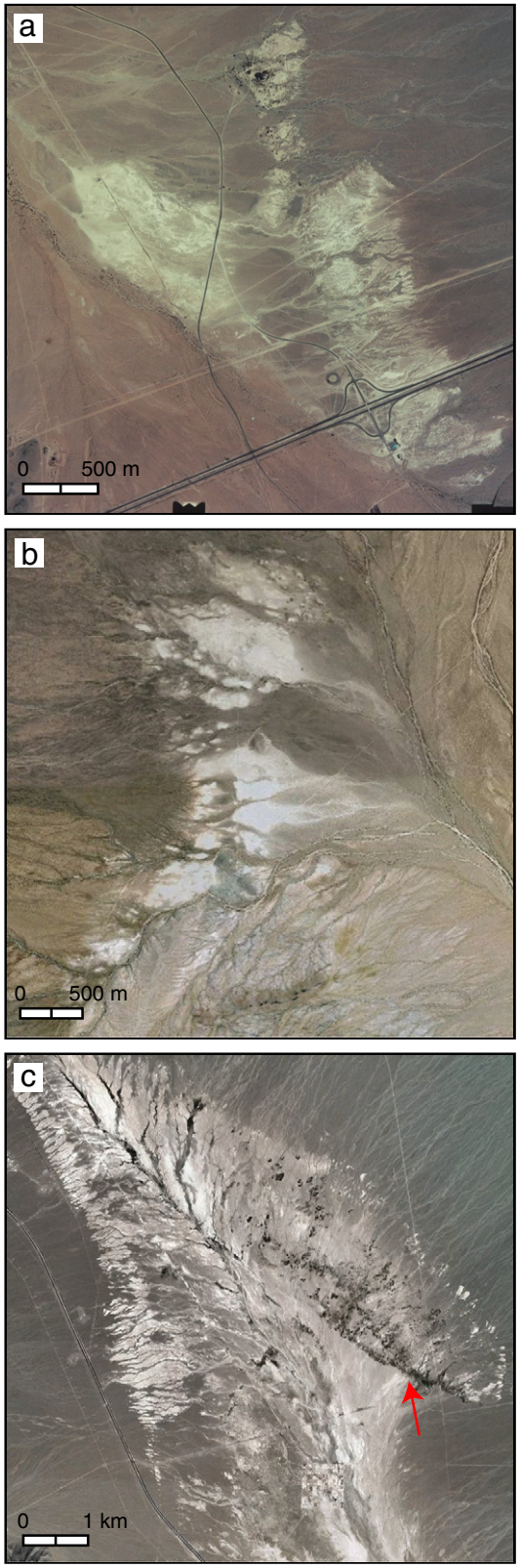

Fig. 2. Aerial photographs of ground-water discharge deposits at (a) Valley Wells, California, (b) Piute Valley, California, and (c) lower Corn Creek flat in the Las Vegas Valley, Nevada. Note the conspicuous nature of the light-colored GWD deposits compared to surrounding alluvial fan sediments at these locations. The red arrow on (c) denotes a linear transect of extant springs positioned along a shallow fault.

3.2. Ground-water precipitates

Ground-water precipitates are formed in desert wetlands when ground water emerges from an aquifer and gases (mainly carbon dioxide) are lost to the atmosphere. For example, low-Mg calcite, the most common precipitate in low-temperature GWD systems, is formed via the reaction

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3(s) + H_2O + CO_2$$

Calcite formation in wetlands is favored by conditions that include low atmospheric humidity, low atmospheric pCO_2, the presence of limestone in the recharge area (which increases Ca, Mg, and HCO_3 in solution), high pH and temperatures, and elevated photosynthetic activity of organisms living in and around the points of discharge. Alone or combined, these factors determine the saturation state of the emergent ground water, a key determinant of whether calcite will form.

In our experience, there are four main types of ground-water carbonates found in GWD deposits (Fig. 3):

(1) *Spring travertine*. If emergent ground water is strongly supersaturated with respect to calcite, then calcite will precipitate as hard, dense travertine at or just downstream of the point of discharge, or as fracture fill (O'Brien et al., 2006). Carbonate formation in these settings is often most clearly related to out-gassing of high pCO_2 spring water (Usdowski et al., 1979). This is the sort of carbonate that many geologists associate with springs, but it is not the way most carbonate forms in desert wetland settings.

(2) *Water-table carbonate*. This is the most common type of ground-water carbonate. It forms in the vadose zone, mostly along the capillary fringe of the water table where calcite saturation is attained through evapotranspiration of ground water. In contrast to hard, layered travertine, water-table carbonate is typically sparry to chalky in appearance. It can occur as nodules, pore-fill, and even hard, thick layers, if given enough time, that are similar in appearance to soil carbonate. In some cases, this form of carbonate cements burrows and bedding structures present in parent sediment, preserving their form even when the host sediments are eroded. In others, lag deposits of "popcorn" carbonate (small, 1–3 cm diameter carbonate nodules) are left behind after deflation.

(3) *Wetland marl*. Marl carbonate forms in shallow wetlands where waters are saturated with respect to calcite upon discharge or where calcite precipitation is aided by biological mediation, akin to the formation of tufa along lake shorelines. This type of carbonate is generally massive to blocky, and often forms in marl flats, i.e., marshy areas where the wetland sediments have accumulated high concentrations of carbonate from strongly alkaline ground water.

(4) *Wetland tufa*. Tufa carbonate forms on the surface of aquatic or terrestrial vegetation both at and below the water surface at ambient temperatures (Ford and Pedley, 1996). At the water surface, carbonate precipitation, driven by evaporation, biological mediation, and other factors, coats the stems of hydrophilic vegetation such as sedges and grasses. Below the surface, carbonate coats the surface of aquatic vegetation, such as charophytes, when the water is saturated with respect to calcite. Holocene-age wetland tufas are generally very porous and often preserve voids of the original plants (see Fig. 3d), whereas Pleistocene and older tufas are often dense because secondary precipitation fills in the void spaces.

Low-Mg calcite is most common in wetland systems, but other types of carbonates (high-Mg calcite, Na-carbonate, dolostone) can develop in a wide range of microsettings. Ground-water silicate, gypsum, and other minerals (e.g., Mn-oxides) are also present, providing clues on the chemical composition and redox state of ground water, as well

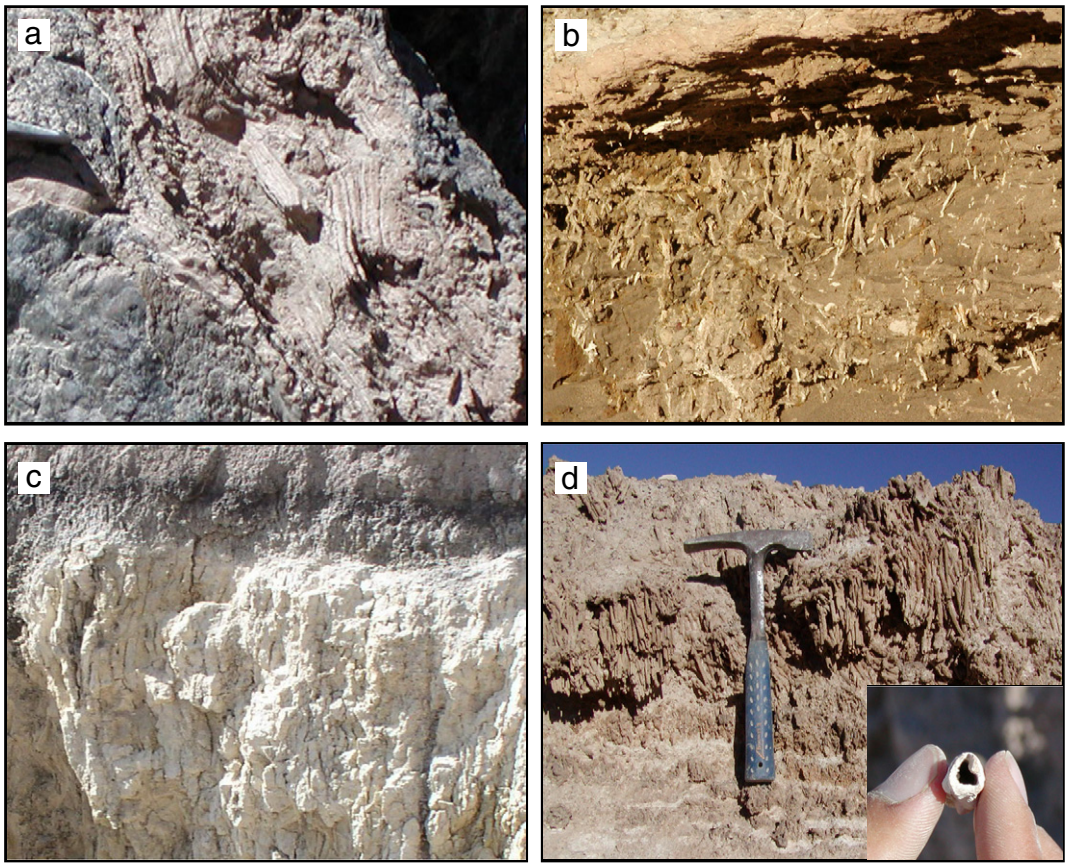

Fig. 3. Photographs of different types of wetland carbonate: (a) spring travertine, (b) water-table carbonate, (c) wetland marl, and (d) wetland tufa. Panels (a), (b), and (c) are ~40–50 cm across. Inset of (d) shows void of the original plant preserved in Holocene-age wetland tufas from northern Chile.

as climate conditions at the time they were formed. For example, Ca–HCO_3-rich ground water in the American Southwest produces authigenic minerals chemically distinct from those formed in silica-rich ground water in the Atacama Desert of northern Chile (Fig. 4). Carbonates dominate the secondary cements of GWD deposits associated with Ca–HCO_3-rich waters, whereas GWD deposits from the Atacama are poor in cements of any type but rich in siliceous biological remains. Accumulation of more soluble salts, such as gypsum and halite, resulting from capillary migration and evaporation of near-surface waters, may indicate periods of exceptionally arid conditions (Quade et al., 2008).

3.3. Organic matter

The remains of aquatic and terrestrial plants that live in desert wetlands are often represented in GWD deposits as dark-colored, organic-rich sediments that are referred to informally as "black mats" (Haynes, 1991; Quade et al., 1998; Haynes, 2008). Black mats are typically well sorted and fine grained, and range from thin (<1 cm) strata with organic matter concentrations of several percent to thick (up to 1 m or more), more diffuse strata that may contain less than one percent organic matter (Fig. 5).

Unlike ground-water carbonates and clastic sediments that persist over geologic time, black mats are often preserved only in the younger GWD deposits. In the American Southwest, for example, many black mats date to the Younger Dryas cold event (YD, 13.0–11.5 calendar ka BP, Haynes, 2008), the last period that many desert wetlands were active. However, they are rarely present in older GWD deposits. Assuming that most, if not all, of the wetlands once supported dense stands of vegetation, the organics initially present in the older GWD deposits must have been destroyed over time, perhaps by exposure to O_2-rich ground water or air. YD-age black mats in the region, in contrast, were left "high and dry" after water tables fell and remained low throughout the Holocene, which allowed for their preservation.

