ABSTRACT

PLUVIAL DEPOSITS IN MUDAWWARA, JORDAN AND THEIR IMPLICATIONS FOR MEDITERRANEAN AND MONSOONAL PRECIPITATION IN THE LEVANT

by Gentry Ann Catlett

Deposits in the hyper-arid Mudawwara basin of Jordan are examined to understand the timing and source of past pluvial episodes in the southern Levant. Mineralogical, geochemical, and radiocarbon analysis of a 2.35m core from dry playa Khabrat Ratiya suggest sedimentation from ~29-21 ka BP, coinciding with the highest lake levels of Paleolake Lisan. Coquina deposits in Mudawwara have been attributed to paleolake(s) sustained by intensified tropical monsoonal precipitation from 88-170 ka by Petit-Maire et al. (2010, Global and Planetary Change 72: 368-373). However, we argue that closed-system behavior has not been demonstrated for the U-series ages on these shells and geomorphologic evidence suggests an older depositional age. We suggest that in southern Jordan (1) pluvial episodes occurred in Khabrat Ratiya ~29-21 ka and resulted from increased winter precipitation from the Mediterranean, and (2) the Mudawwara coquina deposits should not be used as evidence for tropical monsoonal precipitation during interglacial periods.
PLUVIAL DEPOSITS IN MUDAwwARA, JORDAN AND THEIR IMPLICATIONS FOR MEDITERRANEAN AND MONSOONAL PRECIPITATION IN THE LEVANT

A Thesis
Submitted to the
Faculty of Miami University
in partial fulfillment of the requirements for the degree of
Master of Science
Department of Geology and Environmental Earth Science
by
Gentry Ann Catlett
Miami University
Oxford, Ohio
2014

Advisor: ____________________________________________
Jason A. Rech

Reader: ____________________________________________
Ellen Currano

Committee Member: ________________________________
Elisabeth Widom


TABLE OF CONTENTS

1. Introduction ........................................................................................................................................... 1
2. Regional Setting ....................................................................................................................................... 2
   2.1 Modern Climate ................................................................................................................................. 2
   2.2 Paleoclimate Records in the Levant .................................................................................................... 3
      2.2.1 Israel ........................................................................................................................................... 3
      2.2.2 Jordan ......................................................................................................................................... 5
   2.3 Study Area ......................................................................................................................................... 5
3. Materials and Methods ............................................................................................................................. 6
4. Khabrat Ratiya Results ............................................................................................................................. 8
5. Discussion ............................................................................................................................................... 8
   5.1 Khabrat Ratiya Discussion .................................................................................................................. 8
      5.1.1 Depositional environment and age ............................................................................................... 8
      5.1.2 Potential source of precipitation ................................................................................................. 9
   5.2 Mudawwara Coquina Discussion ....................................................................................................... 11
      5.2.1 Depositional environment and age ............................................................................................. 11
      5.2.2 Potential source of precipitation ............................................................................................... 13
6. Conclusions ........................................................................................................................................... 13
8. References ............................................................................................................................................... 15
LIST OF TABLES

Table 1: Soluble Salts ..................................................................................................................... 22
Table 2: Organic Carbon and Nitrogen............................................................................................ 23
Table 3: Stable Isotopes ................................................................................................................... 23
Table 4: Radiocarbon Ages ............................................................................................................ 24
LIST OF FIGURES

Figure 1: Map of Middle East paleoclimate records................................................................. 25
Figure 2: Satellite image of Mudawwara Basin........................................................................ 26
Figure 3: Photos of 'site 7' coquina ........................................................................................... 27
Figure 4: Satellite image of Khabrat Ratiya ................................................................................. 28
Figure 5: Mineralogical and geochemical results from Khabrat Ratiya sediment core... 29
Figure 6: SEM images from Khabrat Ratiya sediment core ....................................................... 29
Figure 7: Graph of effects of contamination on radiocarbon ages.......................................... 30
Figure 8: Khabrat Ratiya age and Lake Lisan curve................................................................. 30
Figure 9: 'Site 7' cross-section and MIS..................................................................................... 31
Figure 10: Regional precipitation sources by latitude ............................................................... 32
ACKNOWLEDGMENTS

Firstly, I want to give special thanks to my advisor, Dr. Jason Rech for the mentorship during this project. I appreciate his knowledge and patience as a teacher and am very grateful for all I have learned from him.

I would like to thank my committee members, Dr. Ellen Currano and Dr. Elisabeth Widom for their time, guidance and advice through the duration of this project. I also appreciate the assistance and fellowship of the Miami University Geology and Environmental Earth Science graduate student body.

I would like to acknowledge my gratitude to Mustafa Al-Kuisi, at the University of Jordan, for his valuable time, guidance and assistance.

I would also like to thank the cooperation of the American Center for Oriental Research. This project was funded by a National Geographic Society grant to Dr. Jason Rech and Dr. Jonathan Levy.
1. Introduction

The Middle East is one of the most water-stressed regions in the world. High water stress results from limited water resources, and is exacerbated by rapid population growth and economic development (Brown and Crawford 2009). Jordan in particular is one of the most water-limited nations in the region and existing water usage is unsustainable (e.g. Haddadin 2006, Wade et al. 2010). Moreover, water scarcity may worsen as climate models project an increase in temperature (4°C) and a decrease in precipitation (-25mm/yr) for most of the Middle East within the next century (Evans 2009). In anticipation of future climate change, comprehensive paleoclimate records are essential for understanding regional climate dynamics and to evaluate future water resource stability (Robinson et al. 2006, Betrams et al. 2012).

Models of future climate in the Middle East and North Africa predict an intensification of the African and Indian tropical monsoon systems and enhanced precipitation (Evans 2009). There is clear evidence that wetter conditions prevailed in north Africa during the Late Pleistocene-Early Holocene as a result of enhanced summer insolation in the Northern Hemisphere and northward migration of the Inter-tropical Convergence Zone (deMenocal et al. 2000; Figure 1). Pluvial conditions with savannah vegetation and sustained lakes are evident from 16°N-24°N with the most humid conditions spanning from ~8.5ka to 5ka, following a prolonged period of aridity since 65ka BP (deMenocal et al. 2000, Kuper and Kröpelin 2006, Szabo et al. 1995, Gasse 2000). Enhanced rainfall in the Sahel was a result of an intensified African-Indian monsoon system in response to increased summer insolation (e.g. Rohling et al. 2002, Waldmann et al. 2010, Arz et al. 2003). There is also evidence for the northward migration of the monsoon precipitation in the Arabian Peninsula. Increased rainfall is recorded by speleothem growth and lacustrine deposits in Oman, Yemen and UAE between ~12-6ka BP (Neff et al. 2001, Fleitmann et al. 2007, Burns et al. 2001, Parker et al. 2006, Lézine et al. 2007, Preusser 2009). However, today the monsoon systems do not contribute to rainfall in the Levant or to the Arabia Peninsula beyond minimal coastal areas, and the northernmost extent of precipitation from intensified tropical monsoons in the past has not been clearly established (Glennie and Singhvi 2002).

Today, rainfall in the Levant is primarily from low pressure systems over the Mediterranean Sea during the winter months (Ziv et al. 2006). The intensity of Mediterranean cyclonic activity during the late Pleistocene has been gauged primarily by robust terrestrial proxies in the region including the high-resolution lake level reconstructions of Lake Lisan and periods of speleothem formation in southern Israel (e.g. Torfstein et al. 2013, Bartov et al. 2002, Vaks et al. 2006, 2010). These proxies have generally been interpreted as indicating wetter conditions in the Levant during glacial periods (Robinson et al. 2006; Enzel et al., 2008), and models predict that precipitation will decrease in the future (Evans 2009). Continuous and well-dated proxies provide a good understanding of past environmental and climatic change in the western Levant, however, little is known about past climate in the more arid regions of the southeast Jordan and northern and central Saudi Arabia, where impacts of future climate change are not as clear.

