Catena 83 (2010) 7–22

Contents lists available at ScienceDirect

Catena

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

Paleolandscape and paleoenvironmental interpretation of spring-deposited sediments in Dakhleh Oasis, Western Desert of Egypt

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ARTICLE INFO

Article history:
Received 20 August 2008
Received in revised form 17 March 2010
Accepted 23 June 2010

Keywords:
Spring mound
Bog iron
Pluvial deposits
Groundwater
Paleolithic
Egypt

ABSTRACT

Iron-rich sediments in Dakhleh Oasis, Western Desert of Egypt, have been recognized as spring mounds and as archaeological sites where Paleolithic materials have been recovered. Detailed sedimentologic investigation and mapping of these features reveal that spring mound sediments were deposited in a shallow vegetated wetland formed by the discharge of iron-rich Nubian Aquifer waters along the southern margin of the oasis, controlled largely by localized faulting and the variable paleotopography of the basin floor. The spring sediments represent peri-lacustrine or lake independent features and can be differentiated from fully lacustrine deposits on the basis of their sedimentary characteristics as well as the presence of goethite and jarosite in a region where authigenic deposition during Pleistocene pluvial activity principally resulted in tufas and lacustrine marls. Spring mound formation incorporated sediment through the ponding of surface water, aeolian entrapment by local vegetation, and the formation of iron precipitates in a low-energy, oxidative and acidic environment that was not dependent upon surface water inputs into the Dakhleh basin. The potentially interpluvial nature of this water resource makes it an important sedimentary archive for archaeological investigations in the basin. The Dakhleh spring mounds record a unique groundwater controlled paleoenvironment, providing the first evidence of a bog iron in Egypt and one of the few occurrences of iron-rich wetland remnants in the modern Sahara.

1. Introduction

The modern Western Desert of Egypt is a hyperarid environment, receiving a mean annual rainfall of 0.7 mm (Shahin, 1985). However, climatic conditions across northern Africa have oscillated between arid and humid (or pluvial) during the Quaternary, as indicated by lacustrine, fluvial and spring-deposited sediments preserved in the modern Sahara (e.g., Gaven et al., 1981; McHugh et al., 1988; Szabo et al., 1995; Crombie et al., 1997; Swezey et al., 1999; Brook et al., 2003; Smith et al., 2004a). The association of archaeological materials with many of these pluvial deposits indicates hominin occupation of the Sahara during humid periods (e.g., Caton-Thompson, 1952; Wendorf et al., 1991; Wendorf et al., 1993; Hill, 2001; Hoelzmann et al., 2001; Kleindienst, 2003; Smith et al., 2004b).

Egypt straddles one of the four likely migration routes, and the only fully terrestrial route, out of the African continent for all major hominin migrations (Derricourt, 2005), making the identification of habitable hominin environments important for the recognition of potential migration corridors. The Western Desert oases provided the resources necessary for early human habitation during humid periods, as indicated by spring and lacustrine deposits found in oasis depressions. These deposits also record a localized climatic signal (e.g., Smith et al., 2004a, 2004b), in contrast to the more regional records, encompassing changes within several climate zones, provided by Nile Valley sediments (Shahin, 1985). Associations of Paleolithic artifacts with water-lain deposits in Dakhleh Oasis therefore provide an opportunity to characterize hominin paleoenvironments in the Western Desert (Kleindienst, 1999), which may have served as a waypoint for early human migration as an alternative to the potentially more dangerous and crowded Nile Valley (e.g., Kleindienst, 2000). Although the timing of enhanced rainfall relative to today was likely a significant control on when desert regions could be used by early human groups (Chiotti et al., 2007), the specific chronology of water resource availability at any particular locality would have been dependent upon hydrologic and geomorphic factors. Detailed examinations of pluvial deposits can clarify the sequence of hydrologic events that occurred in Dakhleh following the onset of pluvial conditions, thereby constraining the extent to which the oasis may have supported hominin survival and migration.

Dakhleh Oasis is one of a series of structural depressions in the Western Desert (Fig. 1), where Pleistocene pluvial sediments occur as iron-rich spring deposits as well as carbonate spring and lacustrine sediments (Brookes, 1993a; Brookes, 1993b; Churcher et al., 1999). Dates obtained from lacustrine deposits in Dakhleh indicate pluvial conditions between 100 and 200 ka (Osinski et al., 2007). However,

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doi:10.1016/j.catena.2010.06.009

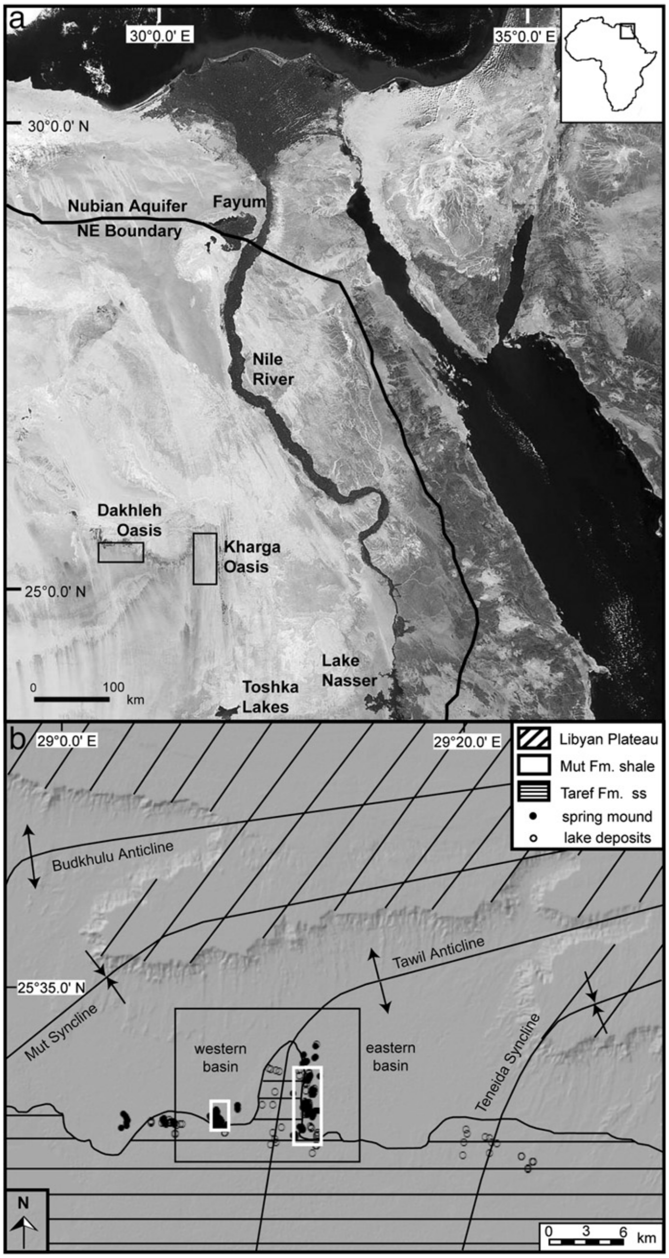

Fig. 1. a. MODIS imagery of Egypt showing the location of Dakhleh and Kharga oases and surrounding landmarks as well as the approximate northeastern boundary (saline-freshwater interface) of the Nubian Aquifer (after Heinl and Brinkmann, 1989; Thorweihe, 1990). Image credit Jacques Descloitres, MODIS Land Science, courtesy of Team Visible Earth (http://visibleearth.nasa.gov/). b. Sketch map of the structure and surface geology of Dakhleh Oasis showing mapped spring mounds and lake deposits. Background image shows a hillshade model of oasis topography. White boxes indicate primary field areas in each basin. Black box indicates area illustrated as modern topography in Fig. 4. Bedrock geology after Barakat and Milad (1966).

dates on Saharan lacustrine deposits (e.g., Miller et al., 1991; McKenzie, 1993; Schild and Wendorf, 1993) as well as tufas in nearby Kharga Oasis (e.g., Smith et al. 2004b; Smith et al., 2007), indicate pluvial activity in Dakhleh more likely occurred principally ca. 120–140 ka, during a commonly recognized humid interglacial period in the Sahara (e.g., Gaven et al. 1981, McKenzie, 1993, Szabo et al. 1995). Lacustrine marls in Dakhleh Oasis (Churcher et al., 1999; Kieniewicz and Smith, 2009) accumulated when increased precipitation and surface runoff during maximum pluvial conditions resulted in a deep, carbonate-rich lake filling much of the Dakhleh depression. In contrast, iron-rich sediments are the result of groundwater discharge from the Nubian Aquifer (Brookes, 1993a) and represent a very different geochemical environment from that of the lake highstand described in these previous investigations.

Brookes (1993a) differentiates spring mound sediments from a closely associated unit known as Ferruginous Spring Sediments, or FSS. More recently (Churcher et al., 1999; Churcher and Kleindienst, in press), this acronym has been used to signify the more general term "Ferruginized Sandy Sediments," although the sedimentary units in question remain the same. FSS is a shallow-water deposit with a complex relationship to the overlying, younger, and fully-lacustrine "Calcareous Silty Sediments" (previously Brookes, 1993a "Calcareous Spring Sediments"), or CSS (Churcher et al., 1999). Spring mound sediments are specifically referred to as "Spring Vent-related Sediments", or SVS (Churcher and Kleindienst, in press). Although the detailed temporal relationships between these discontinuous sedimentary packages are currently unclear, an independent assessment and description of spring mound environments as recorded by SVS is necessary for understanding Dakhleh paleogeography and paleohydrology. The current investigation aims to present a more detailed treatment of Dakhleh's spring mounds as hydrologic entities independent of later lacustrine development. This paper will outline the geomorphology, sedimentology and mineralogic development of spring mound features and examine their relevance to the hydrologic history and hominin activity of Dakhleh Oasis.

