Reconstructing Late Pleistocene And Holocene Paleoenvironments Using Playa-Lunette System Sediments Within The Harney Basin Of Southeastern Oregon, USA

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RECONSTRUCTING LATE PLEISTOCENE AND HOLOCENE PALEOENVIRONMENTS USING PLAYA-LUNETTE SYSTEM SEDIMENTS WITHIN THE HARNEY BASIN OF SOUTHEASTERN OREGON, USA.

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Dedication

This dissertation is dedicated to my beautiful wife and daughter. They have provided me the inspiration to continue my journey through the ups and downs.
RECONSTRUCTING LATE PLEISTOCENE AND HOLOCENE PALEOENVIRONMENTS USING PLAYA-LUNETTE SYSTEM SEDIMENTS WITHIN THE HARNEY BASIN OF SOUTHEASTERN OREGON, USA.

by

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DISSERTATION

Presented to the Faculty of the Graduate School of The University of Texas at El Paso in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Department of Geological Sciences
THE UNIVERSITY OF TEXAS AT EL PASO
December 2016
Acknowledgements

So many people have helped and guided me during my time here at UTEP. First and foremost, I would like to think Dr. Thomas Gill and Dr. Richard Langford for their guidance and encouragement. Their mentorship has been invaluable to me. I also would like to thank my other committee members, Drs. Laura Serpa and Kate Giles of the Department of Geological Sciences at The University of Texas at El Paso, and Dr. Alexandra Ponette-González of the University of North Texas, who were gracious with their support and feedback. I thank Dr. Patrick O’Grady, of the University of Oregon Museum of Natural and Cultural History, and Scott Thomas, of the Bureau of Land Management (BLM), Burns District, for the encouragement, support, and the opportunity to work on the sediments at Rimrock Draw Rockshelter, and Rick Wells, of the BLM, Burns District, for providing me the necessary equipment and support for collecting cores.

I would also like to provide a special word of thanks to all of those students and assistants who helped with this dissertation. I thank the 2013, 2014, and 2015 University of Oregon Geoarchaeological Field School students who trekked all over the study area collecting sediments samples, site descriptions, and GPs locations. I also would like to thank Demetre Flores, Kagan Richard, and Amanda Ostwald, from the Department of Geological Sciences at the University of Texas at El Paso, who helped with field work, photographing, core descriptions and sediment sampling, and countless hours spent processing and measuring sediments on the Malvern. With out their assistance this dissertation could not have been possible.

Financial support for my dissertation came from the 2014 Jonathan Davis Scholarship in Quaternary Sciences sponsored by the Desert Research Institute (DRI), and through awards from the Geological Society of America, Society for American Archaeology, and the UTEP Graduate School.
Abstract

Paleoenvironmental investigations of the Late Pleistocene and Early Holocene in the Harney Basin of eastern Oregon have been limited to date. This dissertation investigates and links the stratigraphy of Rimrock Draw Rockshelter (35HA3855) (RDR) and two surrounding playas, Rimrock Lake and Hay Lake, located on the western margin of the Harney Basin, in order to identify paleoenvironmental shifts during the last ~20 kyr. An emphasis also is given to demonstrating the potential for playas in the Harney Basin to record changes in paleoclimate, as well as the application of multivariate statistics to interpret paleoenvironments from sedimentary grain size data.

Stratigraphy was exposed at RDR and Rimrock and Hay Lakes through backhoe trenching, coring, and archaeological excavations between 2013 and 2015. A total of 498 sediment samples were collected across the study area from 10 sedimentary profiles representing three different environments: fluvial, eolian, and lacustrine. The measured inorganic grain-size distributions (GSD) of the sediment samples were measured using a Malvern Mastersizer 2000 high-dimensional laser diffraction grain-size analyzer and mathematically unmixed using and end-member mixing algorithm (EMMA) in order to characterize the spatial and temporal paleoenvironmental variations across the study area.

EMMA was capable of distinguishing GSDs between littoral, fluvial, and deltaic environments, provided for a more geologically meaningful interpretation of stratigraphy, and characterized the magnitude and relationships of environmental change across the study area. End-member distributions across the study area in conjunction with radiocarbon dating identified several key paleoclimate shifts. Results indicate that Rimrock Lake and Hay Lake playas existed simultaneously by c. 19,000 cal. BP. as springs or marshy areas. Significant fluvial input was identified across the study area between c. 16,000 and 8000 cal. BP, correlating with lake expansion and lake-margin transgression. A relict playa surface exposed beneath marginal sediments was dated to 6,190 - 5,990 cal. BP. and represents an abrupt and significant lake
contraction in response to a shift to a drier climate during the mid-Holocene. Within the relict channel, a shift from a fluvial environment to a marsh environment is identified at c. 10 000 cal. BP., and is followed by a shift to a drier environment with increased eolian activity at c. 8000 cal BP. A thick layer of Mt. Mazama tephra (c. 7800 cal. BP) also is found preserved within the relict channel and suggests that the relict channel was consistently dry after deposition.

Overall, this dissertation contributes to a better understanding of paleoenvironmental change during the Late Pleistocene and Holocene within the Harney Basin in the context and vicinity of an important archaeological site. The results presented in this dissertation also demonstrate the ability of playas in the Harney Basin to record paleoenvironmental changes, and illustrate the utility of end-member mixing analysis to characterize paleoenvironmental these changes through analysis of sediment grain-size distributions.
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Chapter 1

Introduction

I began discussing the possibility of conducting research on Rimrock Draw Rockshelter (35HA3855), a deeply stratified, multi-component Paleoindain Rockshelter located along the western boundary of the Harney Basin, with Dr. Patrick O’Grady, of the University of Oregon, at the 2012 annual meeting of the Society for American Archaeology (SAA). During our conversation it became apparent that there lacked both a detail understanding of the timing and magnitude of environmental change across the Pleistocene-Holocene boundary and a long-term commitment to paleoenvironmental research focused on the Pleistocene and Holocene. This dissertation was, therefore, conceived of as a long term research program focused on characterizing the timing and magnitude of environmental change during the Late Pleistocene and Holocene within the Harney Basin.

The Harney Basin of southeastern Oregon (Figure 1.1) is the northernmost internally draining basin within the North American Great Basin and the largest in Oregon. It covers roughly 13,730 square kilometers and has a range of elevations between 1220 to 2750 meters above mean sea level (masl) (McDowell, 1992; Dugas, 1998; Orr and Orr, 2012). Paleoenvironmental investigations of the Harney Basin are extremely limited and have predominately been focused around the Malheur Lake system. In fact, there exists very little previous work on the timing and direction of environmental change in this area during the Late Pleistocene and Early Holocene, and virtually no studies exist on human environmental adaptability in the area during this time. What little is known comes from only a handful of geomorphological (Dugas, 1993; Dugas, 1998; see also The Great Basin Paleoenvironmental
Database, https://www.dri.edu/gbped) and archaeological studies (i.e., Wriston, 2003; see also O’Grady, 2006).

This dissertation investigates playa sediments as archives for understanding Late Pleistocene and Holocene paleoenvironmental change within the Harney Basin and the surrounding Rimrock Draw Rockshelter. Three broad goals are defined: 1) to identify site formation processes responsible for the creation of the Rimrock Draw Rockshelter stratigraphy, 2) to link the stratigraphy of Rimrock Draw Rockshelter to the surrounding environment in order to provide a regional context to site occupation, and 3) to characterize and compare the geomorphic response and evolution of nearby playa lakes to climatic fluctuations occurring within the Harney Basin.

**Background**

**Rimrock Draw Rockshelter**

Rimrock Draw Rockshelter (RDR), discovered in 2009, is the first deeply stratified, multi-component Paleoindian site discovered in the Harney Basin, and is possibly the oldest site in the western United States (Collins et al., 2016). Since 2012, RDR has been the focus of excavations by the University of Oregon’s archaeological, ethnobotanical, and geoarchaeological field schools. DR is situated against a north facing basalt fault scarp that forms the outside wall of a meander along a relict stream channel. The brow of the shelter juts approximately 3 meters northward from the base and provides the best protection from the rain, sun and winds that consistently arrive from the south-west. The sedimentary deposits in this location are extremely deep by Northern Great Basin site standards, with an accumulation of 3.0 to 3.25 meters. The relict channel in which the site is situated in is fed by two playas located to the southeast and southwest, and within a 3 kilometer radius of RDR. Sediment influx into the channel is derived
from the input of eroded basalt and rhyolite bedrock in the immediate area, and Aeolian processes providing sediment influx over the brow of the fault scarp. With its deep stratification, location within a rockshelter, and its association to several playas, RDR provides a unique opportunity to study human occupation from the Terminal Pleistocene on through the Pleistocene-Holocene transition and well into the Late Holocene, all within an environmental context not yet studied within the Harney Basin.

The archaeology within and surrounding RDR is dominated by Western Stemmed Tradition (WST) projectile points (Heizer and Hester 1978; Beck and Jones, 2009). Artifacts associated with fluted point technology (possibly Clovis) also were recovered from surface concentrations to the north of the channel (O’Grady et al., 2012). The WST projectiles were used from ca. 7000 to ca. 12 000 BP., while the fluted point technology spans a time period from ca. 12 800 to 13 250 BP (Waters and Stafford, 2007). Thus, the timeline for Paleoindian occupation of RDR may extend from 7000 to 13 250 years based on projectile point typologies. However, one significant discovery made in the summer of 2012 may push occupations at RDR even further back in time. A large chert scraper or graver was found 20 cm below both megafaunal tooth enamel fragments and a thin layer of Mount St. Helens Sg tephra (15 800 cal. BP). In any case, the archaeology suggests that RDR may fill an environmental and archaeological gap present in the Harney Basin during the Pleistocene/Holocene transition.

The Harney Basin, Southeastern Oregon

Located within an elevated desert plateau, Harney Basin is the northernmost internally draining basin within the Great Basin and the largest in Oregon, covering roughly 13,730 km² and having an elevation range of 1220 to 2750 meters above mean sea level (amsl) (McDowell, 1992; Dugas, 1998; Orr and Orr, 2012). The environment is semi-arid, with a complex
hydrologic system of streams, rivers, marshes, and lakes fed by precipitation and snowmelt (McDowell, 1992; Oetting, 1992; Orr and Orr, 2012). Occupying the lowest elevations of the basin is one of the largest freshwater marsh habitats in the United States: The Malheur Lake system, a large freshwater marsh habitat which includes Malheur Lake at the upstream end, Mud Lake in the middle, and Harney Lake as the ultimate sump of the system. Under normal conditions Malheur Lake is a broad and shallow marsh with most of its surface covered with aquatic vegetation. Due to the breadth and depth of the Malheur system, a slight rise in lake level results in a significant expansion of surface area (McDowell, 1992; Oetting, 1992; Dugas, 1998).

The Harney Basin is located within the eastern portion of the High Lava Plains province (HLP) of central Oregon (Figure 1.2). The HLP is a Late Tertiary to Quaternary bimodal volcanic field 50 miles wide and 150 miles long, serving as the structural boundary between the Basin and Range province to the south and the Blue Mountains province to the north (Jordan et al., 2004; Orr and Orr, 2012). The bimodal sequence of eruptions in the HLP is reversed compared to typical bimodal volcanism elsewhere, with rhyolites erupting during the earliest stages of eruptions and basalts appearing later on (Orr and Orr, 2012). In broadest context, Harney Basin is characterized by a continuous depositional sequence of volcanic and volcanic-derived sedimentary rocks that can be separated into two terrains: an alluvial lowland and a volcanic upland (McDowell, 1992; Orr and Orr, 2012).

Following rhyolitic eruptions in the Early Miocene, basaltic volcanism began ca. 16 million years ago (mya) along with high-angle faulting, covering most of the northern, eastern, and southeastern parts of the basin. Although radiometric dates from basalts range from about 19 to 12 mya, most were formed between ca. 15.5 and 14.5 mya, syndepositional to the eruptions of the Columbia River Basalt Group to the north, the Steens Basalt Group to the south and west,
and the Owyhee Basalt Group to the southeast. Individual basalt flows range from ca. 10 meters to over 600 meters, forming vertical cliffs, with roughly 1/2 of the land surface in the eastern portion of the basin formed by this stratigraphic unit (McDowell, 1992).

Rhyolitic volcanism began erupting during and after the Miocene basalts from several dozen vents in and around the Harney Basin, with radiometric dates ranging from 15.7 to 2.7 mya. One striking aspect of volcanism in the HLP is the geographical age progression of rhyolitic eruptions that punctuate the basaltic topography and form a broad belt of ca. 100 centers running from the Owyhee Uplands in the east to the Cascade Mountains in the west. The volcanic age progression roughly mirrors the northeastward migration of the silicic volcanism along the Yellowstone-Snake River Plain trend. There are a number of competing hypotheses regarding the relationship between the HLP and the YSRP and will not be summarized here (Jordan et al., 2004).

The Harney Basin was the chronological midpoint in the progressive sequence of rhyolitic volcanism, beginning along the eastern margin with the more andesitic and dacitic Duck Creek Butte in the Miocene ca. 10.4 mya., terminating in the west with the Newberry stratovolcano that started erupting ca. 1.2 mya in the Late Pliocene and ended in the Middle Holocene ca. 7,000 kya (Kuehn and Foit, 2006; Orr and Orr, 2012). After eruption of Miocene basalts, ca. 12 mya, explosive volcanic eruptions began in the Harney Basin, producing three distinct stratigraphic rock units dominated by tephra, pumice, tuff, and associated sedimentary rocks (McDowell, 1992). The Devine Canyon ash-flow tuff erupted between 9.2 and 9.3 mya from a caldera that underlies the northwestern part of the alluvial plain north of Malheur Lake. The Prater Creek ash-flow tuff erupted ca. 8.4 mya from an unknown caldera. The Rattlesnake ash-flow tuff erupted ca. 6.5 mya from a caldera under the present Harney Lake-Dog Mountain-
Freeman Butte area. Essentially, Harney Basin was buried in ash-flow tuffs, and their eruptions most likely played a significant role in shaping the landscape. Today, these Miocene ash-flow tuffs form the surface of the landscape of the northwestern and southwestern sides of the basin (McDowel, 1992).

Structurally, the HLP is dominated by the Brothers fault zone, a west-northwest-trending series of sub-parallel faults (Jordan et al., 2004), that intersects the Harney Basin and accounts for a significant portion of the relief and geomorphic features that are present within the Harney Basin today (McDowell, 1992). The position of Rimrock Draw Rockshelter and the flow of the relict stream channel was influenced by these northwest-trending faults of the Brothers fault zone. Due to faulting and volcanism well into to Holocene, the Harney Basin would serve well as a good study area for those interested in the link between past prehistoric site context, migration, and large scale tectonics and volcanism.

The topography and soil quality is variable and supports mixed plant community. The dominant vegetation is typical of a dry environment, mainly the sagebrush (*Artemisia*), which includes four principal species occupying specific habitats. The Big Sagebrush (*Artemisia tridentata*) is the primary species, and because it prefers relatively deep soils, is found at archaeological sites throughout the Harney Basin. Other common vegetation includes greasewood (*Sarcobatus vermiculatus*), green (*Chrysothamnus viscidiflorus*) and gray rabbit brush (*Chrysothamnus nauseosus*), and bitterbrush (*Purshia tridentata*). Grasses such as the giant wild rye (*Elymus cinereus*), Idaho fescue (*Festuca idahoensis*), Thurber needlegrass (*Stipa thurberiana*), Sandbergs Bluegrass (*Poa sandbergii*), and bluebunch wheatgrass (*Agropyron spicatum*) also are fairly common. The Western Juniper (*Juniperus occidentalis*) is found in and around the Big Sagebrush zone (O’Grady, 2006; Orr and Orr, 2012). The hydrological system
also supports a wide variety of plant life, with willow (*Salix sp.*) and black cottonwood (*Populus trichocarp*) being common around rivers and streams, and cattail (*Typha latifolia*), hardstem bulrush (*Scirpus acutus*), sedge (*Carex sp.*), Baltic rush (*Juncus balticus*), and burreed (*Sparaganiun eurycarpum*) being the dominant emergent varieties of the marshlands. Small pondweed (*Potamogeton pusillus*) and sago (*Potamogeton petinatus*) are common open water plant species, and water milfoil (*Miriophyllum exalbescens*) is the most abundant submergent. Moist soil plants include alkali ryegrass (*Elymus triticioides*), meadow barley (*Hordeum brachyantherum*), spike rush (*Eleocharis palustris*), water plantain (*Alisma planagoaquatica*), broadleaved arrowhead (*Sagittaria latifolia*), hoary nettle (*Urtica holosericea*), and flixweed (*Descurainia Sophia*). The lakeshore margin where seasonally receding waters leave mudflats are home to the chenopods (*Atriplex sp.*, *Chenopodium sp.*, *Suaeda sp.*) (O’Grady, 2006).

**The Paleoenvironmental Record of the Harney Basin**

Paleoenvironmental investigations of the Harney Basin are extremely limited and have predominately been focused around the Malheur Lake system. In particular, very little previous work has been conducted on the timing and direction of environmental change during the Late Pleistocene and Early Holocene, and virtually no studies exist on human environmental adaptability in the area during this time. What little is known comes from only a handful of geomorphological (Dugas, 1998) and archaeological studies (see O’Grady, 2006) (see also the Great Basin Paleoenvironmental Database, https://www.dri.edu/gbped). Though paleoclimatic changes that impact the ecosystem and humans in a particular area may not necessarily have impacts on other areas (Meltzer and Holliday, 2010; Birks et al., in press), the scanty environmental history of the Harney Basin can be supplemented with an understanding of the climatic history of the surrounding region, and of the Western United States in general,
beginning in the Late Wisconsin glacial period (35,000 to 10,000 BP) and on through the Holocene (10,000 BP to present) (Meltzer, 2009).