Modern climate in the Levant has distinct local variability, demonstrating climatic complexities that are likely present in the geologic record as well (Enzel et al. 2008). The
spatial limitation of well-dated paleoclimatic proxies in the Middle East makes it difficult to reconstruct the past boundary between moisture derived from tropical monsoon systems and Mediterranean cyclonic activity. From ~25-30˚N there is a transition zone where the relative influence of winter precipitation from the Mediterranean and summer monsoonal precipitation remains unclear (Kuper and Kröpelin 2006). Constraining the age and depositional environment of pluvial deposits within this transition zone is important to understand the past migration of the tropical monsoonal system into the Levant.

The Mudawwara basin (29˚N) in southern Jordan is located in the northern portion of this transition zone between tropical and mid-latitude precipitation. Coquina deposits of fresh, brackish, and marine fauna have been interpreted as paleolake deposits attributed to a large (>2000km²) and shallow (~30m) water body associated with two or more different humid episodes (Yasin, 2001; Petit-Maire et al. 2010). Uranium series ages of bivalve shells ranged from 170-77ka BP, which the authors used to associate high lake stands to MIS 7a-6e, 5e, and 5c-a (Petit-Maire et al., 2010). A large paleolake in the Mudawwara depression was then reported to be the result of intensified tropical monsoons increasing rainfall to this area during Pleistocene interglacials (Petit-Maire et al. 2010). This interpretation would suggest that increasing temperatures with future climate change may enhance precipitation in this region.

The focus of this research was to examine pluvial deposits in the Mudawwara Depression to better constrain the timing and source of precipitation in southern Jordan. Specifically, I wanted to determine if these pluvial deposits provide direct evidence for the northward migration of tropical monsoon precipitation into the Levant. Moreover, if monsoonal precipitation made it to Mudawwara and the southern Levant in the past, then there should be evidence for wetter conditions in this area dating to the most recent period of enhanced monsoonal precipitation during the early Holocene. This paper presents 1) analytical results and radiocarbon ages of a 2.35m sediment core from dry playa, Khabrat Ratiya, with a clear spillway and 2) a new hypothesis for the age of the Mudawwara coquina deposits and paleoclimatic implications for the tropical monsoon influence in Jordan in the Pleistocene.

2. Regional Setting
2.1 Modern Climate

Modern climate in the Levant is classified as ‘Mediterranean’ with hot, dry summers and precipitation occurring primarily during the cooler winter season (EXACT 1998). During the winter season (October-May), cold air masses form the north Atlantic and Europe move south-southeast over the Mediterranean Sea, rise over the warm sea, and form extratropical cyclones termed ‘Cyprus Lows’ (Sharon and Kutiel 1986, Alpert et al. 1990). Over 65% of the annual rainfall in the Levant is from extratropical cyclones during December-February (Ziv et al. 2006). In the summer months, dry winds from western anticyclones penetrate the Eastern Mediterranean and cause a pronounced dry season (Rossignol-Strick 1995, EXACT 1998). The African monsoon does not penetrate north of the Saharan desert belt, about 20˚N, into the Levant (Arz et al. 2003). The Indian Monsoon contributes only minimally to coastal areas of Oman and Yemen (Glennie and Singhvi 2002, Charabi, 2009: Figure 1).
With negligible summer rainfall, the winter cyclonic system creates extreme seasonality in rainfall in the Levant (Syria, Lebanon, Israel, Jordan) (Ziv et al. 2006). There is also spatial variation in rainfall amounts from the northernmost mountainous area of western Jordan and northern Israel receiving >1200 mm/yr to the hyper-arid desert of southern Israel and eastern and southern Jordan and continuing into Saudi Arabia, receiving <50mm/yr (EXACT 1998). High topography and continentality are responsible for creating this sharp climatic gradient from the western Levant to the hyper-arid regions of the southern Levant (Rambeau 2010, Enzel et al. 2008). Temperatures vary as well in relation to latitude, altitude, and distance from the coast. The southern desert of Jordan, where the study area of Mudawwara is situated, experiences high ranges of seasonal temperatures with summer highs averaging 36˚C with occasional periods of hotter temperatures 10-20˚C above average (EXACT 1998). Winter average temperatures are around 6˚C, however, fluctuations in air masses can also cause occasional drops to below freezing (EXACT 1998).

2.2 Paleoclimate records in the Levant

2.2.1 Israel

One of the primary paleoclimate records for the Levant is the Dead Sea and its precursor, Paleolake Lisan (~70-13ka). Proxies from Lake Lisan have resulted in well dated and continuous records of climatic variability in the Dead Sea catchment during the late Pleistocene and Holocene (e.g. Kaufman et al. 1992, Stein and Goldstein 2006, Bartov et al. 2002, 2003, Torfstein et al. 2013). Stratigraphic and sedimentary analysis of lake-margin environments along with U-series and radiocarbon dating of primary aragonite has constructed a robust chronology of paleo-hydrologic change in the Dead Sea Basin over the late Pleistocene (Kaufman 1971a, Schramm et al. 2000, Bartov et al. 2002). Today, the Dead Sea is 402m below sea level and falling, but at its highstand, the lake reached a maximum elevation of -160m and extended north to the Sea of Galilee (Enzel et al. 2003, Bartov et al 2002). The highstand occurred ~26-23 ka, which coincides with the Last Glacial maximum (LGM) from ~26.5 to 19.5ka (Bartov et al. 2002, Clark et al. 2009). During MIS 2, however, the sharpest drops in lake levels coincided with Heinrich events (Bartov et al. 2003, Torfstein et al. 2013). High lake levels for Lake Lisan have been linked to Northern Hemisphere glacial periods that enhance Mediterranean cyclogenesis and increase precipitation over the catchment basin (Bartov et al. 2003, Torfstein et al. 2013). The sharp drops in lake levels associated with Heinrich events are thought to result from decreased SST in the Mediterranean decreasing the frequency of winter storm generation (Bartov et al. 2003, Torfstein et al. 2013). Fluctuations in the lake level of Lake Lisan have been interpreted as an indicator of rainfall contribution from the Mediterranean cyclonic system to the Dead Sea basin (Enzel et al 2003, Torfstein et al. 2013), although some studies have linked lake level to temperature controls on evaporation (e.g. Bar-Matthews et al. 2003, Gasse et al. 2011).

For Lake Lisan, the reconstructed lake level curve is a continuous record of the hydrologic budget for the Lake Lisan catchment, which spans from the Dead Sea basin through the Jordan valley to the Sea of Galilee (Bartov et al. 2002). In general, high lake levels occurred during MIS 2 and 4 and lower lake levels during MIS 3 (Stein 2001, Bartov et al. 2003). The highest lake levels occurred during the coldest time of the last
glacial period (26-23 ka), while during MIS 3 lake levels were lower and had more fluctuations (Torfstein et al. 2013). The Levant is generally interpreted as experiencing wetter conditions during glacial periods and more arid conditions during interglacials (Bartov et al. 2002, 2003, Schramm et al. 2000, Lisker et al. 2009, Enzel et al. 2008, Frumkin et al. 2011, Robinson et al. 2006). However, other records have shown fluctuations within these larger climatic trends and wetter conditions have been dated amidst interglacial periods, particularly in the southern Levant, prompting some authors to argue for enhanced rainfall in warmer periods, possibly with the attribution of southern monsoonal precipitation (Abed and Yaghan 2000, Issar 2003, Vaks et al. 2003, 2006, Petit-Marie et al. 2010).