1.1. Spring deposits and spring mound environments

The identification of spring sediments can be challenging in environments where multiple hydrologic entities (e.g., lakes, wetlands, springs, and rivers) have coexisted, as is the case in Dakhleh. Spring-related wetland deposits are often identified by the presence of significant thicknesses of biogenic units as well as precipitates (e.g., Rech et al., 2002). However, wetlands are not necessarily spring-related, and the recognition of a spring source is aided by the identification of vents or other areas of direct discharge. Sediment deposited by these spring "seeps" may be silty clay to coarser materials, depending upon the nature of the streams produced by spring flow. The deposition of such sediments in discontinuous units and indications of variable water levels may also provide evidence of spring discharge (Quade and Pratt, 1989; Quade et al. 1995). Spring-related wetland environments often contain highly bioturbated sediment, leading to extremely limited preservation of depositional sedimentary structures (Deocampo, 2002) and a greater likelihood of primarily massive sedimentary units. Geochemical evidence for freshwater environments (e.g., Deocampo et al., 2002) and fossil evidence (e.g., Liutkus and Ashley, 2003) often serve as more specific paleoenvironmental indicators, whereas tufa or other precipitate formation within spring environments provides more definitive evidence for groundwater discharge (Deocampo, 2002). In the case of a geochemically unique groundwater source, the mineralogy of the precipitates produced can provide adequate differentiation between groundwater (spring) deposits and those produced by other surface waters (e.g., Brookes, 1993a).

Mounded spring deposits are a unique subset of spring sediments, which develop through the accumulation of suspended sediment, peat, aeolian material and groundwater precipitates in areas of direct discharge (Fensham et al, 2004). In the few modern environments where they are found, artesian spring mounds are often evaporative systems that allow for carbonate precipitation near active spring vents (e.g., Arp et al, 1998; Mudd, 2000). The precipitates that result from this evaporative process contribute to the overall development of the mound form, while precipitate mineralogy is controlled by groundwater chemistry (Habermehl, 2001).

In Dakhleh Oasis, the iron-rich nature of Nubian aquifer waters and their deposits (Brookes, 1993a) allows for relative ease of differentiation between groundwater deposits and carbonate-rich surface water deposits regardless of their sedimentary placement. However, spring mound features are highly eroded and almost identical in form to remnant lacustrine sediments, due to the yardanged and eroded nature of local bedrock and Quaternary deposits (Brookes, 1993a). This makes it difficult to distinguish between these deposits in the absence of detailed field investigations. Such detailed investigations in Dakhleh provide a starting point for understanding the original extent of groundwater-related deposition in Dakhleh as well as examining the sedimentology and geomorphology of the spring mounds themselves.

1.2. Geologic setting

Dakhleh Oasis (latitude 25.5°N, longitude 29.0°E) stretches 70 km from SE to NW, with maximum north–south dimensions of approximately 20 km (Fig. 1) (Brookes, 1989). The oasis is bounded to the north by the limestone-capped Libyan Plateau (Fig. 1b). Bedrock in the lowland portion of the basin consists of Cretaceous-age Taref Formation sandstone, which unconformably underlies Cretaceous-age Mut (Quseir) Formation shales (Hermina, 1990). Quaternary sediments are found primarily in southern Dakhleh on eroded bedrock surfaces (El-Hinnawi et al., 1975; Hermina, 1990), where spring mounds occur in the vicinity of the contact between the Taref and the Mut Formations (Fig. 1b). Bedrock units dip slightly (<5°) to the north forming gently undulating, NE-plunging synclinal and anticlinal folds within the larger context of the regional Dakhla Syncline (Barakat and Milad, 1966).

The Taref Formation, the local member of the Nubian Aquifer sandstone (Brookes, 1993a), is one of a series of sandstone units that make up the Nubian Aquifer System, which extends through portions of Egypt, Libya, Chad, and Sudan (Fig. 1a) (Thorweihe, 1990). These sandstone units have good hydraulic conductivities and provide a reservoir of “fossil” groundwater recharged during pluvial events of the geologic past (Thorweihe, 1986). Recent ^{81}Kr dating indicates ‘deep’ fossil groundwater ages of 2×10^5 to 1×10^6 years (Sturchio et al., 2004); this deep groundwater was most likely recharged in southwestern Egypt from an Atlantic Ocean source (Sonntag et al., 1979, 1980). In contrast, shallow and locally unconfined sandstone horizons may have been recharged by younger, more localized pluvial events during the Holocene (Brinkmann and Heinl, 1986; Hesse et al., 1987; Heinl and Brinkmann, 1989; Patterson et al., 2005). In the Western Desert, Nubian sandstones comprise multiple layers of isolated and perched aquifers (Shata, 1982), and local groundwater is most likely a mixture of deep water and younger, locally recharged water (Dabous and Osmond, 2001). The groundwater head gradient in Egypt indicates flow from south to north; as a result Dakhleh is the first of the oases to receive groundwater input from its southwestern source (Thorweihe, 1986; Patterson et al., 2005).

Dakhleh Oasis contains two significant depressions separated by an uplifted sandstone ridge, or dividing ridge, associated with the northward-plunging Tawil Anticline (Fig. 1b). The western depression corresponds with the axis of the Mut Syncline; the eastern lowland portion of the basin is also known as the Teneida Syncline (Barakat and Milad, 1966). Lacustrine deposits have been identified in both the eastern and western depressions (Kleindienst et al., 1999; Kieniewicz and Smith, 2009), as have Pleistocene spring mounds (Schild and Wendorf, 1981; Brookes, 1993a). The spring mounds occur primarily along the dividing ridge in the southern portion of the oasis. Similar mounds have also been identified in Kharga Oasis (Fig. 1a), 140 km east of Dakhleh, where they occur along bedrock fractures and faults (Caton-Thompson, 1952; Brookes, 1993a). The lack of such structural features may account for the absence of spring mounds in the region between Dakhleh and Kharga (Brookes, 1993a).

The Dakhleh spring mounds have been described in some detail in previous investigations, most notably by Brookes (1993a), Frizano (1996), and Kleindienst et al. (1999). Spring mound features provide a geologic context for the recovery of archaeological materials, representing environments occupied or utilized by Pleistocene hominins in a number of locations in the Western Desert. Acheulian and Middle Stone Age (MSA) artifacts have been found in association with spring environments at Bir Tarfawi in southern Egypt (Wendorf et al., 1976; Wendorf et al., 1991; Hill, 2001), and Dakhleh spring mound sediments contain both Upper Acheulian and Middle Paleolithic assemblages (Wendorf et al., 1976; Schild and Wendorf, 1977; Brookes, 1993a; Kleindienst, 1999). Understanding the role of spring mounds as local hydrologic features will contribute to models of lake formation and pluvial activity during the Pleistocene while aiding in the identification of habitable paleoenvironments in Dakhleh Oasis.

2. Methods

Fieldwork included survey of a significant portion of Dakhleh Oasis, but detailed sedimentary description focused on spring mounds in two main study areas in the eastern and western basins (Fig. 1b). Stratigraphic sections of 58 spring mounds were described in detail and measured using a Jacob staff and Abney level. An additional 72 mounds were described without measurement. All mounds were digitally photographed and mapped using differential GPS (≤0.5 m vertical, ≤0.2 m horizontal error) and ArcGIS 9.0 software. Ironstone elevations, local high points, and contacts between Quaternary sediment and pre-Quaternary bedrock were mapped on all mounds where applicable. Sediment colors were recorded as dry Munsell soil colors. Grain size determinations of silt- and sand-size fractions were made using pipette analysis (after Gee and Bauder, 1986) following digestion with H_2O_2 and dispersion with sodium metaphosphate. Sand-fraction weight percents were obtained after wet-sieving of sediment.

Texture and identifiable mineralogy of ironstone samples were described in thin section. Additional mineralogical identifications were made by qualitative XRD analysis on a Rigaku D-MAX/A diffractometer using Cu–Kα radiation (35 kV, 35 mA) following calibration using a powdered silica standard. Samples were analyzed as backfilled powder mounts, or where necessary as oriented evaporation mounts, of both whole-sediment and clay-fraction components (Whittig and Allardice, 1986). Samples were step-scanned from 2.0–70.0 2θ at 0.02° step intervals and analyzed using Materials Data, Inc. Jade software. For the purposes of this paper, ironstone refers to indurated iron precipitate-rich units in general, whereas ferricrete refers specifically to iron-cemented sandstones (Bourman, 1993) as a subset of ironstones. Non-ferricrete ironstones described in this study are referred to as iron precipitates.

Mineralogical identifications were made by qualitative X-ray diffraction (XRD) analysis on a Rigaku D-MAX/A diffractometer using Cu–Kα radiation (35 kV, 35 mA) following calibration using a powdered silica standard. XRD samples were analyzed as backfilled powder mounts, or where necessary as oriented evaporation mounts, of both bulk-sediment and clay-fraction components (Whittig and Allardice, 1986). Samples were step-scanned from 2.0–70.0 2θ at 0.04° step intervals and analyzed using Materials Data, Inc. Jade software. X-ray fluorescence (XRF) analyses were obtained for both major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P) and minor (Pb, Nb, Zr, Y, Sr, Rb, Ga, Zn, Ni, Ba, Co, V, Ce) elements using a Siemens SRS-200 sequential spectrometer. Errors for all XRF measurements are equal to or better than ±0.25 (one sigma). Elemental distributions of several polished thin sections were mapped through wavelength dispersive and silicon drift energy dispersive X-ray spectroscopy using a JEOL 733 electron microprobe.

3. Results

3.1. Spring mound morphology

Spring mounds throughout Dakhleh occur as erosional remnants with variable thicknesses of Quaternary sediments; up to six meters of spring sediments may be preserved, but most mounds consist of only remnant silts overlying an erosional “mound” of Mut Formation bedrock shales. Identifiable spring vents are often present, preserved by iron oxidestained silts and sands (Fig. 2a). The elevations of contacts between bedrock and spring sediments indicate the modern surface has been deflated between four and seven meters below the pre-discharge paleosurface, although the degree of erosion varies significantly from mound to mound (Fig. 3). The mounds found farthest north are generally more eroded (Fig. 2b, c), possibly due to the prevailing northerly winds in this region, but additional erosional variation across the study area suggests that preferential preservation of mounds capped by hard ironstone deposits as well as the presence of an irregular paleosurface also played a role in landscape formation during the late Quaternary.