Ground-water discharge deposits that contain multiple black mats within individual stratigraphic sections are present at a few rare localities in the Southwest (Fig. 4b), but are relatively common in the Atacama Desert of northern Chile (Fig. 4d,e) (Grosjean et al., 1997; Betancourt et al., 2000; Rech et al., 2002, 2003; Maldonado et al., 2005; Quade et al., 2008). The presence of multiple mats reflects repeated cycles of wetting and drying, and suggests that subsurface conditions at these locations are more conducive to the preservation of organic matter than sites in the Desert Southwest. The specific reasons for this are unclear, but may be related to the amount of time ground water flowed through the deposits, the level of dissolved oxygen in the ground water, or other factors related to diagenesis of organic matter.

4. Biota in GWD deposits

The remains of large vertebrates (megafauna) are frequently preserved in GWD deposits, particularly teeth and bones of mammoth, horse, bison, and camel, among others (Mawby, 1967; Reynolds et al., 1991; Springer et al., 2009). Such fossils provide opportunities to understand how faunal communities responded to past climate change in arid environments, as well as to investigate the potential ties between extinctions, the arrival of humans, and changes in paleoenvironmental conditions (Haynes, 2008; Scott, 2010).

Ostracodes, gastropods, chironomids, sponges, forams, and algae (mainly diatoms) are also common in both extant desert wetlands and GWD deposits. Ostracode and gastropod assemblages, stable isotope ratios ($\delta^{18}O$, $\delta^{13}C$), and chemical composition often yield hydrologic and environmental information in both extant systems and those active in the past. Diatoms have been studied extensively in lakes

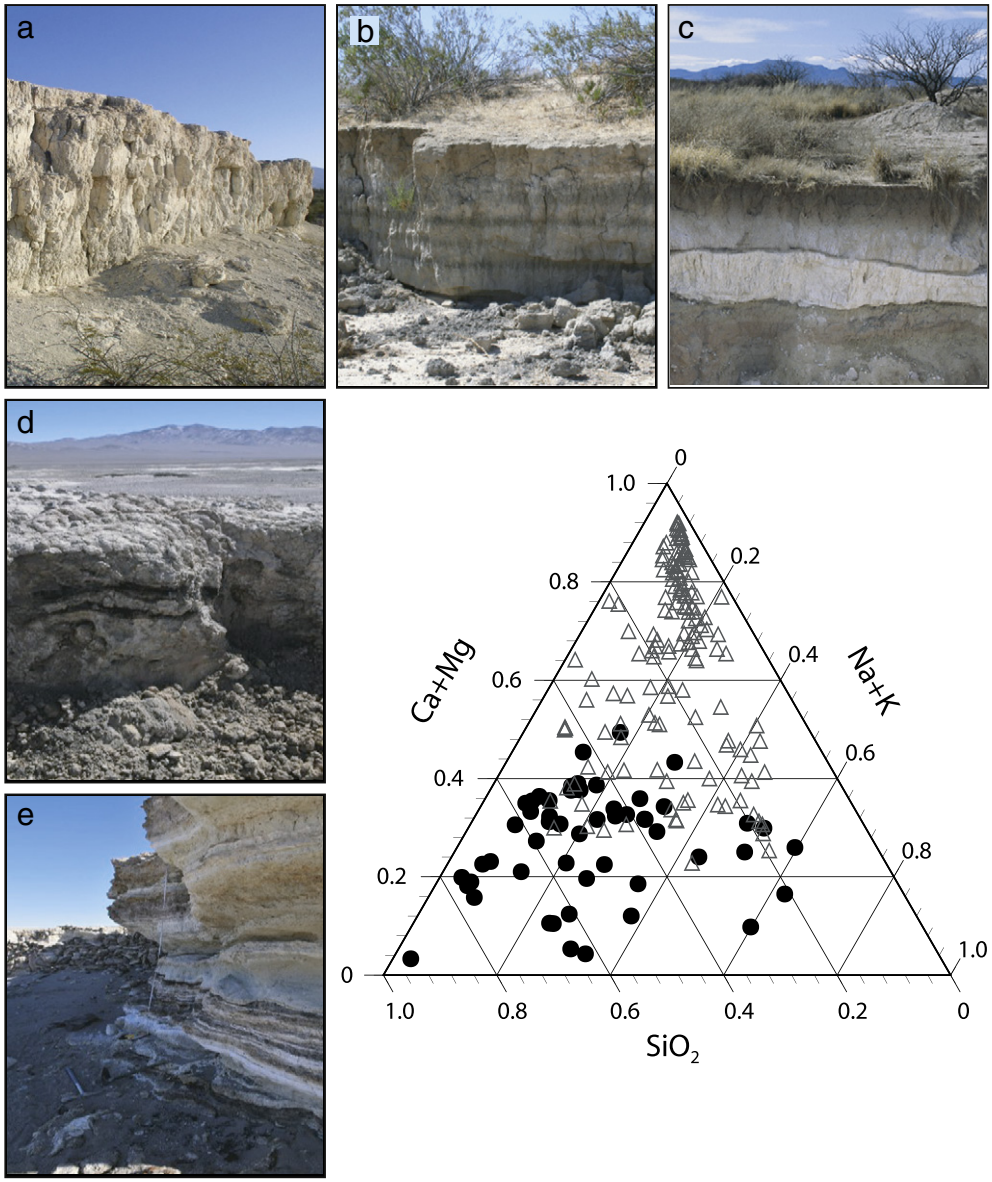

Fig. 4. Ground-water discharge deposits in the American Southwest: (a) Cerros Negros, AZ, (b) Dove Spring, CA, and (c) Murray Springs, AZ, and in the Atacama Desert of northern Chile: (d) Salar de Punta Negra, and (e) Rio Salado. Although the GWDs at these locations are similar in appearance, there are significant differences in the chemical composition of ground and surface waters in the Southwest (carbonate-rich; open triangles) and Chile (silica-rich, filled circles) that are transferred to ground-water precipitates in the deposits. Water chemistry data derived from Thomas et al. (1991), Aravena and Suzuki (1990), Fritz et al. (1981), and Margaritz et al. (1989).

worldwide (e.g., Mackay, 2007), swamps and wetlands in East Africa (Liutkus and Ashley, 2003; Owen et al., 2004), and marshes on California's Channel Islands (Anderson et al., 2009), but little is known about their abundance or distribution in desert wetlands. Even less in known about chironomids, sponges, and forams in these settings. In this section, therefore, we focus our discussion on ostracodes and gastropods as they have been the subject of several recent studies that involved GWD deposits (Forester and Smith, 1994; Forester et al., 2003; Quade et al., 2003; Pigati et al., 2009, 2011).

4.1. Ostracodes

Ostracodes (or ostracods) are a diverse group of generally millimeter-sized crustaceans that inhabit nearly all aquatic environments. Rather than possessing a singular carapace that protects the head (e.g., lobsters and shrimp) or dorsum (e.g., crabs), the ostracode carapace is bivalved and their anatomy has been reduced such that the carapace encapsulates the entire body (Horne et al., 2002). The ostracode carapace is composed primarily of calcite, but also contains a small amount of organic matter and trace elements (Sohn, 1958). Upon death, their soft anatomy quickly decomposes, leaving behind disarticulated valves that are readily preserved in both lacustrine sediments and GWD deposits. Ostracode valves can be identified using morphological characteristics that are unique both at the genus level (e.g., adductor muscle scars) and species level (e.g., size, shape, surface topography).

The distribution of ostracode species in hydrologic settings, while complex, is not random. Many ostracode species are generalists and inhabit a wide range of aquatic environments. Others are more specialized (or limited) in their ecological requirements and display intimate associations with discrete habitats. The primary variables that control ostracode species distributions are the ratio of calcium (Ca) to carbonate alkalinity (ALK), the total dissolved solids (TDS) content and temperature of the host water, and habitat permanence (Forester, 1987; Quade et al., 2003). In the American Southwest, desert wetlands fed by ground water with high Ca/ALK ratios may host indicator species

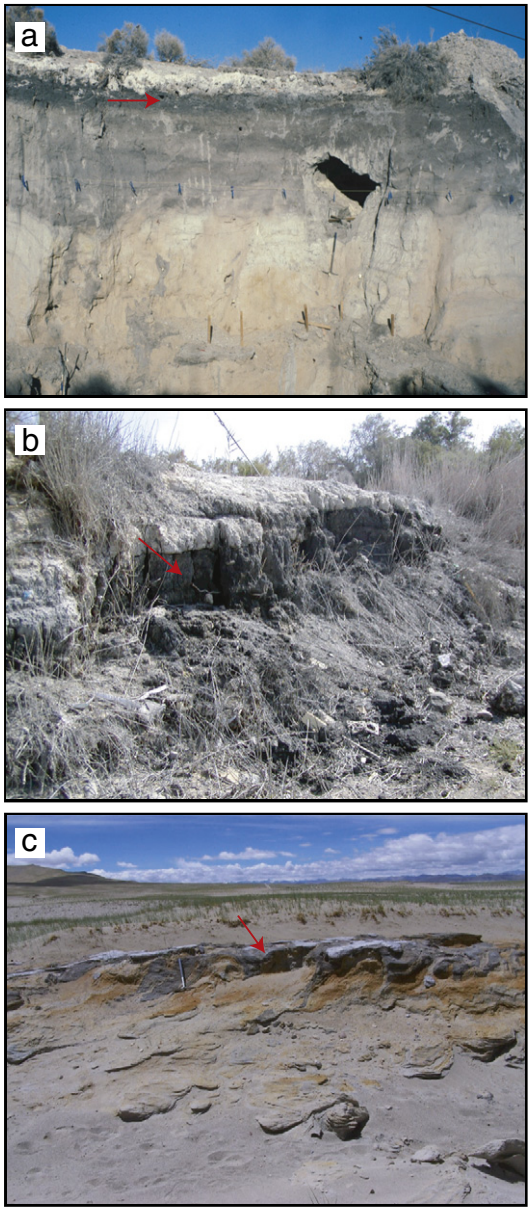

Fig. 5. Photographs of black mats at (a) Las Vegas Valley, Nevada, (b) the Azraq Oasis in eastern Jordan, and (c) in central Tibet near Zhongba. Red arrows point to horizons with the highest concentration of organic matter.

such as *Limnocythere staplini* or species within the genus *Cyprideis* (e.g., *Cyprideis beaconensis*, *Cyprideis salebrosa*), which are marginal marine taxa that can travel inland if conditions are favorable. Wetlands and GWD settings with low Ca/ALK ratios may be inhabited by indicator species such as *Cyprinotus glaucus* and *Limnocythere sappaensis*. In most cases, ostracodes that inhabit water with high Ca/ALK find low Ca/ALK chemistries lethal, and vice versa (e.g., Forester, 1983). Thus, ostracode assemblages found in GWD deposits can be used to infer past chemical conditions of the emergent ground water.

As a whole, ostracodes have one of the largest temperature tolerances in the animal kingdom (Delorme, 1991; Curry, 1999). They have been found in water with temperatures that range from near freezing to ~50 °C (e.g., Delorme, 1991). In the American Southwest, indicator species such as *Cavernocypris wardi* or *Prionocypris canadensis* are found in cold dilute springs (<14 °C, Forester, 1991; Quade et al., 1998), whereas *Physocypria* and other taxa require warmer water (>18 °C) to complete their life cycles (Forester et al., 1987; Forester, 1991). Thus, similar to water chemistry, ostracode assemblages can be used to reconstruct past water temperatures in GWD settings if their ranges in extant settings are well characterized.