Speleothem formations in the southern Levant provides another robust record for paleoprecipitation. Determining whether the primary control on the $\delta^{18}O$ values of these speleothems is the source water or the amount of rainfall can complicate interpretations. This was a concern in the Soreq and Jerusalem West Caves where there is continuous deposition (Bar-Matthews 1997, 1999, Frumkin et al. 2011 Enzel et al. 2008). However, U-series dating the periods of speleothem growth, which is controlled by rainfall amount, can be a successful proxy for local paleoprecipitation in more arid areas with discontinuous deposition. Speleothem formation was dated along present day isohyets in the semi-arid to arid Negev, where speleothems do not form today (Vaks et al. 2006, 2010). These speleothems had deposition during glacial and interglacial cycles. However, there was a north-south decrease in $\delta^{18}O$ values interpreted as Rayleigh distillation effect for Mediterranean precipitation influencing further inland during periods of increased rainfall (Vaks et al. 2006). This N-S gradient in deposition indicate the main source of precipitation is from the Mediterranean during glacials but there may have been some contribution from the tropical monsoon at times during interglacials (Vaks et al. 2006).

Other proxies have also been used in the Levant to decipher periods of aridity. Records in the southern Negev have identified that hyper-arid soil development was established in the middle Pleistocene (Amit et al. 2006). This area remained hyper-arid to the present, even during wetter periods in northern Israel, including during the highest stands of Lake Lisan (Amit et al. 2006, Enzel et al. 2008). There is also evidence of loess accumulation from western sources, most likely dust influx from the Sahara into the northern Negev (Enzel et al. 2008). Determining ages on these deposits is difficult, but OSL methods have generally constrained original deposition to before ~80ka and reworking of the loess into fluvial deposits after ~50ka (Avni et al. 2003, Crouvi et al. 2006). Sand dunes in the Negev have been dated with TL, OSL and relatively dated with archaeological artifacts (Ben David 2003, Enzel et al. 2008). The sand arrived from the west earlier than ~50ka and dune migration in the western Negev was active from ~30-25ka with maximum migration from 27-25ka (Ben David 2003). These records demonstrate a spatial distinction in aridity from the Dead Sea basin and southern Negev over the same time period. This steep N-S gradient in rainfall resulting from topography and distance from the Mediterranean Sea was perhaps stronger than today’s (Enzel et al. 2008).
2.2.2 Jordan

There are few well-dated and continuous paleoclimatic proxy records in Jordan, and among those that have been published, there is little consensus. Studies on the age and nature of alluvial deposits from wadis in central Jordan include the wadis of Madaba-Dhiban Plateau (Cordova et al. 2005), Jurf ed Darawish and Burma of Wadi al-Hasa (Moumani et al. 2003), Wadi Sabra (Betrams et al. 2012), and Wadi Hammeh (Macumber and Head 1991), and Wadi Dana (McLaren et al. 2004). These studies have identified multiple episodes of incision and aggradation from fluvial and aeolian sedimentation back to ~100ka (Moumani et al 2003). However, these studies are not able to attribute sedimentation changes to specific climatic shifts prior to the Holocene (McLaren et al. 2004, Betrams et al. 2012). It is also difficult to differentiate the influence of tectonics and anthropogenic activity from climatic events with these sedimentary deposits (McLaren et al. 2004).

In the more arid regions of eastern and southern Jordan, pluvial deposits within the endorheic basins of Azraq, Mudawwara, and al-Jafr indicate wetter periods in the past. Several studies have suggested that large paleolakes filled basins such as Azraq, Umari (Abed et al. 2008), although poor age constraints and a lack of geomorphic evidence suggest that if these deposits do reflect large lakes they are older than late Pleistocene. The springs of Azraq show clear hydrologic changes in this environment resulting from fluctuations in recharge over the past 60ka. Palustrine deposits indicated the wettest periods were preceding the LGM, with sustained wetness during the LGM and drought conditions from 16-10.5ka (Jones and Richter 2011). Huckreide and Wiesemann (1968) interpreted deposits in the large al-Jafr basin in southeastern Jordan to be lacustrine, but these deposits have no clear ages. Two radiocarbon ages of ~24ka and 16ka were obtained from playa deposits in the Jafr basin from Davies (2005), indicating that there was not a perennial lake in Jafr during the LGM, with the underlying depositional sequence interpreted as being much older.

In general, paleoenvironmental records in Jordan are discontinuous, widely dispersed, and many have limited age constraints, making it difficult to infer past climatic conditions. However, relying on well-dated but isolated paleo-hydrologic records such as those from Lake Lisan alone runs the risk of creating an overgeneralized climatic history unrepresentative of the complex realities for specific localities (Rambeau 2010, Rosen 2007, Enzel et al. 2008). Attaining reliable ages and understanding the paleohydrologic conditions from the more marginal areas of Jordan’s arid southern periphery is key to constraining the potential interplay between mid-latitude and tropical precipitation.

2.3 Study Area

The Mudawwara depression (29°N, 36°E) is located in southern Jordan and northwestern Saudi Arabia, where it is known as the Tabuk depression (Figure 2). The catchment is >700 km² and ranges in elevation from ~860 m in the highlands in the north to 675 m in the center of the basin. The area has low topographic relief with a change in elevation of <200m with a gradient from the NW-SE (Masri 1988). The bedrock in the region is Ordovician and Silurian sandstones, siltstones, and mudstones of the Al Mudawwara Formation. Overlying this in the basin is the late Neogene Hallat Ammar Formation containing sands, gypsum laminae, marls, coquinas, and gravel conglomerates (Masri 1988).
South of the town of Al Mudawwara the deposits of the Hallat Ammar Formation contain coquina shell beds, marls and gravel conglomerates. These deposits contain an abundance of fossilized freshwater and marine taxa and are located in several locations in the Mudawwara depression associated with the surrounding playas and other lacustrine features (Yasin 2001). These sites consist of sands, gravels, and shelly layers of broken and intact bivalve shells, mainly of the species Cardium sp (*Cerastoderma glaucum*). Ostracodes (*Cyprideis torosa* gr., *Candona gr. neglecta*) and sparse gastropod species (*Hydrobia sp., Melania tuberculata*) are also present along with foraminifera (*Ammonia beccarii* tepida, *Elphidium excavates*) and charophytes (Petit-Maire et al. 2010).

Underlying the desert pavement, several localities contain these coquina deposits from ~700-720m elevation as from Petit-Maire et al. (2010) (Figure 2). ‘Site 7’ trench from Petit-Maire et al. (2010) located at 29°18’56”N, 36°02’ 52”E has since been buried by aeolian sand (Figure 3).

Mudawwara is in the hyper-arid southeastern region of Jordan that receives <50 mm a year precipitation during the winter from October to April. The summers from June to September are hot and dry with almost no rainfall and high evaporation (EXACT 1998, Masri 1988). Modern vegetation is sparse and located in the wadis (Figure 2). Local well data show that the water table is ~20m below the surface in the Mudawwara agricultural area. The water table drops eastward reaching ~115m below the surface 20km east of the township (WAJ 2013). There are no perennial or intermittent streams in the catchment. All wadis are ephemeral and only flow for brief intervals during the winter months (Masri 1988).

Survifical deposits consist of Quaternary sediments including occasional sand dunes, wadi deposits, and mudflats, or dry playas that form smaller catchment areas within the Mudawwara catchment basin (Masri 1998). Khabrat Ratiya is a dry playa located at 29°22’N, 36°10’E on the northeastern boundary of the Mudawwara depression (Figure 2). This is a small (<1km²), closed basin with the lowest elevation in the basin of ~724m to ~732m at the periphery. The modern drainage basin for this playa is ~330km² from the higher elevation areas (~1040m) to the north through ephemeral dry streams to the playa (~730m) where seasonal water levels in this area are unknown. There is evidence of an inflowing stream to the north and a spillway to the S-SW (Figure 2). The highest point is west of the playa boundary (~733m) and creates a modern drainage flowing northeast into the playa. The depth to the water table is ~55m at Khabrat Ratiya (WAJ 2013).