Spring mounds in both the eastern and western basins exhibit similar erosional forms and stratigraphies, with iron-rich deposits present in both basins. Ironstones commonly occur as caps on poorly-consolidated, silty sediments (Fig. 3); iron oxides are also found as thin lenses of precipitate and as cement within spring-deposited silts. Throughout both study areas, sedimentary units are similar in terms of elevation, texture, mineralogy and erosional form, suggesting the mound sediments in these two basins were deposited by the same processes and likely during the same time period or periods. However, the stratigraphy of the spring mounds in both basins is often laterally discontinuous over tens or hundreds of meters. The lack of stratigraphic correlation between even adjacent spring mounds suggests isolated deposition of similar units (Fig. 3), although their erosional expression is identical to that of previously continuous paleolacustrine landscapes. Bedrock contacts indicate a paleosurface that dipped away from the Tawil uplift in both basins (Fig. 4). At higher elevations root casts, root traces and blocky peds indicate weak paleosol formation in basal silts. In many cases only remnant silts are present on a low mound of Mut shales, due to the significant deflation of this area.

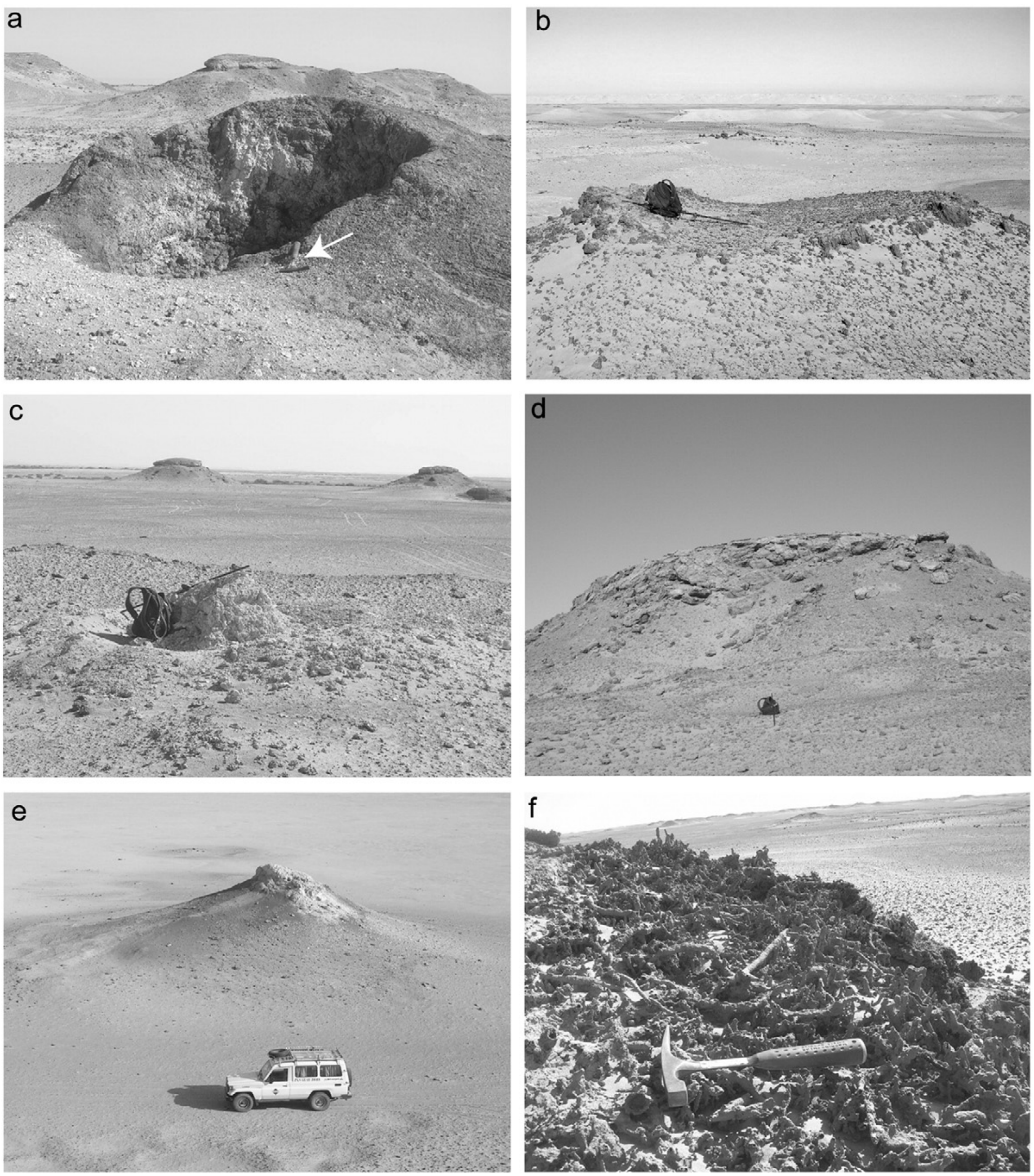

Fig. 2. Field photos from southern Dakhleh Oasis: a) spring vent remnant in Mut Fm. shale, rock hammer (arrow, length 28 cm) for scale, b) circular ironstone deposit along the southern margin of the eastern study area, field pack and Jacob Staff (length 1.5 m) for scale, c) remnant spring deposit at modern ground level with larger mound forms visible in the background (looking southwest), field pack and Jacob Staff for scale d) large iron-capped spring mound, field pack for scale, e) average erosional mound form consisting of spring silts atop Mut Formation shale, Land Cruiser for scale, f) root mats preserved as iron casts with rock hammer for scale.

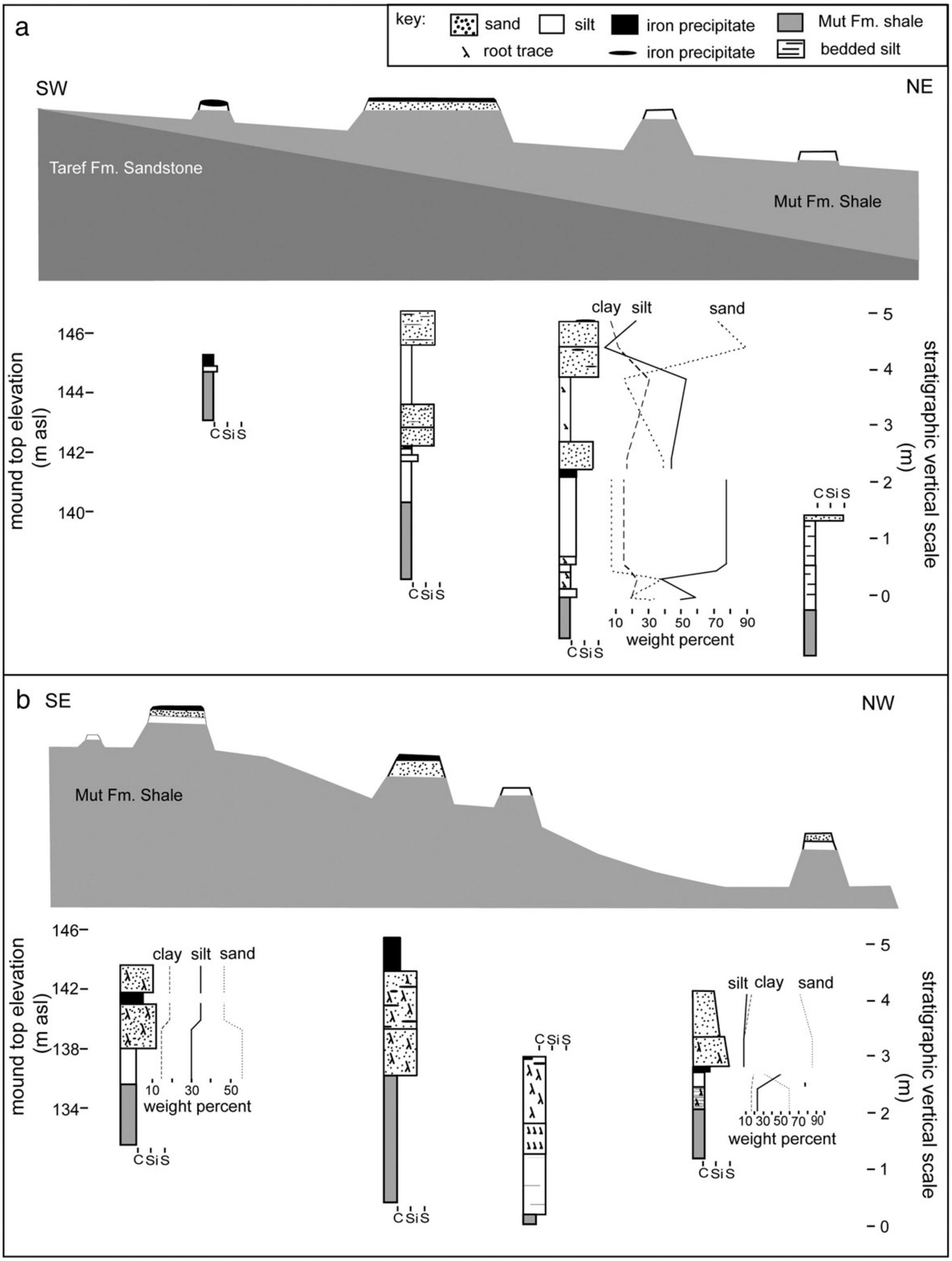

Fig. 3. Schematic view of basin topography with representative spring mound stratigraphy in both the eastern (a) and western (b) basins represented as generalized geomorphic sketches (~35× vertical exaggeration) and detailed stratigraphic sketches of the illustrated mounds with grain size curves where grain size data are available. Elevations of mound sections are based on DGPS data for the tops of mound features. DGPS elevations of mound tops (in meters above mean sea level) are listed on the left, whereas the scale for the sedimentary units depicted in the stratigraphic sections (in meters) is on the right. Horizontal scale is approximate to mound positions indicated by dashes along section lines illustrated in Fig. 4. For additional description of the relationship between spring mound sediments and lacustrine sediments or bedrock deposits please see Brookes (1993a), Churcher et al. (1999), or Churcher and Kleindienst (in press).