The presence of warm indicator species in otherwise cold settings also can be used to identify ground water systems that have been subjected to geothermal heating. For example, the ostracode *Chlamydotheca* is a circumtropical taxon that cannot survive when water temperatures fall below ~20 °C (Forester, 1991). The presence of *Chlamydotheca* valves in Pleistocene GWD deposits in middle to northern latitudes where cold temperatures persisted during glacial times, therefore, would suggest that the emergent ground water was probably influenced by geothermal heating (e.g., Hallman, 2002).

Finally, the isotopic composition of ostracode valves can be used to determine the composition and mobility of host waters in GWD settings. $\delta^{18}O$ values of ostracode valves can be used to quantitatively reconstruct temperatures of emergent ground water and, by proxy, mean annual air temperatures at the point of discharge if host water $\delta^{18}O$ values can be constrained independently (Quade et al., 2003). Coherence between $\delta^{13}C$ and $\delta^{18}O$ values can also be used to evaluate the mobility (i.e., flowing or stagnant water) of surface water in wetland systems (Pigati et al., 2009).

4.2. Gastropods

Gastropods are one of the most successful animal groups on Earth with at least 70,000 extant species occupying terrestrial, marine, and freshwater habitats (Barker, 2001). Like ostracodes, shells of terrestrial and aquatic gastropods are commonly found in GWD deposits, and provide insight into past hydrologic and environmental conditions. Gastropod assemblages in desert wetland environments vary tremendously based on factors that include the type of vegetation present in and around the wetland, the chemical composition and temperature of the emergent ground water, and both seasonal and interannual changes in climate conditions. While not as specialized as ostracodes in terms of their habitat preferences, terrestrial gastropod assemblages can be used to infer the types of plant communities and climate conditions that were present in a particular wetland system (Bequaert and Miller, 1973). Variations in behavioral and physiological factors of gastropods, however, often limit their utility in stable isotope studies (Shanahan et al., 2005).

5. Depositional facies in wetland settings

In modern GWD systems, there are clear relations between the hydrologic regime, floral and faunal assemblages, and the types of sediments preserved in the geologic record (Forester, 1991; Quade et al., 1995). We have encountered several different sedimentary facies in extant and paleowetland systems, including dry alluvial fan environments, phreatophyte flats, wet meadows, marshes, and spring orifices. Each of these facies contains a unique combination of sediments and microfauna that can be used to reconstruct past environmental and hydrologic conditions within wetland systems (Fig. 6). As above, the specific flora and fauna referred to below are primarily associated with wetlands in the American Southwest.

5.1. Dry alluvial fan environments

In deserts, alluvial fan environments that are outside the influence of wetland systems typically support xerophytic plants (e.g., creosote bush, cacti) that are adapted to harsh, dry conditions. These environments are represented in the geologic record by rocky, poorly sorted, and weakly bedded alluvial fan deposits, with low concentrations of organic matter. Sediments representing dry alluvial fan environments generally do not contain either fossils or ground-water precipitates, although they may contain soil carbonate.

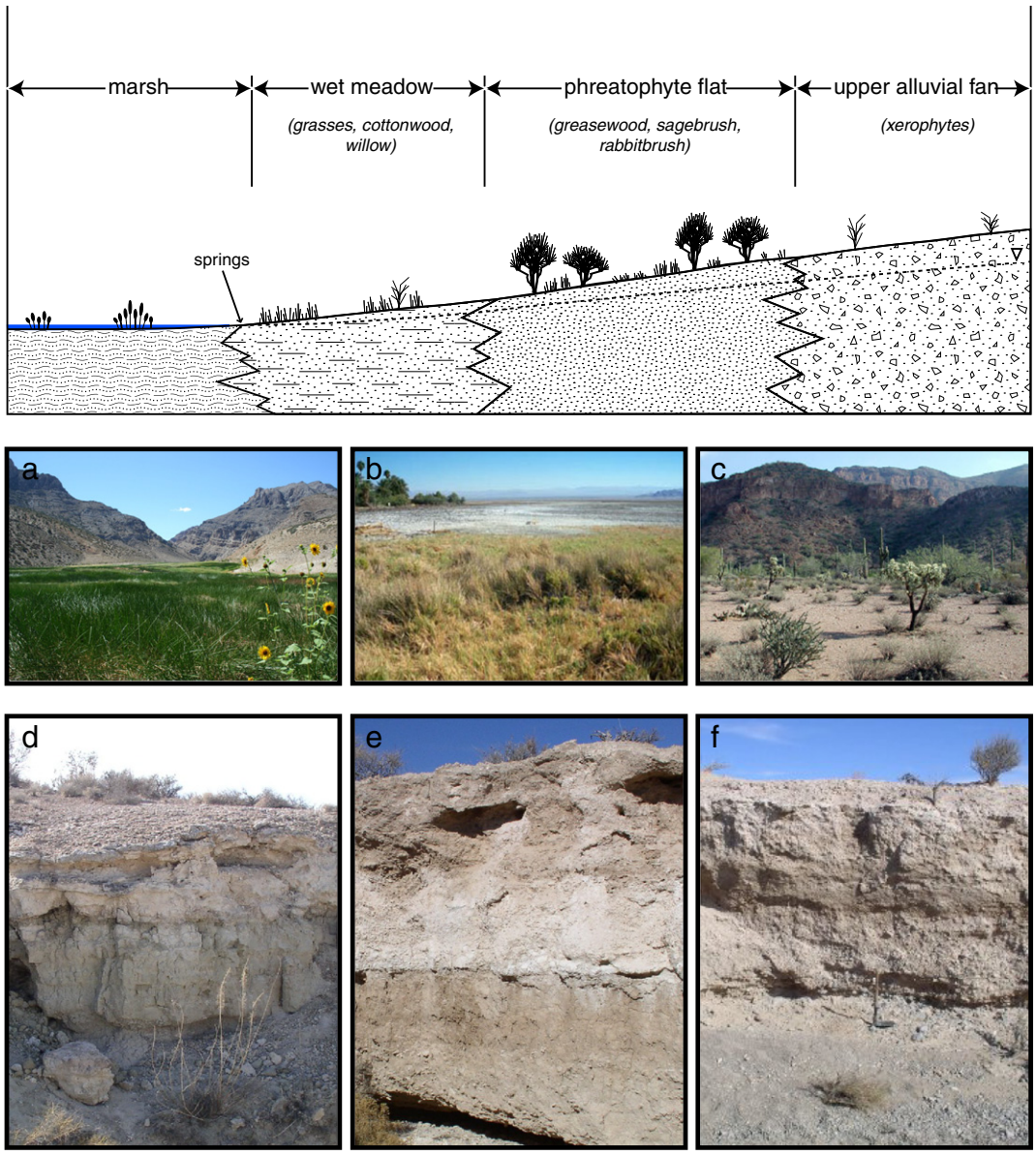

Fig. 6. Schematic diagram of depositional facies in desert wetland systems (after Quade et al. (1995)). Photographs of extant wetlands and GWD deposits representing (a/d) wet meadow facies, (b/e) phreatophyte flat facies, and (c/f) dry alluvial fan facies. The extant marsh is in the Ruby Valley of northern Nevada, the phreatophyte flat is at MC Spring near Zzyzx, California (Soda Lake playa is in the background), and the alluvial fan facies is in the Sonoran Desert of central Arizona. Photographs of the fossil wetland facies were all taken at Valley Wells, California (Pigati et al., 2011).

5.2. Phreatophyte flats

Areas adjacent to wetland systems support phreatophytic plants, such as sagebrush, rabbitbrush, and greasewood, which have root systems that are able to tap into the shallow ground water. These plants trap large amounts of eolian and alluvial fan sediments and, as a result, "phreatophyte flats" are represented in the geologic record by massive to weakly cross-bedded, well-sorted silts and very-fine sands locally mixed with alluvial fan sands and gravels. Water-table carbonate is often present in these sediments as well. Organic matter concentrations in phreatophyte flat areas are greater than in surrounding alluvial fan environments, but are still quite low (typically <1%) and can be highly variable. These areas also typically contain high concentrations of large (3–5 mm) root voids associated with the phreatophytic vegetation. Fossil assemblages from phreatophyte flats may include rare vertebrate remains and/or terrestrial gastropods, but ostracodes and aquatic gastropods are generally absent because of the lack of surface water.

5.3. Wet meadow

Areas covered by dense stands of terrestrial grasses, but without perennial standing water, are represented in the geologic record by mudstones mixed with eolian and alluvial fan sediments. Soils in wet meadows typically have high concentrations of organic matter (histosol/aquoll) and sometimes exhibit gleyed mottling, but thick reduced horizons are generally lacking. Water-table carbonate (common) and even wetland marls (rare) can be present as well, depending on how much surface water is present in the wet meadow. Terrestrial and semi-aquatic gastropods, as well as some ostracodes, are often present in wet meadow settings. Typical fossil assemblages might include small terrestrial gastropods, such as Pupillidae, Discidae, Succineidae, and Valloniidae, and ostracodes such as *Heterocypris incongruens* that have life cycles capable of withstanding episodes of desiccation (Quade et al., 2003). Root voids are often present in these areas, but are generally not as large as those found in the phreatophyte flat facies.

5.4. Marshes

Marshes are similar to wet meadows but are characterized by increased surface water, hydrophilic plants such as sedges and pampa grasses, and reducing conditions in the near subsurface. Marshes are represented in the geologic record by pale-green to white mudstones (wetland marls) and organic-rich silts and clays with relatively small (1–2 mm) root voids, and often contain a mix of terrestrial and semi-aquatic (lung-breathing) gastropods, such as the family Physidae, fully aquatic (gill-breathing) gastropods, such as *Helisoma* and *Gyraulus* (family: Planorbidae), and abundant ostracodes. Ostracodes that are better able to survive dry periods, including *Cypridopsis vidua*, *H. incongruens*, and *Physocypria globulosa*, may be present in transient marshes, whereas taxa such as *Ilyocypris bradyi* and *Candona caudata* that prefer more persistent surface waters are common in more stable systems.

5.5. Spring orifices

Spring orifices account for just a small fraction of the total fine-grained sediment associated with desert wetland systems and are generally hard to find, which is perhaps one of the reasons that GWD deposits are underrecognized in the geologic record. When they are identified, however, there is no question as to their origin and significance (Haynes, 1967; De Narvaez, 1995; Haynes, 2007). Sediments associated with spring orifices generally have steep, cauldron-shaped cross-sectional morphologies that are filled with vertically bedded, well-sorted, medium- to coarse-grained sand. These deposits occasionally contain heavy minerals that are concentrated in vertical beds, which are probably the result of slow, upward bubbling of ground water through the sediment. Spring orifices often contain high concentrations of vertebrate remains, including isolated teeth and smoothed bone pebbles that are formed by constant rolling as ground water emerges from the subsurface. Water flowing from spring orifices generally hosts strong microfaunal indicators, such as the aquatic gastropods *Tyronia* and *Pyrgulopsis* (family: Hydrobiidae), which prefer flowing water and spring pools, and ostracode species that prefer thermally and chemically stable conditions, such as *Strandesia meadensis*, *Candona acuminata*, and *Cypridopsis okeechobei*.