### 3. Methods and Materials

A 2.35-m continuous core was collected from the northwestern sector of Khabrat Ratiya (29°22’11”N, 36°10’37”E) at an elevation of ~728m (Figure 4). Drill cores were attempted in several other localities, but sediments were less consolidated and recovery was poor. The compressed air drill had a 7cm diameter, 3m long hollow drill pipe. The pipe drilled the length of the pipe where it made contact with the bedrock and a single 2.35m core was retrieved. The majority of the sediment core was extracted intact. Intact sections of the core were wrapped with plastic, placed in core boxes, and then separated into ~3cm sections at the American Center for Oriental Research in Amman, Jordan. A few sections of the core were unconsolidated when removed. These sections were placed in bags and labeled as mixed from the appropriate depth. Physical features of the
sediment core such as color, mottling, bioturbation, and mud cracks were described in Jordan. Sediment samples were then taken to Miami University, Ohio, for mineralogical and geochemical analyses as well as characterization by scanning electron microscopy.

Bulk mineralogy was determined on five samples (depths 5, 80, 160, 195, and 235cm) with a Scintag X1 Powder Diffractometer − 40 kV, 35 mA; CuKα radiation − using a fixed slit scintillation detector and scan range of 2–70° 2-theta. MDI Jade 7 software was used to infer mineralogy. Mineralogical micromorphology and grain size studies were carried out on uncoated, freshly broken surfaces using a Zeiss field-emission scanning electron microscope equipped with an energy-dispersive x-ray detector (SEM-EDX). Secondary electron images were captured with a 2 keV acceleration voltage. EDX chemical analysis of minerals was performed using a 20 keV acceleration voltage and 8.5 mm working distance.

Particle size was identified for samples at 20cm depth intervals with a Malvern 2000 Laser Particle Size Analyzer at the Soils Laboratory of Geology and Environmental Change Science Center, USGS. Fourteen samples, each at 20cm depth intervals, were also analyzed for soluble salts by dissolving the soluble salts in water and then analyzing the decanted solution on a Dionex DX-500 HPLC ion chromatograph. Cations from these sample solutions were measured against 3 external solution standards. Solution standards were made from 1mg/ml ICP standards purchased from Alfa Aesar. The analysis was made on an Agilent 720ES axial-viewing ICP-OES. Be and In were used as internal standards. Percent carbonate was estimated from the amount of CO₂ produced by reacting the samples with 100% phosphoric acid during isotopic analysis. Samples at 10cm depth intervals were analyzed for organic carbon and nitrogen using a Flash 2000 NC Soil Analyzer (CE Elantech).

The δ¹³C and δ¹⁸O isotopic values of carbonate minerals were analyzed at the Environmental Isotopes Laboratory, University of Waterloo. Samples for radiocarbon dating were chosen from the highest organic C concentrations at differing depths. Organic material was concentrated at the US Geological Survey Soils Laboratory of Geology and Environmental Change Science Center in Denver. Large siliceous samples were processed through a series of physical and chemical steps. Gravitational settling, centrifugal separation, and sieving enriched the organics within a sample, removing coarse particles as well as clay sized minerals. Hydrochloric and hydrofluoric acids were then used to remove as much of the remaining minerals as possible. The resulting residue had organic C concentrations about two orders of magnitude higher than the original samples, and were therefore suitable for radiocarbon dating. Samples were not chemically pretreated with a base due to the low concentrations of organic material. Organic material was AMS ¹⁴C dated at Aeon Laboratories. Each ¹⁴C age (yr BP) was calibrated with Calib 6.0 online with INTCAL 09 curve selection to create a 2-sigma probability range expressed as calendar yr BP.

The Mudawwara region was examined in Google Earth to identify possible landforms or outcrops that may be related to more pluvial conditions in the past. This region was then field surveyed, focusing on areas of interest from the Google Earth survey, to look for geomorphic evidence of a past lake or wetlands. The Khabrat Ratiya playa was selected for further investigation based on the apparent spillway on the western side of the playa. Several of the coquina outcrops reported by Yasin (2001) and Petit-Maire (2010) were identified and examined.
4. Khabrat Ratiya Results

Field examination of Khabrat Ratiya identified that the apparent spillway on the western side of the playa is a spillway. The current spillway drainage is ~5-8 m above the lowest elevation in the playa, and the modern drainage has a change in flow direction about 50 m south of its connection with the playa. The northern 50m section of the dry stream drains toward Khabrat Ratiya, whereas south of this point the drainage flows to the south. A survey of the Khabrat Ratiya playa failed to identify any outcrops of pluvial facies such as wetland or lake deposits. Based on these results, a decision was made to collect a sediment core from the playa.

The sediment retrieved from the continuous 2.35m drill core was relatively homogenous down to a depth of 2.1 m. The sediment was reddish yellow in color (Munsell 7.5YR 6/6) with an average particle size of ~30% clay, 40% silt, and 30% sand (Figure 5). The particle size is consistent until ~1.5m depth where there is an increase in silt and a decrease in sand. Desiccation cracks, root voids, and evidence of bioturbation were common throughout. Analysis of the cations and anions in solution after samples were agitated in an ultrasonic bath revealed sulfate and chloride salts with concentrations between approximately 1.8 and 4.8% (Table 1). Organic carbon ranged from .06-.17% and nitrogen ranged from .00-.02% (Table 2). The δ13C and δ18O isotopic values of the secondary calcite from this part of the core ranged from 0.16 to 2.58‰VPBD for δ13C and from 0.52 to 4.59‰VPBD for δ18O (Table 3). There was little variability in soluble salt and organic carbon concentrations and stable isotope values through the sediment core. However, sediment in the bottom 25cm of the core showed a change in color (10YR 6/4) and the calcite at this depth resulted in negative stable isotope values, δ13C - 2.69 and δ18O -3.15.

Mineralogical and geochemical results for this sediment do not identify any significant changes in stratigraphy throughout the core that would result from differing environmental conditions. Bulk XRD analysis showed that the mineralogy was predominately quartz and kaolinite, with a lesser abundance of calcite. SEM results showed detrital quartz grains and clays, and identified secondary precipitation of calcite and halite, along with lesser amounts of gypsum (Figure 6).

Radiocarbon ages were obtained on bulk organic material after concentration of the organics through physical and chemical processing. The majority of organic material appeared to be degraded pollen grains. Five samples with the highest organic C concentrations (0.11-0.13%) at differing depths were used with this method resulting in material with 7-10.4% organic carbon. Calibrated 14C ages for these samples are 20.97 ± 0.43, 24.57 ± 0.37, 25.61 ± 0.43, 29.08 ± 0.45, 23.56 ± 0.34 ka BP at 10, 110, 150, 180, and 210cm depth (Table 4).

5. Discussion
5.1 Khabrat Ratiya Discussion

5.1.1 Depositional environment and age

The red sediment color, low organic carbon, mud cracks, root voids, and secondary soluble salts are indicative of a dry lake environment. The high δ18O and δ13C values are comparable to values in other dry playas where evaporative enrichment and kinetic effects are common (e.g., Sinha et al. 2006). At ~150cm depth there is a
decrease in particle size to more silty clay. The variations in stable isotopes, particle size and salt concentrations can be attributed to intermittent influx of water and seasonal evaporation. The calcite in the bottom 25cm of the core resulted in more negative isotope values and the sediment was a more yellow color. This sediment at the basal contact of the playa with the underlying bedrock may be the result of geochemical and mineralogical differences at this contact zone with the impermeable kaolinitic bedrock, or may be the mixture of partially weathered bedrock and playa sediments.

