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# INSIGHTS INTO THE LATE QUATERNARY PALEOENVIRONMENT OF NORTHWESTERN ARIZONA

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ABSTRACT—Because of the nature and process of precipitation, tufa deposits offer the potential to serve as sedimentary signatures of hydrology, climate, ecology, and biodiversity in areas otherwise lacking such historic archives. This study investigated a previously undocumented tufa site located in northwestern Arizona. Field mapping, X-ray diffraction, and thin-section analyses revealed a wedge-shaped deposit of nearly pure calcitic tufa. Leaf and bark molds were identified as closely resembling water birch (*Betula occidentalis*) and conifer species as well. A dense understory of tubular fossils suggestive of horsetails (*Equisetum*) and other wetland species were also found. Biotic content, lack of ikaite, and proximity to pluvial lake systems strongly correlate the deposit's age with numerous lacustrine deposits in the region and possibly extend the lake system to the south.

RESUMEN—Debido a la naturaleza y el proceso de deposición, los depósitos de toba ofrecen el potencial para servir como firmas sedimentarias de la hidrología, el clima, la ecología y la biodiversidad en las zonas que carecen de otro tipo de archivos históricos. Este estudio investigó un sitio con toba previamente indocumentado ubicado en el noroeste de Arizona. Asignación en el campo, difracción de rayos X y análisis de sección delgada revelaron un depósito en forma de cuña de toba calcárea, casi puro. Moldes de hojas y corteza fueron identificados como parecidos a abedul de agua (*Betula occidentalis*) y también especies de coníferas. Un sotobosque denso de fósiles tubulares sugestivos de colas de caballo (*Equisetum*) y otras especies de humedales también fueron encontrados. Contenido biótico, la falta de ikaite, y la proximidad a los sistemas de lagos pluviales correlacionan fuertemente la edad del depósito con numerosos depósitos lacustres de la región y, posiblemente, el sistema de lagos se extiende al sur.

The intimate relationship between geology and biology is a sensitive balance of cycles, events, and variation. The geologic record confirms that conditions altering life over the past 4 billion years have waxed and waned through interdependent cycles of temperature, atmospheric composition, substrate textures, and hydrology (Pierce et al., 2005). To gain an understanding of evolutionary mechanisms over a geologic timescale, it is necessary to interpret changes in both geology and biology. For example, past species composition may provide insight into environments by examining trait evolution, geographic distributions, and chronological range. Conversely, studying the geologic processes that have formed past environments may also shed light on the communities that were present. Tufa environments are an example that can present both opportunities.

Tufas are soft, porous, rocky deposits of minerals (calcite, aragonite, or ikaite) that form below the surface of alkaline, cool-water regimes frequently associated with nearby sources of calcium, such as limestone. These deposits form when carbon dioxide is absorbed into a water body and reacts to form carbonic acid, which is further dissociated to bicarbonate or carbonate ions. Subsequently, as carbon dioxide is released, pH increases and carbonate solubility is reduced, resulting in precipitation. This effect is particularly strong in closed basins with proximal sources of calcium (Benson, 1994; Felton et al., 2006).

Carbon dioxide is most easily released to the atmosphere at higher temperatures, but even at lower temperatures, for example, at a spring source, calcium carbonate may precipitate, particularly if other factors affect the system. For example, aquatic plants may significantly influence absorption and production of carbon dioxide because of photosynthesis and respiration. A reduction in pressure, as sometimes occurs where a spring emerges from the ground, may also result in a release of carbon dioxide along with the associated precipitation of calcium carbonate.

Tufa deposits provide unique insight into local upland ecology, biodiversity, climate, hydrology, and geology often not captured in low-lying deposits found in basins

(Wing and DiMichele, 1992). Because of the rapid nature of preservation, tufas can provide strong temporal and spatial resolution as well as characterization of the environment, providing a discrete snapshot of geologic and ecologic conditions (Pentecost, 1981; Ford and Pedley, 1996; Liutkus, 2009). Biotic references are frequently included because of the hydrologic resource and mechanisms by which they formed (Taylor, 1919; Bradley, 1974; Pentecost, 1981; Ford and Pedley, 1996; Nicoll et al., 1999; Liutkus, 2009). As such, these references provide a detailed record of paleoclimate as well as paleoecology (Pitty, 1971; Marker, 1974; Pentecost, 1981; Pedley, 1990; Mischke and Zhang, 2008). Additionally, variations in tufa textures microscopically viewed in thin section can be used to interpret sources and geochemical conditions (Pedley, 1990; Liutkus, 2009).