Understanding and recognizing the specific hydrologic settings within a particular GWD system are important when attempting to reconstruct changes in water-table levels over time, similar to the way that recognizing different lacustrine facies allows for the reconstruction of changes in lake levels based on sediment cores and outcrops. In GWD deposits, the combination of independent data, such as depositional facies and microfaunal assemblages, provides a strong foundation for reconstructing the complex array of microenvironments that are often present in wetland settings.

6. Differentiation of GWD and lake deposits

For many reasons, GWD deposits have long been misidentified as lake deposits (e.g., Quade, 1986; Quade and Pratt, 1989; Forester et al., 2003; Pigati et al., 2009; Winer, 2010). They both occupy similar positions on the landscape, specifically low-lying areas within broad valleys and basins; they are both typically composed of fine-grained, light-colored sediments that contain chemical precipitates and often erode to form badland topography (e.g., highly-dissected, but smooth, undulating surfaces); and aquatic microfauna preserved in both types of deposits can include freshwater taxa that survive in both wetland and lake environments.

Proper identification of GWD and lake deposits is critical to understanding paleohydrologic and paleoclimatic conditions in desert settings. Low precipitation and high evaporation rates make it difficult to maintain lakes in arid lands. Thus, the presence of lake deposits in deserts today would suggest that conditions were much wetter at some time in the past. Wetland systems, in contrast, can survive periods of relatively low effective precipitation because aquifers that feed wetlands are largely shielded from evaporation. Thus, their presence in the fossil record represents periods of increased effective precipitation compared to today, but substantially less than that required to support lakes in the same region.

The proper identification of lake versus GWD deposits can also have implications for regional tectonics. GWD deposits misidentified as being lacustrine in origin could be used to reconstruct tectonic activity of desert regions over millennial timescales, with the reasoning that if the "lake" deposits were originally horizontal, then any tilt that they might have acquired since their deposition must have resulted from tectonic activity. The gradient of GWD deposits along a valley axis often tracks the gradient of the valley floor (Quade, 1986), thereby potentially giving a false impression of the amount of tilting that may have occurred since their deposition.

In modern settings, wetlands and lakes can be differentiated based on the gradient of the water present: the surface of water in a lake (or pond) is flat, whereas the surface of water in ground-water-fed systems is usually not. Gradients in wetland systems are often very low, but are typically not zero and can be measured directly in extant settings today. (An exception is a marsh or wet meadow that forms in a closed topographic low; i.e., a "closed" wetland.) Differentiating between GWD and lake systems in the geologic record based solely on the gradient of the deposits is rarely possible because the surfaces are often eroded or have settled, slumped, or been subjected to other soft-sediment deformation processes. However, several features can be used to distinguish between GWD and lacustrine deposits (Table 1; Fig. 7).

First, the spatial distribution and geomorphic characteristics of GWD and lake deposits are different. GWD deposits are often distributed asymmetrically along or near a valley axis, whereas lake deposits are not. If we consider the case of a valley with two adjacent mountain ranges, one of which is much higher than the other, we would expect that the higher range would intercept more precipitation than the lower range. Consequently, there would be more recharge to an aquifer on the side of the valley adjacent to the higher range and, as a result, GWD deposits would favor that side of the valley (Quade et al., 2008). A lake present in the same valley would leave behind deposits on both sides without regard for the elevation of the adjacent ranges.

Second, GWD deposits are often found in association with shallow faults. Not only do faults act as conduits for moving ground water laterally through the subsurface, but they can also force ground water up toward the surface. Thus, it is relatively common to find GWD deposits in association with shallow faults (Winograd and Thordarson, 1975; Quade et al., 2008). Lake deposits are rarely bounded by or associated with faults, unless they happen to coincide with past lake levels.

Third, as in modern systems, paleolakes require complete topographic closure, whereas wetlands do not. Wetlands are low-energy and low-gradient systems that leave behind deposits that often track the gradient of the local valley floor. Lakes, in contrast, leave behind "bathtub rings" of deposits at constant elevation in both valleys and closed basins. This simple observation is an exceedingly powerful tool in differentiating Quaternary GWD and lake deposits, and can be implemented by evaluating the local topography to determine if hydrologic closure is physically possible (Quade, 1986). If not, either significant changes – tectonic or geomorphic – in valley bottom topography must be invoked to support the existence of a paleolake.

Fourth, microfaunal assemblages can be used to discern lacustrine and GWD deposits. GWD systems are composed of a wide mosaic of microenvironments, whereas habitat complexity and variability in lacustrine environments are most pronounced along depth transects that extend from the littoral zones to the depocenters of lakes. Ostracode species richness decreases with water depth, such that the deeper parts of lakes typically contain a depauperate ostracode fauna (e.g., Tressler, 1957; Buckley, 1975). For example, Late Pleistocene-aged lacustrine deposits associated with pluvial lakes in southeastern

Table 1
Summary of distinguishing characteristics of wetland and lake deposits.

	Ground water discharge deposits	Lake deposits
Topographic setting	Highly variable, but generally in topographically open settings. Deposits are generally limited spatially to a particular location.	Can only form in topographically closed basins. Deposits generally cover the entire closed-basin area.
Valley asymmetry	Often found on one side of a valley, typically the side adjacent to the higher mountain range that receives greater precipitation.	None.
Tectonic setting	Often associated with faults, with the downslope margin of the wetland deposit being bounded by the fault.	Margins of closed lakes in arid lands rarely coincide with faults.
Sedimentology	Chemical precipitates ($CaCO_3$, gypsum, SiO_2), reduced sediments, and organic matter common. Evidence of bioturbation, root voids, and rhizocretions also common.	Chemical precipitates and reduced sediments common. Evaporites are also common as lake beds desiccate. Lake deposits are typically less bioturbated and are often laminated or finely bedded. Also may contain shoreline facies (beach deposits) or erosional features (wave cut benches).
Microfauna	Typically contain a mix of terrestrial, semi-aquatic, and aquatic taxa. Microfaunal assemblages are often diverse.	May contain fresh and saline-tolerant taxa; can be variable over time. In general, less diversity of taxa than in GWD environments.

*Note: These are general guidelines to some of the major differences between GWD and lake deposits. Continued research will refine the similarities and differences between these types of deposits.

California (Lake Manix, Lake Mojave) and southeastern Arizona (Lake Cochise) contained only four species of ostracodes that are limited almost exclusively to the genus *Limnocythere* (Cameron, 1971; Steinmetz, 1988; Meek, 1999; Wells et al., 2003). Pleistocene GWD deposits in the San Pedro Valley of southeastern Arizona, located just one valley west of pluvial Lake Cochise, in contrast, contained at least 12 species of ostracodes that represent a variety of environments, including *Strandesia meadensis* (spring-discharge), *I. bradyi* (flowing water), *H. incongruens* (stagnant water to marginal environments), and *Scottia* sp. (seep to semi-terrestrial environments) (Pigati et al., 2009). Microfauna can also be used to differentiate lake and GWD deposits in deep geologic time if ostracodes and gastropod shells are preserved.

The presence of certain ostracodes can also be diagnostic of the specific paleohydrologic setting. Ostracodes such as *Candona subtriangulata* and *Cytherissa lacustris* are typically only found in stable lacustrine environments (Delorme, 1991), which would imply the presence of a deep, persistent lake, rather than a GWD setting. Ostracode faunas in lacustrine deposits also differ from GWD deposits in that they often exhibit marked temporal variability, including oscillations between saline-tolerant and fresh-water faunas as lake levels and chemistries fluctuate in response to changes in climate (e.g., Thompson et al., 1990; Carter, 1997). Such variations are rarely seen in GWD settings.

Finally, as discussed above, sedimentary characteristics in many cases distinguish lake and wetland deposits. Identification of facies representing phreatophyte flats, wet meadows, marshes, and especially spring orifices would clearly signify GWD deposits. In general, sediments in all these settings are much more bioturbated than typical lake deposits. Accordingly, root voids and rhizoliths are indicative of GWD deposits, whereas rounded beach gravels, wave-cut benches, and other shoreline features would point to lacustrine processes, as does the presence of well-preserved bedding, evaporite beds in particular (e.g., Ku et al., 1998; Bobst et al., 2001).

7. Chronologic considerations

Many GWD localities contain time-stratigraphic units that represent past episodes of active ground-water discharge. The degree of cementation and hardness of sedimentary outcrops can provide a rough indication of the relative age of the deposits, and these features are often used in mapping surficial deposits. Late Pleistocene and Holocene GWD deposits can be more precisely dated by a number of different techniques, including radiocarbon, luminescence, amino-acid racemization, and uranium-series. In this section, we limit our discussion to radiocarbon and luminescence as they are the most common techniques that have been applied to GWD deposits in recent years.

7.1. Radiocarbon dating of GWD deposits

All materials that yield reliable ^{14}C ages have two things in common. First, when alive, the ^{14}C activity of the material – a plant, for example – is in equilibrium with atmospheric ^{14}C (after accounting for isotopic fractionation). Second, after death, the material behaves as a closed system with respect to carbon; that is, carbon is neither added to the sample nor exchanged with the environment. If both of these criteria are met, then the ^{14}C age of the material is only a function of the current ^{14}C activity, which can be measured by accelerator mass spectrometry or liquid scintillation counting, and the time elapsed since death (i.e., the age of the sample).

Ground-water discharge deposits often contain macrofossils or carbonized wood[1] from vascular plants that can be used for ^{14}C dating. When alive, vascular plants acquire their carbon directly from the atmosphere via photosynthesis and, therefore, are not subject to hard-water (or reservoir) effects that can affect the ^{14}C content of some aquatic plants (Deevey et al., 1954; Geyh et al., 1998). Assuming they act as closed systems with respect to carbon after burial, plant macrofossils and carbonized wood recovered from GWD deposits should yield reliable ^{14}C ages.

The question of whether vascular plant remains act as closed systems with respect to carbon is one of contamination. Contamination of organic material occurs primarily from rootlets and humic acids, the latter being a term used to describe one of the three principal substances of organic material along with fulvic acids and humin. Rootlets from living (or recently dead) plants can infiltrate organic-rich sediments and are often difficult to fully remove. Samples must be visually inspected to ensure that they are free from rootlets before proceeding with chemical pretreatment. Humic acids are removed from the humin component of organic material using a strongly basic solution, usually NaOH or KOH, as humins (humic acids) are insoluble (soluble) in alkali solutions. Humic acids can then be isolated by precipitating them from the solution by adjusting the pH to a value of 1. Fulvic acids remain in solution and are generally discarded.

In practice, the humin component is often favored for ^{14}C dating because humic acids are mobile in the environment and may move from younger to older sediments (or vice versa) via ground-water flow. Thus, humic acids are usually, but not always, considered to be contaminants. Paired ^{14}C dating of the humin and humic acid components of vascular plant remains can provide a powerful tool for investigating the potential impact of contamination at a given site. If the ^{14}C ages of both components of a sample are identical, then we can be confident

[1] Carbonized wood refers to plant remains that have a higher carbon content than living plants because of the relative loss of H, O, N, and trace elements compared to C over time.