The radiocarbon ages for Khabrat Ratiya indicate active playa sedimentation from ~29-21ka BP. It is possible that sediment from the surface could be missing from aeolian deflation, so these ages may not include younger periods of deposition. Also, there is one age reversal in the sample at 210cm depth demonstrating contamination. This sample has a measured age of 23.6ka but if the other ages are correct, then the age for this sample is ~5.5ka too young. Based on the other ages, this sample is expected to have an age of ~30ka or older. Younger organic matter could have penetrated the sediment from the top through surficial cracks or through humic acid dissolved in water. However, the age reversal of only the bottommost sample suggests that contamination from organic matter moving through desiccation cracks is unlikely. Contamination by secondary humic acids is more likely. The young radiocarbon age at 210cm depth is just a few decimeters above the impermeable kaolinite bedrock. As surface water that infiltrated the playa sediments would have perched on this aquiclude, it is likely that the young age of this sample is the result of humic acids transported by surface water. The effects of carbon contamination on the apparent age of a sample has less influence the younger the sample is (Figure 7, Rech et al. 2011). A sample with an apparent age of 23.56ka that has a true age of ~35ka, would represent ~1.5% contamination from modern carbon. However, the stratigraphic consistency of the other four ages and the dry environment with low organic carbon and humic material suggest minimal contamination of carbon with the other samples. The time average of this range of ages is of sufficient precision for this study.

There is no evidence for a perennial lake at Khabrat Ratiya. The modern catchment for Khabrat Ratiya seems to only have deposition in the main drainage areas occasionally. However, the spillway on the western margin of the playa indicates that the dry lake periodically filled with water and overflowed through the spillway. We interpret Khabrat Ratiya as a dry playa with intermittent sedimentation with an active wetter period from ~29-21ka BP. The episodic nature of this playa means that active playa sedimentation resulted directly from enhanced local rainfall into the catchment basin and not from temperature related evaporation.

5.1.2 Potential source of precipitation

Effective moisture was high enough in the Dead Sea catchment from ~70-13ka BP to raise and sustain Lake Lisan between 150 to 240m higher than Holocene levels (Bartov et al 2002, 2003; Enzel et al. 2008). At ~30ka Lake Lisan rose from < -300m to > -200m and peaked at > -167m from ~27-25ka at the beginning of the LGM (Bartov et al 2003, Torfstein et al 2013, Enzel et al. 2008). Active playa sedimentation within Khabrat Ratiya from ~29-21ka BP corresponds with the Lake Lisan highstand from ~27-25ka (Bartov et al. 2002, Torfstein et al. 2013) (Figure 8). At ~25ka Lake Lisan lake levels dropped by ~30m and then were relatively stable at ~200m from 24-21ka. After 20ka,
lake levels dropped steadily to <-315m at around 17ka and then dropped significantly to elevations closer to modern day levels, ~400m (Bartov et al. 2002, Torfstein et al. 2013).

The Negev Desert, in southern Israel, experiences a steep shift from mildly-arid in the north to hyper-arid in the south spanning <150km today (Vaks et al. 2007). Studies on dunes in the Negev concluded that dune migration was at its maximum from 27-25 ka (Crouvi et al. 2010). This was likely the result of intensified W-SW winds from a strengthened cyclonic system in the Mediterranean related to northern hemisphere glaciation, and not primarily from aridity (Enzel et al. 2008, Crouvi et al. 2010). Loess accumulation in the Negev has been studied to constrain periods of aridity, but reliable dates on sequential dust deposition is limited (Enzel et al. 2008). The initial accumulation of loess in the Negev was suggested to have been after ~80ka (Enzel et al. 2008). However, after this period, fluvial reworking of this loess, and poor age constraints complicate interpretations related to atmospheric circulation patterns (Enzel et al. 2008).

Records of speleothem deposition from caves in northern Israel and the Negev Desert show variability in the timing of deposition spatially (Lisker et al. 2010). In northern Israel, caves such as the Soreq cave have had continual deposition throughout the past ~180ka (Bar-Matthews et al. 2000, 2003, Ayalon et al. 2002). However, several caves in central Israel and the Negev desert have shown periods of deposition, and hiatuses from decreased rainfall in the region both during glacial and interglacial periods (e.g. Vaks et al. 2003, 2006, Lisker et al. 2010). Periods of speleothem deposition have been generally dated to MIS 6, 4, 5, and 2 (Vaks et al. 2003, 2006 and Lisker et al. 2010). Vaks et al. (2006) demonstrated a N-S gradient in deposition of speleothems in this central region indicating the rainshadow effect from the Mediterranean during glacial periods. Yet, in caves further south in the Negev, there may have been some contribution from the tropical monsoon at times during interglacials (Vaks et al. 2006).

Paleoclimate records for the southern Arabian Peninsula demonstrate evidence for increased rainfall from the Indian Monsoon from several studies. Speleothem growth and lacustrine deposits in Oman, Yemen and UAE show the tropical monsoon shifted to ~25’N in the Arabian peninsula from ~12-6ka BP (Neff et al. 2001, Fleitmann et al. 2007, Burns et al. 2001, Parker et al. 2006, Lézine et al. 2007, Preusser 2009). However, these studies show aridity prior to this humid period until about 78ka (Burns et al. 2001, Fleitmann et al. 2003, Rosenberg et al. 2011). There is lacustrine evidence for wetter periods further north in Saudi Arabia from several studies, however, obtaining reliable and agreeable ages of these materials has made deciphering the conditions for pluvial episodes challenging for this transition zone (Parton et al. 2013, McLaren et al. 2009). Previous radiocarbon ages from lacustrine sediments in the Rub ’al Khali from southern Saudi Arabia resulted in ages of ~40-20ka BP (McClure 1976, Whitney 1983, Whitney et al. 1983) However, these materials were re-dated with OSL; this, along with other evidence such as dune accumulation records found the ages to be too young (Rosenberg et al 2011, Preusser 2009). OSL ages in central Saudi Arabia (54, 38, and 0.8ka) are inconsistent with other records in the southern Arabian Peninsula and were concluded to reflect local events rather than climatic shifts in the Indian monsoon (McLaren et al. 2009). Humid periods in Saudi Arabia are only constrained to before 75ka BP with one humid period dated in the Holocene ~10-8ka BP (Rosenberg et al. 2011, Ginau et al. 2012, Engel et al. 2012).
Reliable and consistent dates have not been able to constrain the age of deposits in southern Jordan. Although some studies have attributed pluvial periods in the central Arabian Peninsula to enhanced monsoons, this influence has not been clearly identified as far north as Jordan. There is a hiatus in Oman speleothem deposition from 78-10.5ka (Burns et al. 2001), aridity in southern Saudi Arabia from 75-10.5ka (Rosenberg et al. 2011), and aridity in Yemen and U.A.E. before ~10ka (Lézine et al. 2007, Stokes et al. 2013, Parker et al. 2006). Eastern Saharan paleolake records also show aridity from 29-20ka and the LGM marked a dry period for northern Africa (Waldmann et al. 2010, Gasse 2000).

A decrease in precipitation in the southernmost part of the Arabian Peninsula and in northern Africa suggests the tropical monsoon is not the source of moisture to southern Jordan from ~29-21ka. The highstand of Lake Lisan and the maximum dune migration in the Negev from 27-25ka suggest enhanced Cyprus Lows from the Mediterranean at this time. Pluvial conditions for Khabrat Ratiya from ~29-21ka were most likely from enhanced regional precipitation sourced from Mediterranean cyclonic activity around the timing of the LGM.