Although tufa deposits are numerous throughout the world, many have yet to be investigated (Ford and Pedley, 1996). In contrast, extensive tufa research carried out within the Great Basin of southwestern North America documented Quaternary pluvial lake settings and their associated climates (Wright and Frey, 1965; Marker, 1974; Newton and Grossman, 1988; Ford and Pedley, 1996; Waldron and Gaines, 2005; Felton et al., 2006). Benson (1994) also established that Great Basin tufa deposition maximums ended during the Late Pleistocene, ~11,700 years before present (ybp) and occurred at 1,177–1,337 m above sea level. It also has been recognized that fossiliferous spring deposits commonly occurred throughout mid-latitude North America during the Quaternary Epoch (Holman et al., 1988; Saunders, 1988).

In this research, we investigated the morphological and physiochemical properties, as well as biotic content, of a previously undescribed calcareous deposit located in northwestern Arizona. We sought to identify the geologic and ecologic context of the site and hypothesized that the deposit represented a nonthermal tufa associated with the Great Basin pluvial lake system geology and paleoclimate, indicating an alternate ecology to that presently observed.

Materials and Methods—*Study Area*—The study site is located within the Lizard Point Quadrangle of northern Mojave County, Arizona at 36.898522°N, 113.583358°W and ranges in elevation between 1,106 and 1,115 m. The geology of the study site is mapped as Quaternary alluvium, alluvial fans, and landslide deposits (Billingsley, 1990). Located on Bureau of Land Management property ~160 km south of the southernmost reaches of ancient Lake Bonneville at its maximum, the site rests unconformably atop the Lower Triassic Shnabkaib Member of the Moenkopi Formation. Calcareous deposits identified below the exposed deposit suggested a potential shared hydrologic relationship. Small tubular plant-like structures were immediately visible within the exposed deposit and spurred further study of the area.

Presently, the site represents the Mojave Desert Lower Sonoran life zone. Vegetation is dominated by woody shrubs including creosote bush (*Larrea tridentata*), black brush (*Coleogyne ramosissima*), bursage (*Ambrosia dumosa*), and shadscale (*Atriplex confertifolia*). Banana yucca (*Yucca baccata*) and prickly pear cactus (*Opuntia*) are prevalent, as well as winterfat (*Krascheninnikovia lanata*) and an abundance of joint fir (*Ephedra torreyana*). Scattered honey mesquite (*Prosopis glandulosa*), wolfberry (*Lycium torreyi*), white burrobrush (*Hymenoclea salsola*), and dried remnants of cottonwood (*Populus fremontii*) occur in dry channels immediately adjacent to the deposit.

*Collection and Analysis of Data*—Field mapping of lithologic contacts was completed in 2012 using aerial photographs and satellite images provided by Google Earth© 7.1.1.1888 (2012), in addition to the U.S. Geological Survey Lizard Point Quadrangle geologic map, northern Mojave County, Arizona (Billingsley, 1990) and global positioning system. Rock samples were collected and examined in the geology and botany laboratories at Southern Utah University. The crystallography of tufa samples was determined through X-ray diffraction (Rigaku Minflex) and through thin-section analysis of two representative samples. Fossil identification efforts focused on texture and form comparisons with known samples and extant species.

Results—Quaternary deposits are situated unconformably above the Lower Triassic (Olenekian) Shnabkaib Member of the Moenkopi Formation. We found the presence of a capping tufa deposit resting above the Shnabkaib Member that is easily observed at the NE corner of the study area. This area includes approximately 2 m of loosely consolidated carbonate mudstone with local lenses of high-spired gastropods between the Shnabkaib Member and capping tufa. At the NE corner of the study area, an exposed stratigraphic section includes approximately 45 cm of thin beds of alternating black, white, and orange carbonate mudstones above the consolidated carbonate mudstone. Local lenses of breccia lie below the capping tufa deposit, but between the mudstones to the east and west.