3.2. Spring mound sedimentology

Spring-deposited sediments found within the Dakhleh mounds take a number of forms. The contact between Mut bedrock shales and spring mound sediments in both study areas is most often defined by the presence of bioturbated and well-sorted, jarosite ($KFe_3(OH)_6(SO_4)_2$) and goethite (FeOOH)-stained quartz silts (Figs. 3 and 5). These silts vary from massive to weakly bedded quartz, defined in part by jarosite (2.5Y8/4, pale yellow) and goethite (10YR5/8, yellowish brown) staining in otherwise pale (2.5Y8/2, pale yellow) quartz silts. Limited

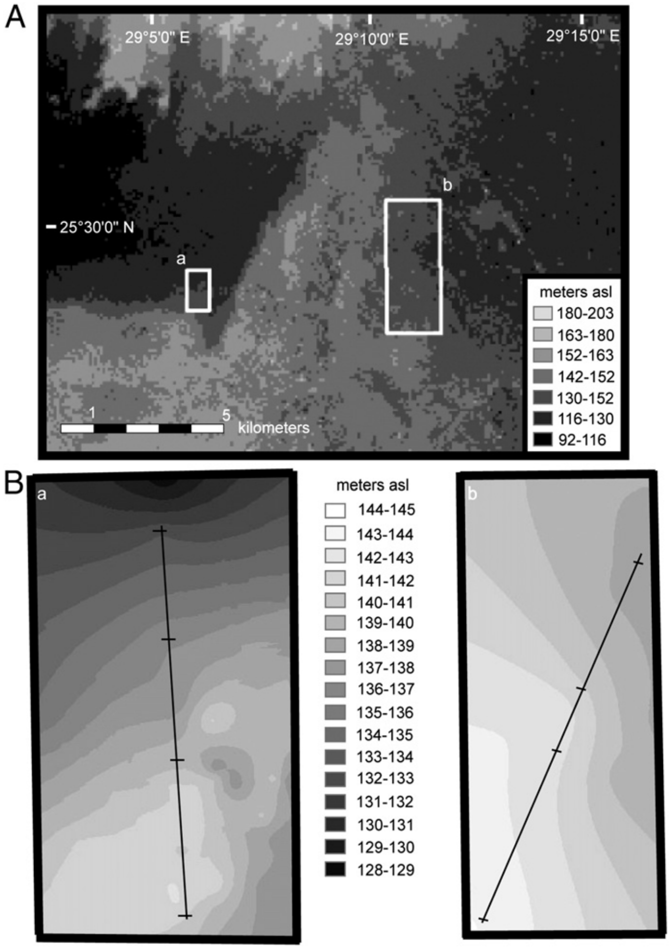

Fig. 4. A) Modern topography (boxed area shown in Fig. 1b) from regional DEM data, and B) paleotopography of study areas in the western (a) and eastern (b) basins as defined by boxes in A (see also Fig. 1b). Paleotopography (B) is reconstructed from bedrock contacts measured using DGPS (meters above mean sea level) and is illustrated at the same scale for both study areas. Section lines and dashes indicate positions of mounds sketched in Fig. 3.

hematite (Fe_2O_3) staining is present in some silt units in the western basin, forming distinctive reddish lenses (5YR4/3, reddish brown) or red mottling in otherwise goethite-rich, yellowish-brown sediments. Bedding is often weak and occurs more often in units occupying paleotopographic lows, possibly due to deeper standing water and limited bioturbation in these lower, potentially anoxic regions. In the eastern basin these bedded sediments include both the northernmost spring mounds and those farthest from the eastern edge of the basin.

Where several meters of sediment have been preserved (e.g., Fig. 2d, e), basal bioturbated spring-deposited silts are overlain by goethite-stained (7.5YR5/8, strong brown) sandstones; in some cases these sandstones are found directly on Mut shales or within spring vents, which are found throughout both study areas (Fig. 2a). These sands preserve oxide-rich casts of root mats (Fig. 2f) and may also be cemented into hard ferricrete deposits (Fig. 6a) that cap the modern erosional mound forms. However, sand-free iron precipitate is also present throughout the study area as a capping ironstone unit on spring mounds, and occasionally as a band of iron precipitate within iron-cemented silts (Fig. 6b). Petrographic data do not indicate any spatial patterns in the degree of sediment sorting in iron-cemented spring mound sandstones in either basin, nor do they indicate any obvious structural or spatial controls on the occurrence of iron precipitate. The modern erosional forms of the mounds and their spatial distribution within the oasis are therefore not related to the type of ironstone (ferricrete or precipitate) present. Instead, precipitates occur as caps and bands within silt-dominated spring mound sediments, where lower-energy standing-water environments allowed for the accumulation of silts and the development of iron precipitates without coarser sedimentary inputs.

Although there are several possible depositional sources for coarse sands, including channel sedimentation and avulsion within wetland distributary systems (McCarthy et al., 1998; Ellery et al., 2003a, 2003b; McCarthy, 2006), grain size frequency curves (Coudé-Gaussen, 1989; Sun et al., 2002) from the capping goethite-rich units found on Dakhleh spring mounds support a non-fluvial source for spring mound sands (Fig. 7). Although grain size measurement and sampling resolution were limited both by small sample sizes and analytical methods, the absence of a bimodal signature in frequency curves for these sediments suggests deposition by non-fluvial processes (Sun et al., 2002). Further environmental distinction is difficult, as frequency curves for lacustrine and desert environments are variable due to differences in localized controls such as sediment sources and depositional setting (Sun et al., 2002), and the sorting of sediments of aeolian origin may be altered by variations in wind velocity (Chen and Fryrear, 1996). The similarity of grain size curves from both study areas supports similar, likely aeolian, depositional processes in both basins (Fig. 7)

3.3. Spring mound mineralogy and geochemistry

3.3.1. Mineralogy

Petrographic analysis of thin sections allowed for the identification of quartz sandstones within ferricrete samples (Fig. 6a). However, X-ray diffraction (XRD) analyses of bulk ground ironstone samples as well as some associated sediments allow for much more accurate determination of the major mineralogy of these samples (Fig. 5). The facies differentiation between ferricretes and precipitates is easily identifiable through the primary expression of quartz in ferricrete samples (Fig. 5a, d, e), which are often goethite-stained. Jarosite and halite may also be present (Fig. 5b, d). Precipitates are often goethites containing minor quartz, but also include jarosite in some cases (Fig. 5a, b).

3.3.2. Elemental chemistry

Major elemental analyses of 22 samples provide the predictable differentiation of ferricretes and precipitates through a comparison of iron and silica content, where silica-rich samples are iron-cemented sandstones and more iron-rich samples are sand-free (Fig. 8A, Appendix A). Loss on ignition varies directly with iron content for goethite-bearing units as well (Fig. 8B), most likely due to the loss and dehydration of oxides (Sutherland, 1998; Heiri et al., 2001). The salt content in sample SM13-1 may have resulted in slight inaccuracies in XRF analyses for this sample; SM13-1 has been labeled when it occurs as an outlier (Fig. 8A).

Samples labeled "SM" and "IH" come from the western basin in Dakhleh, whereas samples labeled "S" originated in the eastern basin (Fig. 1; Appendices A and B). There is no spatial patterning in the distribution of either major or minor elements in either basin. Separation of elemental comparisons by both ironstone type (ferricrete versus precipitate) and basin of origin (east versus west) also indicates no identifiable difference between samples from different areas, whereas the association between ferricretes versus precipitates is much stronger (Fig. 8). These similarities support the hypothesis of simultaneous deposition of these deposits, or at least deposition during similar depositional and groundwater conditions. The lack of spatial patterning in ironstone elemental composition additionally suggests that the effects of surface kinetics (e.g., Herbert, 1996) had little influence on the elemental composition of these deposits.

Electron microprobe mapping (Fig. 9) of several ironstone samples from both basins indicates the presence of "clean" iron precipitates, containing minimal quartz inclusions (indicated by silica-rich areas, Fig. 9g) and no significant aluminum-replacement within goethite given the minor amounts of Al present and the lack of association

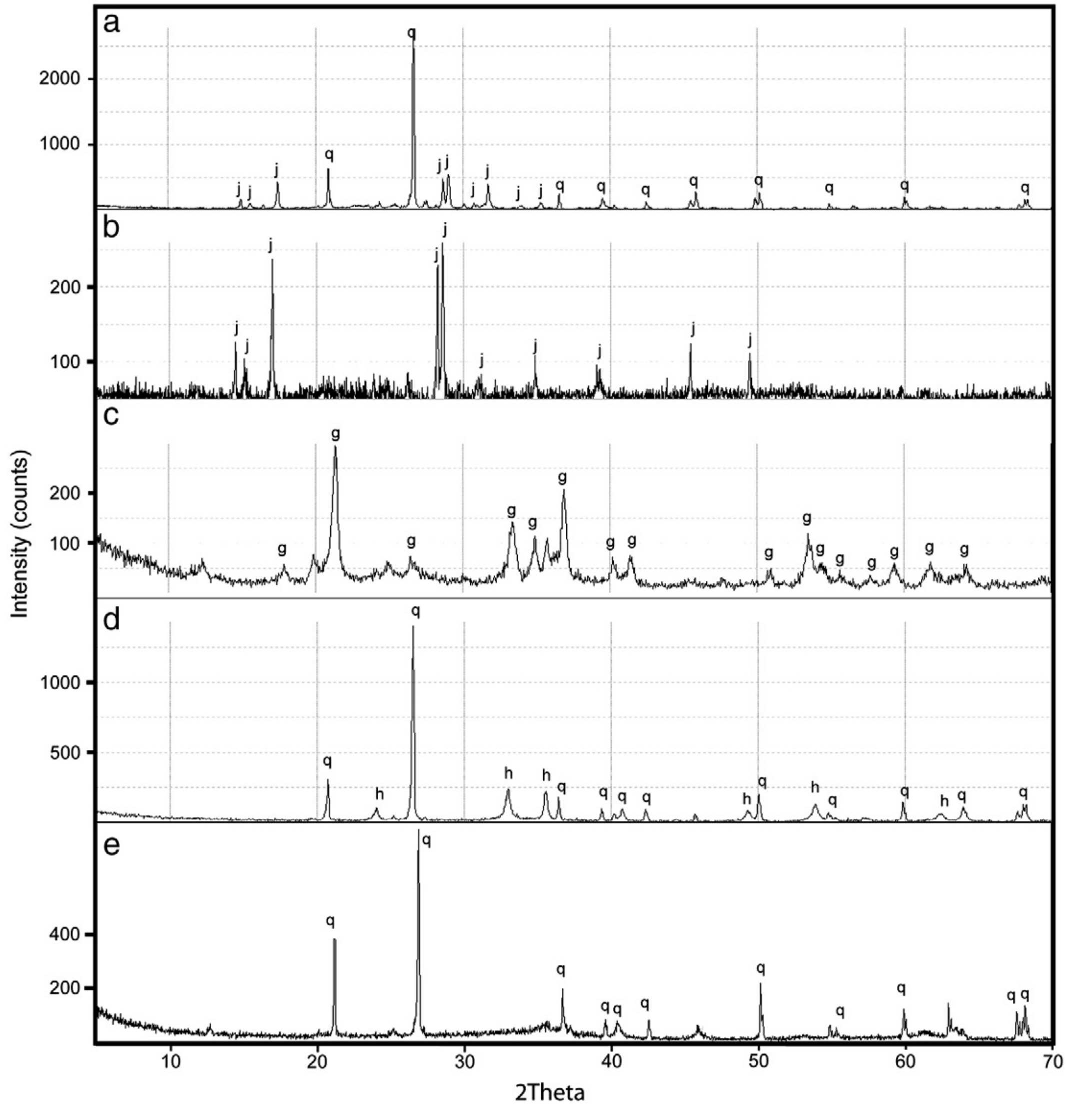

Fig. 5. X-ray diffraction spectra of Dakhleh Oasis samples: a) bulk sediment sample, jarosite-stained (j) quartz (q) silt, b) clay-fraction sample of jarosite-bearing silt illustrating the presence of jarosite (background removed), c) clay-fraction sample of goethite-bearing (g) sand unit illustrating the presence of goethite, d) bulk sediment sample of hematite-stained (h) quartz silt illustrating the only occurrence of hematite in this study area, e) bulk ferricrete sample, quartz sand with goethite and jarosite.