During the Late Wisconsin, between ca. 18,000 to 14,000 BP, the glaciers of northern North America reached their maximum extent. During this time sea levels fell by ca. 125 meters to their minimum level, expanding current coastlines by about 50 km beyond their current locations (Dail and Wunsch, 2014; Meltzer, 2009). This period of expanding glaciers and falling sea levels is known as the Last Glacial Maximum (LGM; 19,000 - 23,000 years ago) (Clark and Mix, 2002; Dail and Wunsch, 2014). The LGM landscape would be virtually unrecognizable today, with three massive ice sheets (the Laurentide, Cordilleran, and Inuitian) covering most of Canada and the northernmost United States (Meltzer, 2009). There is a general consensus that the massive ice sheets influenced the global climate by affecting albedo, atmospheric and ocean circulation, and the hydrological cycle (Clark et al., 1999; Clark and Mix, 2002). For example, during the LGM, when ice sheets were at their maximum extent, the North America Polar Jet Stream (NAPJS) and its storm tracks may have been pushed south over the current drylands of the southwestern USA and northern Mexico, bringing increased precipitation and filling basins in the southern portion of the Basin and Range Province. Enzel et al. (1989, 2003) hypothesized that the Mojave River pluvial lakes formed as a result of the NAPJS shift. Similarly, Benson et al. (2003), based on organic carbon and oxygen proxy records at Owens, Pyramid, Summer, and Mono Lakes, suggests that climatic conditions in the western U.S. between 47 000 and 21 000 years ago were dependent on the position of the NAPJS. This southward displacement also kept temperatures in the southwestern drylands about 2-3 degrees cooler than at present (Thompson et al., 1993; Tchakerian and Lancaster, 2002). The LGM was subsequently followed by increased incoming solar radiation, a warming climate, retreating ice sheets, and rising sea levels, causing
an interglacial (warm) period (Birks et al., In Press; Lecavalier, 2014; Meltzer, 2009), and the subsequent shift in the NAPJS. These changes were, for the most part, unidirectional, occasionally punctuated by massive meltwater releases from ice sheets and the occasional reversal of the overall warming trend (Mensing, 2001).

The Bølling-Allerød warm period followed the LGM and caused the collapse of the North American ice sheets, weakening their climate-modifying effects (Meltzer, 2009). This collapse allowed the southern branch of the NAPJS and its winter storm track to shift north again. This warming period was temporarily punctuated by a short-term cooling reversal known as the Younger Dryas (YD) chronozone, and is generally acknowledged to have occurred between ca. 12,900-11,600 cal. B.P. (Goebel et al., 2011; Metzer, 2009; Meltzer and Holliday, 2010) as the Pleistocene Epoch was coming to an end. By some estimates this abrupt cold period was perhaps the most dramatic millennial-scale change in climate and ecology following the LGM (Lowe and Walker, 1997).

As the late Pleistocene came to a close, temperatures were relatively cool and conditions wetter. These cooler and more effectively wetter conditions resulted in the the regions closed basins to fill with water, forming Lake Bonneville in western Utah, Lake Lahontan in western Nevada, and other smaller lakes and marshes in Nevada, Oregon, and California (Goebel, et al., 2011). The Lahontan and Bonneville Basins possess one of the best records of environmental change in a continental environment. Lake Bonneville, for example, has been intensively studied for more than a century (Rhode and Madsen, 1995) and has had hundreds of radiocarbon ages generated over the last forty years, constraining lake-level and vegetation changes, fluvial aggradation, drought, eolian activity, and alluvial fan deposition (Adams et al., 2008), demonstrating that it has fluctuated widely in response to changes in climate between 30 and 10
Late Pleistocene to Holocene lake level histories of Lake Bonneville and Lake Lahontan indicate that there was a lake high stand between 16,000 and 13,000 B.P in both basins, reflecting a glacial-period climate, shortly after the LGM. Beginning about 13,000 B.P. in the Lahontan Basin and about 14,000 B.P. in the Bonneville Basin, lake levels dropped rapidly, reflecting a shift in climate from the colder glacial to the warmer and drier postglacial interval known as the Bølling-Allerød warm period (mentioned above). Between 11,500 and 10,000 B.P. lake levels in both basins saw a minor rise, and it is suggested that this may have been brought on by the Younger Dryas cooling event (Rhode and Madsen, 1995). The Bonneville and Lahontan Basins thus can be considered larger scale analogs to what may have been happening in the Harney Basin during the Late Pleistocene and Early Holocene.

Within south-central Oregon, Pluvial Lake Chewaucan filled four sub basins that are now occupied by modern Summer Lake, Upper and Lower Chewaucan Marshes, and Lake Abert (Cohen et al., 2000; Licciardi, 2001, Wigand and Rhode, 2002). Using prominent shoreline features, at least six distinct stages of water level fall of the Pluvial Lake Chewaucan are identified following the maximum high stand. Interestingly, however, the lake level high of Pluvial Lake Chewacaun at around 12 ka occurred during a period of low lake-levels in the Bonneville and Lahontan basins, and post dates the high stands of these lakes by at least 1000 years (Licciardi, 2001). The earliest known Quaternary paleoenvironmental record in the Harney Basin comes from the Tulelake-64 tephra deposited at wave base around the Malheur Lake system between ca. 70,000 – 80,000 years ago (Dugas, 1998). Based on dates obtained from shell material within preserved beach berms, moderate-sized lakes may have existed in the Malheur Lake system between ca. 32,000 to 29,500 and again at ca. 9,500 years BP during the
Holocene. Smaller lake systems also were present ca. 8,400, 7,800, and 7,400 years B.P. (Dugas, 1998). There are no dated lake-levels available at Malheur Lake for the period between ca. 7,400 and 5,000 years B.P., though it is suggested by Wigand (1985, 1987) that drier conditions were established after 7,500 years B.P., with a series of wet periods ca. 5,300 years B.P., and between ca. 4,000 and 2,000 years B.P. (Dugas, 1998).

**Playas as Archives of Environmental Change**

Playas are ephemeral endorheic lakes found throughout arid and semiarid regions of the world (Shaw and Bryant, 2011) and are particularly ubiquitous in the Harney Basin of eastern Oregon (Figure 1.1). By their nature, playas represent unique receptacles of fluvial, eolian, and lacustrine sediments (Cooke et al., 1993; Holliday et al., 2008; Bowen and Johnson, 2012; Adams and Sada, 2014). Many playas also have downwind marginal landforms called lunettes (Hills, 1940) that are generally characterized as being crescent-shaped eolian dunes along the leeward margin of a playa, varying in height from 1 to 150 meters (Goudie, 2013; Rich, 2013). Playas and their lunettes have been studied in South America, Africa, Australia, Arabia, and the USA in places such as California, the High Plains, and the Great Basin (Cooke et al, 1993; Gustavson et al., 1995; Shaw and Bryant, 2011; Bowen and Johnson, 2012, 2015; Rich, 2013). These geomorphically distinct features are jointly known as playa-lunette systems (Bowen and Johnson, 2012), and their combined configuration makes them one of the most comprehensive, high-resolution archive of environmental proxies for changing climates, hydrology, and ecology of a region (Morrison, 1966; Bowler, 1973, 1983; Lancaster, 1978; Cooke et al., 1993; Rich, 2013; Bowen and Johnson, 2012, 2015).
The Dynamic Grain Size Population

Sedimentary grain-size distributions offer a powerful proxy of past environmental conditions that relate to sediment sorting, as the emission, transportation, and deposition of sediments are linked to changes in paleoclimate (Folk and Ward, 1957; Prins et al., 2007; Dietze et al., 2012, 2013, 2014). These processes tend to sort sediments in characteristic ways depending on the properties of the sediment source, availability, and transport energies (Tsoar and Pye, 1987; Dietze et al., 2014). However, a feature of sedimentary deposits is that they are typically multimodal mixtures of different grain-size subpopulations. When sediments from different local and regional sources and transport processes (fluvial, eolian, lacustrine) across a region are deposited in a sedimentary sink (i.e., a playa) they become mixed (i.e., bioturbation, pedoturbation), creating a sedimentary archive representing a combination of all the physical processes responsible for its creation (Deitze et al., 2012). For example, downstream fluvial sediment transport and eolian processes will deposit and mix sediment grains within a sediment sink (i.e., playa) simultaneously. These sedimentary processes contributing to a sediment sink are grain-size-selective and will contribute to fractionation of sediments into distinct grain size ranges termed a dynamic population (DP; Weltje and Prins, 2003; 2007).

A DP provides a link between grain size variations observed within sediment samples and the physical laws that govern sediment production and transportation (Weltje and Prins, 2003; 2007). Each distinct spatio-temporal sediment sample measured across a study area will contain multiple DPs that will have been subjected to time-averaging effects such as bioturbation, erosion, human occupation, and accumulation. The mathematical equivalent of a DP can be obtained by regarding the measured GSDs as a series mixture of end members (EM). Thus, the application of grain size analysis to environmental reconstruction is to estimate the
number of EMs and their distribution in order to characterize the mixing structure of the sedimentary matrix.

**End-Member Mixing Analysis (EMMA)**

This dissertation uses an end-member mixing algorithm (EMMA) first developed by Weltje (1994) as a solution to the “mixing problem,” and then expanded upon by Dietze et al. (2012), to mathematically decompose the measured GSDs of sediments from multiple sedimentary archives across the study area into volumetrically significant end-members, or DPs. In most cases, the spatial heterogeneity of sediments is described as a linear mixing model, which is expressed as mixtures of a fixed number of end-members. For example, any sandstone composition represented on a ternary diagram (100% quartz, 100% feldspar, and 100% lithics). It becomes a trivial exercise to predict the composition of any mixture of sediments if the composition of the end-members and their proportional contributions is known. Unfortunately, the opposite occurs in nature, in which the compositional variation of sediment is assumed to reflect mixing, but the mixing process is unknown. Thus, the “mixing problem” manifests itself whenever the compositional variation among a series of sediment samples are recast in terms of a mixing model (Weltje, 1994). Applying EMMA to the grain-size distributions of genetically related sedimentary archives of a study area can improve landscape evolution modeling.

EMMA is an enhanced form of Q-mode factor analysis (Weltje, 1997) that extracts end-members from the three-dimensional eigenspace of a data set in which each point represents a sample that is understood to represent the mixing of discrete sources (Dietze et al., 2013). The sedimentary archives identified and analyzed in this dissertation represent such an attribute space. By treating them as a three-dimensional attribute space, EMMA performs an eigenspace analysis of all sediment samples simultaneously from across the study area, identifying
genetically related end-members (Weltje and Prins, 2003, 2007; Dietze et al., 2012) that can then be interpreted and linked to the timing and magnitude of environmental changes acting on the entire study area.

EMMA is statistically more robust than the often used descriptive moments of single sediment samples such as mean, skewness, and kurtosis (Folk and Ward, 1957; Boggs, 2006), as this method is limited, requiring some *a priori* understanding of the natural subpopulations contributing to the bulk sediment sample (Klovan, 1966; Flemming, 2007; Hartmann, 2007; Weltje and Prins, 2007; Dietze et al., 2012, 2013) and is inappropriate for such multimodal GSDs measured from high-dimensional, state-of-the-art laser-diffraction analysis such as the Malvern Masetersizer 2000 used in this study (Dietze et al., 2014). For more extensive reviews of EMMA see Klovan (1966), Klovan and Imbrie (1971), Weltje, (1997), Weltje and Prins (2003, 2007), Dietze et al. (2012; 2013), and Ijmker et al. (2012).

The sedimentary archives in and surround playas (alluvial fans, deltas, ephemeral channels, etc.) are genetically related across space and time, representing a three-dimensional attribute space of interrelated processes that can be thought of as a geo-archive. The sedimentary archives used in this dissertation represent such an attribute space, as they are genetically linked by fluvial, lacustrine, and eolian processes. Combining the archives across the study area creates a three-dimensional attribute space, or eigenspace, of interrelated processes in which the eigenvectors identified represent underlying processes as linear combinations of the observed grain-size distributions (Dietze et al., 2012).
REFERENCES


Hills, E.S., 1940, The lunette, a new landform of Aeolian origin. *Australian Geographer* 3:15-21


Figure 1.1. Outline of the Harney Basin, Oregon. The Rimrock Draw study area is outlined in yellow. Note the white and gray circular features that dot the landscape in the western portion of the basin.
Figure 1.2. Location of the Harney Basin in relationship to the High Lava Plains (HLP; dashed red line) with small and large faults identified (Ford et al., 2013)
Chapter 2

End-member mixing analysis (EMMA) applied to sediment grain size distributions to characterize formational processes of the main excavation block, Unit 2, of Rimrock Draw Rockshelter (35HA3855), Harney Basin, Eastern Oregon (USA)*

* Published as:

ABSTRACT

End-member mixing analysis (EMMA) was conducted on the grain size distributions (GSD) of 13 sediment samples collected from the main excavation block, Unit 2, of Rimrock Draw Rockshelter, a deeply stratified, multi-component Paleoindian rockshelter in the Harney Basin of eastern Oregon, USA. EMMA confirmed the three stratigraphic units (SU) observed in the field and identified three sedimentary end-members (EM) that account for 95.52% of Unit 2 site formation. EM 1 comprises 70.72% of the total measured grain size variation and represents fluvial deposition, correlating with the bottom stratigraphic unit, SU 3. EM 2 comprises an additional 17.74% of the total measured grain size variation and represents fluvially reworked eolian deposition, correlating with the upper stratigraphic unit, SU 1. EM 3 comprises the remaining 7.06% of the total measured grain size variation and represents possibly a two-component eolian deposition of suspension and short-term saltation, correlating with the middle unit, SU 2. The results presented demonstrate the ability of EMMA as a technique to (1) unbiasedly distinguish between the SUs identified in the field using only the measured grain size distributions, (2) provide genetically meaningful and quantitative grain-size end-members to identify multiple major depositional processes of site formation, and (3) provide a geologically meaningful interpretation of site formation that is capable of facilitating the formulation of more focused hypotheses regarding human and environment interactions at the site.
INTRODUCTION

We report the results of an end-member mixing analysis (EMMA) conducted on the measured grain size distributions (GSD) from the east wall of the main excavation block, Unit 2, of Rimrock Draw Rockshelter (Figure 1 and 2), a deeply stratified paleoindian rockshelter in southeastern Oregon, USA. The EMMA technique, which has been frequently used by sedimentologists, provides the potential to enhance interpretations of site formation processes by unmixing the measured GSDs (Weltje, 1997; Weltje and Prins, 2003; 2007; Dietze et al., 2012; 2013). The technique has been demonstrated to successfully extract a more robust geologically meaningful interpretation of the GSDs from deep sea sediment cores (Prins et al., 2002; Stuut, 2002; Weltje and Prins, 2003; Holz et al., 2004), lake cores and surface samples (Dietze et al., 2012; 2013), and provide an unbiased confirmation of field and proxy data used in paleoenvironmental reconstruction. This technique, when applied to sedimentary data in an archaeological context also can facilitate development of a more geologically significant interpretation of site formation, providing for the placement of occupations within a more precise paleoenvironmental context, and also facilitate the development of more focused hypotheses related to human and environment interactions. It must be stressed that, in this study, we are attempting to demonstrate the applicability of end-member mixing analysis in a geoarchaeological context; we are not here attempting to describe the complete context of the site archaeology or stratigraphy, as excavations are still ongoing, but only on the main excavation block.

SEDIMENTARY GRAIN SIZE DISTRIBUTIONS (GSD) AND THE DYNAMIC SEDIMENTARY GRAIN SIZE POPULATION

The sedimentary matrix of an archaeological site may be described in terms of observable, quantifiable GSDs that represent a combined result of multiple physical process interactions. For example, downstream fluvial sediment transport and eolian processes will
deposit and mix sediment grains within a sediment sink simultaneously. These sedimentary processes are grain-size-selective and will therefore contribute to the fractionation of sediments into distinct grain size ranges termed a dynamic population (DP). A DP can be visualized as an assemblage of grains that are likely to occur together since they respond in a similar way to the dynamics of sediment production and dispersal within an inherently complex sedimentary system (Weltje and Prins, 2003; 2007). A DP therefore provides a direct link between the grain size variation observed in a sediment sample and the physical laws governing sediment production and transportation (Weltje and Prins, 2003; 2007). Conceptually, one can distinguish each measured grain size class comprising a sediment sample as a DP. Practically, however, only those DPs representing a volumetrically significant proportion of the sedimentary matrix under study are useful, as they allow for the compact yet statistically significant description of the observed grain size variation across a series of measured GSDs (Weltje and Prins, 2003; 2007).

Each distinct spatio-temporal sediment sample taken from the sediment matrix will contain multiple DPs which have been subjected to time-averaging effects such as bioturbation, erosion, human occupation, and accumulation, and thus should therefore be regarded as a spectra of DPs. The mathematical equivalent of a DP can be obtained by regarding the measured GSDs as a series mixture of end members (EM). Thus, the application of grain size analysis to environmental reconstruction is to estimate the number of EMs and their distribution in order to characterize the mixing structure of the sedimentary matrix.

The use of univariate grain size parameters (e.g., sand, silt, and clay relative percentages) and their associated statistical methods of moments (e.g., mean, skewness, and kurtosis) have very little interpretive value (Klovan, 1966; Boggs, 2006) and are vulnerable to bias when applied to multi-modal grain size populations, relying on the validity of additional a priori assumptions (Klovan, 1966; Flemming, 2007; Hartmann, 2007; Weltje and Prins, 2007; Dietze et al., 2012; 2013). For this reason, with the exception of single grain size percentages for comparison, these univariate methods are omitted here. This is not to say that univariate descriptive statistics of sedimentary samples have no value, only that some interpretive
information is lost and, ultimately, the ability to form a genetically meaningful grain size connection between environments across space and time is diminished.

Following from the above discussion, this study applies EMMA to the measured GSDs of 13 sediment samples extracted from the east wall of Excavation Unit 2 of Rimrock Draw Rockshelter (35HA3855) (Figures 1 and 2). The questions driving this demonstrative study are, (1) Can EMMA distinguish between stratigraphic units identified during field work, and (2) Can a more robust, geoscientifically meaningful interpretation of grain size be facilitated by the EMMA procedure? Three calibrated radiocarbon dates from Unit 2 are used for chronological control. To our knowledge, this is the first detailed sedimentary description of stratigraphy at an archaeological site using EMMA, and the first detailed paleoenvironmental analysis of an archaeological site in the Harney Basin of eastern Oregon.

A BRIEF DISCUSSION OF END-MEMBER MIXING ANALYSIS (EMMA)

End-member mixing analysis (EMMA) is an enhanced form of Q-mode factor analysis (Weltje, 1997) that has been widely and successfully applied to remote sensing, hydrochemical, geochemical, and sedimentological problems (Klovan and Imbrie, 1971; Meisch, 1976, 1980). For example, EMMA is called spectral mixing analysis (SMA) in remote sensing and frequently used to derive subpixel information on vegetation cover, identify severity of burns following wildfires, and to map tree and shrub leaf area indices of peatlands (Song, 2005; Robichaud et al., 2007; Sonnentag et al., 2007). In the hydrological and geochemical sciences end-member algorithms have been used to distinguish hydrological flow paths from soil water chemistry (Burns et al., 2001), examine nutrient drawdown due to biological uptake within the euphoric zone (Wang et al., 2014), and to quantify phosphorus retention and release in rivers and watersheds (Jarvie et al., 2011). In sedimentological studies, EMMA has been shown to be useful for identifying sediment transport mechanism (traction, saltation, suspension) responsible for deposition (Dietze et al., 2012; Vandenberghhe, 2013).
Essentially, EMMA extracts end-members from the three-dimensional eigenspace of a data set where each point (end-member loadings) represents a sample that is understood to represent the mixing of discrete sources (i.e., grain size classes vs. the composition in the sample space) (Dietze et al., 2013). The loadings are then scaled to be geologically meaningful using a weight transformation after Klovan and Imbrie (1971). EMMA used in this study follows the techniques of Klovan and Imbrie (1971), Weltje (1997), and Dietze et al. (2012; 2013) that is based on Principal Component Analysis (PCA), factor rotation, variable data scaling, and a nonnegative least-square estimation to derive previously unknown, geologically-meaningful end-members from the grain size measurements. The grain size components of multi-modal sediments have been successfully correlated with different modern transportational and depositional processes (Sun et al., 2002; Vandenberghe, 2013) and, as such, the end-members derived from EMMA used in this study are interpreted in the same way (Klovan, 1966; Ijmker et al., 2012; 2013). For more extensive reviews of EMMA see Klovan (1966), Klovan and Imbrie (1971), Weltje, (1997), Weltje and Prins (2003, 2007), Dietze et al. (2012; 2013), and Ijmker et al. (2012).