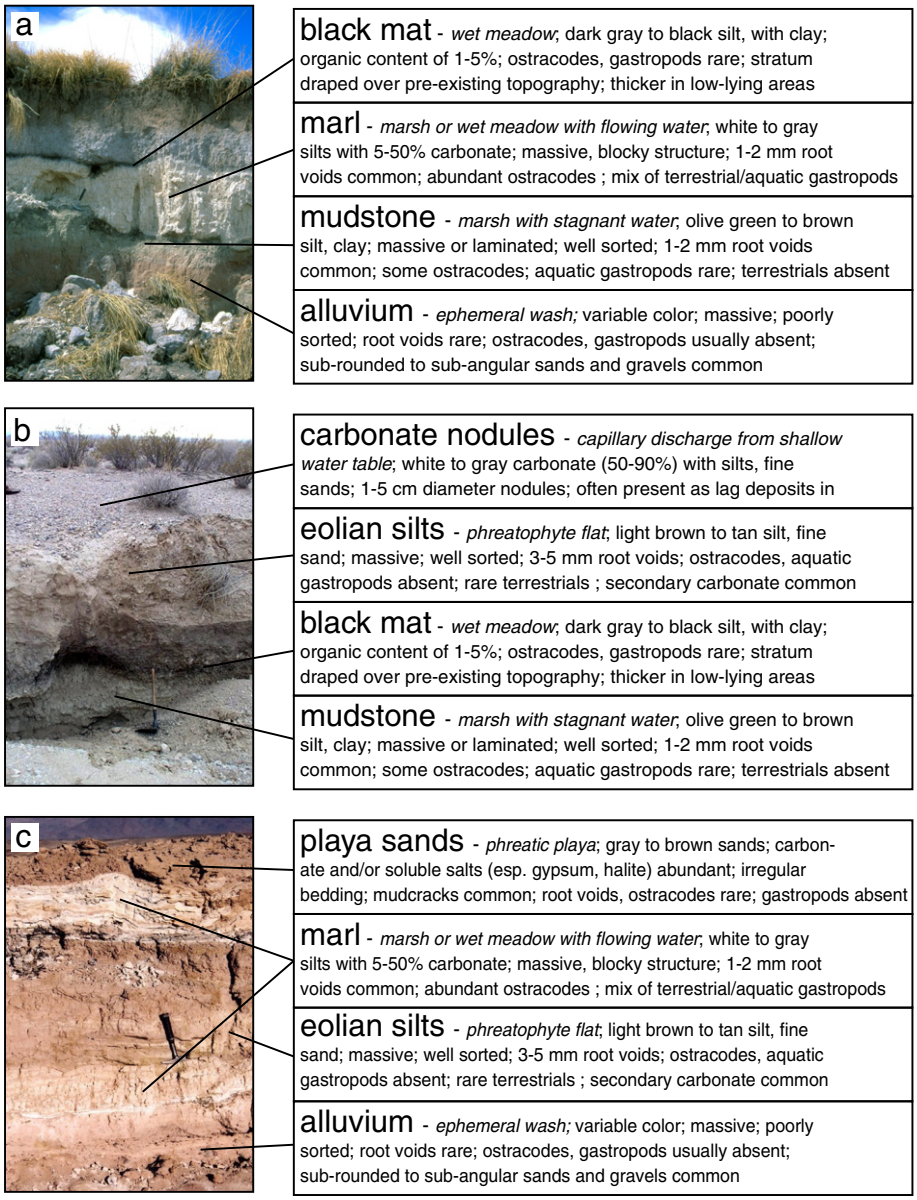

Fig. 7. Stratigraphic sections at (a) Murray Springs, Arizona, (b) Valley Wells, California, and (c) Salar de Imilac in the Atacama Desert of northern Chile with a summary of the strata, environmental interpretation, sedimentology, bedding structures, geochemical indicators, and microfauna used in interpreting specific environments represent by the sediments.

that the ages are robust. In such cases, any humic acids that are present in the sample must have originated from the sample material itself, a process called self-humification, rather than being introduced as a contaminant (Cohen-Ofri et al., 2006). If, however, the ^{14}C age of the humic acid component is significantly younger (older) than the ^{14}C age of the humin fraction, then we might conclude that the humic acids were contaminants derived from younger (older) sediments. In those cases, we would likely consider the ^{14}C age of the humin fraction to best represent the true age of the sample if we were confident that rootlets were fully removed from the sample.

The age of GWD deposits can also be constrained using ^{14}C dating of small terrestrial gastropod shells. Like vascular plants, terrestrial gastropods acquire most of their shell carbon from the atmosphere via respiration and water sources (dew, soil moisture, standing water, and precipitation), as well as from plants and organic detritus. However, terrestrial gastropods can also acquire ^{14}C-deficient (or "dead") carbon from limestone or other carbonate rocks when building their shells. The potential impact of dead carbon on the measured ^{14}C age of a gastropod shell depends on the amount of carbonate that was ingested and ultimately incorporated during the shell building process. The more limestone-derived carbon that was incorporated in the shell, the more the measured age will deviate from the true age. This phenomenon has been referred to as the "Limestone Problem" (Goodfriend and Stipp, 1983), and can cause ^{14}C ages of gastropod shells to be as much as ~3000 yrs too old.

Several recent studies have shown that some small terrestrial gastropods (those with a maximum shell dimensions of 10 mm or less) avoid the Limestone Problem even when living in environments in which carbonate rocks are readily available (Brennan and Quade, 1997; Pigati et al., 2004, 2010). These taxa, which include at least five genera, *Catinella*, *Columella*, *Discus*, *Gastrocopta*, and *Succinea*, are relatively common in extant and paleowetland settings and could potentially be used to date GWD deposits if the shells behave as closed systems after burial. As above, closed-system behavior of shell material is a question of contamination. For gastropod shells, we can evaluate the presence of contamination using scanning electron microscope techniques to identify secondary mineralization (Rech et al., 2011) or x-ray diffraction to differentiate primary shell material (aragonite)

from secondary sources (calcite). If free of contamination, then these gastropod shells should yield reliable ^{14}C ages in late Quaternary GWD deposits.

Aquatic mollusks in GWD deposits can, but often don't, suffer from ^{14}C reservoir effects so common in lake fauna. Aquatic mollusks obtain their carbon from dissolved inorganic carbon in water, which is potentially out of ^{14}C equilibrium with the atmosphere. These disequilibrium effects are well documented in aquatic taxa at the spring discharge point (Damon et al., 1964; Haynes et al., 1966; Riggs, 1984). The persistence of ^{14}C disequilibrium away from the discharge point depends on a variety of factors, such as water depth, turbulence, and biotic activity. The shallow nature of discharge channels, wet meadows, and wetlands probably explains the near-equilibrium displayed by many aquatic taxa from some GWD deposits (Brennan and Quade, 1997; Quade et al., 2003). In other instances, significant disequilibrium in ^{14}C activities between the atmosphere and spring water is maintained for kilometers downstream (Copeland et al., 2012).

7.2. Luminescence dating of GWD deposits

Luminescence dating is based on solid-state dosimetric properties of natural mineral grains. Minerals react to ionizing radiation that is generated by radioactive isotopes, including K, U, Th and Rb, which are present in most terrestrial sediments, as well as by cosmic radiation. Ionizing radiation creates charge pairs/carriers (e^-, h^+) in mineral crystals that are mobile within the crystals, but can become trapped in lattice defects (Aitken, 1993; Rhodes, 2011). Over time, the number of trapped charge carriers builds up in a way that can be described by a saturating exponential function. Exposure to heat, light, or high pressures can release charge carriers from the trap sites and permit recombination, which "resets" the system within the mineral grains. In terrestrial environments, resetting occurs during exposure of the grains to sunlight (Liritzis et al., 2013) or when temperatures exceed 400 °C (Duller, 2008; Rhodes, 2011).

In the laboratory, sediments are stimulated by exposure to light of specific wavelengths (optically-stimulated luminescence, OSL; infrared-stimulated luminescence, IRSL), or heat (thermoluminescence, TL), in prescribed manners (Duller, 1991; Murray and Wintle, 2003; Wintle and Murray, 2006; Singhvi et al., 2010). Upon stimulation, sediments emit light, which is quantitatively measured and filtered from the light of the stimulating source. The intensity of the emitted light is a function of the trapped charge population, which, in turn, is a function of the total absorbed radiation dose of the sediments (Rhodes, 2011). Using dose rates that are either measured directly in the field or calculated based on the geochemical properties of the sediments (Aitken, 1985; Snyder and Duval, 2003; Liritzis et al., 2013), we can determine the amount of time elapsed since the sediments were last exposed to light or heat (i.e., the time since burial).

In wetland settings, eolian sediments that are captured by hydrophilic and phreatophytic plants are ideally suited for OSL/IRSL dating because the luminescence signals in their crystal lattices are reset during transport (Singhvi and Porat, 2008). IRSL dating of fine-grained feldspars has been used successfully to establish chronologies of GWD deposits in southeastern Arizona and the central Mojave Desert, including some that are beyond the limit of ^{14}C dating (~40,000 years) (Pigati et al., 2009, 2011). The upper limit of luminescence dating in GWD settings depends on the local dose rate, but can approach or even exceed 100 ka (thousands of calendar years) if dose rates are sufficiently low (Rhodes et al., 2006; Mahan et al., 2007; Li and Li, 2012).

8. Strengths and limitations of GWD deposits

Ground-water discharge deposits offer several advantages as a source of paleohydrologic information. First, GWD deposits provide unequivocal evidence of past elevations of water-table levels. In many instances, the elevation of discharge waters (and therefore ground-water levels) can be identified to within a few centimeters. Second, GWD deposits often crop out over fairly large areas, which afford researchers the opportunity to examine and interpret complex features, such as cut-and-fill sequences and laterally variable depositional facies. This eliminates the guesswork and interpolation required in situations in which only sediment cores are available. Third, chronologic frameworks of GWD deposits can be established by ^{14}C dating vascular plant remains or small terrestrial gastropod shells, and luminescence (OSL, IRSL), thus avoiding problems with carbon reservoir effects that can affect lake systems. Additional dating techniques, including uranium-series and amino-acid racemization, may also be utilized if conditions are favorable. Fourth, specific environmental and hydrologic environments can be reconstructed for desert wetlands based on independent sources of evidence, such as microfauna and sedimentological facies. Finally, GWD deposits are relatively common in valley floors and basins in the world's arid lands and, therefore, can be used to reconstruct paleohydrologic conditions on a variety of spatial and temporal scales. The prevalence of GWD deposits in desert environments may allow for the reconstruction of past hydrologic conditions along geographic and elevation transects, including areas not covered by other types of hydrologic records.

The main limitation of GWD deposits is that currently it is not possible to relate the magnitude of climate change, in terms of quantitative estimates of precipitation and/or evapotranspiration (P/ET), to changes in the local or regional hydrologic budget. Once a wetland system reaches a critical threshold, additional input via increased precipitation or decreased evapotranspiration is lost to overland flow. Modeling ground-water discharge via overland flow has been addressed in complex regional wetland systems (Restrepo et al., 1998) but not in small desert watersheds. Thus, much like lakes that overtop their spillways, the amount of water required to raise the water table up to the elevation of GWD deposits must be viewed as a minimum value. A second complicating factor is that desert springs and wetlands commonly act as discharge points of shallow aquifers that are unconfined or semi-confined. Quantifying the relationship between water table levels and P/ET in these types of aquifers is difficult because the permeability and hydraulic conductivity of near surface sediments are not well characterized in most small desert watersheds.