5.2 Mudawwara Coquina Discussion

5.2.1 Depositional environment and age

The Mudawwara coquina deposits were interpreted as evidence of a large (>2000km²), shallow (~30m) perennial paleolake(s) in the Mudawwara basin (Yasin 2000, Petit-Maire et al. 2010). The faunal assemblage contains marine foraminifera and saline-tolerant gastropods, ostracodes and bivalves, suggesting a freshwater to brackish aqueous environment(s) with species adapted to varying salinities (Masri 1988, Petit-Maire et al. 2010).

At ‘site 7’, within 3 m of the desert pavement, the bivalves are mostly unbroken and are frequently closed with both valves intact indicating a low energy depositional environment (Masri 1988, Petit-Maire et al. 2010). The depositional environment for these deposits is a low energy water body with species habitable in variable salinities. Wetlands could be sustained in more arid environments, but the abundance of bivalves in these deposits have not previously been seen in wetland environments. Although lacustrine features such as shorelines are missing, the faunal assemblage, particularly the bivalves, suggest this to have been a lake environment.

To obtain age constraints on these deposits, uranium series dating with alpha spectrometry was conducted on eleven samples of bivalve shells of the species Cardium sp. by Petit-Maire et al. (2010). Seven samples were from various localities in the Mudawwara depression and four from different depths at a single outcrop (‘Site 7’, Figure 9). Paleoclimatic implications of these coquina deposits are reliant upon the validity of the U-series ages to place these lacustrine deposits within the temporal climatic context of Pleistocene interglacial cycles and to compare with other records. However, Petit-Maire et al. (2010) did not provide sufficient evidence that closed-system behavior occurred to produce robust ages.

The reliability of U-series methods has been examined for marine fossil mollusks, and generally concluded that this method is problematic for this material unless closed-system behavior has remained or open-system dynamics are constrained and can be
accounted for (e.g. Kaufman et al. 1971b, Edwards et al. 2003). The exact manner of this open-system behavior, such as the timing and rate of any post-mortem U incorporation into the shell, is not entirely understood and cannot be known a priori (Eggins 2005). Results usually include an increase in U with time, an increase of U$^{234}$/U$^{238}$ with time, and discordance among dating methods (Ivanovich and Harmon 1992, Arslanov 2002, Kaufman et al. 1996).

Modern marine mollusks shells have low uranium concentrations ranging from 0.05-0.1ppm, however fossil marine mollusks have higher values, 0.5-1.0ppm (Kaufman et al. 1996, Edwards et al. 2003). This indicates U uptake resulting in U concentrations increased by an order of magnitude and can result in age underestimations (Edwards et al. 2003). Terrestrial mollusks have the additional complication of unknown initial U$^{234}$/U$^{238}$ and possible variations in continental water values over time resulting in no closed system assurance with this dating method alone. The U concentrations from Petit-Maire et al. (2010) vary by a factor of ten (0.523 to 4.73ppm) in the eleven samples all from the same species and the authors confirm they are significantly higher than modern and Holocene values for shells. The authors acknowledge that migration of both U and Th is a possibility for these samples.

Individual ages from the Mudawwara coquina deposits have been used to represent a continuous pluvial period from 88-170ka for southern Jordan (Armitage et al. 2011, Cordova et al. 2011, Drake et al. 2013). However, analyses was done on ten individual samples from different localities and only at ‘site 7’ were individual samples dated from multiple stratigraphic layers in one outcrop (4 total samples at roughly .75m apart). The ages on the shells from ‘site 7’ were 88, 152, 135 and 170ka at depths of 60, 130, 190 and 265cm below the surface (Petit-Marie et al. 2010) (Figure 9). No two shells were dated from a single stratigraphic layer, so without any age reproducibly it is possible that the resulting ages are only a range reflecting varying U/Th ratios amongst the shells. If these ages are correct, the resulting sedimentation rate would have been ~.0036cm/yr for lacustrine deposition.

Although alternative dating methods are not viable with these deposits, we argue that any certainty of closed-system behavior has not been demonstrated with these samples. The resulting U concentrations and variability signifies that caution should be taken with these ages. Replicate ages from samples of different shells in the same depositional layer, along with combining dating methods such as concordant Th/U and Pa/U ages could provide more evidence for closed-system behavior.

Without reliable age control for the Mudawwara coquina, we examined several lines of geomorphological evidence that suggest an older depositional age. No geomorphic landforms such as shorelines or deltas are preserved, and there are almost no exposures of these deposits (e.g. badlands) on the landscape as is typical for late Pleistocene lake deposits where there have been large changes in local base level. Petit-Maire et al. (2010) attribute the wetness to warm interglacial periods, but the U-series ages also span glacial period MIS 6 (Figure 9). Also, there is no evidence in Mudawwara of Early Holocene pluvial deposits, although there is evidence for enhanced monsoons at this time from other records in the southern Arabia Peninsula and Africa. Moreover, it would be extremely difficult to sustain a large, shallow, non-saline lake during interglacial periods when temperatures are similar to today because of the high evaporation rates. Geomorphology of these deposits suggest that perhaps this lake was
older than Pleistocene. At this age, the conditions sustaining a lake of this dimension
may be related to other controls such as tectonics, and regional climatic controls would
not be analogous to modern Jordan.

5.2.2 Potential source of precipitation

Petit-Maire et al. (2010) associated the age of these coquina deposits to similar
faunal assemblages from three locations in the Sahara (Libya, Mali, Tunisia) (e.g. Petit-
records of more moisture in Northern Africa from MIS 7-5a. These authors also
conclude that high evaporation rates at this latitude and this particular faunal assemblage
would require contribution of both summer and winter precipitation to maintain a lake of
this dimension. Petit-Maire et al. (2010) concluded that the Mudawwara paleolake
resulted from increased monsoonal precipitation during Pleistocene interglacials in the
Arabian Peninsula paralleling an intensified African Monsoon in the Sahara
contemporaneously.

Although the summer monsoon penetrated southern portions of the Arabian
2001, Parker et al. 2006, Lézine et al. 2007, Preusser 2009), the latitudinal extent is still
not well defined beyond 25˚N (Figure 10). Records in Saudi Arabia do not establish
clear pluvial events linked to the tropical monsoon. We argue that the Mudawwara
coquina deposits also lack reliable ages and there is not sufficient evidence for the
tropical monsoon to have reached as far north as the Mudawwara basin during the
Pleistocene.

6. Conclusions

There is a transition zone in the Middle East from 25-30˚N where the past
dynamics of Mediterranean and monsoonal precipitation is not clearly understood.
Understanding the relationship of past climatic systems to regional rainfall amounts is
critical in anticipation of climate change and future water resource stability in the Middle
East. Identifying the timing and spatial distribution of past humid periods in the Middle
East is also key to understand human migration ‘out of Africa’ and the Arabian Peninsula
into the Levant (e.g. Parker 2009, Shea 2008, Derricourt 2005, Frumkin et al. 2011).

Pluvial deposits in Mudawwara were examined to better constrain the timing and
source of precipitation in southern Jordan. Geochemical and mineralogical results from a
2.35m sediment core from Khabrat Ratiya are comparable to other dry playa
environments with intermittent sedimentation. Sedimentological evidence such as mud
cracks, root voids, and a spillway to the west indicate Khabrat Ratiya had increased
pluvial deposition in the past, however, there is no evidence of a perennial lake.
Sedimentation in Khabrat Ratiya resulted directly from enhanced local rainfall into the
catchment basin recording wetter periods in southern Jordan. The radiocarbon ages for
Khabrat Ratiya indicate active playa sedimentation from ~29-21ka BP, corresponding to
the sustained high levels of Lake Lisan (Bartov et al. 2002, Torfstein et al. 2013). The
radiocarbon ages of ~29-21ka obtained from Khabrat Ratiya are also significant as there
are no other ages on surficial deposits in Mudawwara.