between Al-rich and Fe-rich regions within the samples. The presence of secondary salts is indicated by areas rich in Mg, Na, and K within pore spaces. Sulfur occurrences along pore edges throughout the precipitate samples may be a function of variations in the water composition or acidity over time, or of concentration of sulfates within pore waters compared to other areas (e.g., Herbert, 1999). The occurrence of Ca-rich pore coatings as well likely indicates the presence of gypsum (Fig. 9).

Minor elemental chemistry of Dakhleh's ironstones (Appendix B) indicates a similar lack of spatial patterning and no obvious separation of ironstone facies by trace elemental composition. Trace element levels in ironstones also fall within the range exhibited by modern groundwater precipitates in the area (Modern 1 and Modern 2, Appendix B). These data support the idea that groundwater composition, and the composition of groundwater precipitates, has not changed significantly in this region since spring activity was present during the Pleistocene. The similarities between modern and Pleistocene precipitate composition additionally suggest that variation in the age of ironstone deposits would not be identifiable through comparison of either major or trace elemental compositions of these units.

Modern groundwaters sampled from artesian wells in Dakhleh Oasis are commonly $NaSO_4$ and $NaHCO_3$ waters, with less than 200 mg/L total dissolved solids (Swanberg et al., 1984). PHREEQC saturation indexes (Packhurst and Appelo, 1999) calculated using measured groundwater chemistry (Swanberg et al., 1984) at modern temperature and pH indicate that these groundwaters would support the precipitation of goethite, quartz and hematite but not K-jarosite, gypsum or halite. The precipitation of these salts as well as jarosite in the spring mounds of Dakhleh would require higher levels of dissolved solids as well as higher SO_4^{2+} concentrations. The presence of both gypsum and halite in XRD analyses indicate some evaporative effects on precipitation in this region, suggesting that evaporative concentration of dissolved solids and sulfate ions may have played a role in the development of ironstones in Dakhleh.

4. Discussion

Paleogeographic models of paleolake formation in Dakhleh have included spring mound development as shallow-water or lake-margin features (e.g., Churcher and Kleindienst, in press). However, the localized development of spring deposits does not require concurrent lacustrine development, as illustrated for the western United States (Quade and Pratt, 1989; Quade et al., 1995). In Dakhleh Oasis, energy balance and isotopic mass balance models for lacustrine

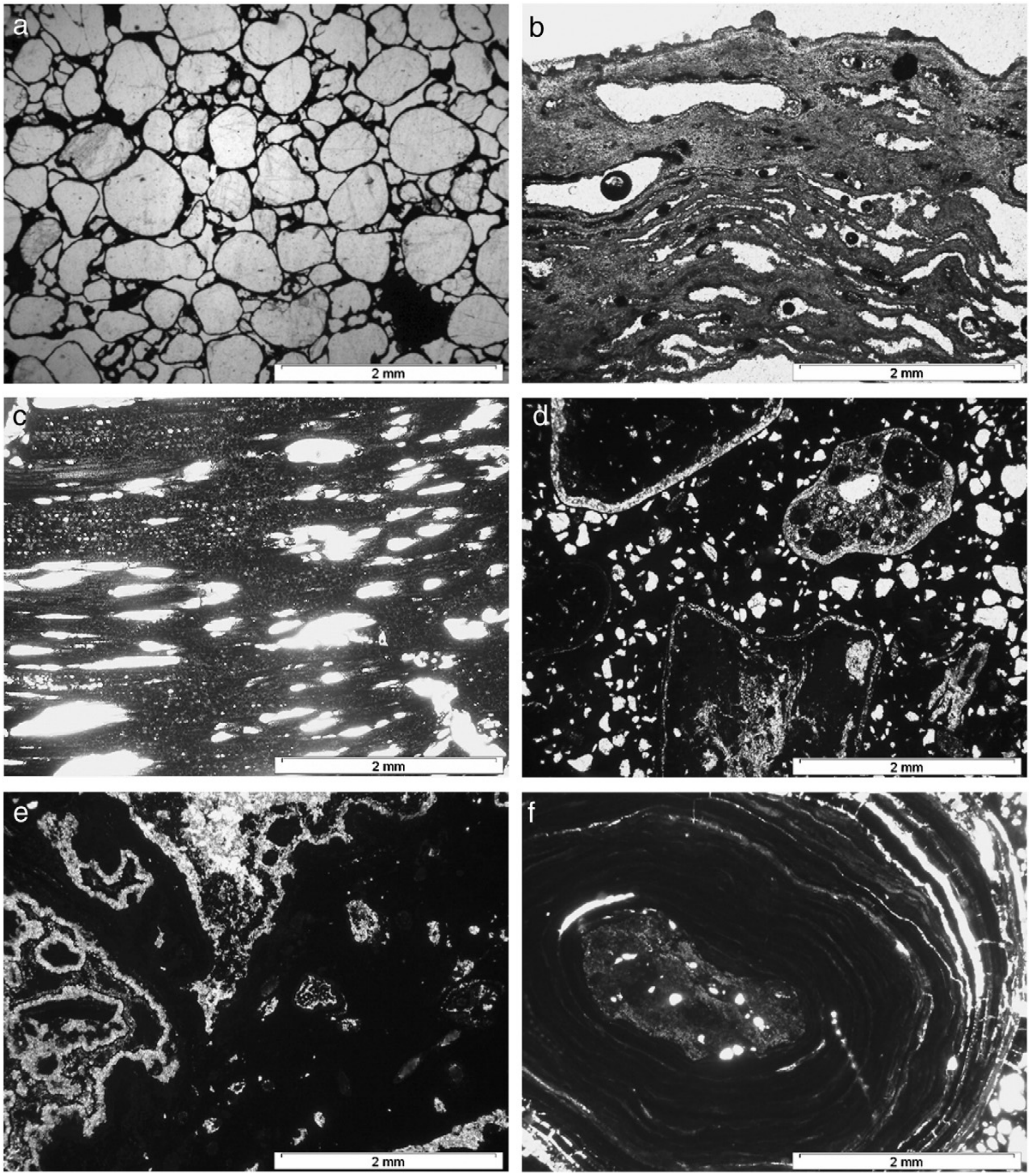

Fig. 6. Photomicrographs of a) ferricrete (PPL), b) iron precipitate with possible biogenic layering (PPL), c) biogenic feature in iron precipitate (PPL), d) reworked sediment including quartz sand, ironstone fragments and calcite, found along the dividing ridge (PPL), e) ironstone vugs with calcite infilling (XPL) from the westernmost spring mounds of Dakhleh Oasis, f) pisolith from a pisolitic ironstone underlying lacustrine carbonates (PPL).

carbonates and associated deposits indicate significant pluvial inputs (up to 670 mm/yr) into the Dakhleh paleolake at its highstand (Kieniewicz and Smith, 2009). Although groundwater discharge likely played a role in maintaining this lake, the deposition of carbonate lacustrine sediments required carbonate-rich waters. The only available source of carbonate in the Dakhleh region, the Garra and Kurkur formations capping the Libyan Plateau to the north (Churcher et al, 1999), would not have influenced lake chemistry without significant pluvial inputs and surface runoff into the Dakhleh basin.

The spring mound features described here are not associated with carbonate facies, potentially due to the erosion of overlying, less resistant carbonate units. Elsewhere in the oasis lacustrine carbonates are found at both equivalent and higher elevations compared to ironstone spring mounds (Kieniewicz and Smith, 2009), indicating that areas of spring mound development would have been inundated during the lacustrine highstand. The occurrence of the most iron-rich FSS units, including a pisolitic ironstone (Brookes, 1993a), beneath these carbonate sediments suggests that the primary phase of ironstone deposition predated the lacustrine highstand in Dakhleh. Spring mound formation may have occurred prior to lacustrine development in the oases, or these features may have formed marginal to a shallower surface water- or groundwater-dominated lake (e.g., Churcher and Kleindienst, in press).