The capping tufa deposit is approximately 15–30 cm thick and forms a wedge that dips and thickens to the SE until it terminates in a dry channel trending along the SE edge of the deposit. Carbonate mudstones to the SW of the deposit, at least 0.6 m in thickness, were overlain with capping nonfossiliferous tufa approximately 10–20 cm thick. This transitions to capping fossiliferous tufa accumulations approximately 15–30 cm in thickness located predominantly in the SE region of the study area. An arroyo bisected the eastern edge of the deposit, with fewer fossils found at this interface. However, cylindrical impressions up to 13 cm in width (Fig. 1a) were found predominantly to the north of the arroyo in nonfossiliferous deposits that terminated at a second dry channel to the north. No additional calcareous deposits were observed on the opposite sides of the surrounding dry channels to the north or south.

Trace fossils include the numerous tubular molds, frequently 4–6 mm in width, that were first observed on the study site (Fig. 1b). Upon closer examination, several of these show internal longitudinal striations and possible nodes (Fig. 1c). Deciduous leaves without margins (Fig. 1d), lenticel impressions on curved surfaces (Fig. 1e), as

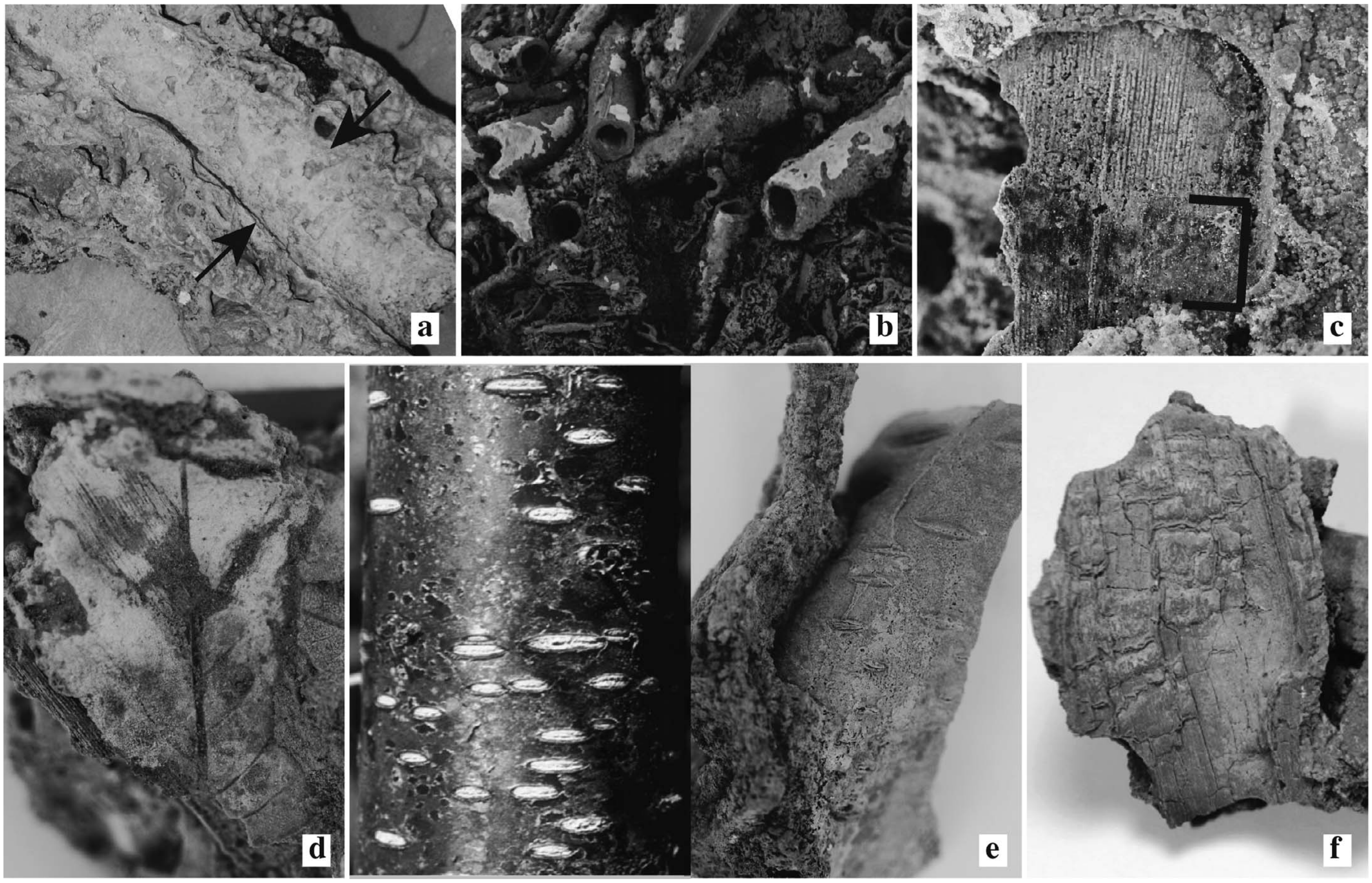


Fig. 1—Fossil flora collected from the study area and flora life zones. a) Woody stem mold approximately 5 cm in diameter; arrows indicate opposite edges of the stem; b) representative sample of numerous tubular molds indicative of *Equisetum*, *Scirpus,* or *Juncus* species; c) *Equisetum* node with grooved stem; the right side of the node is bounded by black indicators and grooves are observed above the node; d) deciduous leaf mold; note the lack of identifiable margins; e) comparison illustrates potential relationship between extant water birch (*Betula occidentalis*) lenticels (L) and fossil bark lenticels (R); f) suspected conifer bark.

well as nodular masses and fibrous rectangular impressions on curved surfaces (Fig. 1f) were also identified. One mold contained blackened material suggestive of carbon content, but the sample was insufficient for radiocarbon dating.

X-ray diffraction and petromicrographs (Fig. 2) confirmed nearly pure, radiating calcitic tufa morphology indicative of subaqueous formation. Petromicrographs revealed fossil content indicating a nonthermal hydrology, including suspected vascular plant cells (Fig. 2a), as well as a gastropod of the same species as that found in the older Late Quaternary strata (Fig. 2b).