THE STUDY SITE

Rimrock Draw Rockshelter (RDR), discovered in 2009 within a relict stream channel, stands out as the first deeply stratified, multi-component Paleoindian site discovered (see Figure 1) in the Harney Basin, the northernmost internally draining basin within the North American Great Basin and the largest in Oregon (13,730 km$^2$). Geologically, Harney Basin is located within the eastern portion of the High Lava Plains province (HLP) of central Oregon, a Late Tertiary to Quaternary bimodal volcanic field that is comprised of basalt intercalated with rhyolitic ash flow tuffs and tuffaceous sediments with scattered rhyolite dome complexes (Jordan et al., 2004). The relict channel in which the site is located trends northwest, and is structurally
controlled by two fault scarps related to the Brothers Fault Zone (Lawrence, 1976; Orr and Orr, 2012) that have offset the uppermost basalt, providing topographic relief resistant to erosion.

RDR is positioned against the north-facing basalt fault scarp that forms the outside wall of a meander along the relict channel. The brow of the shelter (the outward-jutting portion of the scarp that acts as the shelter) juts approximately three meters northward from the base, providing the best protection from the rain, sun, and winds that consistently arrive from the southwest. Sedimentary deposits in this location are extremely deep by northern Great Basin site standards, with an accumulation of 3.0 to 3.25 meters. Excavation Unit 2 is located directly below the brow and to the west of a colluvial wedge (Figure 2). The channel in which the site is situated was fed by Rimrock Lake and Hay Lake playas within the basin (see Figure 1), with sediment influx into the relict stream channel predominately derived from the input of eroded basalt and rhyolite bedrock in the immediate area, and eolian processes providing sediment influx over the brow of the fault scarp. The current surrounding topography and soil quality is variable and supports a wide range of plant communities that are characteristic of a cold desert environment, with the dominant vegetation being the sagebrush (*Artemisia*) (McDowell, 1992; O’Grady, 2006; Orr and Orr, 2012).

**Archaeology of Excavation Block Unit 2**

Rimrock Draw Rockshelter and the surrounding lithic scatter are dominated by Western Stemmed Tradition (WST) projectile points such as Parman (Types 1 and 2), Haskett, Windust, Black Rock Concave Base, and Great Basin Transverse (Heizer & Hester, 1978; Beck et al., 2009). All have been collected in both surface and buried contexts. Artifacts associated with fluted point (possibly Clovis) technology (overshot flakes, bifaces with overshot flake scars, fluted bifaces and scrapers, and fluting flakes) were recovered from a surface concentration across the stream channel to the north (O’Grady et al., 2012). Artifacts with overshot technological attributes are regular finds during excavation. WST projectiles were utilized from
ca. 7,000 to 12,000 BP. Fluted point technology spans a time period from 12,800 to 13,250 BP based on a recent reconsideration of previously reported dates conducted by Waters and Stafford (2007). The chronology of fluted point occupations in the northern Great Basin remains unclear; some researchers believe that Clovis arrived to the region later than in other portions of North America. Thus, the timeline for Paleoindian occupation of Rimrock Draw may extend from 7,000 to 13,250 years based on projectile point typologies (Oetting, 1994; Waters and Stafford, 2007). Middle-to-late Holocene (ca. 1,000 to 7,000 BP) projectile point varieties have been found at the site as well, including an Eastgate arrow point (n=1), Elko Series dart points (n=4), a Gatecliff Split-Stemmed dart point (n=1), and Northern Side-Notched dart points (n=20). Northern Side-notched points date from 4,000 to 7,000 years in age. The paucity of more recent point types (Eastgate, Elko, and Gatecliff) suggests that the Northern Side-notched points may have been deposited closer to 7,000 years ago. Excavation Unit 2 produced three projectile point fragments, thirteen bifaces, twenty edge-modified flakes, eight cores, two overshot flakes, and over 3500 pieces of debitage from 25 (ten centimeter) excavation levels. A cache of 88 obsidian flakes, one scraper, and one biface with evidence of Sage grouse (*Centrocercus urophasianus*) blood residue was also recovered in Unit 2.

One significant discovery occurred during the summer of 2012, when a large chert scraper/graver was found 20 cm beneath megafaunal tooth enamel fragments associated with a thin layer of Mount St. Helens Sg tephra (13,000 RCYBP, or 15,800 cal. B.P). All were buried under the scarp collapse, protected from erosion that affected the coherence of the overlying deposits. Rimrock Draw Rockshelter thus fills an environmental and archaeological gap present in the Harney Basin during the Pleistocene/Holocene transition.

**Radiocarbon Chronology**

Charcoal samples were collected *in situ* during the course of excavation and extracted from bulk sediment samples through laboratory flotation. Juniper (*Juniperus sp.*), sagebrush
(Artemesia sp.) and rabbitbrush (Chrysothamnus sp.) charcoal was recovered throughout the deposits (Helzer, personal communication, 2014). Hearth deposits contained those and other plant species not present at the site today, originating from upland, lacustrine, and riparian settings. The analyses of botanical and pollen samples from the site are in progress and we herein limit our discussion to only those samples utilized for AMS dating. All in situ charcoal samples were submitted to Dr. Margaret Helzer (with assistance from Ph.D. Candidate Jaime Dexter) for archaeobotanical analysis. Identified specimens that were from short-lived or no longer extant species and considered to have strategic importance for answering questions related to site chronology were then forwarded to Beta Analytic, Inc., for AMS radiocarbon dating.

Four distinct hearth features were sampled, returning dates that span the Holocene. A fragment of sagebrush charcoal from hearth Feature 1, located in Unit 1 (less than one-meter south of Unit 2) produced a date of 3,990±30 BP (4,420-4,520 Cal. BP). Feature 1 was identified in the east wall of Unit 1 at an elevation of 62 to 94 cm below the surface. Willow (Salix sp.) charcoal from hearth Feature 3 returned a date of 5,760±40 BP (6,450-6,660 Cal. BP). Feature 3 was located in Unit 2, Quad B at an elevation of 189.5 to 195 cm below the surface. Hearth Feature 4, located at a depth of 195 to 205 cm below the surface, generated a date of 8,730±40 BP (9,290-9,840 Cal. BP) on a single burned bulrush (Scirpus sp.) seed. The feature was located in Quad D of Unit 2. Three hearth features (Features 2, 3, & 4) are present in Unit 2 (see figure 2), Quads B and D, from 150 to 205 cm below the surface. Hearth Feature 2 is currently undated. A fifth hearth, Feature 5, was noted in the east wall of Unit 2 at 235-245 cm below the surface. Willow charcoal (Salix sp.) produced a date of 8,830±30 (with intercepts at 10,130-10,060, 10,035-10,025, 10,010-9,990, and 9,945-9,740 Cal. BP).

Two dates were returned on opportunistic sampling from Excavation Unit 2 and nearby Excavation Square 7. A fragment of sagebrush charcoal collected in situ from a bedding contact located in Quad C of Unit 2, at a depth of 163 cm below the surface, produced a date of 1,090±30 (930-1,060 cal. BP). The sample was chosen to define the chronology of a transition from eolian sediments to dense cultural deposits, but we consider the date too recent to be
associated with the cultural deposits. A burned willow twig was recovered from a composite charcoal sample in Quad D of Unit 7 at a depth of 245 to 250 cm. The twig dated to 2,180±30 (2,120-2,210 cal. BP). Unit 7 is located just west and contiguous with Unit 2. This sample was chosen to clarify the age of a stemmed point found just underneath, but the date is not in keeping with the temporal distribution of such artifacts. The results from opportunistic charcoal sampling were inconsistent with the results from samples collected from sequentially-defined hearths in Units 1 and 2, and highlight the complexity of depositional and erosional sequences at the site. Ongoing geomorphic and sedimentological interpretations of the deposits at Rimrock Draw Rockshelter may help to explain these inconsistencies.

**MATERIALS AND METHODS**

During the 2013 field season, in-depth wall profiling and sediment sampling were conducted on the east wall of Excavation Unit 2 (Figure 2 and 3). Wall profiling was focused on the identification of distinct stratigraphic units (SU) and erosional boundaries, with each SU identified numerically from top to bottom. Column samples (n=13) were collected from top to the current base roughly equal distance apart in order to sample variation within the units, with the exception of the very top of the profile. A sample was extracted from the middle of SU 1 (see Figure 3), but was omitted after a preparation mishap.

Prior to grain size analysis, sediment samples were split using a box splitter to ensure homogeneity, with one half of each sample used for grain size analysis. Samples were weighed and dry sieved through 1, 2, and 4 mm sieves. The remaining fraction (<1mm) was homogenized and split into ~.2 to .5 gram subsamples. Organics were removed from the subsamples by pretreating for 48 hours with 40% H₂O₂ on a hot plate set at 105°C. Afterwards they were deflocculated using 10 ml of a dispersing agent (sodium hexametaphosphate; 50g/1 liter) and agitated for 24 hours. The GSD of each subsample was then measured by laser diffraction on a Malvern 2000G Hydro particle size analyzer using the Mastersizer software package version 5.6.
Machine optical properties were set to a particle refractive index of 1.544 (silica) with absorption at 1. Pump and stirrer speeds were set to 2000 RPM and 800 RPM, respectively. All Sample obscurations fell within an acceptable range (17 and 31%; Malvern Instruments Ltd, 1999). For complete machine protocols see Sperazza, et al. (2004). Each sample was measured three times and reported as the average. Three measurements of Powder Technology Inc.: ISO 12103-1, A4 Coarse Test Dust were used to monitor machine precision and accuracy.

The volume percentages of 12 grain size classes ranging from 1000 µm to 0.49 µm were measured from each sample. These results were then transformed to represent a percentage of the total bulk sample weight by multiplying by the percentage of the sample smaller than 1000 µm. The sieve fractions greater than 1000 µm were then added and normalized to bring the total to 100%. In all, thirteen sediment samples were analyzed producing a GSD dataset of 13 observations (samples) and 14 variables (grain size classes) the Malvern Mastersizer 2000 has the capability to measure. Whole phi grain size classes were used for two reasons: 1) the coarser fraction of the bulk sample was sieved using whole phi intervals and, because EMMA requires uniform catagories for analysis, was maintain throughout the analysis, and 2) to demonstrate that the method for measuring size classes are independent of EMMA and that results using a whole phi resolution provides.

**RESULTS**

**Field descriptions and grain size analysis**

A digitized column profile and the stratigraphic units (SU) identified during field work are presented in Figure 3. SU 1 is the upper most portion of Excavation Unit 2, extending from the surface to ca. 141 cm deep (samples 1 - 7). SU 1 is a very dark brown (10YR 3/2) to dark grayish brown (10YR 4/2) poorly sorted silty sand. Present within this SU are subangular to subrounded pumice and basalt clasts ranging in size from fine sand to fine gravel with no apparent bedding structures. There are, however, several groups of preserved laminations of
alternating silt and pumice (Figure 3). The clay fraction is relatively low, increasing downward from 8.8% to 12.5%. The silt fraction also increases downward from 28.8% to 37.47%. The sand fraction generally decreases downward, from 60.6% to 48.9% near the bottom. The gravel fraction ranges from 1.8% to 3.6%. The sand fraction does, however, increase to 57.3% at the base, along with a corresponding increase in the gravel fraction (3.7%) with corresponding decreases in the clay (10.1%) and silt (28.8%) fractions. SU 2 is much finer grained and the abrupt increase in silt and clay, a decrease in sand between SU1 and SU2, and the visually sharp contact suggests an unconformity.

SU 2 (samples 8 - 11) is a ca. 40 cm thick deposit of very grayish brown (10YR 4/2) poorly sorted sandy silt. This unit has the highest clay fraction ranging from 16.8% to 18.8%, and the lowest sand fraction ranging from 35.3% to 39.6%. Two soil sub-horizons were identified based on field observations of ped structure. The upper portion (sample 8) of the unit is a massive clay layer while the lower portion (samples 9 - 11) exhibits prismatic to blocky clay peds. This unit also has the highest gravel fractions, ranging from 2.6% to 7.5%. In the middle of SU 2, separating the upper and lower sub-horizons, are large subangular basalt boulders possibly derived from the brow of the basalt scarp or the colluvial wedge directly to the east. The lower boundary of SU 2 is also unconformable by large, angular basalt boulders. The transition from SU 2 to SU 3 is marked by a dramatic change in sand, silt, and clay percentages.

SU 3, capped by the large, angular basalt boulders, is a ca. 30 cm thick unit (samples 12 and 13) of olive brown (2.5Y 4/4) well sorted silty sand. This unit has the lowest silt fractions with both samples having at 23.5%, and the highest sand fractions at 62.8% and 63.9%. The clay fraction is low at 9.3% and 8.6%, compared to SU 2, and the gravel fractions are 4.3% and 4%. Though not sampled, a single gravel lens is present at the very base of this unit. There also are no apparent bedding structures or large clasts present.

Determining the composition of the Excavation Unit 2 archaeological components is a complex undertaking due to varying erosional and depositional mechanisms affecting the deposits. Artifact densities and variability among tool types across the site suggest that Unit 2 is
situated in the area preferred by site occupants for at least ten-thousand years. Two concentrations of artifacts were noted in the deposits there; one at 90 to 110 cm below the surface, and another, denser deposit from 165 to 250 cm. The latter is associated with the two distinct clay layers that mantle the rockshelter scarp collapse. Artifacts underneath the collapsed roof deposits are infrequent and believed to be truly ancient, exceeding ten-thousand years in age and pre-dating the Pleistocene/Holocene transition.

The three SUs described above were easily distinguishable through field observations and by grain size percentages, but the transportation and depositional processes responsible for site formation were not determined from this data because no relationship could be identified between the univariate grain size fractions, providing very little information on site deposition. However, EMMA applied to the grain size distributions provides an opportunity to determine whether this method will independently sort the samples into similar units and provide additional geologically meaningful information not evident from field observations or single grain size methods.

**End-member modeling**

EMMA yielded an optimal model of three end-members (EM) comprising a combined 95.52% of the total variance within the measured GSDs across all samples measured (Figure 4A). The three end-members were selected partly on the inflection point of the explained cumulative variance curve of eigenvectors (<95%), their model goodness-of-fit (mean total $r^2$), and the principle of parsimony (smallest number of end-members possible). The composition of each sample was explained by the 3-EM model to more than 78% in all cases (Figure 4B), as well as an almost complete representation of phi sizes 1, 7, 8, 9, and 10 over 90% (Figure 4C). An analysis was performed with four end members, but the model goodness-of-fit and explained cumulative variance were not significantly better, nor did the fourth end-member represent any
difference in site formation interpretation. However, the 4-EM model may have identified human influenced modification pending artifact distribution analysis:

EM 1, representing 70.75% of the total measured variance, has a unimodal population with a narrow peak (mode at 500 μm) positioned in the coarse to medium transition sand range and a fine “tail” (Figure 4B). The highest EM 1 scores (Figure 5A and 6) are found in samples 12 (96%) and 13 (100%), within SU 3; scores then drop dramatically in sample 11, making up only 15%. EM 1 is not found in samples 8, 9, and 10, but reappears again in sample 7, comprising 51.5% of the sample. EM 1 is again found in small amounts within samples 3 through 5, roughly in the middle of SU 1, ranging from 4.3% to 26.8%, and increasing to 46.7% and 58.3% in samples 1 and 2, respectively.

EM 2 is trimodal with peaks in the coarse-to-medium sand range (mode at 500 μm), very coarse silt range (mode at 63 μm), and very fine silt range (mode at 7.8 μm) (Figure 4B). EM 2 is found in significant proportion in SU 1 with the highest scores found in samples 4 through 6, where they account for 86.8% to 95.7% of the samples (Figure 5A and 6).

EM 3 is bimodal with a narrow peak at the medium to fine sand transition (mode at 250 μm) and a broad peak at the fine to very fine silt transition (mode at 8 μm) (Figure 4B). EM 3 is found predominantly in association with the weak clay horizon, SU 2 (samples 8, 9, 10, and 11) making up 72% to 85% of the samples, and is also represented in sample 6 at 5.3% of the total (Figure 5A and 6).

**DISCUSSION AND INTERPRETATION**

**End-member distributions**

End-member distributions are compared to sample depth, single grain size percentages, and stratigraphy in Figure 6. The unmixing of the sediments using EMMA identified three sedimentary components responsible for 95.52% of total unit formation and, additionally, was
able to discriminate between the three stratigraphic units identified during field work. The 3-EM model also identified clear markers for specific transportational and depositional processes along with their relationship to one another within the sediment matrix, making for a more robust and meaningful interpretation of site formation above and beyond what field observations and single grain size percentages could have provided. The end-member loadings (i.e., the grain size distributions) derived from the 3-EM model are interpreted and linked to depositional processes identified through a classical understanding of grain size sorting and distribution during sedimentation, and can thus be correlated across depositional environments. Additionally, the EM scores provide quantitative information for representing the degree to which an EM contributes to each sample, thus providing detailed information as to the relative timing of the transportational and depositional processes responsible for Unit 2 formation.