9. GWD deposits in deep geologic time

Since Pleistocene ground-water discharge deposits were first systematically described in the American Southwest in the 1980s, researchers working in the deeper geologic record (pre-Quaternary) have also developed a better understanding of wetland and palustrine depositional environments (Alonso-Zarza, 2003; Alonso-Zarza and Tanner, 2010). Some examples of this work include the identification of wetland environments in the Jurassic Morrison Formation in the western USA (Dunagan and Turner, 2004), recognition of Eocene tufas and travertines in the Chadron Formation in the badlands of South Dakota (Evans, 1999), description of thick palustrine systems in the Upper Miocene–Pliocene Opache Formation in the Atacama Desert of northern Chile (May et al., 1999; Rech et al., 2010), and extensive work on Plio–Pleistocene wetland deposits in the African Rift Valley (Ashley, 2001; Deocampo, 2002; Deocampo et al., 2002; Liutkus and Ashley, 2003; Ashley et al., 2004; Owen et al., 2004).

Although there are certainly similarities between Quaternary GWD deposits and palustrine deposits described in the deeper geologic record, there are also some important differences. While extensive Quaternary palustrine/lacustrine systems do exist, such as the Zarand Basin in Iran (Djamali et al., 2005), the majority of Quaternary GWD deposits that have been mapped and described are usually small, comprising surface areas of up to a few km^2 and vertical thicknesses of perhaps 2 to 10 m. In contrast, many palustrine systems identified in the deeper geologic record often represent large areas and are much thicker than their younger counterparts. Palustrine limestones of the Upper

Miocene/Pliocene Opache Formation in the Atacama Desert, for example, encompass hundreds of km^2 and are up to ~70 m thick (Rech et al., 2010). Smaller deposits are likely present in older deposits as well, but may be difficult to recognize as being related to wetlands.

There are also key differences in the approaches used by geologists studying palustrine systems in the deeper geologic record and those interested in Quaternary GWD deposits. Palustrine limestones are typically described by standard carbonate petrographic description of features such as root voids, mud cracks, and pseudo-microkarst features, as well as microfaunal assemblages. Many Quaternary studies do not focus as much on carbonate petrology and instead place a greater emphasis on the geomorphic setting of the deposits and the use of radiometric dating techniques to identify time-stratigraphic units. Improved communication and greater overlap in the methods used to describe and investigate these deposits should facilitate a better understanding of Quaternary and older GWD deposits in the geologic record.

10. Summary

Desert wetlands are common features in broad valleys and basins in the world's arid lands, and are preserved in the geologic record as ground-water discharge (or GWD) deposits. GWD deposits are relatively common in desert environments and have been identified in all four major deserts of the American Southwest, the Atacama Desert of northern Chile, the Middle East, North Africa, Australia, and Tibet.

The physical appearance and geochemistry of GWD deposits, which are also referred to as “spring” or “wetland” deposits, vary widely from place to place because of differences in ground-water chemistry, the density and types of plants living in and around the paleowetland system, the availability and mobility of surface waters, and diagenesis, among other factors. GWD deposits are generally composed of fine-grained, light-colored sediments that include up to three distinct components: ground-water precipitates, clastic sediments, and organic matter. These deposits contain multiple depositional facies, including dry alluvial fans, phreatophyte flats, wet meadows, marshes, and spring orifices, which exhibit diagnostic sedimentary features and microfauna assemblages.

GWD deposits have the potential to provide an unambiguous record of changes in water-table levels over time in desert environments. Under favorable conditions, we can identify the elevation of discharge waters (and therefore ground-water levels) to within a few centimeters at various points in time. GWD deposits can be accurately dated using a variety of chronometric techniques, including radiocarbon dating of vascular plants and terrestrial gastropod shells, and luminescence techniques (OSL, IRSL). Studies of GWD deposits at multiple localities can be used to reconstruct the magnitude and timing of changes in the hydrologic cycle on different spatial and temporal scales, including areas in which lakes, speleothems, and other sources of paleohydrologic information are not available.

We view the future of desert wetland research to include a myriad of important topics in addition to the standard types of paleoclimatic and paleohydrologic research being done today. For example, similar to diatoms, the species assemblages, isotopic ratios, and geochemical signatures of chironomids and foraminifera have been used for years to study water chemistry and environmental conditions in lake and marine settings (Fontes et al., 1985; Porinchu and MacDonald, 2002). Forams have been found previously in GWD deposits (Yasin, 2000) and chironomids are likely present as well, but neither have been studied systematically in extant or fossil desert wetlands. Understanding the distribution and environmental controls on various microbiota in desert wetlands may yield new tools that can be used in reconstructing past hydrologic and climatic conditions. Modeling of P/ET relations in small desert watersheds is also necessary if we are to quantitatively reconstruct these parameters based on GWD deposits. Finally, geologists working in the Quaternary, as well as deeper in geologic time, need to be able to recognize GWD deposits and differentiate them from lake deposits in arid environments. Deposits associated with desert wetlands must be identified and interpreted correctly if we are to realize the potential for extracting climate and hydrologic information from these unique and complex systems.

Acknowledgments

We thank Paco van Sistine (USGS, Denver) for assistance with drafting Fig. 2. This manuscript benefited from constructive reviews by Gene Ellis, Dan Muhs, Dave Miller, and an anonymous reviewer. This project was funded by the U.S. Geological Survey's Climate and Land Use Change Research and Development Program.

References

Aitken, M.J., 1985. Thermoluminescence Dating. Academic Press, London (359 pp.).
Aitken, M.J., 1993. Optical dating: a non-specialist review. Quat. Sci. Rev. 13, 503–508.
Alfaro, C., Wallace, M., 1994. Origin and classification of springs and historical review with current applications. Environ. Geol. 24 (2), 112–124.
Alonso-Zarza, A.M., 2003. Palaeoenvironmental significance of palustrine carbonates and calcretes in the geological record. Earth Sci. Rev. 60, 261–298.
Alonso-Zarza, A.M., Tanner, L.H., 2010. Carbonates in continental settings: facies, environments, and processes. In: van Loon, A.J. (Ed.), Developments in Sedimentology, 61. Elsevier (378 pp.).
Amoroso, L., Miller, D.M., 2012. Surficial geologic map database of the Cuddeback Lake 30′ x 60′ quadrangle, San Bernardino and Kern Counties, California (1:100,000 scale). Scientific Investigations Map 3107.
Anderson, R.S., Starratt, S., Jass, R.M., Pinter, N., 2009. Fire and vegetation history on Santa Rosa Island, Channel Islands, and long-term environmental change in southern California. J. Quat. Sci. 25 (5), 782–797.
Aravena, R., Suzuki, O., 1990. Isotopic evolution of river water in the northern Chile region. Water Resour. Res. 26 (12), 2887–2895.
Ashley, G.M., 2001. Archaeological sediments in springs and wetlands. In: Stein, J.K., Farrand, W.R. (Eds.), Sediments in Archaeological Contexts. University of Utah Press, Salt Lake City, UT, pp. 183–210.
Ashley, G., Maitima Mworia, J.M., Muasya, A.M., Owen, R.B., Driese, S.G., Renaut, R.W., Hover, V.C., Goman, M.F., Mathai, S., Blatt, S.H., 2004. Sedimentation and evolution of a freshwater wetland in a semi-arid environment, Loboi Swamp, Kenya, East Africa. Sedimentology 51 (6), 1–21.
Barker, G.M. (Ed.), 2001. The Biology of Terrestrial Mollusks. CABI Publishing, Wallington, U.K. (558 pp.).
Bedford, D.R., Miller, D.M., Phelps, G.A., 2010. Surficial geologic map of the Amboy 30′ x 60′ quadrangle, San Bernardino County, California (1:100,000 scale). Scientific Investigations Map 3109.
Bequaert, J.C., Miller, W.B., 1973. The Mollusks of the Arid Southwest, with an Arizona Check List. University of Arizona Press, Tucson (271 pp.).
Betancourt, J.L., Latorre, C., Rech, J.A., Quade, J., Rylander, K.A., 2000. A 22,000-year record of monsoonal precipitation from northern Chile's Atacama Desert. Science 289, 1542–1546.
Bobst, A.L., Lowenstein, T.K., Jordan, T.E., Godfrey, L.V., Ku, T.-L., Lu, S., 2001. A 106 ka paleoclimate record from drill core of the Salar de Atacama, northern Chile. Palaeogeography, Palaeoclimatology, Palaeoecology 173 (1–2), 21–42.
Brennan, R., Quade, J., 1997. Reliable late-Pleistocene stratigraphic ages and shorter groundwater travel times from ^{14}C in fossil snails from the southern Great Basin. Quat. Res. 47, 329–336.
Bryan, K., 1919. Classification of springs. J. Geol. 27 (7), 522–561.
Buckley, S.B., 1975. Study of Post-Pleistocene Ostracode Distributions in the Soft Sediments of Southern Lake Michigan. University of Illinois (293 pp.).
Cameron, S.P., 1971. Ostracodes of Pluvial Lake Cochise, Cochise County, Southeastern Arizona. Arizona State University, Tempe, AZ (66 pp.).
Carter, C., 1997. Ostracodes in Owens Lake core OL-92: alteration of saline and freshwater forms through time. In: Smith, G.I., Bischoff, J. (Eds.), An 800,000-Year Geologic and Climatic Record from Owens Lake, California: Core OL-92. Geological Society of America Special Paper 317, Boulder, Colorado, pp. 113–120.
Cohen-Ofri, I., Weiner, L., Boaretto, E., Mintz, G., Weiner, S., 2006. Modern and fossil charcoal: aspects of structure and diagenesis. J. Archaeol. Sci. 33, 428–439.
Copeland, A., Quade, J., Watson, J., McLaurin, B., Villalpando, E., 2012. Stratigraphy and geochronology of La Palya archeological site, Sonora, Mexico. J. Archaeol. Sci. 39, 2934–2944.
Costa, K.C., Navarro, J.B., Shock, E.K., Zhang, C.L., Soukup, D., Hedland, B.P., 2009. Microbiology and geochemistry of great boiling and mud hot springs in the United States Great Basin. Extremophiles 13 (3), 447–459.
Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T., 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Jamestown, ND: Northern Prairie Wildlife Research Center Online. http://www.npwrc.usgs.gov/resource/wetlands/classwet/index.htm (Version 04DEC1998).
Crossey, L.J., Fischer, T.B., Patchett, P.J., Karlstrom, K.E., Hilton, D.R., Newell, D.L., Huntoon, P., Reynolds, A.C., 2006. Dissected hydrologic system at the Grand Canyon: interaction between deeply derived fluids and plateau aquifer waters in modern springs and traverting. Geology 34, 25–28.