The lack of primary carbonate sedimentation in spring mounds indicates that the deposition of spring mound sediments did not occur within a carbonate-bearing lake. In addition, the massive and iron-rich nature of spring mound sediments support the presence of a shallow-water, groundwater-dominated environment. A more

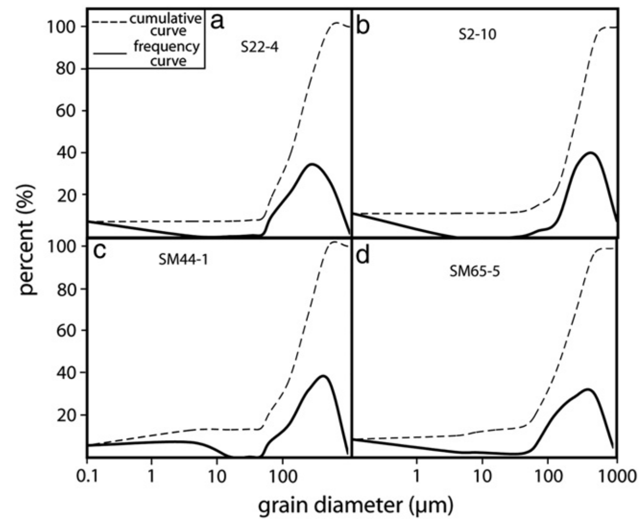

Fig. 7. Cumulative and frequency grain size curves for capping sandy units in the eastern (a, b) and western (c, d) depressions of Dakhleh Oasis.

detailed description of the relationship between these mounds and any potential lacustrine environment is not currently possible given the available stratigraphic evidence. The following discussion focuses on spring mound fields as an independent depositional landscape,

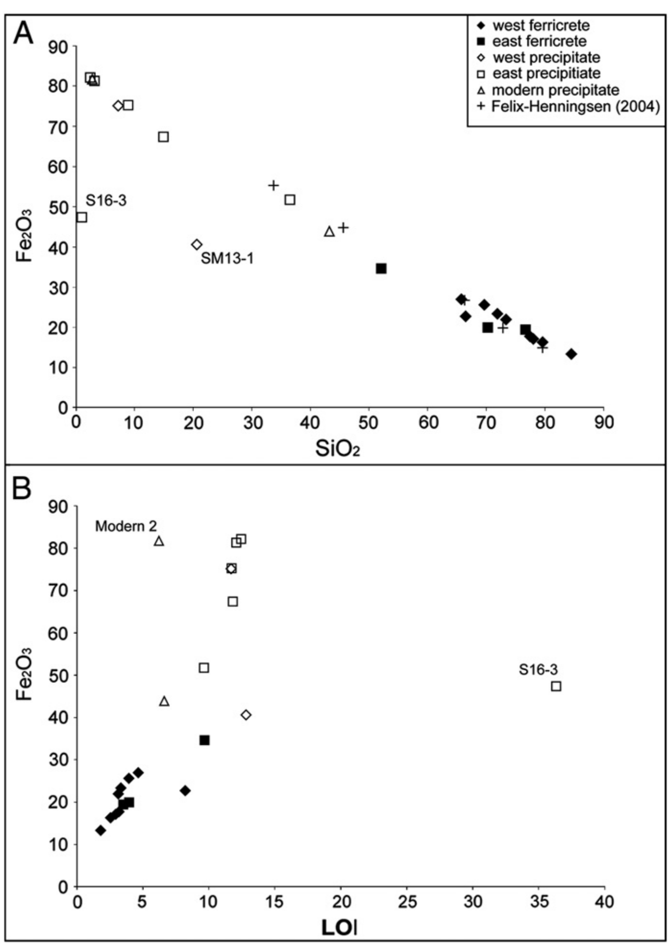

Fig. 8. A. Fe_2O_3 weight percent values for ironstone samples versus SiO_2 weight percent. S16-3 again falls off the trend, as does SM13-1, which contained XRD-identifiable halite. Other values come from Nigerian swamp ores analyzed by Felix-Henningsen (2004). B. Fe_2O_3 weight percent values for ironstone samples versus LOI. Sample S16-3 falls off the general trend, and was the only sample identified as primarily jarosite (Appendix A). Modern 2 value likely due to incomplete ignition.

wherein the precise temporal relationship between spring discharge and other hydrologic events in Dakhleh is still uncertain.

4.1. Geomorphological interpretations

Modern analog environments provide valuable insight into the probable mound building processes which shaped the Dakhleh landscape. Active evaporitic spring mounds have been described in Tunisia (Roberts and Mitchell, 1987), and similar features are found in the Great Artesian Basin of Queensland, Australia, where groundwater discharge leads to the formation of mounded wetland complexes (Watts, 1975; Harris, 1981; Fensham and Fairfax, 2003; Fensham et al., 2004). In these settings, large mounds develop until hydrostatic head has been reached, at which point they may be abandoned in favor of topographically lower discharge points (Fensham et al., 2004). Mound development in Dakhleh may have followed a similar pattern; the location of groundwater discharge along the southern margin of the oasis was likely controlled by the shallow nature of the Taref sandstone aquifer along this southern boundary, as well as the presence of small-scale faulting associated with the Tawil uplift (Kleindienst et al., 1999).

Discharge patterns may have varied temporally as the topography of the wetland was altered through continual groundwater discharge and deposition (Fig. 10). Topographic differences between the mounds are therefore not necessarily indicative of their relative ages, and may not imply bedrock deflation between periods of spring discharge. Although lowering water tables would also lead to topographically lower discharge points over time (Neal and Motts, 1967), variability in spring mound elevation may have been present prior to changes in potentiometric surface elevations as an inherent characteristic of the original wetland, as paleotopography reconstructed from bedrock contacts indicates no obvious terracing of spring deposits (Fig. 4).

The lack of sedimentary structures and the degree of bioturbation of the southern Dakhleh sediments are similar to characteristics of modern wetland deposits (Deocampo, 2002). The bioturbated, variably white and yellow silt and clay found at the base of many mound sequences superficially resemble modern sediments described by Quade and Pratt (1989) originating from spring seeps into “wet meadow” environments. Fine-grained deposits associated with spring formation can also be produced in topographic depressions when the regional water table is high enough to produce standing water (Quade et al., 1995). In either case, these silts and clays are deposited directly by groundwater discharge and ponding. The basal silts found in Dakhleh spring mounds were likely deposited in similar low-energy environments.

The water available in spring mound environments would have supported vegetation, which may have led to the development of “phreatotype” or “dune” mounds, in which windblown sediments could be trapped and accumulated (Fig. 10). The mounds would increase in height until the root system of the vegetation forming the mound was no longer able to reach the underlying water table (Neal and Motts, 1967). Mound formation could continue above the regional potentiometric surface in the presence of deep root systems. The fact that the highest mounds found in southern Dakhleh are topped by cemented, root-rich sands suggests that entrapment of aeolian sand in vegetated areas may have led to the formation of larger mounds at the same time that less-vegetated areas were limited in development by the potentiometric surface and deposition of silts in areas directly affected by groundwater discharge (Fig. 10).

Once sands had accumulated within Dakhleh's spring mounds, whether in spring vents or as caps on spring-deposited silts, these sediments would have been cemented by iron oxide precipitation to form resistant ferricrete caps. Biogenic and subaerial exposure of the iron-rich Nubian Aquifer groundwater (Dabous, 2002) would have provided an oxidative environment for the formation of iron oxides.

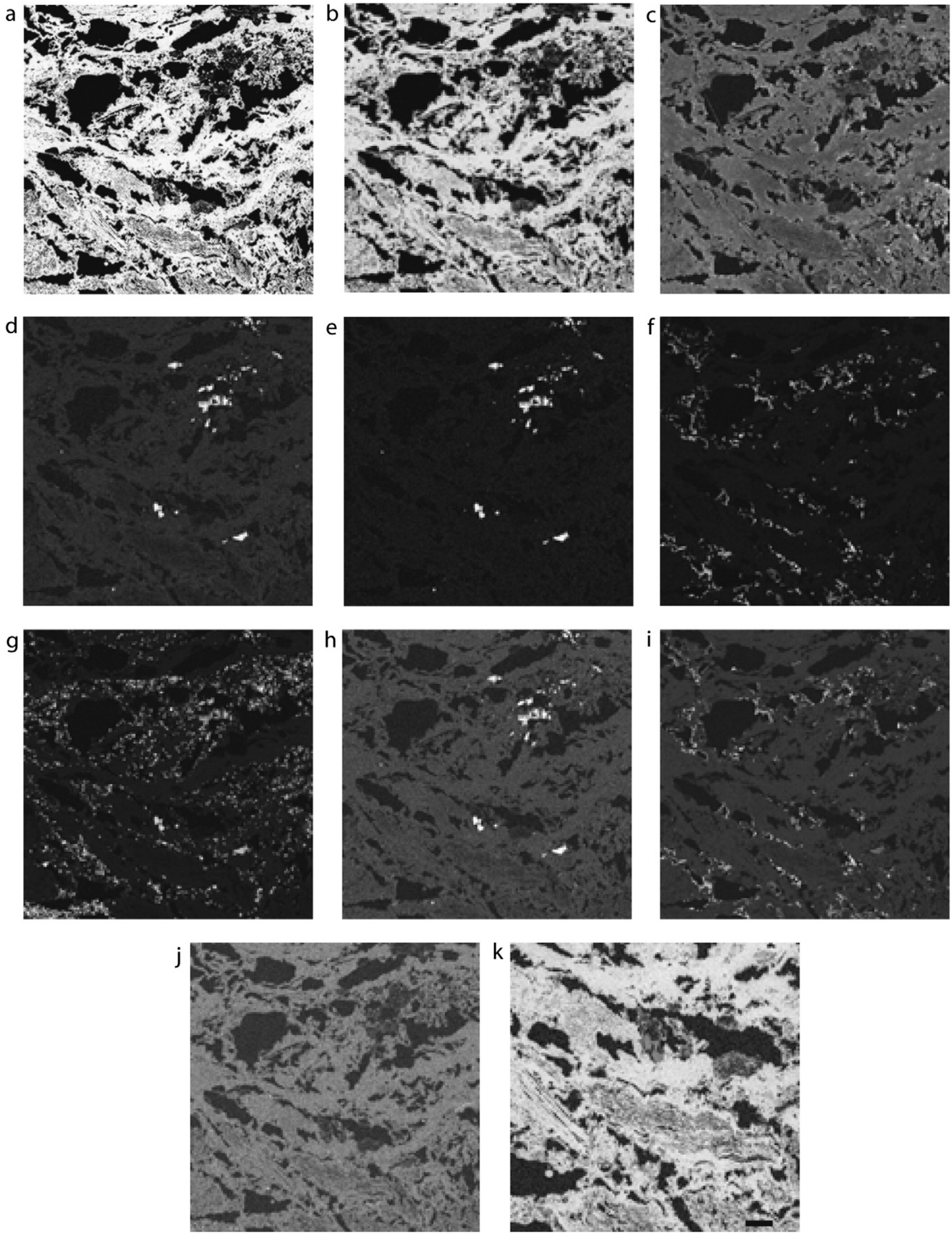

Fig. 9. Elemental maps of precipitate ironstone IH 3-1, a representative ironstone sample from the western study basin. Field of view 12.8 × 12.8 mm for all but k. a) backscatter electron image, b) Fe, c) Al, d) Mg, e) Na, f) S, g) Si, h) K, i) Ca, j) Ti, k) close-up BSE image, scale bar 600 μm. Al, Si, Ti, and Ca determined using silicon drift dispersive spectrometer, others determined with wavelength spectrometer. All images illustrate relative contrast, where bright spots indicate the presence of particular elements.