Dry playas are common across desert landscapes and sedimentation occurs in
response to local rainfall events. However, organic matter is generally insufficient for
radiocarbon ages and OSL ages are not obtainable on drill cores making the timing of wetter conditions hard to constrain. This study had successful age determination by removing the silicate material to concentrate organic material in sediment to obtain material appropriate for radiocarbon analysis in material that would otherwise yield less reliable results. The accuracy of this method should be further tested in similar material with known ages, but this method shows high potential to successfully date material with low organic carbon and where other dating methods are not available.

The age of the Mudawwara coquina deposits is still unclear. Although lake features are lacking in Mudawwara, the bivalve shells suggest these coquina deposits are lacustrine. The faunal assemblage and extent of the Mudawwara coquina represent a large >2000km² lake environment that was sustained in the past. Geomorphological evidence supports an older depositional age than the U-series ages obtained from Petit-Marie et al. (2010). Closed-system assurance has not been demonstrated for these shells and the U-series ages may or may not represent meaningful ages. Therefore, climatic implications should not be based on these U-series ages. Although there are records of enhanced tropical monsoons in the southern Arabian Peninsula, evidence of tropical monsoonal precipitation from the south reaching as far north as southern Jordan in the Early Holocene-Late Pleistocene is still lacking.
7. References


EXACT (Executive Action Team, Middle East Water Data Banks Project). 1998 Overview of Middle East water resources—water resources of Palestinian, Jordanian, and Israeli interest. See http://water.usgs.gov/exact/overview/index.htm.


### Table 1. Soluble Salts

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth cm</th>
<th>Total Salt wt. %</th>
<th>F wt. %</th>
<th>Cl wt. %</th>
<th>NO₂ wt. %</th>
<th>Br wt. %</th>
<th>NO₃ wt. %</th>
<th>PO₄ wt. %</th>
<th>SO₄ wt. %</th>
<th>Ba wt. %</th>
<th>Ca wt. %</th>
<th>Fe wt. %</th>
<th>K wt. %</th>
<th>Mg wt. %</th>
<th>Na wt. %</th>
<th>Sr wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16</td>
<td>5</td>
<td>4.8</td>
<td>0.001</td>
<td>1.49</td>
<td>0.0</td>
<td>0.0</td>
<td>0.40</td>
<td>0.0</td>
<td>1.18</td>
<td>0.0</td>
<td>0.53</td>
<td>0.0</td>
<td>0.03</td>
<td>0.03</td>
<td>1.17</td>
<td>0.01</td>
</tr>
<tr>
<td>A14</td>
<td>15</td>
<td>4.0</td>
<td>0.001</td>
<td>1.43</td>
<td>0.0</td>
<td>0.0</td>
<td>0.68</td>
<td>0.0</td>
<td>0.45</td>
<td>0.0</td>
<td>0.25</td>
<td>0.0</td>
<td>0.02</td>
<td>0.02</td>
<td>1.16</td>
<td>0.01</td>
</tr>
<tr>
<td>A10</td>
<td>40</td>
<td>2.9</td>
<td>0.001</td>
<td>0.99</td>
<td>0.0</td>
<td>0.0</td>
<td>0.30</td>
<td>0.0</td>
<td>0.49</td>
<td>0.0</td>
<td>0.17</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.88</td>
<td>0.00</td>
</tr>
<tr>
<td>A8 19-24</td>
<td>60</td>
<td>2.0</td>
<td>0.001</td>
<td>0.70</td>
<td>0.0</td>
<td>0.0</td>
<td>0.20</td>
<td>0.0</td>
<td>0.34</td>
<td>0.0</td>
<td>0.09</td>
<td>0.0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.66</td>
<td>0.00</td>
</tr>
<tr>
<td>A8 0-6</td>
<td>80</td>
<td>2.1</td>
<td>0.001</td>
<td>0.64</td>
<td>0.0</td>
<td>0.0</td>
<td>0.20</td>
<td>0.0</td>
<td>0.47</td>
<td>0.0</td>
<td>0.12</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.64</td>
<td>0.00</td>
</tr>
<tr>
<td>A6 33-37</td>
<td>100</td>
<td>2.3</td>
<td>0.001</td>
<td>0.57</td>
<td>0.0</td>
<td>0.0</td>
<td>0.09</td>
<td>0.0</td>
<td>0.78</td>
<td>0.0</td>
<td>0.23</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.58</td>
<td>0.00</td>
</tr>
<tr>
<td>A6 15-16</td>
<td>120</td>
<td>2.0</td>
<td>0.008</td>
<td>0.55</td>
<td>0.0</td>
<td>0.0</td>
<td>0.06</td>
<td>0.0</td>
<td>0.65</td>
<td>0.0</td>
<td>0.18</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>A5 28-32</td>
<td>140</td>
<td>2.7</td>
<td>0.001</td>
<td>0.54</td>
<td>0.0</td>
<td>0.0</td>
<td>0.07</td>
<td>0.0</td>
<td>1.14</td>
<td>0.0</td>
<td>0.34</td>
<td>0.0</td>
<td>0.02</td>
<td>0.02</td>
<td>0.57</td>
<td>0.00</td>
</tr>
<tr>
<td>A5 8-12</td>
<td>160</td>
<td>3.1</td>
<td>0.001</td>
<td>0.54</td>
<td>0.0</td>
<td>0.0</td>
<td>0.07</td>
<td>0.0</td>
<td>1.47</td>
<td>0.0</td>
<td>0.44</td>
<td>0.0</td>
<td>0.02</td>
<td>0.02</td>
<td>0.59</td>
<td>0.01</td>
</tr>
<tr>
<td>A3 18-21</td>
<td>180</td>
<td>2.7</td>
<td>0.001</td>
<td>0.53</td>
<td>0.0</td>
<td>0.0</td>
<td>0.07</td>
<td>0.0</td>
<td>1.16</td>
<td>0.0</td>
<td>0.34</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.55</td>
<td>0.00</td>
</tr>
<tr>
<td>A3 0-4</td>
<td>195</td>
<td>1.8</td>
<td>0.001</td>
<td>0.42</td>
<td>0.0</td>
<td>0.0</td>
<td>0.05</td>
<td>0.0</td>
<td>0.65</td>
<td>0.0</td>
<td>0.18</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.46</td>
<td>0.00</td>
</tr>
<tr>
<td>A2 18-21</td>
<td>200</td>
<td>2.1</td>
<td>0.001</td>
<td>0.50</td>
<td>0.0</td>
<td>0.0</td>
<td>0.05</td>
<td>0.0</td>
<td>0.77</td>
<td>0.0</td>
<td>0.19</td>
<td>0.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.56</td>
<td>0.00</td>
</tr>
<tr>
<td>A2 0-2</td>
<td>220</td>
<td>3.3</td>
<td>0.003</td>
<td>0.30</td>
<td>0.0</td>
<td>0.0</td>
<td>0.03</td>
<td>0.0</td>
<td>1.88</td>
<td>0.0</td>
<td>0.66</td>
<td>0.0</td>
<td>0.02</td>
<td>0.02</td>
<td>0.34</td>
<td>0.01</td>
</tr>
<tr>
<td>A1</td>
<td>235</td>
<td>2.9</td>
<td>0.001</td>
<td>0.29</td>
<td>0.0</td>
<td>0.0</td>
<td>0.05</td>
<td>0.0</td>
<td>1.62</td>
<td>0.0</td>
<td>0.56</td>
<td>0.0</td>
<td>0.02</td>
<td>0.02</td>
<td>0.31</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Table 2. Organic Carbon and Nitrogen