Curry, B.B., 1999. An environmental tolerance index for ostracodes as indicators of physical and chemical factors in aquatic habitats. Palaeogeogr. Palaeoclimatol. Palaeoecol. 148, 51–63.
Damon, P.E., Haynes, C.V., Long, A., 1964. Arizona radiocarbon dates V. Radiocarbon 6, 91–107.
De Narvaez, C., 1995. Paleohydrology and Paleotopography of a Las Vegas Spring. Northern Arizona University, Flagstaff, AZ (89 pp.).
Deevey, E.S.J., Gross, M.S., Hutchinson, G.E., Kraybill, H.L., 1954. The natural ^{14}C contents of materials from hard-water lakes. Proc. Natl. Acad. Sci. 40, 285–288.
Delorme, L.D., 1991. Ostracoda. In: Thorp, J.H., Covich, A.P. (Eds.), Ecology and Classification of North American Freshwater Invertebrates. Academic Press, San Diego, California, pp. 691–722.
Deocampo, D.M., 2002. Sedimentary processes and lithofacies in lake-margin groundwater-fed wetlands in East Africa. Sed. Cont. Rifts 73, 295–308.
Deocampo, D.M., Blumenschine, R.J., Ashley, G.M., 2002. Wetland diagenesis and traces of early hominids, Olduvai Gorge, Tanzania. Quat. Res. 57, 271–281.
Djamali, M., Esu, D., Gliozzi, E., Okhravi, R., Soulié-Marsche, I., 2005. Palaeoenvironment of a lacustrine–palustrine carbonate complex: Zarand Basin, Saveh, Central Iran. Palaeogeogr. Palaeoclimatol. Palaeoecol. 237, 315–334.
Duller, G.A.T., 1991. Equivalent dose determination using single aliquots. Nucl. Tracks Radiat. Meas. 18, 371–378.
Duller, G.A.T., 2008. Luminescence Dating: Guidelines on Using Luminescence Dating in Archaeology. English Heritage, Swindon (45 pp.).
Dunagan, S.P., Turner, C.E., 2004. Regional paleohydrologic and paleoclimatic settings of wetland/lacustrine depositional systems in the Morrison Formation (Upper Jurassic), Western Interior, USA. Sediment. Geol. 167 (3–4), 269–296.
Evans, J.E., 1999. Recognition and implications of Eocene tufas and travertines in the Chadron Formation, White River Group, Badlands of South Dakota. Sedimentology 46, 771–789.
Fontes, J.C., Gasse, F., Callot, Y., Plaziat, J.C., Carbonel, P., Dupeuble, P.A., Kaczmarska, I., 1985. Freshwater to marine-like environments from Holocene lakes in northern Sahara. Nature 317, 608–610.
Ford, T.D., Pedley, H.M., 1996. A review of tufa and travertine deposits of the world. Earth Sci. Rev. 41, 117–175.
Forester, R.M., 1983. Relationship of two lacustrine ostracode species to solute composition and salinity: implications for paleohydrochemistry. Geology 11, 435–438.
Forester, R.M., 1987. Late Quaternary paleoclimate records from lacustrine ostracodes. In: Ruddiman, W.F., Wright Jr., H.E. (Eds.), North America and Adjacent Oceans During the Last Deglaciation. Geology of North America. Geological Society of America, Boulder, Colorado, pp. 261–276.
Forester, R.M., 1991. Ostracode assemblages from springs in the western United States: implications for paleohydrology. Mem. Entomol. Soc. Can. 155, 181–201.
Forester, R.M., Smith, A.J., 1994. Late glacial climate estimates for Southern Nevada: the fossil ostracode record. Proceedings of the 5th Annual International High Level Radioactive Waste Management Conference, pp. 2553–2561.
Forester, R.M., Delorme, L.D., Bradbury, J.P., 1987. Mid-Holocene climate in northern Minnesota. Quat. Res. 28, 236–273.
Forester, R.M., Miller, D.M., Pedone, V., 2003. Ground water and ground-water discharge carbonate: deposits in warm deserts. In: Reynolds, R.E. (Ed.), Land of Lost Lakes: the 2003 Desert Symposium Field Trip. California State University, Desert Studies Consortium, pp. 27–36.
Forester, R.M., Lowenstein, T.K., Spencer, R.J., 2005. An ostracode based paleolimnologic and paleohydrologic history of Death Valley: 200 to 0 ka. Geol. Soc. Am. Bull. 17 (11–12), 1379–1386.
Fouke, B.W., Famer, J.D., Des Marias, D.J., Pratt, L., Sturchio, N.C., Burns, P.C., Discipulo, M.K., 2000. Depositional facies and aqueous-solid geochemistry of travertine-depositing hot springs (Angel Terrace, Mammoth Hot Springs, Yellowstone National Park, USA). Soc. Sed. Geol. 70 (3), 565–585.
Fritz, P., Suzuki, O., Silva, C., Salati, E., 1981. Isotope hydrology of groundwaters in the Pampa del Tamarugal, Chile. J. Hydrol. 53, 161–184.
Geyh, M.A., Schotterer, U., Grosjean, M., 1998. Temporal changes of the ^{14}C reservoir effect in lakes. Radiocarbon 40 (2), 921–931.
Goodfriend, G.A., Stipp, J.J., 1983. Limestone and the problem of radiocarbon dating of land-snail shell carbonate. Geology 11, 575–577.
Grosjean, M., Nunez, L., Cartajena, I., Messerli, B., 1997. Mid-Holocene climate and culture change in the Atacama Desert, northern Chile. Quat. Res. 48, 239–246.
Hallman, P., 2002. Paleobiological Assessment of Late Pleistocene Mollusks from Desert Dry Lake, Lincoln County, Nevada. Northern Arizona University, Flagstaff, AZ, 248 pp.
Hancock, P.L., Chalmers, R.M.L., Altunel, E., Cakir, Z., 1999. Travitonics: using travertines in active fault studies. J. Struct. Geol. 21 (8–9), 903–916.
Haynes Jr., C.V. (Ed.), 1967. Quaternary Geology of the Tule Springs Area, Clark County, Nevada. Pleistocene Studies in Southern Nevada, 13. Nevada State Museum of Anthropology, Carson City, NV. 1–104 pp.
Haynes Jr., C.V., 1991. Geoarchaeological and paleohydrological evidence for a Clovis-age drought in North America and its bearing on extinction. Quat. Res. 35 (3), 438–450.
Haynes Jr., C.V., 2007. Quaternary geology of the Murray Springs Clovis site. In: Haynes Jr., C.V., Huckell, B.B. (Eds.), Murray Springs: A Clovis Site with Multiple Activity Areas in the San Pedro Valley, Arizona. The University of Arizona Press, Tucson, pp. 16–56.
Haynes Jr., C.V., 2008. Younger Dryas "black mats" and the Rancholabrean termination in North America. Proc. Natl. Acad. Sci. 105 (18), 6520–6525.
Haynes, C.V., Damon, P.E., Grey, D.C., 1966. Arizona radiocarbon dates VI. Radiocarbon 8, 1–21.
Horne, D.J., Cohen, A., Martens, K., 2002. Taxonomy, morphology and biology of Quaternary and Living Ostracoda. In: Holmes, J.A., Chivas, A.R. (Eds.), The Ostracoda: Applications in Quaternary Research. American Geophysical Union, Washington D.C., pp. 5–36.
Jones, B., Renaut, R.W., 2003. Sedimentology of hot spring systems. Can. J. Earth Sci. 40 (11), 1439–1442.
Ku, T.L., Luo, S., Lowenstein, T.K., Li, J., Spencer, R.J., 1998. U-series chronology of lacustrine deposits in Death Valley, California. Quat. Res. 50, 261–275.
Li, B., Li, S.H., 2012. Luminescence dating of Chinese Loess beyond 130 ka using the non-fading signal from K-feldspar. Quat. Geochronol. 6, 468–479.
Liritzis, I., Singhvi, A.K., Feathers, J.K., Wagner, G.A., Kadereit, A., Zacharias, N., Li, S.-H., 2013. Luminescence dating in archaeology, anthropology, and geoarchaeology: an overview. Springer Briefs in Earth System Sciences, VIISpringer (70 pp.).
Liutkus, C.M., Ashley, G.M., 2003. Facies model of a semiarid freshwater wetland, Olduvai Gorge, Tanzania. J. Sediment. Res. 73, 691–705.
Mackay, A.W., 2007. Quaternary diatom records from large lakes. In: Elias, S. (Ed.), Encyclopedia of Quaternary Research. Elsevier, pp. 548–557.
Mahan, S.A., Miller, D.M., Menges, C.M., Yount, J.C., 2007. Late Quaternary stratigraphy and luminescence geochronology of the northeastern Mojave Desert. Quat. Int. 166 (1), 61–78.
Maldonado, A., Betancourt, J.L., Latorre, C., Villagran, C., 2005. Pollen analyses from a 50,000-yr rodent midden series in the southern Atacama Desert (25° 30′S). J. Quat. Sci. 20, 493–507.
Margaritz, M., Aravena, R., Peña, H., Suzuki, O., Grilli, A., 1989. Water chemistry and isotope study of streams and springs in northern Chile. J. Hydrol. 108, 323–341.
Mawby, J.E., 1967. Fossil vertebrates of the Tule Springs site, Nevada. In: Wormington, H.M., Ellis, D. (Eds.), Pleistocene Studies in Southern Nevada. Nevada State Museum Anthropological Papers, pp. 105–128.
May, G., Hartley, A.J., Stuart, F.M., Chong, G., 1999. Tectonic signatures in arid continental basins: an example from the Upper Miocene–Pleistocene, Calama Basin, Andean forearc, northern Chile. Palaeogeogr. Palaeoclimatol. Palaeoecol. 151, 55–77.
Meek, N., 1999. New discoveries about the late Wisconsin history of the Mojave River system. In: Reynolds, R.E., Reynolds, J. (Eds.), Tracks Along the Mojave: Quarterly of the San Bernardino County Museum Association, pp. 113–117.
Meinzer, O.E., 1927. Large springs in the United States. USGS Water-Suppl. Pap. 557, 1–94.
Mensing, S., Smith, J., Norman, K.B., Allan, M., 2008. Extended drought in the Great Basin of western North America in the last two millennia reconstructed from pollen records. Quat. Int. 188, 79–89.
Mensing, S.A., Sharpe, S.E., Tunno, I., Sada, D.W., Thomas, J.T., Starratt, S., Smith, J., 2013. The Late Holocene Dry Period: multiproxy evidence for an extended drought between 2800 and 1850 cal yr BP across the central Great Basin, USA. Quat. Sci. Rev. 78, 266–282.
Mifflin, M.D., 1968. Delineation of groundwater flow systems in Nevada. Desert Research Institute Water Resources Center Report, H-W 4 1–111.
Miller, D.M., 2010. Surficial Geologic Map of the Ivanpah 30′ x 60′ Quadrangle, San Bernardino County, California, and Clark County, Nevada (1:100,000 scale), Scientific Investigations Map 3206.
Murray, A.S., Wintle, A.G., 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. Radiat. Meas. 37, 377–381.
Nicholas, G.P., 1998. Wetlands and hunter–gatherers: a global perspective. Curr. Anthropol. 39 (5), 720–731.
O'Brien, G.R., Kaufman, D.S., Sharp, W.D., Atudorei, V., Parnella, R.A., Crossey, L.J., 2006. Oxygen isotope composition of annually banded modern and mid-Holocene travertine and evidence of paleomonsoon floods, Grand Canyon, Arizona, USA. Quat. Res. 65 (3), 366–379.
Owen, R.B., Renaut, R.W., Hover, V.C., Ashley, G.M., Muasya, A.M., 2004. Swamps, springs, and diatoms: wetlands regions of the semi-arid Bogoria–Baringo rift, Kenya. Hydrobiologia 518 (1–3), 59–78.
Paces, J.B., Forester, R.M., Whelan, J.F., Mahan, S.A., Bradbury, J.P., Quade, J., Neymark, L.A., Kwak, L.M., 1996. Synthesis of ground-water discharge deposits near Yucca Mountain. U.S. Geological Survey Milestone Report 3GQH671M to DOE-YMPSCO (75 pp., Accessed January 22, 2010 at www.lsnnet.gov, Participant Accession Number ALA.20040511.4255).
Paces, J.B., Whelan, J.F., Forester, R.M., Bradbury, J.P., Marshall, B.D., Mahan, S.A., 1997. Summary of discharge deposits in the Amargosa Valley. U.S. Geological Survey Level 4 Milestone Report SPC333M4 to DOE-YMPSCO (52 pp., Accessed January 22, 2010 at www.lsnnet.gov, Participant Accession Number MOL.19990105.0231).
Phelps, G.A., Bedford, D.R., Lidke, D.J., Miller, D.M., Schmidt, K.M., 2012. Preliminary surficial geologic map of the Newberry Springs 30′ x 60′ quadrange, California (1:100,000 scale). U.S. Geological Survey Open-File Report 2011–1044.
Pigati, J.S., Quade, J., Shanahan, T.M., Haynes, C.V.J., 2004. Radiocarbon dating of minute gastropods and new constraints on the timing of spring-discharge deposits in southern Arizona, USA. Palaeogeogr. Palaeoclimatol. Palaeoecol. 204, 33–45.
Pigati, J.S., Bright, J.E., Shanahan, T.M., Mahan, S.A., 2009. Late Pleistocene paleohydrology near the boundary of the Sonoran and Chihuahuan Deserts, southeastern Arizona, USA. Quat. Sci. Rev. 28, 286–300.
Pigati, J.S., Rech, J.A., Nekola, J.C., 2010. Radiocarbon dating of small terrestrial gastropods in North America. Quat. Geochronol. 5, 519–532.
Pigati, J.S., Miller, D.M., Bright, J., Mahan, S.A., Nekola, J.C., Paces, J.B., 2011. Chronology, sedimentology, and microfauna of ground-water discharge deposits in the central Mojave Desert, Valley Wells, California. Geol. Soc. Am. Bull. 123, 2224–2239.
Porinchu, D.F., MacDonald, G.M., 2002. The use and application of freshwater midges (Chrinomidae: Insecta: Diptera) in geographical research. Prog. Phys. Geogr. 27 (3), 378–422.
Quade, J., 1986. Late Quaternary environmental changes in the upper Las Vegas Valley, Nevada. Quat. Res. 26, 340–357.
Quade, J., Pratt, W.L., 1989. Late Wisconsin groundwater discharge environments of the Southwestern Indian Springs Valley, southern Nevada. Quat. Res. 31, 351–370.
Quade, J., Mifflin, M.D., Pratt, W.L., McCoy, W.D., Burckle, L., 1995. Fossil spring deposits in the southern Great Basin and their implications for changes in water-table levels near