EM 1 represents deposition under fluvial conditions, indicated by the well-sorted coarse component and the poorly-sorted fine component typical of fluvial sands (Sun et al., 2002). EM 1 is the most dominant end-member (70.72%) throughout the sediment matrix, demonstrating the importance of fluvial processes during site formation, particularly in SU 3, prior to ca. 9480 cal. BP. and in SU 1, after ca. 6,660 cal. BP. EM 1’s dominant presence within the samples in SU 3 also reflects site development during a wetter climate when water was able to move freely down the relict channel. This stage of site development correlates also with the moderate paleolake-levels of the Malheur Lake system within the Harney Basin (Dugas, 1998). EM 1’s declined presence at the base of SU 2, directly above the rock fall, indicates continued yet declining fluvial activity. The abrupt loss of EM 1 and the increase in EM 2, moving up the profile in SU 2, indicates a change from a dominantly fluvial environment to a relatively dry environment where eolian processes dominate. Directly above the erosional boundary EM 1 increases to more than 50% of the sample and then disappears, suggesting that the erosional boundary is the result of increased fluvial activity during this time. Additionally, the abrupt increase in EM 1 and the decrease in EM2 between sample three and four could be used to indicate an additional SU.
EM 2 is the second most dominant end-member (17.74%) and represents eolian deposition intercalated with sporadic alluvium/colluvium as indicated by the trimodal end-member loadings, typical of fluvially reworked eolian deposits including both coarse and fine eolian components and a fluvial component. This occurs in two manners: either 1) transported and deposited in hydraulic environments to form a typical reworked deposit, or 2) directly deposited in lakes or rivers (Sun et al., 2002). EM2’s distribution within Unit 2 indicates the dominance of eolian deposition in the later stages of site development after ca. 9480 cal. BP. and potentially identifies the eolian transportation of sediment from the desiccation of Rimrock Lake to the southwest sometime after ca. 9480 cal. BP. The intercalated alluvium/colluvium also indicates the continued influence of the unit’s location directly below the brow of the rockshelter and adjacent to the colluvial wedge, after ca. 6,660 cal. BP. Thus, caution must be maintained when considering the artifact context and radiocarbon dates within this SU, as date reversal could be caused by erosion down the colluvial wedge.

EM 3 is the third most dominant end-member (7.06%) and represents a depositional environment dominated by eolian transportation. The fine-skewed bimodal grain size distribution can be explained as either a two-suspension component eolian system of very-fine silt, transported in suspension, and medium-to-fine sand, transported in short-term saltation close to the surface (Sun et al., 2002) or as aggregates of fine silt and clay and/or coatings on the larger sand grains (Mason et al., 2003). EM 3’s confined presence by unconformities, its bimodal distribution of coarse to fine silts and clay, and its correlation with a Bt horizon indicates a more stable time during site formation. The small presence of EM 3 in sample 6, coupled with EM 2, seems to indicate a dry period where aeolian processes are solely responsible for site deposition.

The distribution of EMs compared to depth down the profile allows us to recreate the major transportational and depositional processes responsible for site formation much more quantitatively than the traditional granulometric methods and univariate interpretations typically used for environmental reconstruction in archaeology. By identifying end-members that represent the major transportational and depositional processes of site formation, geologically
meaningful links can be made between the archaeology and the environments in which they are found. Correlations and comparisons between other sites within the region and the local environment also can be made.

CONCLUSION

This study demonstrates the advantage of a statistical end-member approach to separating sedimentary components of multi-modal grain size distribution to confirm and quantify the stratigraphy identified in the field and the transportational and depositional processes responsible for the majority of a unit’s formation. EMMA applied to sediments at Unit 2 of Rimrock Draw Rockshelter successfully demonstrated the ability to (1) distinguish between depositional units, (2) provide geologically meaningful and quantitative grain size end-members, and (3) provide geological meaningful interpretations of paleoenvironments.

However, it must be cautioned that before the particle size end-members can be more definitively interpreted additional particle size data needs to be collected and analyzed by the same laser diffraction methods from a variety of modern analogues in the surrounding area. Also, a complete paleoenvironmental interpretation of the site cannot be solved without taking into account the geological context of the GSDs, which can only be captured by the analysis of grain size classes across a series of GSDs sampled from multiple depositional environments in the surrounding area and across all excavation units at the site (Weltje and Prins, 2007). Additional studies are currently being conducted by the lead author on linking depositional environments of RDR with the surrounding area, specifically to the playa-lunette dune system in the vicinity. This will not only increase the confidence in end-member interpretations but also allow for the link between on- and off-site transportation and depositional processes to their climatic triggers, placing the site into a precise regional paleoenvironmental context. Additionally, the correlation
of EMs with artifact density also is pending and will be used to provide an understanding of human/environmental interactions at the site.

EMMA will be widely applicable to sites where both fluvial and aeolian derived sediment influx account for site formation and/or make interpretations of site formation difficult, and where an unbiased confirmation of environmental interpretation is needed. We also recognize that a complete interpretation of paleoenvironments require the addition of proxy data, as grain size analysis alone is not enough. However, EMMA provides a more quantitative way to identify transportational and depositional processes using grain size data than traditional methods currently used in geoarchaeology.
ACKNOWLEDGMENTS

A special word of thanks goes to the 2013 and 2014 University of Oregon Geoarchaeological Field School students. We also offer thanks to the Department of Geological Sciences, Graduate School, and College of Science at the University of Texas at El Paso, the University of Oregon Museum of Natural and Cultural History, Scott Thomas of the Bureau of Land Management (BLM), Burns District, and Dr. Margaret Helzer for their help and support of this research project. Additionally, we would like to thank the two anonymous reviewers who helped to make this manuscript better. Support for this project was funded in part by the 2014 Jonathan O. Davis Scholarship in Quaternary Sciences, given by the Desert Research Institute (DRI), and awarded to the first author.
REFERENCES


Lawrence, R.D., 1976, Strike-slip faulting terminates the Basin and Range province in Oregon.  


O’Grady, W.P., 2006, Before Winter Comes: Archaeological Investigations of Settlement and
Subsistence In Harney Valley, Harney County, Oregon. Ph.D. Dissertation, University of
Oregon, Eugene, Oregon.

Oregon Archaeology Field School at Rimrock Draw Rockshelter. Current
Archaeological Happenings in Oregon 37(2-3):4-6.


P.Z. Vroon, 2002, Ocean circulation and iceberg discharge in the glacial North Atlantic:
Inferences from unmixing of sediment size distributions. Geology 30(6):555-558.


Sedimentology 61:1157-1174.

Postfire soil burn severity mapping with hyperspectral image unmixing. Remote Sensing

Song, C., 2005, Spectral mixture analysis for subpixel vegetation fractions in the urban
environment: How to incorporate end member variability. Remote Sensing of
Environment 95:248-263.

Mapping tree and shrub leaf area indices in an ombrotrophic peatland through multiple


Figure 2.1. Location of Rimrock Draw Rockshelter. A) Hydraulic map of Harney Basin and its location within Oregon. Black star marks the location of Rimrock Draw Rockshelter (modified from Oetting, 1992), b) Google image of the surrounding area, including Rimrock Lake and Hay Lake playas. C) Google image inset showing the Rimrock Draw Rockshelter site within the relict channel. The relict channel is outlined in white.
Figure 2.2. Photograph of the rockshelter facing south. Note that Unit 2 and the colluvial wedge are identified. B) Schematic map view of excavation layout. Unit 2 is highlighted by the black box.
Figure 2.3. Unit 2 East wall photograph and digitized column profile drawing with stratigraphic units and their description. Location of calibrated radiocarbon dates are indicated by the black arrow. Column sediment samples also are identified.
Figure 2.4. a) Explained cumulative curve of end-members (eigenvectors). The inflection point used in this study is marked at end-member 3, representing 95.52% of the total variation. B) Variable-wise (Grain Size $\phi$) and c) sample-wise (Sample #) coefficients of determination ($r^2$) as quantitative error estimate.
Figure 2.5. End-member scores (%) showing proportion of variance explained by the end members of each sample. B) End-member loadings representing unmixed grain size distributions.
Figure 2.6. End-member scores (%) compared to column sample depth; sand, silt, and clay percentages; and stratigraphic units (SU) identified during field work.
Chapter 3
Characterizing the Formation Processes of Rimrock Lake, a Late Pleistocene-Holocene Playa-Lunette System in the Harney Basin, southeastern Oregon (USA), using End-Member Mixing Analysis (EMMA)

ABSTRACT

Playa-lunette systems collect and mix sediments derived from different sources and transported by multiple geomorphic processes (aeolian, fluvial, lacustrine). Mixing of the populations during transport and deposition produces multimodal grain-size distributions (GSD) reflecting different sources related to paleoenvironmental variations. Here, we use end-member mixing analysis (EMMA) to derive end members from measured GSDs of 256 sediment samples from Rimrock Lake (late Pleistocene/Holocene playa-lunette system in the northern Great Basin, southeastern Oregon) and a nearby relict channel with archaeological significance. The end-members derived from EMMA are used to characterize the timing, magnitude, and relationships of sedimentary processes shaping their evolution.

EMMA identified six sedimentary end-members (EM) representing 97.76% of the GSD variance. Three of these end-members correlate with fluvial (EM 1), lacustro-aeolian (EMs 2 and 6), and littoral (EM 5) depositional environments. Their spatial and temporal associations were correlated using nine radiocarbon dates across the study area. The spatio-temporal relationships between end-members and their reference to sediments of known origin across the site based on a classical understanding of sedimentation and transportation (i.e., aeolian vs. fluvial), as well as the sediment descriptions (i.e., bulk grain-size and textural classification), were used to reconstruct a geologically meaningful interpretation of the timing and magnitude of environmental conditions.

Results of this study indicate Rimrock Lake existed by c. 18,535 cal. BP., with lake expansion and lake-margin transgression through the Late Pleistocene and Early Holocene,
followed by desiccation beginning around ca. 6,190 cal. BP. A relict playa surface, exposed beneath lunette sediments and radiocarbon dated to 6,190 - 5,990 cal. BP., represents a shift to a drier climate causing desiccation of the lake, deflation of the playa floor, and subsequent formation of the lunette dune. The lunette also is characterized by the coarsest end-members, EMs 1 and 5, and the finest end-member, EM 6, representing multiple depositional processes responsible for its formation: silt and clay aggregates deflated from the playa floor, washed/inblown material along the lake margin, sediment recycling, and alteration by lake-level rise.
INTRODUCTION

Playas are ephemeral lakes found throughout arid and semiarid regions of the world (Shaw and Bryant, 2011). Many playas have related downwind marginal landforms called lunettes that were first named by Hills (1940). Lunettes are generally characterized as being crescent-shaped eolian dunes along the leeward margin of a playa that vary in height from 1 to 150 meters (Goudie, 2013; Rich, 2013). These geomorphically distinct features are jointly known as playa-lunette systems (Bowen and Johnson, 2012). Due to their ephemeral nature playa-lunette systems are highly sensitive to climatic fluctuations and are influenced, often simultaneously, by fluvial, lacustrine, and eolian processes (Bowen and Johnson, 2012, 2015; Holliday, 1997; Holliday et al., 2008; Rich, 2013), making them useful paleoenvironmental archives.

Paleoenvironmental investigations have been limited in the Harney Basin (Dugas, 1993, 1998; O’Grady, 2006), the northernmost internally draining basin in the Great Basin and the largest in Oregon, covering roughly 13,730 km² and having an elevation range of 1220 to 2759 meters above sea level. Occupying the lowest elevation of the basin is one of the largest freshwater marsh habitats in the Unites States: The Malheur Lake system (see Figure 1; McDowell, 1992; Oetting, 1992; Dugas, 1998; Orr and Orr, 2012). Very little work has been conducted within the Harney Basin that describes the timing and magnitude of environmental change during the Late Pleistocene and Early Holocene (Dugas, 1998; O’Grady, 2006; also see the Great Basin Paleoenvironmental Database, http://www.dri.edu/gbped). The lack of a paleoenvironmental framework during this time is a major hindrance to current and future paleoenvironmental and archaeological research. Fortunately, playa-lunette systems are particularly ubiquitous in the Harney Basin of southeastern Oregon (see Figure 1), and represent potentially high-resolution archives of paleoenvironmental change.

Playas and lunettes have been described in Africa, Australia, Arabia, and in California and the High Plains of the western US (Goudie and Wells, 1995; Shaw and Bryant, 2011).
Despite the considerable amount of research conducted on playas worldwide, the timing and processes responsible for playa-lunette evolution still remains unclear (Bowen and Johnson, 2012). Previous work on lunettes have shown them to form along the leeward margin of playas through the build-up of aggregated silt and clay pellets deflated from the dry exposed playa surface during dry conditions (Stephens and Crocker, 1946; Campbell, 1968; Bowler, 1973, 1983; Lancaster, 1978; Goudie and Thomas, 1986), as well as from washed or in-blown material accumulating along the margin during wetter conditions, either as beach deposits or from river deltas (Bowler, 1973, 1986; Thomas et al., 1993; Hipondoka et al., 2004). Lunettes also have been shown to form through a more complex process, with sediment recycled from older lunettes and neighboring linear dunes (Telfer and Thomas, 2006). It is also suggested that alteration of lunettes may be due to wave processes along the downwind margin of the basin when water level is high, with finer sediment subsequently deflated from the exposed beach as water level falls (Campbell, 1968).

Despite the different ways in which playa-lunette systems have been shown to develop, their evolution is commonly not due to a single process (Gustavson et al., 1995; Holliday et al., 1996). The difficulty in understanding the sedimentary processes responsible for their evolution is due, in part, to the complex nature inherent in the transportation and mixing of their sediments. The measured grain-size distributions within any sedimentary system will represent the combined result of all possible physical processes interacting with the sediments, with each assuming to contribute to the overall population of sediment. Therefore, each spatially and temporally distinct sediment sample will contain a grain-size distribution composed of multiple grain-size populations having been subjected to time-averaging effects such as transportation, bioturbation, erosion, and accumulation.

Understanding playa-lunette response to past climatic fluctuations is essential for creating a paleoenvironmental framework of the Harney Basin. Therefore, this study is focused on Rimrock Lake (RLP; 43° 29’ 55” N, 119° 49’ 31” W), a playa-lunette system, and the associate relict channel that drains the fault terrace in which the playa is located (Figure 1). The relict
channel also has archaeological significance, as it contains Rimrock Draw Rockshelter (35HA3855), a deeply stratified, multicomponent Paleoindian site discovered in 2009 and currently still being excavated by the University of Oregon’s archaeological field school (O’Grady et al., 2012; Collins, et al., 2016).

Two questions were asked: First, can the timing and magnitude of paleoenvironmental change be distinguished within the sediments of Rimrock Lake playa-lunette system? Second, can those environments and processes be correlated or linked to those identified in the relict channel (see Figure 1). In order to answer these questions, an end-member mixing algorithm (EMMA; Dietze et al., 2012) is used to mathematically derive end-members from the measured inorganic grain-size distributions (GSD) of 256 sediment samples collected from cores and trenches across the study area. The end-member distributions are then used to model changes in both paleoenvironments and sedimentary processes. Nine radiocarbon dates, spanning ca. 18 535 cal. years B.P, are used for temporal control.

**Regional Setting**

Rimrock Lake is a small tectonically controlled ephemeral playa located along the western margin of the Harney Basin, USA, with geoarchaeological significance (Collins et al., 2016) (see Figure 1). The topography and hydrologic systems surrounding Rimrock Lake Playa (RLP) are controlled by the terraced volcanic stratigraphy typical of the High Lava Plains province of central Oregon, a Late Tertiary to Quaternary bimodal volcanic field (50 km by 150 km) (Jordan et al., 2004). RLP is roughly circular and has a surface area approximately 0.46 km² and is bounded on all but the eastern margin by basalt fault scarps offset by the Brothers Fault Zone that trends NW (Lawrence, 1976; Johnston and Donnelly-Nolan, 1981; Orr and Orr, 2012). The surface is light gray to white, relatively flat, dry, and non-vegetated. The surrounding vegetation is characteristic of a cold desert environment, with the Big sagebrush (A. tridentata)
and rabbitbrush (*E. nauseosa*) dominating (McDowell, 1992; O’Grady, 2006; Orr and Orr, 2012).

Hay Lake (HL) playa-lunette system is located on the same terrace ca. 3.5 km to the east of RLP (see Figure 1) and may have been connected to RLP as either a single playa or marsh, or by channel confluence prior to draining down the relict channel. The relict channel is located between RLP and HL, and receives input from both the faulted terrace and from Juniper Ridge, a rhyolitic dome located to the east of the study area. The relict channel flows northwest between two fault walls and into a lower terrace. Numerous other playas of varying size also are located within other volcanic terraces to the north and southeast of RLP (see Figure 1). These playas and their hydrological systems also are controlled by tectonics and volcanic stratigraphy, typically being drained along fault boundaries with some playas possibly receiving input from others as overflow.

The Rimrock Lake playa-lunette system has at least seven identifiable geomorphologically distinct zones: the playa floor, annulus, bench, inflow channels, deltas, lunette, and colluvial wedges (Figure 2A). The western margin of the playa is bounded by a fault scarp resistant to erosion, providing a topographic relief of up to 7 meters (Figure 3.3). Multiple colluvial wedges have formed at the playa margin where the fault scarp has collapsed (Figure 3.3). The playa floor is along the southwestern margin of the basin and is still intermittently inundated with water. The annulus is the steeply sloping zone between the playa floor and the wide playa bench that serves as an inner shoreline when the playa is inundated. The bench also acts as the playa floor during times of more inundation. A lunette dune has formed along the eastern margin, accumulating against the northeastern fault scarp, and terminates on both ends against the two deltas that have formed on the northern and southern margin due to fluvial sediment input from two ephemeral channels during wetter times. A bench has been cut around the playa margin, and represents a period of time when deep water filled the basin. The bench is most developed along the eastern portion of the playa, and is visible along the lunette dune.
Paleoenvironmental Background

The timing and magnitude of paleoclimatic change during the late Pleistocene and early Holocene are poorly understood within the Harney Basin, with the majority of studies focused on the Malheur Lake system identified in Figure 1 (Dugas, 1998; O’Grady, 2006). The earliest Quaternary paleoenvironmental record of the Harney Basin comes from the presence of Tulelake-64 tephra deposited at wave base around the Malheur Lake system between ca. 70,000 and 80,000 years ago (Dugas, 1998). Radiocarbon dates from shell material preserved in beach berms around the Malheur Lake system indicate two periods of moderate-sized lakes between ca. 32,000 to 29,500 and at ca. 9,500 years BP. Smaller lake systems were present between ca. 8,400 and 7,400 years B.P. and between ca. 4,000 and 2,000 years B.P. (Dugas, 1998), with a series of wet periods around ca. 5,300 years B.P. Pollen analysis from sedimentary cores extracted from Diamond Pond, located in southern Harney Basin, suggest that the Harney Basin experienced a shift to drier conditions between ca. 6,000 and 5,400 years B.P., with a change to wetter conditions beginning shortly after. By 3,450 years B.P. Diamond Pond was at its deepest (Wigand, 1987), reflecting the onset of the Medithermal (Antev, 1948) and wetter conditions than today. These wetter conditions were punctuated by distinct drought episodes until ca. 2,600 B.P. when a drying trend began. Since ca. 2,000 years B.P., there have been fluctuations in effective moisture and droughts (Wigand, 1987; Oetting, 1992).