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Depth cm</th>
<th>C(%)</th>
<th>N(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16</td>
<td>5</td>
<td>0.17</td>
<td>0.02</td>
</tr>
<tr>
<td>A15</td>
<td>10</td>
<td>0.13</td>
<td>0.02</td>
</tr>
<tr>
<td>A14</td>
<td>15</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>A12</td>
<td>30</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>A10</td>
<td>40</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>A9 5-10</td>
<td>50</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>A8 19-24</td>
<td>60</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>A8 12-14</td>
<td>70</td>
<td>0.11</td>
<td>0.02</td>
</tr>
<tr>
<td>A8 0-6</td>
<td>80</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>A7 4-8</td>
<td>90</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>A6 33-37</td>
<td>100</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>A6 21-25</td>
<td>110</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td>A6 13-16</td>
<td>120</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>A6 3-6</td>
<td>130</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>A5 28-32</td>
<td>140</td>
<td>0.10</td>
<td>0.00</td>
</tr>
<tr>
<td>A5 16-20</td>
<td>155</td>
<td>0.11</td>
<td>0.00</td>
</tr>
<tr>
<td>A4 6-9</td>
<td>170</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>A3 18-21</td>
<td>180</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>A3 7-10</td>
<td>190</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>A2 18-21</td>
<td>200</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>A2 10-13</td>
<td>210</td>
<td>0.12</td>
<td>0.00</td>
</tr>
<tr>
<td>A2 0-2</td>
<td>220</td>
<td>0.12</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 3. Stable Isotopes

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Depth cm</th>
<th>δ¹³C</th>
<th>δ¹⁸O</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16</td>
<td>5</td>
<td>1.11</td>
<td>2.47</td>
</tr>
<tr>
<td>A14</td>
<td>15</td>
<td>1.16</td>
<td>2.47</td>
</tr>
<tr>
<td>A10</td>
<td>40</td>
<td>1.41</td>
<td>3.49</td>
</tr>
<tr>
<td>A8 19-24</td>
<td>60</td>
<td>1.42</td>
<td>3.30</td>
</tr>
<tr>
<td>A8 0-6</td>
<td>80</td>
<td>1.51</td>
<td>3.38</td>
</tr>
<tr>
<td>A6 33-37</td>
<td>100</td>
<td>2.41</td>
<td>4.59</td>
</tr>
<tr>
<td>A6 13-16</td>
<td>120</td>
<td>2.01</td>
<td>3.40</td>
</tr>
<tr>
<td>A5 28-32</td>
<td>140</td>
<td>1.70</td>
<td>3.74</td>
</tr>
<tr>
<td>A5 8-12</td>
<td>160</td>
<td>2.58</td>
<td>3.49</td>
</tr>
<tr>
<td>A3 18-21</td>
<td>180</td>
<td>0.71</td>
<td>2.14</td>
</tr>
<tr>
<td>A3 0-4</td>
<td>195</td>
<td>1.58</td>
<td>2.53</td>
</tr>
<tr>
<td>A2 18-21</td>
<td>200</td>
<td>1.37</td>
<td>2.95</td>
</tr>
<tr>
<td>A2 0-2</td>
<td>220</td>
<td>0.16</td>
<td>0.52</td>
</tr>
<tr>
<td>A1</td>
<td>235</td>
<td>-2.69</td>
<td>-3.15</td>
</tr>
</tbody>
</table>
### Table 4. Radiocarbon Ages

Summary of AMS sample information, carbon-14 ages, and calibrated ages. Material for each sample was organics.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>AMS #</th>
<th>Unit</th>
<th>Depth (cm)</th>
<th>δ13C (VPDB)</th>
<th>Calendar age (ka BP)</th>
<th>14C age (14C ka BP)</th>
<th>Age (cal ka BP)</th>
<th>Age (cal ka BP)</th>
<th>P#</th>
</tr>
</thead>
<tbody>
<tr>
<td>A15</td>
<td>1367</td>
<td>C</td>
<td>-10</td>
<td>-20.5</td>
<td>20.97 ± 0.43</td>
<td>17650 ± 80</td>
<td>20544</td>
<td>21394</td>
<td>1</td>
</tr>
<tr>
<td>A6 21-25</td>
<td>1366</td>
<td>C</td>
<td>-110</td>
<td>-20.1</td>
<td>24.57 ± 0.37</td>
<td>20540 ± 100</td>
<td>24205</td>
<td>24944</td>
<td>1</td>
</tr>
<tr>
<td>A5 16-21</td>
<td>1365</td>
<td>C</td>
<td>-150</td>
<td>-20.3</td>
<td>25.61 ± 0.43</td>
<td>21470 ± 90</td>
<td>25179</td>
<td>26043</td>
<td>1</td>
</tr>
<tr>
<td>A3 18-21</td>
<td>1364</td>
<td>C</td>
<td>-180</td>
<td>-20.2</td>
<td>29.08 ± 0.45</td>
<td>24380 ± 130</td>
<td>28637</td>
<td>29529</td>
<td>1</td>
</tr>
<tr>
<td>A2 10-13</td>
<td>1363</td>
<td>C</td>
<td>-210</td>
<td>-19.8</td>
<td>23.56 ± 0.34</td>
<td>19700 ± 90</td>
<td>23214</td>
<td>23899</td>
<td>1</td>
</tr>
</tbody>
</table>

1. Depth from surface.

2. Calibrated ages were calculated using CALIB v. 6.0.0, IntCal09.14C dataset; limit 50.0 calendar ka B.P. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are reported as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater. Multiple ages are reported when the probability of a calibrated age range exceeds 0.05.

3. P = probability of the calibrated age falling within the reported range as calculated by CALIB.
Figure 2. Mudawwara region (29°N, 36°E) in southern Jordan with locations of the playa Khabrat Ratiya, and ‘site 7’ and other coquina deposits from Petit-Maire et al. 2010. Contour line at 730m shows the closed basin of Mudawwara and Tabuk in Saudi Arabia, and demarks the extent of a paleolake if the basin were filled.
Figure 3. Photographs of Mudawwara ‘site 7’. a) Exposed coquina at the surface of the trench site (lower right corner) from Petit-Maire et al. 2010 b) Close up of coquina; primarily the bivalve Cardium sp. c) Small, broken shells exposed at the surface of the desert pavement.
Figure 4. Aerial photograph of dry playa Khabrat Ratiya (29°22’N, 36°10’E) with drill site for ~3m core. Primary drainage that flows into the playa is located on the north side of the basin, and the inactive spillway is situated on the eastern margin.
**Figure 5.** Sediment core from Khabrat Ratiya with location of $^{14}$C samples, particle size analysis, geochemistry, isotopic analyses of carbonate minerals, and organic C content.

**Figure 6.** SEM images of primary sediment and secondary precipitates within the Khabrat Ratiya sediment core. a) Gypsum from 15cm depth b) Secondary halite precipitation from 220cm depth. c) Quartz grains at 160cm depth. d) Gypsum 80cm depth.
Figure 7. The effect of the amount of contamination by modern carbon on the true ages (Rech et al. 2011.)

Figure 8. Radiocarbon ages from Khabrat Ratiya sediment core compared to Holocene-Pleistocene lake level fluctuations of Lake Lisan (Torfstein et al. 2013).
**Figure 9.** Section of coquina from Mudawwara ‘site 7’ with U-series ages (Petit-Maire et al., 2010) and MIS on left spanning U-series ages from coquina strata. MIS curves drawn from Martinson et al. 1987 and Shackleton and Pisias 1985.