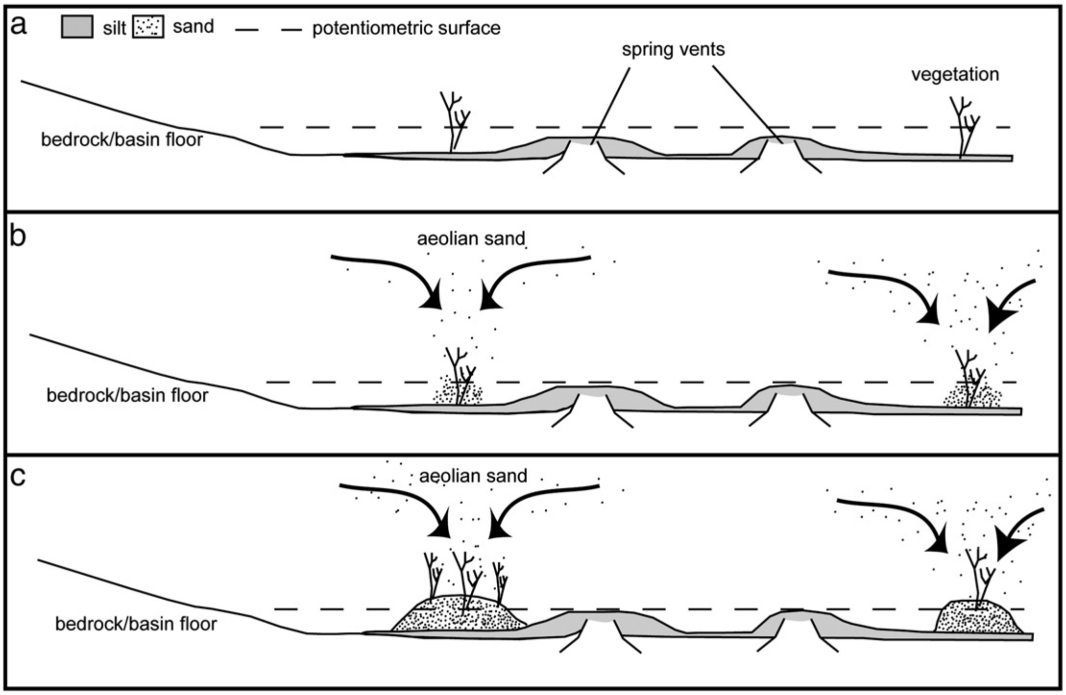

Fig. 10. Model of spring mound formation; a) spring discharge leads to silt deposition and encourages the growth of vegetation, b) aeolian sands are trapped by densely vegetated areas, leading to localized buildup of sand, c) vegetated mounds build above local potentiometric surfaces. The elevations of root systems are constrained by groundwater availability, allowing for vegetation and sand entrapment above the potentiometric surface. In contrast, silt deposition in non-vegetated areas is constrained by direct discharge. Jarosite deposition would be concentrated in silty units, though not universally present. All sandy units are goethite-rich.

4.2. Mineral phase stability and biogenic influences

The modern, pumped Nubian Aquifer waters in Dakhleh are only mildly acidic (pH ~6.3), making the development of acidic deposits in spring mound environments difficult to reproduce given minimal changes in groundwater composition, as would be likely in this fossil groundwater setting. This presents a problem for the formation of jarosite, which is stable in acidic, oxidizing environments, generally as a product of pyrite oxidation or goethite formation (Brown, 1971; Nickel, 1984; Arslan and Arslan, 2003). Jarosite formation is common in modern acid mine drainage environments, where the conversion of goethite from precursors such as schwertmannite releases sulfate and iron (Bigham et al., 1996; Gagliano et al., 2004). However, jarosite may also precipitate as a result of evaporitic processes in waters containing K, SO^4 and Fe^{3+} (Long et al., 1992). Even if jarosite is undersaturated in the groundwater itself, it may form in pore spaces if acidic conditions and high sulfate concentrations develop within these microenvironments (Herbert, 1996, 1999; Wallace et al. 2008). Jarosite formation may therefore have occurred within the pore spaces of spring-deposited silts in Dakhleh due to the presence of evaporitic conditions, removing the requirement of an extensive acidic wetland environment (e.g., Benison et al., 2007) during jarosite formation. The presence of jarosite only in fine-grained silty deposits in Dakhleh, as opposed to coarser sands, may indicate that pore acidity could not be maintained within larger pore environments.

Microbial metabolic processes may also have played a significant role in the oxidation of iron (e.g., Noike et al., 1983; Bigham et al., 1990) and silicates in this iron-rich freshwater environment (e.g., Tazaki, 1997). Biogenic mediation of iron deposits in modern acid mine-drainage environments (e.g., Crerar et al., 1979; Nordstrom, 1982; Singh et al., 1999) indicates that bacterial activity may promote iron deposition even in very acidic environments; a potentially acidic macro- or micro-environment present during jarosite and goethite deposition in Dakhleh would therefore not preclude a microbial role in the development of ironstones. Jarosite precipitation in particular may be mediated by bacterial oxidation of iron under acidic, high-sulfate conditions (Bigham et al., 1992). In such acidic conditions bacterial oxidation of iron can increase oxidation rates more than 10^6 times the abiotic rate (Singer and Stumm, 1970), leading to much faster precipitation of iron oxyhydroxides and formation of iron deposits.

The coexistence of jarosite and goethite is possible over a very small range of Eh-pH values (Arslan and Arslan, 2003). However, jarosite may persist despite a change in environmental conditions (e.g., increasing pH) due to the presence of arid conditions, or it may remain due to the slow rate of transformation from jarosite to goethite (Brown, 1971). Goethite, in contrast, is a very stable iron oxide and a common crystalline product of both schwertmannite and ferrihydrite, or even of jarosite, and may be present across a wide range of pH values (Brown, 1971; Chukhrov, 1977; Bigham et al., 1996). Goethite is sometimes preserved as a resultant mineral phase in older acid-mine drainage environments (Singh et al., 1999), suggesting that similarly acidic environments could be represented as goethite-rich deposits in the geologic record. These characteristics of jarosite and goethite preservation indicate that initially jarosite-rich deposits may be represented by modern goethite-rich sediments, making the determination of original geochemical environments difficult. However, the presence of goethite is not necessarily tied to a jarosite precursor.

The abundance of vegetation present in Dakhleh's spring mounds may have provided a medium for biogenic precipitation of goethite during periods of wetland formation. In wetland plants the rhizosphere is often characterized by significant microbial activity, as the release of organic compounds and oxygen by root systems provides an oxidizing environment and a region of stimulated microbial growth (Armstrong, 1967; Grayston et al., 1996; Küsel et al., 2003). Under acidic conditions, acidophilic bacteria can form goethite-rich coatings along root surfaces through oxidation of available Fe(II) (Küsel et al., 2003; Neubauer et al., 2007), which would be soluble in environments of low pH but may remain stable for up to a year even in acidic conditions after the death of the plant (Wang and Peverly, 1996). Iron oxidizing bacteria are abundant in modern wetlands, and may provide for more active cycling and precipitation of iron in these environments than would be present in an adjacent soil (Weiss et al., 2003). Vegetation in flooded soils also decrease local pH values through carbon dioxide transfer, iron oxidation, cation exchange processes and by providing organic matter for decomposition (Halbach, 1975; Higuchi, 1982; Ahmad and Nye, 1990; Begg et al., 1994), which may have provided localized low-pH conditions within the surface waters in Dakhleh during ironstone formation.

The presence of microlaminations within the iron precipitates of Dakhleh suggests microbial activity as a potential source of precipitation of goethite or its precursor (Fig. 6b, c), although there is no observed concentration of trace elements along any physical surface or lamination that would indicate the presence of bacterial surfaces during oxide formation (Fig. 9, Casanova et al., 1999). Some voids found within goethite precipitates are similar in form to shrinkage voids that result from the decay of cyanobacterial mounds (Arp et al., 1998), supporting the hypothesis of a microbial presence (Fig. 6b). In addition, many of the structures present at the macroscopic (Fig. 2f) scale within ironstones indicate the presence of vegetation, and therefore potential associated microbial activity, during iron precipitation. Microbial mats can serve as stabilizing structures for spring mound sediments (e.g., Dahanayake and Krumbein, 1986); a microbial presence in Dakhleh's ironstones may have aided in the formation of the mound forms preserved in this region today.

The remnant iron deposits of Dakhleh Oasis resemble swamp ore deposits described from Niger (Felix-Henningsen, 2004), and are also texturally and mineralogically similar to bog iron deposits described from the Holocene around the world (Moore, 1910; Starkey, 1962; De Geyter et al., 1985; Breuning-Madsen et al., 2000; Kaczorek and Sommer, 2003; Bricker et al., 2004). Bog irons are commonly composed of oxyhydroxide minerals including goethite and ferrihydrite (Bricker et al., 2004; Kaczorek et al., 2004), which may be precipitated by microbial activity (e.g., Madsen et al., 1986). Ferrihydrite precipitation by geothermal waters, which are commonly found in the Western Desert (Swanberg et al., 1976), may have been mediated by the presence of iron-depositing bacteria (e.g., Casanova et al., 1999). Further mineralogical and geochemical work will be necessary to identify the level of biogenic mediation of iron precipitation in spring mound environments and to determine whether these mineral phases accurately document the paleoenvironmental conditions present during the Pleistocene.