Discussion—Through mapping and stratigraphic correlation, our results suggest that the study site represents a perched spring concurrent with the geology and paleoclimate of the pluvial lake system within the Great Basin. Pure calcite supports a nonthermal regime that may have originated from a local limestone source. As lower layers contain substantial micrite and other hydrologically significant carbonate morphologies, it is possible that this system is related to a currently active, albeit distant (>1 km), local spring that may have experienced intermittent flows of varying rates and emergence locations. The morphology of the deposit is indicative of diffusion across a shallow slope to form

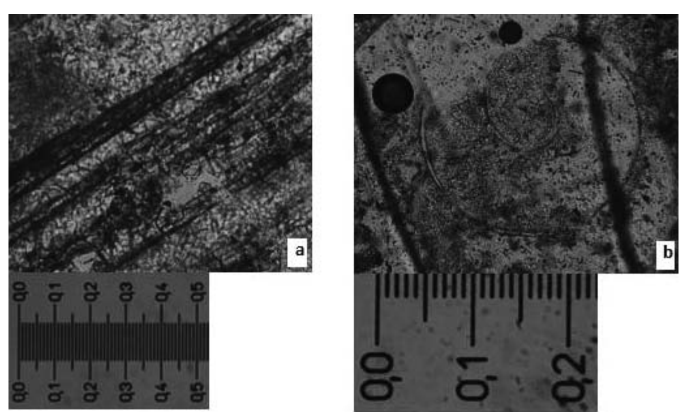


Fig. 2—Photomicrographs: a) Fossiliferous sample at 200× magnification containing possible vascular plant material. b) Fossiliferous sample at 400× magnification with gastropod inclusion.

paludal conditions that terminated in a barrage-like morphology as spring water converged with flow in a previously active, perennial channel. Additionally, a lack of aragonite within the sample indicates an alkaline pH below 9 (Felton et al., 2006), supportive of the growth of suspected species within the site at the time of formation.

Biotic content was identified on the basis of observed extant species and published literature. Tubular molds with impressions of internal striations and nodes were determined to represent horsetails (*Equisetum*), whereas nonstriated impressions may include rush (*Juncus*) and bulrushes (*Scirpus*). Broader, flattened impressions with more widely spaced striations and lacking nodes were hypothesized to represent cattail (*Typha*). *Equisetum* preference for calcareous soils and frequent colonization of newly created wetlands support these conclusions (Channing et al., 2011).

Lenticel-covered bark fossils resemble extant water birch (*Betula occidentalis*), a common large shrub that occurs along higher-elevation waterways in the Great Basin (Fig. 1e). In contrast, lenticel spacing and morphology did not correlate with other regional riparian shrubs, including chokecherry (*Prunus virginiana*), Mexican alder (*Alnus oblongifolis*), or red osier (*Cornus sericea*). The prevalence of water birch and horsetails at the convergence of spring water with the channel edge supports our perched spring model with water diffusing across the shallow slope. Fewer of these species molds were found closer to the presumed springhead lying to the NW. This model also may explain the larger-diameter unidentified stem fossils located more distally from this very wet confluence with the main channel.