In the Dietz Basin of Lake County, Oregon, southwest of the Harney Basin, Pinson’s (2008; 2011) geoarchaeological excavations have demonstrated that wetter regimes existed in the area during the Younger Dryas (11,000 to 9,800 years B.P.), followed by several hundred years of a wet-dry precipitation regime that led to the desiccation and formation of a playa-lunette system. Following ca. 9,000 years B.P. dryer conditions persisted into the Middle Holocene, as evidenced by the stabilization of the lunette dunes and the formation of pre-Mazama soil, with a return to slightly wetter conditions afterwards (Pinson, 2008; 2011).
Studies identifying the timing and magnitude of paleoclimatic change from the surrounding area help provide an understanding of the paleoclimatic change within the Harney Basin. However, caution is advised, since differences in the spatial pattern of lake-level fluctuations across the Great Basin have been observed, specifically between the Bonneville, Lahontan, Chewaucan, and Owens Lake basins (Oviatt, 1997; Cohen et al., 2000; Liccardi, 2001; Wigand and Rhode, 2002). Paleolake-level fluctuations across the western US are thought to be dominantly controlled by a shifting polar jet stream that serves as the boundary between warm tropical air masses and cold polar air masses (Antevs, 1948; Hostetler and Benson, 1990; Liccardi, 2001). It therefore can not be assumed that similarities can be drawn between basins in an attempt to provide paleoenvironmental context to archaeological questions. For example, Liccardi (2001) points out that the ca. 12 $^{14}$C ka lake-level high in pluvial Lake Chewaucan basin, Oregon, is coeval with low stands in the Bonneville and Lahontan basins and wetter conditions in the Owens Lake basin, representing a variable synoptic response to climatic forcing that may highlight non-climatic mechanisms for lake-level fluctuations within basins (Licciardi, 2001). It also has been observed that there is a discordance in paleoprecipitation proxies between lake vs. upland pollen records in the western North America Pleistocene record (Cohen et al., 2000), with differing sensitivity or response rate of different systems to the same climatic factor being one possible explanation (Wigand and Rhode, 2002).

**MATERIALS AND METHODS**

Stratigraphy of RLP and relict channel was exposed during the 2013 and 2014 summer field campaigns using a PowerProbe 9600 corer and a backhoe excavator provided by the Burns District Bureau of Land Management (BLM). Four sedimentary cores were extracted from the playa floor and bench, in conjunction with a backhoe trench bisecting the lunette dune (Trench 2), along a single east-west transect (Figure 2). The stratigraphy of the relict channel was exposed by trenching (Trench 1) across the channel, and supplemented through the examination
of wall profiles exposed within two archaeological excavation units (Unit 2 and Unit 22) from the Rimrock Draw Rockshelter site (35HA3855) located within the channel upstream from the Trench 1 (Figure 2). The archaeological excavations at Rimrock Draw Rockshelter are still ongoing, but have exposed approximately 4 meters and at least four distinct stratigraphic units (SU). Photographs of the sedimentary archives are presented in Figure 2. Excavation Unit 2, the main excavation block of Rimrock Draw Rockshelter, has been examined in detail and reported in Collins et al. (2016).

Cores were collected in 1.22 m sections in clear plastic liners. The ends were sealed with tape, wrapped in plastic shrink wrap, and transported back to the University of Texas at El Paso. In-depth wall profiling and sediment sampling was conducted on the trenches and excavation walls. The sediment samples were collected from top to bottom in ca. 10 cm increments. The core sediment samples (ca. 1 gram) were taken in 5 cm increments along each core in conjunction with a detailed description of core stratigraphy (i.e., Munsell color, texture, structure, redoximorphic features, and carbonate occurrence).

The column sediment samples extracted from the exposed trench and excavation walls were split and homogenized using a box splitter and then weighed and dry sieved through 1, 2, and 4 mm sieves. The 4 mm fraction was insignificant and therefore omitted from the analysis and not reported. The fine fraction (<1mm) collected from sieving was further homogenized and split into 2 to 5 mg subsamples and pretreated with 40% H₂O₂ to remove organics. Both core and profile samples were deflocculated using a sodium hexametaphosphate solution (50 g/L). The inorganic grain size distribution (GSD) of each sample was then measured three times and averaged using a Malvern Mastersizer 2000 laser diffraction particle-size analyzer equipped with a Hydro 2000G pump accessory and generally following the protocols recommended by Sperazza et al. (2004). The results were compiled using the Mastersizer software package. Duplicate samples and a standard coarse test dust (Powder Technology Inc.: ISO 12103-1, A4 Coarse Test Dust) was used to monitor machine precision and accuracy.
In total, the volume percentages of 12 grain size classes ranging from 1000 µm (0 phi) to 0.244 µm (12 phi) were measured from each sample. The results of the column subsamples were transformed to represent a percentage of their total bulk weight by multiplying by the percentage of the sample smaller than 1000 µm. The sieve fractions greater than 1000 µm were then added back and normalized to bring the total to 100%. In all, the measured data combined to produce a GSD dataset of 256 observations (samples) and 14 variables (grain size classes). The resulting GSD matrix was then mathematically unmixed by an end-member mixing algorithm (EMMA) using the MatLab program from Dietze et al. (2012). Standard deviation (mathematical expression of sorting) was calculated for the measured samples using Microsoft Excel and classified using Folk (1974). Sediment texture of each sample was classified from the GSD using the US Department of Agriculture (USDA) classification scheme.

**End-member mixing analysis (EMMA)**

Different approaches to the decomposition of grain size distributions have been widely applied to divide grain size components of terrestrial, fluvial, and eolian sediments. Examples include Weibull-distribution fitting (Sun et al., 2002, 2004, Sun et al., 2008), lognormal-distribution fitting (Qin et al., 2005, Xiao et al., 2009, and Xiao et al., 2013), and the EMMA method used in this study (Weltje, 1997; Weltje and Prins, 2003; Dietze et al., 2012; Dietze et al., 2013; Dietze et al., 2014; Collins et al., 2016; and Langford et al., 2016). Unlike multivariate statistical methods such as principal component analysis (PCA) and factor analysis (FA), EMMA performs a simultaneous interpretation of all variables within the dataset for every sample and does not require any a priori assumptions (i.e., the number of end-members and their shapes do not have to be specified). EMMA assumes the samples are formed through the mixing of distinct sediment populations (i.e., fluvial, eolian, and lacustrine) deposited from a limited number of processes (i.e., traction, saltation, and suspension), or from a limited number of distinct sources exhibiting a linear mixing relationships (Dietze et al., 2012).
EMMA is an eigenspace decomposition technique with various scaling procedures designed, when applied to sedimentary GSDs, to extract genetically meaningful end-member grain-size distributions and their percentages within each sample (Weltje, 1997; Dietze et al., 2012, 2013). The end-members, representing a series of fixed compositions, can then be regarded as distinct subpopulations within the analyzed dataset (Weltje, 1997). By simultaneously unmixing the entire GSD dataset, the volumetrically significant sedimentary end-members across genetically related environments can be characterized, providing more valuable results than interpreting site-specific anomalies using individual samples. The end-members (EMs) can then be interpreted in terms of sediment transport processes, allowing for the characterization of depositional environments (following e.g., Folk and Ward, 1957) and their evolution across space and time.

EMMA is particularly well suited to the unmixing of multimodal grain size distributions (Dietze et al. 2012), and has most recently been used successfully to unbiasedly confirm field descriptions of exposed stratigraphy from the main excavation block of Rimrock Draw Rockshelter (Collins et al., 2016), identify the downwind mixing of grain size populations in order to segregate different depositional processes of a gypsum dune field (Langford et al., 2016), and characterize transport and deposition of specific eolian sediments (Prins et al., 2007; Vandengerghe, 2013). For an excellent review, see Weltje and Prins (2007) and Dietze et al. (2012).

**Radiocarbon Dating**

Nine AMS radiocarbon dates were obtained by Beta Analytic Radiocarbon Dating Laboratory and are used for temporal control across the study area. See Figures 3.6 and 3.7 for location of radiocarbon dates. Reports of calibration of radiocarbon age to calendar years are provided in Appendix A. Six dates come from the organic fraction of sediment sample taken from RLP. Three additional radiocarbon samples were selected from the playa, but were unable
to be dated due to the lack of organic material within them. Three dates come from charcoal material excavated from Unit 2 within the relict channel and are reported in detail in Chapter 2. The ages mentioned throughout this chapter refer to the 2-sigma calibrated results reported by Beta Analytic, Inc. The bottom two radiocarbon dates reported within the lower portion of Core 2 are out of order, however, their age ranges fall within 300 years of each other and can be explained by bioturbation or erosion, ruling out contamination during sampling. Dates reported within Unit 2 are in chronological order, but are located adjacent to a colluvial wedge and may have been transported down slope due to colluvial movement down the wedge.

**RESULTS AND INTERPRETATION**

**Sediments and Stratigraphy**

Eight distinctive stratigraphic units (SU) were identified across the study area and are illustrated in Figure 6. SUs 1, 2 and 3 are located within the relict channel and SUs 4, 5, 6, 7, and 8 are located within the playa-lunette system. The measured GSDs (Figure 4), Munsell color, and textural classification (Figure 5) vary across all SUs and are summarized in Table 1. Figure 3.4 provides the measured GSDs for each SU.

- **SU 1** is composed of the upper 147 cm of sediments, and is laterally extensive across all three units exposed within the relict channel. It is highly bioturbated and pedoturbated and exhibits a broad range of colors: brown (10YR 3/2) pale yellow (5Y 8/2) across the top to dark grayish brown (10YR 4/2) and white (5Y 8/1) across the bottom. Sediment texture is classified as a sandy loam, with sand- to granule-sized pumice clasts visible. The sediments are mostly massive, with thin laminations present in the upper portion. The lower portion is gradational with a deposit of Mt. Mazama tephra (7,600 cal. BP) found across the relict channel, and sits unconformably atop SU 2. The measured GSDs are all bimodal, with modes
in the medium- to coarse-grained sand range (0.5 to 1.5 phi) and coarse-grained silt range (4.5 phi). A few samples in Trench 1 do, however, exhibit modes of fine silt (6.5 phi) and fine sand (2.5 phi) (see Figure 4). The average median grain size is 103.6 µm (very fine sand).

- **SU 2** is a distinctive ca. 1-meter-thick B horizon found within the relict channel and has an upper erosional boundary unconformable with SU 1. It displays a grayish brown (10YR 5/2) to dark grayish brown (10YR 4/2) color throughout. Sediment texture is classified as loamy and has several large subangular boulders of basalt found throughout. In general, it can be divided into a massive upper portion and blocky to prismatic lower portion. The measured GSDs are unimodal, with a mode in the fine silt range (6.5 phi). The GSDs of the sediments closest to the fault scarp in Unit 2, however, are bimodal, with a mode in the fine silt range (6.5 phi) and a mode in the medium sand range (1.5 phi). The average median grain size is

- **SU 3** is the lowest unit across the relict channel and is a massive ca. 30 cm thick unit of olive brown (2.5Y 4/4) sediment. Closest to the fault scarp in Unit 2 it is capped by large, angular basalt boulders. Moving north toward the center of the channel it has an upper erosional boundary unconformable with SU 2 above. The base of SU 3 in Trench 1 sits within well rounded cobbles (Figure 3.4), and has a sand and sandy loam texture with well rounded gravel clasts of basalt and rhyolite, representing the local flood basalt bedrock and nearby rhyolitic intrusion, Juniper Ridge. No pumice clasts are evident. The measured GSDs are unimodal with a mode in the coarse sand range (0.5 phi) and exhibiting a fine tail of fine silt. The average median grain size is the coarsest of all SUs at 198 µm (fine sand).

- **SU 4** is a massive 70 cm thick unit and found within Trench 2 bisecting the playa margin. It is generally massive, but does exhibit a platy structure and sometimes
fine laminations within the upper ca. 20 centimeters. It has a consistent very dark grayish brown color (10YR 3/2). It is thickest near the playa margin and rapidly thins toward the playa bench. The surface is wave-cut and vegetated with rabbitbrush (*Ericameria nauseosa*) (Figure 3.4). The texture is classified as a sandy loam. The measured GSDs have modes in the fine to coarse sand range (2.5 and 0.5 phi) and clay to coarse silt range (10.5 and 4.5 phi). The median grain size is 159 µm (fine sand).

- **SU 5** comprises the upper ca. 10 centimeters of the playa floor and bench and is light gray (5Y 7/2) to white (5Y 8/1) in color. Sediment texture ranges from a loam to sandy loam texture. The measured GSDs are multi-modal on the playa bench and uni-modal across the playa floor. The modes range from fine silt (7.5 phi) to fine sand (2.5 phi). The average median grain size of 46.68 µm (coarse silt).

- **SU 6** is a massive very dark grayish brown (10YR 3/2) unit located below SU 4 in Trench 2. It has an upper unconformable boundary that is identified as a relict playa surface sitting 82 centimeters below the surface, and 8 cm above the current playa bench. The lower 40 centimeters exhibits a weakly developed upper Bk horizon and a weakly developed lower Bt horizon with iron oxide mottling. The very base of SU 6 has a gley color indicating groundwater saturation for long periods of time. Sediment texture is classified as a sandy loam and is nearly visually the same as SU 4 above it. The measured GSDs throughout SU 6 also generally exhibit nearly the same distribution as SU 4, though with much more sorted coarse modes, and only a slightly coarser median grain size of 167.18 µm (fine sand). Visually evident within the unit are rounded to sub-rounded sand-sized clasts of basalt and rhyolite that exhibit no apparent bedding structures.

- **SU 7** is characteristic of a dark lacustrine mud and is located across all cores. It has a massive structure with faint laminations present. It has little to no carbonate,
few isolated granules or pebbles, and a texture that varies from a clay to a silt loam. It is thickest (ca. 420 centimeters) in Core 1, closest to the basalt scarp, and thins toward Core 4, closest to Trench 2, with its thinnest portion in Core 3. Color gradually changes from grayish brown (10YR 5/2) in the upper ca. 100 cm to a pale yellow (5Y 7/3) in the remaining lower portion. At the noted color change boundary, isolated pebbles and cobbles are present, along with pedogenic carbonate, in Cores 1, 2, and 4. The measured GSDs across all cores are generally unimodal with modes at the very fine to fine silt transition (7 phi) and have an average median grain size of 6.03 µm (very fine silt).

- **SU 8** comprises the remaining portion of all cores. It is thickest in Core 3 (370 centimeters) and thinnest in Core 4 (110 centimeters). It is lighter in color than SU 7, ranging from pale yellow (5Y 7/4) to light gray (5Y 7/2). Sedimentary texture ranges from loam to fine sand, with the coarsest sediments forming a ~50 cm thick layer within Core 2 beginning ~350 centimeters below the surface. The measured GSDs are generally unimodal with modes in the medium to fine sand range (1 phi to 3 phi) and the fine to very fine silt range (7.5 phi to 6.5 phi). The average median grain size is 57 µm (coarse silt).

The sorting values of all sediment samples fell between 1.56 and 5.01 phi (moderately sorted to very poorly sorted), with an average of 3.98 phi (very poorly sorted). Only one sample from Core 2 could be classified as moderately sorted. The poorly sorted nature of almost all of the sediments demonstrates the mixing nature of playa-lunette systems and the multimodal nature of their sediments. The poorly sorted nature of the sediments also demonstrates the large amount of mixing from deposits originally existing as well sorted units of discrete origin through bioturbation, pedoturbation, or other depositional and transportational processes reworking the deposits across the study area.
End-member Modeling

Mathematically unmixing the measured GSDs using EMMA generated six end-members (EM) that explain a combined 97.76% of the total variance across all samples measured. The end-members were selected, in part, by their explained cumulative variance curve of eigenvectors (>95%), their goodness-of-fit (mean total $r^2$), and parsimony (Figure 6). The end-member loadings (i.e., their GSDs) were interpreted and linked to sedimentary processes identified through both a classical understanding of grain-size sorting and distribution during sedimentation and field observations, and then correlated across the playa-lunette system and relict channel (Figure 3.6 and 3.7).

- **EM 1** explains 59.06% of the total measured variance within the measured GSD dataset. It is bimodal with a narrow mode positioned in the medium and coarse sand range (phi 0.5 and 1.5) and a broad mode within the fine silt (phi 6.5) range. EM 1 is found to overwhelmingly contribute (< 90%) to the bottom three samples of Trench 2 (Figure 8A). These samples were collected from sediments exposed within the finer fraction above and within the channel lag in the middle of the relict channel and were identified in the field as fluvial channel sediment. EM 1 also is found predominantly in the lower portions of Cores 2, 3, and 4, and throughout the relict channel sediments, with a significant volumetric contribution to the middle of Core 2. It is found almost always in conjunction with EM 5 and contributes varying proportions in all core surface samples and all but three lunette samples. EM 1 is interpreted to contain a grain size distribution most closely resembling fluvial transport, which exhibits non-overlapping well sorted coarse-grained and poorly sorted fine-grained components representing both fluvial saltation mixed with eolian suspension fractions (Sun et al., 2002). The presence of EM 1 in all surface samples is likely due to the contribution of coarser
material being dispersed by fluvial processes into the channel and playa surfaces during heavy rainfall.

- **EM 2** represents 19.05% of the total variance within the measured GSD dataset. It is bimodal with modes in the coarse silt (4.5 phi) range and sand (0.5 phi) range. It is predominantly found throughout Cores 1 and 4, and in the upper portions of Cores 2 and 3. It also contributes minor proportions to most samples within SU 1 and SU 2 within the relict channel, with the exception of Unit 2 (Figure 3.6). EM 2 is found almost always in association with EM 6, except within the lunette dune. EM 2 is interpreted here to contain a GSD reflecting eolian transportation and deposition. Its contribution to the sediment samples across the study area can be explained by the simultaneous deposition of aggregated coarse silt and coarse sand into the playa and relict channel.

- **EM 3** represents 8.34% of the total measured variance within the GSD dataset and is trimodal with modes at the coarse to very coarse sand transition (0 phi), the fine to very fine sand transition (3 phi), and the very fine silt to clay transition (8 phi). It is mostly found in the relict stream channel where it makes up varying proportions of the samples. Though virtually absent in the core sediments, it does dominate volumetrically in isolated portions of Core 1 and 2, and the upper portion of Core 3. EM 3’s trimodal nature is interpreted to reflect a deposited mixture of the EM’s identified across the study area and represents a stable depositional environment, possibly of established vegetation or marsh, receiving input from multiple transport processes.

- **EM 4** represents 4.86% of the total measured variance within the GSD dataset and is bimodal, exhibiting a narrow mode at the medium to fine sand transition (phi 2) and a broad mode in the medium to fine silt range (phi 6 and 7). EM 4 has a relatively significant granule component (-2.5 phi) at 2.8% and is the most spatially constrained, being found only in Unit 2 and associated with the colluvial
wedge directly to the east. The GSD and constrained spatial distribution suggests EM 4 represents movement of sediments down slope as either debris flow, dry grain flow, or solifluction (Bertran et al., 1997) down the wedge and into the channel.