Yucca Mountain, Nevada, during Quaternary time. Geol. Soc. Am. Bull. 107 (2), 213–230.
Quade, J., Forester, R.M., Pratt, W.L., Carter, C., 1998. Black mats, spring-fed streams, and late-glacial-age recharge in the southern Great Basin. Quat. Res. 49, 129–148.
Quade, J., Forester, R.M., Whelan, J.F., 2003. Late Quaternary paleohydrologic and paleotemperature change in southern Nevada. In: Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts. Geological Society of America Bulletin Special Paper, 368, pp. 165–188.
Quade, J., Rech, J.A., Betancourt, J.L., Latorre, C., Quade, B., Rylander, K.A., Fisher, T., 2008. Paleowetlands and regional climate change in the central Atacama Desert, northern Chile. Quat. Res. 69, 343–360.
Rech, J.A., Quade, J., Betancourt, J.L., 2002. Late Quaternary paleohydrology of the central Atacama Desert (22–24 S), Chile. Geol. Soc. Am. Bull. 114 (3), 334–348.
Rech, J.A., Pigati, J.S., Quade, J., Betancourt, J.L., 2003. Re-evaluation of mid-Holocene wetland deposits at Quebrada Puripica, northern Chile. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 207–222.
Rech, J.A., Currie, B.S., Shullenberger, E.D., Dunagan, S.P., Jordan, T.E., Blanco, N., Tomlinson, A.J., Rowe, H.D., Houston, J., 2010. Evidence for the development of the Andean rain shadow from a Neogene isotopic record in the Atacama Desert. Chile Earth Planet. Sci. Lett. 292 (3–4), 371–382.
Rech, J.A., Pigati, J.S., Lehmann, S.B., McGimpsey, C.N., Grimley, D.A., Nekola, J.C., 2011. Assessing open-system behavior of carbon-14 in terrestrial gastropod shells. Radiocarbon 53 (2), 325–335.
Restrepo, J.I., Montoya, A.M., Obeysekera, J., 1998. A wetland simulation module for the MODFLOW ground water model. Ground Water 36 (5), 764–770.
Reynolds, R.E., Jefferson, G.T., Reynolds, R.L., 1991. The sequence of vertebrates from Plio–Pleistocene sediments at Valley Wells, San Bernardino County, California. In: Reynolds, R.E., Reynolds, J. (Eds.), Mojave Desert Quaternary Research Center Symposium, Zzyzx, CA, pp. 72–77.
Rhodes, E.J., 2011. Optically-stimulated luminescence dating of sediments over the past 200,000 years. Annu. Rev. Earth Planet. Sci. 39, 461–488.
Rhodes, E.J., Singarayer, J.S., Raynal, J.P., Westaway, K.E., Sbihi-Alaoui, F.Z., 2006. New age estimates for the Palaeolithic assemblages and Pleistocene succession of Casablanca, Morocco. Quat. Sci. Rev. 25, 2569–2585.
Riggs, A.C., 1984. Major carbon-14 deficiency in modern snail shells from southern Nevada springs. Science 224, 58–61.
Schmidt, K.M., McMackin, M., 2006. Preliminary surficial geologic map of the Mesquite Lake 30′ X 60′ Quadrangle, California and Nevada (1:100,000 scale). U.S. Geological Survey Open-File Report 2006-1035: 1-89.
Scott, E., 2010. Extinctions, scenarios, and assumptions: changes in latest Pleistocene large herbivore abundance and distribution in western North America. Quat. Int. 217, 225–239.
Shanahan, T.M., Pigati, J.S., Dettman, D.L., Quade, J., 2005. Isotopic variability in the aragonite shells of freshwater gastropods living in springs with nearly constant temperature and isotopic composition. Geochim. Cosmochim. Acta 69 (16), 3949–4966.
Singhvi, A.K., Porat, N., 2008. Impact of luminescence dating on geomorphological and palaeoclimate research in drylands. Boreas 37, 536–558.
Singhvi, A.K., Chahan, N., Biswas, R.H., 2010. A survey of some new approaches in maximum age limit and accuracy of luminescence application to archaeological chronometry. Mediterr. Archaeol. Archaeom. 10 (4), 9–15.
Smith, J.R., Giegengack, R., 2003. Spatial and temporal distribution of fossil-spring tufa deposits, Western Desert, Egypt: implications for palaeoclimatic interpretations. In: Bowen, G., Hope, C. (Eds.), Oasis Papers III. Oxbow Press, pp. 103–112.
Smith, J.R., Giegengack, R., Schwarcz, H.P., 2004a. Constraints on Pleistocene pluvial climates through stable-isotope analysis of fossil-spring tufas and associated gastropods, Kharga Oasis, Egypt. Palaeogeogr. Palaeoclimatol. Palaeoecol. 206, 157–175.
Smith, J.R., Giegengack, R., Schwarcz, H., McDonald, M.M.A., Kleindienst, M., Hawkins, A., Churcher, C.S., 2004b. A reconstruction of Quaternary pluvial environments and human occupations using stratigraphy and geochronology of fossil-spring tufas, Kharga Oasis, Egypt. Geoarchaeology 19 (5), 1–34.
Snyder, S.L., Duval, J.S., 2003. Design and construction of a Gamma-ray Spectrometer system for determining natural radioactive concentrations in geological samples at the U.S. Geological Survey in Reston, Virginia. U.S. Geological Survey Open-File Report 03-29 (http://pubs.usgs.gov/of/2003/of03-029/).
Sohn, I.G., 1958. Chemical constituents of ostracodes: some applications to paleontology and paleoecology. J. Paleontol. 32, 730–736.
Springer, K.B., Scott, E., Sagebiel, J.C., Manker, C.R., 2009. The Tule Springs local fauna: late Pleistocene vertebrates from the upper Las Vegas Wash, Clark County, Nevada. In: Foss, S.E., Cavin, J.L., Brown, T.A., Kirkland, J.I., Santucci, V.L. (Eds.), Proceedings of the Eighth Conference on Fossil Resources, pp. 108–109.
Steinmetz, J.J., 1988. Biostratigraphy and Paleoecology of Limnic Ostracodes from the Late Pleistocene Manix Formation. California State Polytechnic University, Pomona, CA (64 pp.).
Thomas, J.T., Lyles, B.F., Carpenter, L.A., 1991. Chemical and isotopic data for water from wells, springs, and streams in carbonate-rock terrane of southern and eastern Nevada and southeastern California, 1985–88. U. S. Geological Survey Open-File Report 89-422 (24 pp.).
Thompson, R.S., Toolin, L.J., Forester, R.M., Spencer, R.J., 1990. Accelerator-mass spectrometer (AMS) radiocarbon dating of Pleistocene lake sediments in the Great Basin. Palaeogeogr. Palaeoclimatol. Palaeoecol. 78, 301–313.
Tooth, S., McCarthy, T.S., 2007. Wetlands in drylands: geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Prog. Phys. Geogr. 31, 3–41.
Tressler, W.L., 1957. Ostracoda of Great Slave Lake. J. Wash. Acad. Sci. 47, 415–423.
Usdowski, E., Hoefs, J., Menschel, G., 1979. Relationship between ^{13}C and ^{18}O fractionation and changes in major element composition in a recent calcite-depositing spring: a model of chemical variations with inorganic $CaCO_3$ variations. Earth Planet. Sci. Lett. 42, 267–276.
Wells, S.G., Brown, W.J., Enzel, Y., Anderson, R.Y., McFadden, L.D., 2003. Late Quaternary geology and paleohydrology of pluvial Lake Mojave, southern California. In: Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts. Geological Society of America Special Paper 368, Boulder, CO, pp. 79–114.
Winer, E.R., 2010. Interpretation and Climatic Significance of Late Quaternary Valley-Fill Deposits in Wadi Hasa, West-Central Jordan. Miami University (97 pp.).
Winograd, I.J., Thordarson, W., 1975. Hydrologeologic and hydrochemical framework, south-central Great Basin, Nevada California, with special reference to the Nevada Test Site. U.S. Geological Survey Professional Paper, 712-C 1–126.
Wintle, A.G., Murray, A.S., 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. Radiat. Meas. 41, 369–391.
Yasin, S.M., 2000. Quaternary Paleolimnology of the Mudawara Area (Southern Jordan, 29 °N). University of Jordan, Amman, Jordan (264 pp.).