Without margins, it was impossible to substantiate the fossil leaf molds as anything other than from a dicot plant, perhaps from a deciduous tree or shrub. These impressions may represent water birch leaves, particularly since most were observed near possible *B. occidentalis* bark molds (Fig. 1e). Root molds resembling calcareous rhizoconcretions were similar to others discovered locally within the Early Jurassic Moenave (Kirkland and Milner, 2006) and Kayenta formations (Difley and Ekdale, 2006). Comparisons of what were thought to be conifer bark molds with lower-elevation pinyon pine (*Pinus monophylla*) revealed little similarity. However, these rectangular impressions were comparable with those observed on the internal face of extant ponderosa pine (*Pinus ponderosa*) bark.

The majority of tufa research that investigated biological content offered detailed descriptions of bryophyte, algae, and microscopic evidence (Pitty, 1971; Pentecost, 1981; Preece and Day, 1994; Détriché et al., 2009), yet considerably less information regarding vascular plant species was available. Researchers have used microscopic evidence to identify associated plant species such as gyrogonites, the fossilized female reproductive structures of some stonewort species (Détriché et al., 2009), and pollen content (Preece and Day, 1994). A general lack of plant fossil evidence might be due to the delicate nature of tufa and its susceptibility to deformation that results in loss of fossil structure integrity.

Freshwater gastropods also were found in thin section and in older Late Quaternary strata. We have not yet determined if the gastropod found in thin section is specifically associated with the tufa formation environment or if it may be reworked from earlier Late Quanternary strata.

A strict interpretation of the age of this deposit through isotopic dating was not pursued because of limited material and the physiochemical nature of the tufa itself. Though Pazdur and Pazdur (1986) used isotopic methods for dating tufa sites, isotopic dates may be inaccurate because of weathering and reprecipitation (Marker, 1974). Reworking of the deposits by movement of soft, freshly formed tufa due to moving water or earthquakes also may create error in tufa age analysis (Mischke and Zhang, 2008). Isotopic dating was performed on calcareous shells of ostracods contained within tufa samples (Taylor et. al, 1994), but whether similar tests are relevant on the calcareously shelled gastropod contained in thin section is not yet known.

Previous literature on climate and associated flora of the Great Basin and surrounding regions provides valuable insights into the vascular plant content and ecology of the region during the postglacial period and suggests a method for dating the tufa deposit. Grayson (2011) depicts an only slightly wetter but much cooler (6.6°C lower than present) environment below 1,800 m elevation within the Great Basin approximately 13,000 ybp. This environment included widespread woodlands composed of limber pine (*Pinus flexilis*), big sagebrush (*Artemisia tridentata*), and buffalo berry (*Shepherdia*). By 10,000 ybp, shallow marshes in the region reflected cattail and bulrush diversity but within a desert biome as pluvial lakes disappeared. Concurrently, evidence of numerous springs and perennial streams with marshy edges and associated black mats were found to the south of the Great Basin at lower elevations just NW of what is now Las Vegas (Grayson, 2011). Black mat is a general term for often dark layers rich in organic content that are distinct from surrounding strata and indicative of moist soils associated with high water tables (Haynes, 2008). By 6,300 ybp, black mats were gone and falling water tables were evident, resulting in the current Mojave Desert Lower Sonoran life zone. Arizona life zones describe belts of vegetation and associated animals that transition across elevational and latitudinal gradients (Merriam, 1890).

On the basis of previous literature, present-day geologic evidence, and identification of biotic content, our results suggest that a paludal environment sourced from a perched spring was established 22,600–6,700 ybp at the northwestern Arizona tufa site. This date range may