- **EM 5** represents 3.95% of the total measured variance within the GSD dataset and is unimodal with a narrow mode at the fine to very fine sand transition and has a fine tail in the clay range. Though it is found throughout the cores, it is found only in dominating quantities in the lower portion and in every sample of T1. EM 5’s association with fluvial sediments in the lower portion of the cores, and its overwhelming association with the wave-terraced lunette dune samples suggests that its GSD is derived not from eolian deposition but from near-shore wave-action during positive hydrological stages, in which the finer grained fraction is deflated from the exposed beach as the water level falls (Campbell, 1968).

- **EM 6** represents 2.5% of the total measured variance within the GSD dataset. Similar to EM 2, this EM is bimodal with a mode in the fine sand range (2 to 3 phi) and at the very fine silt to clay transition (8 phi). It is distributed throughout Core 1 and and the lunette dune, and contributes significantly to SU 7 of Cores 2, 3, and 4. It is virtually absent in the relict channel, but is found within SU 2. Most notably, EM 6 makes up the majority of sample 7 within Trench 2, located within the center of the relict channel. EM 6 also is found mostly in association with EM 2, with the exception of Trench 2. EM 2 is interpreted to be derived from a two-suspension component eolian depositional system of very fine silts and clays and medium to very fine sands that were either transported in suspension and short-term saltation close to the surface or as aggregates close to the ground.
DISCUSSION

The timing and magnitude of environmental change across the study area can be characterized by interpreting end-member distributions as being related to stratigraphy and depositional environments. Figure 3.7 presents the sequence stratigraphy interpreted from the end-members identified from EMMA. Radiocarbon dating and the presence of EM 3 in the deepest (ca. 6 meters) sediment sample from Core 1 suggests RLP was probably established as a stable, shallow-water environment receiving minor fluvial input (EM 1) by at least ca. 18,535 cal. BP. EM composition between 590 and 440 cm below surface indicates a shift to a deeper lacustrine environment that experienced alternation in water depth (EM 2 and EM 6) with associated littoral influence on the sediments (EM 5) and then a return to a marsh or spring environment similar to that at the base of the Core. Coarse grained texture and end-members dominate at the bottom of the other cores as this alternation takes place within core 1, indicating that the playa was relatively confined to a lower elevation along the fault scarp. The timing of this alternation is undated due to a lack of organic preservation, but probably took place after ca. 18,535 and before ca. 9,000 ca. BP, based on the dates returned from the sediment in the lower portion of Core 2. Following the return to a stable marsh environment at 440 cm below surface around ca. 9,000 ca. BP., a lacustrine environment dominates the rest of the core. An abrupt shift in end-member composition is identified across the other cores and is identified in Figure 3.7 as the boundary between SU 7 and SU 8.

The coarsest-grained end-members, EM 1 and EM 5, are found to dominate SU 8 within the lower portion of the Cores 2, 3, and 4, while the finest-grained end-members, EM 2 and EM 6, are found to dominate SU 7 within the upper portion of all cores (Figure 3.6). This distinctive boundary between coarse- and fine-grained end-members is interpreted to represent a flooding surface in response to playa expansion. Abrupt textural change from predominantly fine sand to silt loam also takes place across this boundary (Table 3.1; Figure 3.6). Radiocarbon dates above and below the boundary indicate that Rimrock Lake expansion occurred between ca. 6290 and
8070 cal. BP. A radiocarbon date of 6190 to 5990 cal. B.P. from sediments directly below the identified relict playa surface between SU 4 and 6, exposed along Rimrock Lake margin (Trench 2) (Figure 3.3A), suggests that water level dropped ca. 1,000 years after this identified lake level expansion. The 190 cm of overlying lacustrine sediments above the radiocarbon date of 6400 to 6290 cal. B.P. within Core 2 (Figures 3.6 and 3.7) and the lack of an identifiable deflation surface suggest that the playa probably only experienced only partial desiccation at this time. End-member composition of the sediments above and below the relict playa surface suggest that sedimentary processes contributing to deposition along the playa margin did not change during this drop in lake level (Figure 3.6) and that the playa margin migrated rather quickly in response to lake level drop in order to preserve the surface.

SU 1 and SU 2 within the relict channel exhibits the most variation in end-members (Figure 3.5A) and grain-size distributions (Figure 3.4) across the study area and represents an environment in which both eolian and fluvial sediments have been deposited simultaneously for the last 10 ca. ka BP (Figure 3.7). Additionally, the similarity between the modes of EM 3 and EM 4 found predominantly within SU 1 in the channel to those end-members found predominantly in the playa suggests that the relict channel acted as the depocenter for sediments moving down wind and down stream from the playa during this time, and provides an end-member link between the two environments.

A radiocarbon date of 6660 to 6450 cal. BP. reported at the base of SU 1 within Unit 2 and the presence of Mt. Mazama ash (Figure 3.3 B and C) dated to ca. 6800 cal. BP at its base suggests that increased eolian deposition related to aridity began prior to the lake level drop in water level identified by the relict playa surface exposed at the margin of RLP. Mt. Mazama ash is not visually represented within the playa or its margin. This probably indicates that there were other times in the history of RLP before the identified lake level drop when the playa surface was completely exposed, resulting in tephra fallout on a dry lake bed and the subsequent deflation of the tephra out of the playa and into the relict channel. Future micro-tephra analysis could resolve this issue.
Surprisingly, more similarity exists between SU 4 and 6 found above and below the relict playa surface exposed in Trench 2 than exists between grain-size distributions and end-members found within SU 5 and 7 in the upper portion of the cores (Figure 3.4 and Figure 3.7). This could be due to several reasons. SU 6 may have been a discrete layer across a portion of the playa that has since been deflated due to playa desiccation, causing it to be deposited on top of itself along the margin, creating a typical lunette dune derived from aggregates deflated from the surface. Alternatively, SU 6 could represent marginal sediments derived from confined and unconfined fluvial deposition that stepped backwards as water level rose, creating a relict playa surface when water level dropped again, sometime around ca. 6 cal ka BP, and marginal sediments built out on top of SU 6. Both scenarios consider that SU 4 and 6 are comprised of those end-members interpreted as representing lacustrine, fluvial, and littoral processes. However, the lack of EM 2, which is nearly always associated with EM 6 across the study area, and the sometimes dominating presence of EM 5 identified across the study area as a littoral environmental signature, seems to indicate the latter scenario mentioned above, with EM 2 being comprised of those fine sediments deflated from the margin and reworked farther into the basin. In any case, the marginal sediments identified in this study are apparently influenced by a combination of eolian, fluvial, and littoral processes.

CONCLUSION

Performing EMMA on the RLP and relict channel GSDs allowed for both the characterization of the timing and magnitude of paleoenvironmental change and provided an unbiased link between sedimentary processes across the study area. The utility of EMMA has been demonstrated in analyzing playa stratigraphy in order to identify paleoenvironmental shifts and in linking sedimentary processes between different sedimentary archives. Additionally, EMMA separated out three environmental signatures responsible for formation of the marginal sediments identified in Trench 2, demonstrating that lunette features are, in this case, a product...
of multiple sedimentary processes. Additional data from playa-lunette systems in the Harney Basin should be obtained and analyzed to see if this is a common feature.

This study also identifies landscape response to climatic change along the western margin of the Harney Basin that generally match what previous studies have identified and also fills a paleoenvironmental gap that is missing along the western margin of the Harney Basin, particularly between 18,535 and 6000 cal. BP., placing Rimrock Draw Rockshelter into a larger paleoenvironmental context. Lake level rise and fall identified during the early- to mid-Holocene fills a gap between ca. 7400 and 5000 years B.P. for which no lake levels have been identified for the Harney Basin (see Dugas, 1998). The shift to a more arid environment dominated by eolian processes identified in the relict channel starting ca. 8 cal ka BP also generally matches periods of aridity identified by Dugas (1998) in the Malheur Lake system and Pinson (2008) in the Dietz Basin to the southwest, and occurs ca. 1,000 years prior the arid conditions identified by Wigand (1985; 1987) at higher elevations at Diamond Pond. Future work in the area should focus on linking stratigraphy between playas in order to develop a more precise spatial and temporal context for basin response throughout the Late Pleistocene and Early Holocene.
ACKNOWLEDGMENTS

A special word of thanks goes to the 2013 through 2015 University of Oregon Geoarchaeological Field School students and laboratory assistants Kagan Richard and Amanda Ostwald, from the Department of Geological Sciences at the University of Texas at El Paso. I also offer thanks to Rick Wells of the Bureau of Land Management (BLM), Burns District, for use of his coring rig. Last, and certainly not the least, I would like to thank Drs. Thomas Gill and Richard Langford for their help and support in this study. Support for this project was provided in part by the 2014 Jonathan O. Davis Scholarship in Quaternary Sciences given by the Desert Research Institute (DRI), the University of Texas at El Paso Graduate School, the Geological Society of America, and the Bureau of Land Management.
REFERENCES


Thompson, R.S., C. Whitlock, P.J. Barlein, S.P. Harrison, and W.G. Spaulding, 1993, Climatic Changes in the western United States since 18,000 B.P. In: *Global Climates since the last Glacial Maximum*, edited by H.E.J. Wright, University of Minnesota Press, Minneapolis, pp. 468-513.


Table 3.1. Characteristics of stratigraphic units identified in Rimrock Draw Rockshelter and Rimrock Lake Playa-Lunette System.

<table>
<thead>
<tr>
<th>Stratigraphic Units</th>
<th>Location</th>
<th>Thickness (cm)</th>
<th>Sediment Texture</th>
<th>Munsell Color</th>
<th>End-member composition</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU 1</td>
<td>Relict Channel</td>
<td>120 - 160</td>
<td>sandy loam</td>
<td>brown, pale yellow, grayish brown, white</td>
<td>All</td>
<td>Eolian</td>
</tr>
<tr>
<td>SU 2</td>
<td>Relict Channel</td>
<td>60 - 110</td>
<td>loam</td>
<td>grayish brown, dark grayish brown</td>
<td>All</td>
<td>Lacustro-Eolian</td>
</tr>
<tr>
<td>SU 3</td>
<td>Relict Channel</td>
<td>30 - 40</td>
<td>sand - sandy loam</td>
<td>olive brown</td>
<td>1, 3, 4, 5,</td>
<td>Fluvial</td>
</tr>
<tr>
<td>SU 4</td>
<td>Playa margin</td>
<td>70</td>
<td>sandy loam</td>
<td>very dark grayish brown</td>
<td>1, 5, 6</td>
<td>Eolian, littoral</td>
</tr>
<tr>
<td>SU 5</td>
<td>Playa</td>
<td>5 - 10</td>
<td>loam - sandy loam</td>
<td>light gray, white</td>
<td>1, 2, 5, 6</td>
<td>Lacustro-Eolian</td>
</tr>
<tr>
<td>SU 6</td>
<td>Playa margin</td>
<td>&lt;110</td>
<td>sandy loam</td>
<td>very dark grayish brown</td>
<td>1, 5, 6</td>
<td>Eolian, littoral</td>
</tr>
<tr>
<td>SU 7</td>
<td>Playa</td>
<td>80 - 420</td>
<td>silt loam</td>
<td>grayish brown, pale yellow</td>
<td>2, 6</td>
<td>Lacustro-Eolian</td>
</tr>
<tr>
<td>SU 8</td>
<td>Playa</td>
<td>100 - 290</td>
<td>loam - fine sand</td>
<td>pale yellow, light gray</td>
<td>1, 2, 3, 5, 6</td>
<td>Fluvial, littoral</td>
</tr>
</tbody>
</table>
Figure 3.1. Location of Harney Basin within Oregon. Malheur Lake is identified. Inset showing a general overview of the study area, with Rimrock Lake, Hay Lake, and Rimrock Draw Rockshelter identified.
Figure 3.2. A) Modified Google Earth image of Rimrock Lake with geomorphic features, core locations, and Trench 2 identified. B) Modified Google Earth image of Rimrock Draw Rockshelter with Excavation Units, Trench 1, and channel boundaries identified. Dashed line represents channel boundary.
Figure 3.3. Picture of the fault scarp along the western margin of Rimrock Playa facing north.
Figure 3.4. Photographs of sedimentary archives. A) Relict playa exposed in Trench 2. B) West wall of Unit 22 showing sediment sample column. Note the white layer is Mt. Mazama ash sitting on top of SU2. C) East wall of Trench 1. Inset is picture of channel gravels and cobbles at base. D) East wall of Unit 2. Not the large angular basalt boulders indicating brow collapse. E) East view of Rimrock Lake lunette dune. White bracket identifies the dune.
Figure 3.4. Measured grain-size distributions for each SU.
Figure 3.5. End-member statistics. A) End-members unmixed by EMMA. B) Mean total $r^2$ of data modeled by the six end-members versus variable (Grain Size) and sample space (Sample ID). C) Explained cumulative variance of end-members identified.
Figure 3.6. Sedimentary and end-member stratigraphy of Rimrock Lake and Rimrock Channel. Dates reported as 2-sigma cal. BP.
Figure 3.7. Sequence stratigraphy of Rimrock Lake and Rimrock Channel. Interpreted from a combination of sediment description and end-members identified. Dates reported as 2-sigma cal. BP.
Chapter 4

Stratigraphic relationship between Rimrock Lake and Hay Lake playas, Harney Basin, eastern Oregon, USA.

ABSTRACT

End-member mixing analysis (EMMA) was conducted on the grain-size distributions (GSD) of 455 sediment samples collected from seven cores from Rimrock Lake and Hay Lake playas (eastern Oregon, USA) in order to characterize their stratigraphic relationship through time. EMMA identified five end-members (EM) that explain a combined 97.23% of the total variance across all samples measured and represent two major environments of deposition: lacustro-eolian and fluvio-lacustrine. EM 1 and EM 5 explain a combined 70.5% of the variance and are interpreted to represent lacustro-eolian deposition. EM 2 and EM 4 explain a combined 19.28% of the variance and are interpreted to represent fluvio-lacustrine deposition. EM 3 represents 7.46% of variance and is interpreted to represent a wet marsh or backshore environment that receives colluvial, fluvial, and eolian sediments.

In Rimrock Lake playa, EM 1 and EM 5 are found together in the upper portions of the cores, while EM 2 and EM 4 are found together in the lower portion of the cores, forming two distinctive sedimentary facies separated by a distinctive and abrupt boundary. In Hay Lake playa, EM 2 is found in association with EM 1 and EM 5 in the lower portion of the cores, while EM 4 forms a narrow interval across the upper portion of the cores. Eight radiocarbon dates suggest that Hay Lake and Rimrock Lake were established as marshy environments during the Late Pleistocene, ca. 19.5 cal ka BP, and experienced increased fluvial activity during the Late Holocene, between ca. 9000 and 8000 cal years BP. The depth of the latest radiocarbon dates also suggest that Rimrock Lake playa continued to experience a relatively deep lacustrine environment with alternating lake levels well into the Late Holocene, after ca. 6000 cal years BP., even during times of increased aridity, as evidenced by previous studies, and that tectonics
may have played a role in diverting ephemeral channels towards Rimrock Lake playa and away from Hay Lake.
INTRODUCTION

The Harney Basin is the northernmost internally draining basin in the Great Basin and the largest in Oregon, USA, covering roughly 13,730 km² and having an elevation range of 1220 to 2759 meters above sea level (Figure 4.1) (McDowell, 1992; Dugas, 1993, 1998; Orr and Orr, 2012). Paleoenvironmental investigations have been limited in the Harney Basin (Dugas, 1998; O’Grady, 2006), with very little work describing the timing and magnitude of environmental change during the Late Pleistocene and Early Holocene (Dugas, 1993, 1998; O’Grady, 2006; also see the Great Basin Paleoenvironmental Database, https://www.dri.edu/gbped). What little has been done has focused on the Malheur Lake system, which occupies the lowest elevation in the basin and is one of the largest freshwater marsh habitat in the United States (Figure 4.1) (McDowell, 1992; Oetting, 1992; Dugas, 1993, 1998; O’Grady, 2006; Orr and Orr, 2012).

Paleolake-level fluctuations identified across the Great Basin are thought to be controlled by a shifting polar jet stream that serves as the boundary between warm tropical air masses and cold polar air masses, thus controlling precipitation (Antevs, 1948; Hostetler and Benson, 1990; Liccardi, 2001). However, lake response to climatic fluctuations within the Great Basin are not uniform. For example, there are documented differences in the spatial pattern of lake-level fluctuations between the Bonneville, Lahontan, Chewaucan, and Owens Lake basins (Oviatt, 1997; Cohen et al., 2000; Liccardi, 2001; Wigand and Rhode, 2002). There are no records of differences between lake-level fluctuations within the Harney Basin or between the Harney Basin and other surrounding basins. Liccardi (2001) points out that the ca. 12 $^{14}$C ka lake-level high in pluvial Lake Chewaucan basin, Oregon, is coeval with low stands in the Bonneville and Lahontan basins and wetter conditions in the Owens Lake basin, representing a variable synoptic response to climatic forcing that may highlight non-climatic mechanisms for lake-level
fluctuations within basins. It also has been observed that there is a discordance in paleoprecipitation proxies between lake vs. upland pollen records in the western North America Pleistocene record (Cohen et al., 2000), with differing sensitivity or response rate of different systems to the same climatic factor being one possible explanation (Wigand and Rhode, 2002).

Playas are particularly ubiquitous along the western and southern boundary of the Harney Basin (Figure 4.1) and represent potentially high-resolution terrestrial archives of paleoenvironmental information. Playas are not unique to the Harney Basin and have been identified throughout arid and semiarid regions of the world (Cooke et al., 1993; Goudie and Wells, 1995; Shaw and Bryant, 2011; Bowen and Johnson, 2012; 2015; Rich, 2013). They have been demonstrated to record temporal climatic fluctuations, as they collect sediments that have been deposited, often times simultaneously, by fluvial, lacustrine, and eolian processes (Cooke et al., 1993; Holliday, 1997; Holliday et al., 2008 Bowen and Johnson, 2012, 2015; Rich, 2013; Adams and Sada, 2014). Understanding playa stratigraphy in the Harney Basin therefore can be a valuable tool for understanding basin response to both large- and small-scale climatic change. However, playa stratigraphies and their response to climatic fluctuations are poorly understood in the Harney Basin, and individual playa response could differ from one another significantly across the basin. The ability to identify the timing and magnitude of climatic fluctuations and link playa stratigraphies across a basin can be a powerful tool in understanding small-scale basin response to large scale climate fluctuations, provide a detailed description of landscape evolution, and provide a context for archaeology, ecology, and paleoenvironmental studies. Also, understanding fluctuations within multiple playas encompassing sub-basins of a larger basin can indicate small-scale responses to tectonics and precipitation run-off.

Late Pleistocene to Holocene lake level histories of Lake Bonneville and Lake Lahontan
indicate that there was a lake high stand between 16,000 and 13,000 B.P in both basins, reflecting a glacial-period climate, shortly after the LGM. Beginning about 13,000 B.P. in the Lahontan Basin and about 14,000 B.P. in the Bonneville Basin, lake levels dropped rapidly, reflecting a shift in climate from the colder glacial to the warmer and drier postglacial interval known as the Bølling-Allerød warm period (mentioned above). Between 11,500 and 10,000 B.P. lake levels in both basins saw a minor rise, and it is suggested that this may have been brought on by the Younger Dryas cooling event (Rhode and Madsen, 1995). The Bonneville and Lahontan Basins thus can be considered larger scale analogs to what may have been happening in the Harney Basin during the Late Pleistocene and Early Holocene.

Within south-central Oregon, Pluvial Lake Chewaucan filled four sub basins that are now occupied by modern Summer Lake, Upper and Lower Chewaucan Marshes, and Lake Abert (Licciardi, 2001). Using prominent shoreline features, at least six distinct stages of water level fall of the Pluvial Lake Chewaucan are identified following the maximum high stand. Interestingly, however, the lake level high of Pluvial Lake Chewacaun at around 12 ka occurred during a period of low lake-levels in the Bonneville and Lahontan basins, and post dates the high stands of these lakes by at least 1000 years (Licciardi, 2001). The earliest known Quaternary paleoenvironmental record in the Harney Basin comes from the Tulelake-64 tephra deposited at wave base around the Malheur Lake system between ca. 70,000 – 80,000 years ago (Dugas, 1998). Based on dates obtained from shell material within preserved beach berms, moderate-sized lakes may have existed in the Malheur Lake system between ca. 32,000 to 29,500 and again at ca. 9,500 years BP during the Holocene. Smaller lake systems also were present ca. 8,400, 7,800, and 7,400 years B.P. (Dugas, 1998). There are no dated lake-levels available at Malheur Lake for the period between ca. 7,400 and 5,000 years B.P., though it is suggested by
Wigand (1985, 1987) that drier conditions were established after 7,500 years B.P., with a series of wet periods ca. 5,300 years B.P., and between ca. 4,000 and 2,000 years B.P. (Dugas, 1998).

This study investigates the record of sediment transportation and deposition signals recorded within two small playas, Rimrock Lake and Hay Lake (Figure 4.2), located along the western boundary of the Harney Basin. Previous data on the stratigraphy of Rimrock Lake playa reported in Chapter 3 is compared to the stratigraphy of Hay Lake playa. The aim of this study is to characterize and link the timing and magnitude of signals of transportational and depositional signals recorded in both playas. An end-member mixing algorithm (EMMA) is used to distinguish populations within the combined dataset. Eight radiocarbon dates are used for temporal control.

**STUDY AREA**

Rimrock Lake playa (RLP) and Hay Lake playa (HLP) (Figure 4.1 and 4.2) are located in the Harney Basin within 3 km of each other between two rhyolitic domes, Juniper Ridge and Sheep Mountain, which supply sediments during wetter times. The playas are also structurally bound by the same faulted terrace, a result of the west-northwest-trending series of sub-parallel faults related to the Brother’s Fault Zone that crosses the Harney Basin (Jordan et al., 2004; Orr and Orr, 2012). Two ephemeral channels supply sediments eroded from the domes into the playas (Figure 4.2). Overflow is carried down Rimrock channel and empties onto another faulted terrace. A channel from Juniper Ridge supplies Hay Lake, while a channel from Sheep Mountain splits and supplies both playas. An additional ephemeral channel supplies sediments to Rimrock Lake playa from the north. Overflow from both playas are drained by a single ephemeral stream that drains the faulted terrace, in which Rimrock Draw Rockshelter, an important archaeological site, (O’Grady et al., 2012; Collins, et al., 2016) is located (see Figure 4.2).
The streams have formed deltas along the playa margins and represent interacting dynamic processes related to lacustrine environments, such as wave energy and tidal regimes, which could have modified and dispersed fluvially deposited sediments transported into the playas. The deltas within Rimrock Lake are more defined than those within Hay Lake. The delta along the southern margin of RLP is large, well defined, and has braided channels that have resulted in the continued ephemeral discharge from the stream channel during wetter periods. Two small deltas, now more reminiscent of alluvial fans are present along the eastern and southern margin of Hay Lake, suggesting a longer period of playa floor deflation and less fluvial input for a much longer time compared to RLP. Along the eastern margin of both playas crescent-shaped eolian features known as lunette dunes (Hill, 1940) have formed in response to desiccation and subsequent deflation of their floors during dry periods.

**METHODS AND MATERIALS**

Stratigraphy for each playa was examined by collecting a series of cores along transects (Figure 4.2) in May, 2014, using a PowerProbe 9600 corer provided by the Burns District Bureau of Land Management (BLM). The cores were collected in 1.22 meter sections in clear plastic liners. The ends were sealed with tape, wrapped in plastic shrink wrap, and transported back to the University of Texas at El Paso. A total of 455 sediment samples were collected from the cores at 5 centimeter increments in conjunction with detailed core descriptions (i.e., Munsell color, texture, structure, redoximorphic features, and carbonate occurrence).

The inorganic grain-size distribution (GSD) of each sample was measured using a Malvern Mastersizer 2000 laser diffraction particle-size analyzer equipped with a Hydro 2000G pump accessory following the procedures of Collins et al. (2016) and Sperazza et al. (2007). Results were compiled using the Mastersizer software package. Triplicate samples and a standard coarse test dust (Powder Technology Inc.: ISO 12103-1, A4 Coarse Test Dust) was used to monitor machine precision and accuracy. In total, the volume percentages of 26 grain size
classes ranging from 2000 µm (-1 phi) to 0.345 µm (11.5 phi) were measured from each sample. The measured grain size data was combined into a single matrix and mathematically unmixed by an end-member mixing algorithm (EMMA) using the MatLab program developed by Dietze et al. (2012). Sediment texture was classified using the US Department of Agriculture (USDA) classification scheme (Soil Survey Staff).

EMMA is an eigenspace decomposition with various scaling procedures designed, when used with regards to sediment granulometry, to extract genetically meaningful end-member grain-size distributions and their percentages within each sample (Weltje, 1997; Dietze et al., 2012, 2013). The end-members represent a series of fixed compositions that can then be regarded as distinct subpopulations within the analyzed dataset (Weltje, 1997). By unmixing the end-members simultaneously across the entire data matrix, the volumetrically significant sediment types within genetically related environments can be characterized instead of interpreting site-specific anomalies, providing more valuable results than from individual samples. EMMA is particularly well suited to the unmixing of multimodal grain size distributions (Dietze et al. 2012), and has most recently been used successfully to unbiasedly confirm field descriptions of exposed stratigraphy from the main excavation block of Rimrock Draw Rockshelter (Collins et al., 2016). It has also been used to identify the downwind mixing of grain size populations in order to segregate different depositional processes of a gypsum dune field (Langford et al., 2016), and characterize transport and deposition of specific eolian sediments (Prins et al., 2007; Vandengergh, 2013). For an excellent review, see Weltje and Prins (2003) and Dietze et al. (2012). The end-members (EMs) can be interpreted in terms of sediment transport processes, allowing for the characterization of depositional environments (following e.g., Folk and Ward, 1957), their evolution across space and time, and their link between genetically related environments. Using the method of Dietze et al. (2013), the normalized difference between the finest and coarsest end-members

\[
(EM_{\text{diff}} = (EM_{\text{coarse}} - EM_{\text{fine}}) ÷ (EM_{\text{coarse}} + EM_{\text{fine}}))
\]
was calculated as a visual proxy for lake-level change between both playas, assuming that the finest sediments are deposited in calm, deeper water, while coarser sediments settle close to the shore, shortly after entering the lake.

In Chapter 3, the grain-size measurements from Rimrock Lake cores were combined with those from the Rimrock Lake lunette dune and the exposed stratigraphy within the relict channel in order to place Rimrock Draw Rockshelter archaeological site and channel stratigraphy into a broader environmental context. The grain-size matrix used in this chapter compares those sediment samples from Rimrock Lake and Hay Lake playa stratigraphy, and includes just 10 samples from the upper stratigraphic unit in the relict channel. Nine radiocarbon dates were obtained by Beta Analytic Radiocarbon Dating Laboratory and are used for temporal control between both playas. See Figures 4.5 and 4.6 for location of radiocarbon dates. Reports of calibration of radiocarbon age to calendar years are provided in Appendix A. All dates are from the organic fraction of sediment sample taken from the playas.

**EMMA Results and Interpretation**

Applying EMMA to the matrix identified five end-members (EM) that explain a combined 97.23% of the total variance across all samples measured. The end-members were selected, in part, by their explained cumulative variance curve of eigenvectors (>95%), their goodness-of-fit (mean total \( r^2 \)), and parsimony (Figure 4.4) (Weltje, 1997; Deitze et al., 2012). The end-member loadings (grain size distributions; Figure 4.3) were interpreted and linked to sedimentary transport and depositional processes based on a classical understanding of grain-size sorting and distribution during sedimentation and are correlated between Rimrock Lake playa and Hay Lake playa in order to compare their evolution through time. Two environments of deposition are identified from the end-member distributions, lacustro-eolian and fluvio-
lacustrine, representing shifts from a wet climate to a more arid climate. End-member sequence stratigraphy is presented in Figure 4.6.

*Lacusto-eolian deposits*

EM 1 and EM 5 are bimodal and represent a combined 70.5% of the total measured variance within the GSD dataset (Figure 4.4A). EM 1 is the finest-grained end-member, with a clay mode at 8.5 phi (5.85 µm) and a fine sand mode at 2.5 phi (200 µm). EM 5 has modes with a very fine to fine silt transition at 7 phi (11.7 µm) and medium sand at 1.75 phi (375 µm) (Figure 4.5). Their fine-grained and coarse-grained bimodal distributions can be explained in several ways. They could represent a two-suspension component eolian transportation of clay and fine silt in near-surface suspension clouds and fine to medium sand transported by short-term saltation close to the surface (Vandenberghe, 2013; Diezte et al., 2014; Mason et al., 2003, 2011) or as aggregates from both local and non-local sources close to the ground or in suspension (Bowler 1973; Mason et al., 2003; Mason et al., 2011). These wind-transported aggregates are often pedogenic in origin, eroded from topsoil, but can be transported by wind from dry lake beds and other bare surfaces of fine-grained sediment (Mason et al., 2011). An alternative explanation for EM 1 and EM 5 is that their fine-grained mode represents a continuous background of dust deposition that reflects the distance the fine-grained fraction has traveled (Aarons et al., 2016) and subsequent reworking with fluvial component during settling in a lacustrine setting. Since eolian transportation is not a uniform process and can occur in modes reflecting the source area conditions and wind energy (Vandenberghe, 2013). The differences in modal size and changes in proportional representation between EM 1 and EM 5 may represent changes in wind, fluvial, and lacustrine regimes affecting distance traveled during transportation, changes in sediment source, or changes in lake level fluctuations (Vandenberghe, 2013; Aarons et al., 2016). In any case, the grain-size distributions and their association with each other are interpreted as representing a lacusto-eolian environment.
These end-members are found in association with each other and throughout all cores. The exception being in Cores 2 and 3, where they occur only in the upper portions in which only lacustrine sediments are found. A radiocarbon date of 6400 to 6290 cal. BP, at the base of the lacustrine sediments in Core 2 (Figure 4.5), suggests these end-members dominate RLP during the mid-Holocene and into the Late Holocene. In HLP, this end-member combination is found to dominate in the upper portions of all cores after a radiocarbon date of 8405 to 8340 cal. BP found in Core 6 (Figure 4.5), and within a thick interval in Cores 8 that thins toward Core 7. A radiocarbon date of 19,540 to 19,260 cal. BP is found at the upper boundary of this interval in Core 8 (Figure 4.5). A similar zone with associated dates is absent in RLP. These end-members also closely match EM 2 and EM 6 previously identified in the EMMA results presented in Chapter 3 (Figure 3.5A).

**Fluvio-lacustrine deposits**

EM 2 and EM 4 represent a combined 19.28% of the total measured variance within the GSD dataset (Figure 4.4A). Both end-members exhibit non-overlapping, well sorted coarse-grained modes and poorly sorted fine-grained tails (Figure 4.3). EM 2 is finer-grained, with a broad coarse silt mode at 4.5 phi (47 µm) and a poorly sorted clay tail at 9.25 phi (1.64 µm). EM 4 has a narrow fine-to-medium sand mode at 2 phi (250 µm) and a very fine poorly sorted silt tail positioned at 7.5 phi (11.7 µm). EM 2 is interpreted to represent low-energy, near-shore wave-action by which the finer-grained fraction is deflated from re-worked unconfined alluvial or fluvial sediments in a littoral setting when flow velocity reduces and the finer particles get washed farther down into the lake basin (Dietze et al., 2013). EM 4 is interpreted to contain a grain size distribution most closely resembling fluvial transport, which exhibits non-overlapping well sorted coarse-grained and poorly sorted fine-grained components representing both fluvial saltation mixed with eolian suspension fractions (Sun et al., 2002). In Chapter 2 and Chapter 3, a similar grain size distribution to EM 4 was found to correspond to fluvial sands at the base of the
relict channel (Figure 3.5A) and is interpreted to represent a deposit by fluvial transport in which both fluvial saltation and eolian suspension fractions are contributing to deposition (Sun et al., 2002; Dietze, 2012; Vandenberghe, 2013). The association between EM 2 and EM 4 in close proximity to the delta along the southern boundary within Rimrock Lake playa (Figure 4.5) reflects the general fluvial transport mechanism delivering sediments to the playa by creep and saltation in relatively high energy fluvial suspension and then being dispersed and re-mixed in a littoral setting where the delta and lacustrine environments overlap.

In RLP, both end-members occur together in the lower portion of Cores 2, 3, and 4, and are association with three radiocarbon dates found in the bottom of Core 2 that have a range that spans 8990 and 8070 cal. BP (Figure 4.5). In HLP these end-members occur together at a much shallower depth in a relatively thin interval across the upper portion of the cores. However, the upper boundary of this interval returned a similar date found in RLP of 8405 to 8340 cal. BP. EM 2 occurs without EM 4 in the bottom portion of Core 1, within RLP, and Cores 6, 7, and 8, within HLP (Figure 4.5), where it is found associated with the lacustrine-eolian end-members (EM 1 and EM 5) (Figure 4.5). Radiocarbon dates of 16,540 to 16,255 cal. BP from the deepest sediments in Core 6 in Hay Lake and a radiocarbon date of 18,535 to 18,310 ca. BP. from the deepest sediments in Core 1 from RLP suggests that the playas were shallow-water environments until around the Pleistocene/Holocene boundary when a fluvial sediments started to dominate.

EM 3 has the coarsest mode and represents 7.46% of the total measured variance within the GSD dataset. It is tri-modal with a mode positioned in the very fine silt range at 7.75 phi (4.64 µm), a mode in the coarse silt range at 4.5 phi (45.75 µm), and a mode at the coarse and very coarse sand boundary at 0 phi (1 mm). It occurs mostly in the bottom portions of the Rimrock Lake cores and in the upper portions of the Hay Lake cores, generally in association with the coarser fluvio-lacustrine sediments, with the exception of Core 1 (Figure 4.5). EM 3 is similar to an end-member found to dominate the upper sediments with the relict channel, which has experienced large amounts of bioturbation in conjunction with minor colluvial and fluvial input. Its tri-modal nature is interpreted to reflect a stable deposit of sediments in which high-
energy confined or unconfined fluvial sediments are deposited and mixed with eolian sediments, possibly representing a wet marsh or backshore environment that receives colluvial and fluvial sediments during wet periods.

The EM\(_{\text{diff}}\) between the fluvial end-member, EM 4, and the finer lacustrine end-member, EM 1, presents a more pronounced pattern than the combined end-member stratigraphy presented in Figure 4.5 for visualizing the relative energy within the system (Figure 4.7 and Figure 4.8). The more negative the value the lower the energy and vice versa. Comparing the EM\(_{\text{diff}}\) and radiocarbon dates between both playas (Figures 4.7 and 4.8) shows that RLP experienced a negative value throughout all of Core 1 and the upper portion of Cores 2, 3, and 4, and are associated with lacustrine-type sediment textures and end-members. Positive values are found within the lower portion of cores 2, 3, and 4, and are associated with littoral/fluvial type sediment textures and end-members (Figure 4.7). There are alternations between negative and positive EM\(_{\text{diff}}\) values found in the lower portion of all cores within RLP, representing brief shifts from fluvial to lacustrine (seen in Cores 2 and 4) or lacustrine to fluvial environments (seen in Core 1). These shifts probably represent alternations in lake-level through time. In HLP, positive EM\(_{\text{diff}}\) values are seen in the upper portions of Cores 6 and 8. Core 7 never experiences negative EM\(_{\text{diff}}\) values, though they do become less negative in the upper portion.

**DISCUSSION**

Comparison of end-member timing and EM\(_{\text{diff}}\) with radiocarbon dates allowed for the relationship between Hay lake and Rimrock Lake to be characterized. Despite being only 3 km from each other and within the same faulted terrace, their geomorphic evolution is quite different and is characterized below. Three end-member facies were found to characterize Rimrock Lake playa: a deltaic facies (EM 2 and EM 4), lacustrine facies (EM 1 and EM 2), and a marginal lacustrine facies (EM 1, EM 2, and EM 5) (Figure 4.6). The deltaic facies dominates the lower portion of Cores 2 through 4 and is in close proximity to the delta feature on the southern margin
of Rimrock Lake (Figure 4.2). The lacustrine facies dominates most of Core 1 and the upper portions of Cores 2 through 4. The marginal lacustrine facies dominates only in the very bottom portion of Core 1.

Hay Lake playa, in contrast, is missing the deltaic facies found in Rimrock Lake and, instead, is characterized by the alternation of three end-member facies: a marginal lacustrine facies (EM 1, EM 2, and EM 5), lacustrine facies (EM 1 and EM 5), and a fluvial facies (EM4). The marginal lacustrine facies dominates the lower halves of Cores 6, 7, and 8, just like in the bottom portion of Core 1, while the lacustrine facies is generally located in the upper portion of the cores. However, the lacustrine facies does periodically punctuate the marginal lacustrine facies found in the bottom of HLP cores. The marginal lacustrine facies occurs again at the top of Cores 6 and 7. A fluvial facies dominates in a narrow zone across the upper portion of Cores 6 and 8, but is weakly present in Core 7. The only end-member facies found in both playas is the lacustrine facies.

Generally, the end-member stratigraphy identifies a moderate lacustrine environment during the Late Pleistocene and into the Early Holocene, with a shift to shallower lacustrine environments into the Early and Middle Holocene.