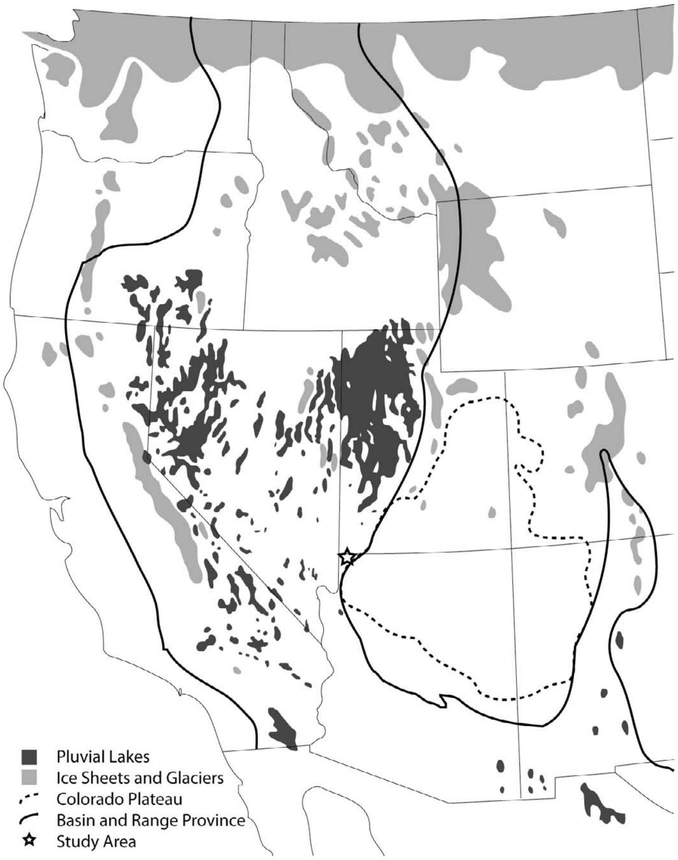


FIG. 3—Map of Pleistocene pluvial lake distributions in relation to the Basin and Range Province and Colorado Plateau (figure adapted from The Geological Society, http://sp.lyellcollection.org/content/301/1/51/F1.large.jpg). The study site, designated with a star, is located in an area previously lacking pluvial documentation. Basin and Range boundary from Faulds and Varga (1998).

have included environments similar to the present-day Upper Sonoran Chaparral, Upper Sonoran Woodland, and Transition life zones and their ecotones. All three environments are described by an increased moisture regime that allows the growth of large shrubs and trees. Larger shrubs that dominate chaparral scrublands of the southern Great Basin include live oak (*Quercus turbinella*) and silk tassel (*Garrya flavescens*). The Upper Sonoran Woodland life zone adds trees such as juniper (*Juniperus osteosperma*), pinyon pine, and scattered ponderosa pines near channels or springs. It is not until the Transition life zone, however, that ponderosa pine forests dominate the landscape. Water birch is a species found in present-day Chaparral and Woodland life zones in the southern Great Basin, but its distribution is hydrologically constrained to flowing channels or very boggy wetlands.

Our inferred age rests heavily on the confirmation of conifers, gastropods, or both, included within the environment in which the tufa was formed. Inclusion of either significantly constrains the age of the deposit. The biotic content suggests a paleoclimate significantly cooler and moister than that found today, though not so dissimilar as to suggest an age greater than that of similar Late Pleistocene lake deposits. Glacial period precursors to the Late Pleistocene lake deposits often contained ikaite (Bischoff et al., 1993), and this was not found in our samples. Biotic content, lack of ikaite, and proximity to pluvial lake systems strongly correlate the deposit's age with the numerous lacustrine deposits that occur in the region (Fig. 3). Finally, evidence of water tables dropping after 6,300 ybp in northern Nevada (Grayson, 2011) provides a near-term bracket on the possible age of this deposit as higher water tables are more likely to provide a perennial system of adequate flow rate to develop such an environment and the associated tufa deposit.

Pluvial lake distributions throughout the western United States and into Mexico indicate a noticeable gap in the geologic record of lake deposits in the northwestern corner of Arizona and Utah's southwestern region (Fig. 3). We propose that hydrologic associations extended beyond these lakes into surrounding regions, including the southwestern boundary of the Colorado Plateau Province. We interpret our site, and possibly others in this area, as being a byproduct of hydrologic associations with pluvial lakes and their incurring significant ecological impacts.

By identifying past species distributions in both geologic and ecologic contexts, ecologists are able to develop models that compare abundance and distribution of extant species to gain insight into current and future species distributions. This is particularly important when considering ground-fed water sources such as springs that have the potential to influence multiple ecosystems. Reviewing information provided through past species distributions over varying climatic regimes on a geologic scale has the potential to allow predictions on future distributions in a rapidly changing climate.

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