**Late Pleistocene to Early Holocene (ca. 19.5 to 9 cal ka BP)**

Radiocarbon dating and the presence of EM 3 in the deepest (ca. 6 meters) sediment sample from Core 1 suggests Rimrock Lake was probably established as a stable, shallow-water environment receiving eolian input modified by low-energy fluvial input by as early as ca. 18,535 cal. BP. The presence of end-members 1, 2, and 5 between intervals dominated by EM 3 suggest shallow-lake levels alternated within RLP till around ca. 9,000 cal BP, when major fluvial processes began to dominated RLP in Cores 2, 3, and 4. In HLP, the presence of EM 3 at the base of Core 6 suggests the same environment was present at ca. 16,540 16,255 cal. BP.
However, an older date of 19,540 to 19,260 cal. BP. is found in lacustrine sediments in Core 8. As is the case in Core 1 within RLP, a shallow-water environment receiving eolian input modified by low-energy fluvial input is present within HLP until ca. 9,000 cal BP, when fluvial processes began to dominate the sediments.

The presence of a lacustrine environment in RLP and HLP during the Late Pleistocene and Early Holocene match the lake high stands between 16,000 and 13,000 BP reported in the Bonneville and Lahontan basins. The timing of the abrupt appearance of EM 4, representing increased fluvial input, prior to the radiocarbon date of 8405 to 8340 cal. BP., corresponds with the moderate-sized lakes identified in the Malheur Lake by Dugas (1998) at ca. 9,500 years B.P.

**Early Holocene to Late Holocene (ca. 9 cal ka BP to Present)**

Between 8 and 9 cal ka BP, Rimrock Lake experienced an abrupt lake level expansion and delta progradation along its southern margin, as indicated by the combination of EM 2 and EM 4 associated with the remnants of the delta just south of the core transect (Figure 3.2A). Around this time and prior to 8405 to 8340 cal BP, Hay Lake was also experiencing increased fluvial deposition. A radiocarbon date of 6190 to 5990 cal. BP. taken from just below the relict playa surface exposed in Trench 2 along the margin of the playa, reported in Chapter 3 (Figure 3.6), suggests that the lake level in Rimrock Lake began to drop around this time, probably due to increased aridity. This is evidenced by the preservation of the relict playa surface by marginal sediments that prograded basinward, covering the relict playa, as water level in Rimrock Lake dropped. It is unclear at what time Hay Lake became dry. However, based on a radiocarbon date of 8450 to 8340 cal BP just 60 cm below surface in Core 6 (Figure 4.5) it was much earlier than Rimrock Lake. This suggests that precipitation run-off and fluvial activity continued to influence Rimrock Lake playa while Hay Lake experienced long-term dessication and deflation, possibly due to tectonics that rerouted fluvial activity towards Rimrock Lake and away from Hay Lake.
Rimrock Lake continued to receive fluvial input well past ca 6 k cal BP considering that 190 cm of lacustrine sediments sit above the carbon date of 6400 to 6290 cal BP reported in Core 2 and the fact that the marginal sediments that preserve the relict playa surface is wave-terraced (see Figure 3.4D and 3.6).

**Conclusion**

This study represents the first comparison between playas within the Harney Basin and the first use of EMMA to characterize the stratigraphy between two different playas. This study also demonstrates the utility of using EMMA to model end-members between two different playas, to characterize the relationship between their sedimentary processes, allowing for a more robust landscape evolution model and spatial understand of past environmental changes surrounding the Rimrock Draw Rockshelter area.

Additional playas in the area need to be cored and compared with Rimrock Lake and Hay Lake playas to confirm playa response across the Pleistocene/Holocene boundary within the Harney Basin, particularly the increased fluvial activity identified during the Late Holocene, between ca. 9000 and 8000 cal. years BP, to determine if it is a consistent marker across other playas. Additional research should also be focused on the tectonic component to these playas. The evidence presented in this chapter suggests that there is a tectonic component to the rise and fall of lake level and with the timing between lacustrine stratigraphy within Rimrock Lake and Hay Lake playas, rerouting fluvial activity or increasing accommodation space.
REFERENCES


Figure 4.1. Map of Harney Basin and study area.
Figure 4.2. Map of the study area and related hydrology.
Figure 4.3. End-member grain-size distributions.
Figure 4.4. End-member mixing statistics. A) Explained cumulative variance of end-members. B) Mean total $r^2$ of end-members used in this study.
Figure 4.5. Sediment descriptions and end-member stratigraphy identified in this study.
Figure 4.6. End-member sequence stratigraphy of Rimrock Lake and Hay Lake playas.
Figure 4.7. $EM_{diff}$ values of Rimrock Lake playa compared to end-member stratigraphy.
Figure 4.8. $EM_{diff}$ values of Hay Lake playa compared to end-member stratigraphy.
Chapter 5

Conclusions

The three goals for this dissertation were: (1) to identify site formation processes responsible for the creation of the Rimrock Draw Rockshelter stratigraphy, (2) to link the stratigraphy of Rimrock Draw Rockshelter to the surrounding environment in order to provide a regional context for site occupation through time, and (3) to characterize and compare the geomorphic response and evolution of Rimrock Lake and Hay Lake playas. To accomplish these goals, stratigraphy of the study area was exposed through back-hoe trenching, playa lake coring, and archaeological excavation between 2013 and 2015. A combined total of 498 sediment samples was collected across the study area from 10 sedimentary profiles representing three different modern depositional environments: fluvial, eolian, and lacustrine. The measured inorganic grain-size distributions (GSD) of the sediment samples were unmixed using and end-member mixing algorithm (EMMA) described throughout this dissertation to characterize the spatial and temporal paleoenvironmental variations across the study area to accomplish these goals.

EMMA has proven to be particularly powerful tool in modeling spatial and temporal landscape evolution across the study area, as it was flexible in the inclusion and exclusion of sedimentary samples depending on the study aims. In this dissertation, EMMA was performed separately for each chapter on a combination of different measured grain-size distributions in order to evaluate end-member modeling accuracy across the different depositional environments and sedimentary archives in the study area. For example, in Chapter 2 EMMA was performed on only 13 sediment samples from a single sedimentary archive, Excavation Unit 2 from Rimrock Draw Rockshelter, located within the relict channel, in order to unmix the detrital subpopulations responsible for formation. Chapter 2 was limited in scope by design, as it was concerned only with unbiasedly confirming the observed stratigraphy identified by men and others in the field, and to provide only a site specific paleoenvironmental context for the artifacts found in that
excavation unit. EMMA identified three volumetrically significant end-members responsible for Unit 2 formation (see Figure 2.5) and was able to unbiasedly confirm the field stratigraphy. EM 1 was the dominant end-member and was interpreted based on its grain-size distribution to represent deposition under fluvial conditions. EM 2 was the second most dominant end-member and was interpreted to represent a mix between eolian and colluvial deposition. EM 3 was the third most dominant end-member and was interpreted as representing either a two-suspension or aggregate eolian deposition. These same end-members were also identified off site when the EMMA analysis was expanded to include other genetically related sedimentary archives and serve to confirm their original interpretation.

The data matrix was expanded in Chapter 3 to include sediment samples from additional depositional environments spanning the relict channel and the Rimrock Lake playa-lunette system (Figure 4.5) with the goal of correlating sedimentary processes across the sites in order to provide a more spatial context to those processes identified in Unit 2. All three environments are genetically linked by fluvial and eolian processes, as the playa-lunette system contributes fluvial transported sediments to the relict channel during wetter periods and eolian transported sediments into the relict channel during desiccation of the playa floor during dry periods. When EMMA was performed on the expanded data set six volumetrically significant sedimentary end-members were identified. Significant overlap occurred with the three end-members previously identified from Chapter 2. EM 1 identified in both datasets has a similar mode in the medium-to-coarse sand range and correlates well with fluvial sediments found within the channel gravels identified at the base of the relict channel archive (Trench 1; See Figure 3.4). Both represent a significant proportion of the total measured variation (>59%) within each dataset and demonstrates the importance of fluvial deposition across both environments. EM 2 and EM 5 identified in the expanded dataset also display similar modes as EM 3 identified in Chapter 2, with a significant correlation with the characteristic lacustrine sediments found in the cores from Rimrock Lake playa and the middle of Unit 2. All three end-members contain a combination of modes characteristic of eolian transported sediments either as a two-suspension component
system of clay and fine silt in near-surface suspension clouds and fine-to-medium sand transported by short-term saltation close to the surface, or combined as aggregates saltating close to the ground. EM 3 identified in the expanded data set stands out as being spatially restricted to Excavation Unit 2 within the relict channel and has a grain-size distribution that correlates with EM 2 identified in Chapter 2. Both end-members exhibit a very poorly sorted bimodal distribution of medium sand and fine silt and were interpreted as representing an eolian deposition reworked by fluvial and colluvial deposition of sediment associated with the colluvial wedge near Excavation Unit 2.

By expanding the dataset from Chapter 2 to include more spatially distinct geomorphic environments from the surrounding area, Unit 2 was identified as being a unique deposit, as it is the only archive that contains EM 3. The grain-size data matrix was again altered in Chapter 4 to include Hay Lake playa sediments and exclude the relict channel, as the focus was only on the relationship between the sedimentary archives of Rimrock Lake and Hay Lake. Even though the relict channel was omitted, the end-members overlapped with those end-members previously identified. One outcome of omitting the relict channel was that the fluvial end-member (EM 1 in Chapters 2 and 3) went from representing at least 59% of the total measured variance to representing only ~ 5 % (EM 4), while the lacustrine-eolian sediments went from representing a combined 23.91% (EM 2 and EM 4 in Chapter 3) to a combined 70.5% (EM 1 and EM 5) in Chapter 4.

This dissertation has contributed to a better understanding of paleoenvironmental change during the Late Pleistocene and Holocene within the Harney Basin. This dissertation also demonstrates the ability of playas within the Harney Basin to record those changes, and illustrates the utility of an end-member mixing analysis to characterize these changes. These contributions are represented by:

- The identification of an abrupt rise in lake-level within Rimrock Lake after the Younger Dryas, sometime between ca. 9 and 6 cal ka BP, represented by a drastic change in end-member composition within its cores. This could represent tectonic
activity or increased precipitation in the area. Research on other playas in the area needs to be conducted to determine the cause.

- The identification of an abrupt drop in lake level sometime after ca. 6 cal ka BP, leading to the preservation of a relict playa surface due to build up of sediments and the basinward migration of the Rimrock Lake playa margin. Again, additional research needs to be conducted along margins of other playas to determine if this is a regional response.
- The identification of increased aridity ca. 6.5 cal ka BP represented by the increased eolian deposition into the relict stream channel and preservation of Mt. Mazama tephra. Mt. Mazama tephra is absent in both Rimrock Lake and Hay Lake playa and warrants further micro-tephra analysis.
- The classification of lacustrine, littoral, fluvial, and deltaic environments across the study area using end-members.
- The ability of EMMA to provide a more geologically meaningful interpretation of stratigraphy within an archaeological context.
- The characterization of the geomorphic relationship between Rimrock Lake playa, Hay Lake playa, and Rimrock Draw relict channel.
APPENDIX A

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Database used: INTCAL13

References

Laboratory number: Beta-390348

Conventional radiocarbon age: 5550 ± 30 BP

2 Sigma calibrated result: Cal BC 4450 to 4340 (Cal BP 6400 to 6290)

95% probability: Cal BC 4450 to 4340 (Cal BP 6400 to 6290)

Cal BC 4360 (Cal BP 6310)

1 Sigma calibrated results: Cal BC 4445 to 4420 (Cal BP 6395 to 6370)

68% probability: Cal BC 4445 to 4420 (Cal BP 6395 to 6370)

5550 ± 30 BP

Database used
- INTCAL13

References
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -24.5 o/oo : lab. mult = 1)

Laboratory number  Beta-390349
Conventional radiocarbon age  7360 ± 30 BP

2 Sigma calibrated result
95% probability
Cal BC 6330 to 6315 (Cal BP 8280 to 8265)
Cal BC 6255 to 6210 (Cal BP 8205 to 8160)
Cal BC 6135 to 6120 (Cal BP 8085 to 8070)

Intercept of radiocarbon age with calibration curve  Cal BC 6230 (Cal BP 8180)

1 Sigma calibrated results
68% probability
Cal BC 6240 to 6220 (Cal BP 8190 to 8170)

Database used
INTCAL13

References
Mathematics used for calibration scenario

References to INTCAL13 database

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -23.8 o/oo : lab. mult = 1)

Laboratory number Beta-406659

Conventional radiocarbon age 7580 ± 30 BP

Calibrated Result (95% Probability) Cal BC 6465 to 6415 (Cal BP 8415 to 8365)

Intercept of radiocarbon age with calibration curve Cal BC 6440 (Cal BP 8390)

Calibrated Result (68% Probability) Cal BC 6455 to 6430 (Cal BP 8405 to 8380)

Database used
INTCAL13

References
Mathematics used for calibration scenario

References to INTCAL13 database

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -26.1 o/oo : lab. mult = 1)

Laboratory number Beta-390351

Conventional radiocarbon age 7960 ± 30 BP

2 Sigma calibrated result 95% probability
Cal BC 7040 to 6695 (Cal BP 8990 to 8645)

Intercept of radiocarbon age with calibration curve
Cal BC 6905 (Cal BP 8855)
Cal BC 6685 (Cal BP 8835)
Cal BC 5825 (Cal BP 8775)

1 Sigma calibrated results 68% probability
Cal BC 7030 to 6875 (Cal BP 8980 to 8825)
Cal BC 6865 to 6775 (Cal BP 8815 to 8725)

Database used
INTCAL13

References

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -25.6 o/oo : lab. mult = 1)

Laboratory number Beta-420099 : C2S4 BOT 1

Conventional radiocarbon age 15150 ± 50 BP

Calibrated Result (95% Probability) Cal BC 16585 to 16360 (Cal BP 18535 to 18310)

Intercept of radiocarbon age with calibration curve Cal BC 16460 (Cal BP 18410)

Calibrated Result (68% Probability) Cal BC 16525 to 16405 (Cal BP 18475 to 18355)

Database used INTCAL13

References
Mathematics used for calibration scenario
References to INTCL13 database

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -23.7 o/oo : lab. mult = 1)

Laboratory number Beta-427307 : RCPS
Conventional radiocarbon age 5310 ± 30 BP
Calibrated Result (95% Probability) Cal BC 4240 to 4040 (Cal BP 6190 to 5990)

Intercept of radiocarbon age with calibration curve
Cal BC 4225 (Cal BP 6175)
Cal BC 4205 (Cal BP 6155)
Cal BC 4165 (Cal BP 6115)
Cal BC 4130 (Cal BP 6080)
Cal BC 4115 (Cal BP 6065)
Cal BC 4100 (Cal BP 6050)
Cal BC 4075 (Cal BP 6025)

Calibrated Result (68% Probability) Cal BC 4230 to 4190 (Cal BP 6180 to 6140)
Cal BC 4180 to 4050 (Cal BP 6130 to 6000)

Database used
INTCAL13
References

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
**CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS**

(Variables: C13/C12 = -24.6 o/oo : lab. mult = 1)

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<td>Intercept of radiocarbon age with calibration curve</td>
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Database used: INTCAL13

References:

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -24.8 o/oo : lab. mult = 1)

Laboratory number  Beta-449107 : C6, SEC. 5, 120 CM

Conventional radiocarbon age  13610 ± 50 BP

Calibrated Result (95% Probability)  Cal BC 14590 to 14305 (Cal BP 16540 to 16255)

Intercept of radiocarbon age with calibration curve  Cal BC 14420 (Cal BP 16370)

Calibrated Result (68% Probability)  Cal BC 14515 to 14360 (Cal BP 16465 to 16310)

Database used
INTCAL13

References

Beta Analytic Radiocarbon Dating Laboratory
4985 S.W. 74th Court, Miami, Florida 33155 • Tel: (305)667-5167 • Fax: (305)663-0964 • Email: beta@radiocarbon.com
CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -26 o/oo : lab. mult = 1)

Laboratory number: Beta-449108 : C8, SEC. 5, 80 CM

Conventional radiocarbon age: 16080 ± 50 BP

Calibrated Result (95% Probability): Cal BC 17590 to 17310 (Cal BP 19540 to 19260)

Intercept of radiocarbon age with calibration curve: Cal BC 17490 (Cal BP 19440)

Calibrated Result (68% Probability): Cal BC 17545 to 17405 (Cal BP 19495 to 19355)

Database used
INTCAL13

References
Mathematics used for calibration scenario

References to INTCAL13 database
Sample Grain-size distributions for sedimentary archives used in this dissertation.

### APPENDIX B

#### TRENCH 1, TRENCH 2, UNIT 2, and UNIT 22

**Excavation and Trench Sample Grain-size Distributions (in whole phi)**

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### Table Descriptions

- **Sample ID**: Identifiers for each sample.
- **Sample Location**: Describes the location of the sample within the trench or unit.
- **Trench 1**: Grain-size distribution data for Trench 1.
- **Trench 2**: Grain-size distribution data for Trench 2.
- **Unit 2**: Grain-size distribution data for Unit 2.
- **Unit 22**: Grain-size distribution data for Unit 22.

Each column represents a different grain-size class, with numerical values indicating the frequency or percentage of occurrence for each class within the sample.
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**Note:** The table above contains the raw data extracted from the document. Each cell represents a value from the experiment, with columns indicating different conditions or variables. The values are numerical and likely represent measurements or observations from a scientific study.
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Core 1 Sample grain-size distributions (half phi)
Vita

Joe Collins joined the United States Army in September of 1999, and, in 2006, was retired due to wounds received during combat action in Mosul, Iraq. After his return home, he began academic studies at Mississippi State University, where he received a B.A. in Anthropology (2010) and an M.S. in Geosciences (2012). He then joined the Ph.D. program in Geological Sciences at UTEP. Dr. Collins supported his dissertation research through contracts with the Bureau of Land Management, as the national winner of the Jonathan Davis Scholarship sponsored by the Desert Research Institute, and through awards from the Geological Society of America, Society for American Archaeology, and the UTEP Graduate School. Dr. Collins has served as an instructor for the University of Oregon’s Geoarchaeological Field School, as an instructor at El Paso Community College, and as a teaching assistant and research associate at UTEP.

Dr. Collins’ research interests, broadly defined, are the reconstruction of Pleistocene and Holocene paleoenvironments of North America and the sedimentology and geomorphology of playas and their margins. He has presented his research at national and international meetings of the American Geophysical Union, American Quaternary Association, Society for American Archaeology, and Geological Society of America. His work has already been published in Archaeometry and The Journal of Archaeological Science. Dr. Collins’ dissertation entitled “Reconstructing Late Pleistocene and Holocene Paleoenvironments Using Playa-Lunette System Sediments Within the Harney Basin of Southeastern Oregon, USA” was supervised by Dr. Thomas Gill and Dr. Richard Langford. Dr. Collins accepted a position at Texas A&M University- San Antonio in Fall 2016. This dissertation was typed by Joe D. Collins, Jr.