4.3. Groundwater discharge in the hydrologic history of Dakhleh Oasis

The groundwater necessary for the development of wetland environments in the southern Dakhleh basin may have originated from locally recharged shallow Nubian Aquifer waters, from deeper and older waters recharged in southwestern Egypt and Sudan, or from a mixture of the two (Dabous and Osmond, 2001). Initial discharge likely occurred due to an increase in hydraulic head following recharge of shallow, localized aquifer units. Recharge may have occurred southwest of the oasis proper, providing groundwater inputs without significant local rainfall. Historic discharge rates for the Western Desert measured 3×10^8 m^3/yr (Thorweihe, 1986), illustrating that active pluvial inputs and associated groundwater recharge are not necessary for groundwater discharge in the oasis. Discharge rates would have increased during pluvial periods, but spring discharge would have continued despite a decrease or cessation of recharge (Heinl and Brinkmann, 1989). Ironstone deposition could have occurred whenever spring discharge served as the primary water source in the southern portion of the oasis, whereas the overlying authigenic carbonate sediments would have been deposited only when surface waters were dominated by local carbonate-rich surface water inputs rather than Nubian Aquifer discharge.

The iron content of sediments (FSS) found outside of spring mound settings increases visibly with proximity to localized spring vents and ironstone deposits, indicating localized groundwater flow into an otherwise shallow or marginal lacustrine environment. The most iron-rich sands include reworked ironstone fragments (Fig. 6d), indicating that at least some of the iron-rich units in Dakhleh were reworked during shallow lacustrine development in the southern portion of the oasis. Although groundwater contributions to early lake formation may have been significant, the formation of ironstone deposits within spring mound environments appears to have preceded the onset of fully lacustrine conditions.

There has been no identifiable replacement of either iron or calcite minerals in any iron-rich units, although minor sparry calcite has been observed in the pore spaces of some ironstone samples (Fig. 6e). Iron-bearing groundwater may have contributed to the development of iron-rich sediments near wetland environments during initial stages of lacustrine development. The occurrence of reworked ironstone and iron pisoliths (Fig. 6f) along the dividing ridge suggest that a standing-water environment larger than that indicated by spring mound formation alone, yet significantly shallower than the lake highstand, preceded carbonate sedimentation. Groundwater discharge likely played a role in the development of shallow wetland environments and possibly a smaller, iron-rich lake prior to lake-level increases following increased pluvial activity. Some of the uncertainty in the precise sequence of hydrologic events occurring in Dakhleh Oasis is due to the possibility of repeated episodes of spring discharge into the southern portion of the oasis. Direct dates on spring deposits from different geomorphic contexts will be necessary to determine whether iron deposition resumed in southern Dakhleh once pluvial, surface-water inputs had decreased.

4.4. Dakhleh as an archaeological landscape

The spring mounds of Dakhleh Oasis represent a shallow-water, bog-like environment that existed prior to lacustrine development in the oasis. This landscape was utilized in some manner by Paleolithic groups, as indicated by the recovery of artifacts from spring mound vents and sediments. In the eastern basin Acheulian and Middle Paleolithic materials have been found within spring sediments at several different vents (Wendorf and Schild, 1980), whereas in the western basin artifacts belonging to several different Middle Paleolithic phases have been excavated from a single vent (Dakhleh Oasis Project, 2000/2001). These artifacts are described as “fresh” (unweathered) with potential spring polish, suggesting deposition during active spring discharge (M. Wiseman, 2007, personal communication). Recent field observations also indicate the presence of MSA materials within ironstone units and Later Stone Age (LSA) materials deposited on top of, if not within, spring-deposited sediments (M. Kleindienst, 2007, personal communication).

These archaeological data indicate the exploitation of Dakhleh's spring-dominated environments by both Acheulian and MSA groups, and potentially by LSA peoples as well. In addition, the presence of these archaeological materials suggests that a spring-dominated, pre-lacustrine habitable landscape must have been present in Dakhleh during the Pleistocene. The presence of several technological types within a single spring vent suggests long-term spring activity, or repeated reactivation of spring vents, and potential averaging of archaeological assemblages deposited in these environments over time. Human use of Dakhleh Oasis in the middle Pleistocene between pluvial maxima was likely controlled by the availability of groundwater, making spring mounds an important source of archaeological data for interpluvial hominin land use.

Groundwater-dominated, closed-basin wetlands have been described as important hydrologic and archaeological settings in the East African Rift (Deocampo, 2002), where they are most often preserved adjacent to faults (Ashley et al., 2004). These fault-controlled wetland environments were important as perennial water sources (Ashley et al., 2002), in which the value of the water source as a resource and the potential for artifact concentration have been linked directly to water quality (Deocampo et al., 2002). These studies suggest that fault-controlled groundwater discharge produces wetland deposits with high preservation potential, likely providing equally high preservation potential for associated archaeological materials. In Dakhleh, the potential for isolated areas of jarosite formation, as well as evidence for significant similarities between modern and paleo-groundwater precipitates, indicate that groundwater sources were likely as potable during the Pleistocene as they are today, and would have served as an available resource for any early human groups moving through the Western Desert. Age constraints on spring mound formation and reactivation in Dakhleh Oasis will be necessary to determine the timing of potential resource utilization in this region, but the spring mounds of Dakhleh may have been important water sources for early human inhabitants of the Western Desert, particularly between pluvial periods when lakes were minimal or non-existent.

5. Conclusions

The limited preservation and significant deflation of the Pleistocene deposits of Dakhleh Oasis makes the interpretation and reconstruction of this paleolandscape difficult at best. However, basic sedimentary description and stratigraphy of the paleolake basins of Dakhleh have provided some insights into the sequence of hydrologic events occurring in the Western Desert during the Pleistocene. Initial recharge of the Nubian Aquifer allowed for the formation of wetlands along the southern margin of Dakhleh Oasis, where iron-rich groundwater discharged into the basin through spring vents associated with localized bedrock contacts and structural variations. Restricted discharge in an area of variable topography led to the development of standing water and the growth of vegetation. Mound formation through sediment accumulation and iron precipitate formation in standing water resulted in additional topographic variations, which were subsequently enhanced by the accumulation of aeolian material in vegetated mounds.

Carbonate deposition elsewhere in the oasis seems to be largely unrelated to this wetland, representing a later stage of lacustrine development or a higher lake level than was present during periods of ironstone deposition. Rising carbonate-rich lake waters would have eliminated the relatively more acidic conditions necessary for ironstone deposition. Jarosite formation was likely limited in its extent, driven by evaporative processes and acidic microenvironments associated with pore spaces and oxidative vegetated environments. Precipitate formation as a whole was mediated by microbial action within the rhizosphere of wetland vegetation. Although stratigraphic evidence indicates that iron-rich wetland deposits were present prior to lacustrine development in Dakhleh, we cannot eliminate the possibility of repeated episodes of groundwater discharge and spring mound development associated with later, smaller pluvial events or continued groundwater discharge following the pluvial maximum. Spring discharge in marginal- and early-lacustrine settings would have led to wetland development as well as increasing lake levels and contributed to the development of non-SVS (spring vent) units such as FSS. Future work on the spatial and temporal variation in the geochemistry and timing of deposition of these groundwater-dominated deposits will provide additional insights into the hydrologic evolution of this region.

Acknowledgements

This project was funded by National Science Foundation Grant EAR-0447357 and American Chemical Society Petroleum Research Fund Grant 40650-G8 (to JRS). In addition, this work was supported by an NSF Graduate Research Fellowship, a Sigma Xi Grant-in-Aid of Research, two Geological Society of America Student Research Grants, the Douglas C. Kellogg Award from the Society for American Archaeology Geoarchaeology Interest Group, and the Claude C. Albritton, Jr. Award from the Geological Society of America Archaeological Geology Division (to KAA). The fieldwork component was made possible by the resources of the Dakhleh Oasis Project under the direction of Tony Mills. Petrographic and instrumental analyses and imaging were aided by Bob Dymek, Rex Couture, and

Appendix A. Major elemental composition of ironstone samples obtained through XRF analysis. All values reported as weight percents. "Modern1" and "Modern2" are modern groundwater precipitates, whereas other values are spring mound samples. "Modern2" values reported are an average of two separate analyses of the same sample (variation either zero or ± 0.01 wt.%); other values are single analyses for each sample. Balance of "Modern2" presumed to be a result of incomplete ignition of the sample. XRD indicates primary mineralogy as identified using XRD analysis, presented in order of peak strength (strongest first): Q = quartz, G = goethite, J = jarosite, H = halite. Samples labeled "SM" and "IH" come from the western basin in Dakhleh, whereas samples labeled "S" originated in the eastern basin

Sample	Type	XRD	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
IH1-2	Ferricrete	Q, G	84.50	0.08	0.47	13.36	0.04	0.02	0.13	0.03	0.07	0.08	1.80
IH2-1	Ferricrete	Q, G	69.66	0.21	0.41	25.64	0.03	0.03	0.26	0.03	0.04	0.16	3.94
SM10-1	Ferricrete	Q, G	73.35	0.12	0.65	21.97	0.05	−0.02	0.39	0.13	0.05	0.18	3.14
SM23-1	Ferricrete	Q, G	71.88	0.17	0.68	23.37	0.03	−0.03	0.22	−0.02	0.05	0.14	3.33
SM24	Ferricrete	Q, G	79.60	0.10	1.23	16.32	0.04	0.05	0.11	0.14	0.23	0.17	2.55
SM47	Ferricrete	Q, G	65.74	0.09	1.29	26.98	0.06	0.17	0.71	0.11	0.14	0.54	4.65
SM54-1	Ferricrete	Q, G	77.44	0.08	0.65	17.77	0.06	0.12	0.92	−0.03	0.07	0.07	3.19
SM71-1	Ferricrete	Q, G	78.01	0.10	0.71	17.15	0.03	0.00	0.55	0.08	0.29	0.07	2.94
SM8-1	Ferricrete	Q, J, G	66.48	0.69	0.43	22.74	0.02	0.00	0.02	0.20	1.18	0.11	8.21
S35-1	Ferricrete	Q, G	76.70	0.02	0.27	19.45	0.01	−0.04	0.06	0.14	0.02	0.06	3.52
S4-1	Ferricrete	Q, J, G	52.07	0.23	0.43	34.64	0.01	0.03	0.58	0.05	0.86	0.07	9.68
S8-3	Ferricrete	Q, G	70.26	0.08	0.53	19.94	0.02	0.21	2.65	0.07	0.03	0.20	3.97
SM74-1	Precipitate	G	7.21	0.13	1.27	75.13	0.06	0.10	1.22	0.22	0.08	0.11	11.69
SM13-1	Precipitate	Q, G, H	20.62	0.36	1.35	40.61	0.05	1.46	0.28	11.42	0.37	0.13	12.82
S34-1	Precipitate	G	8.91	0.10	1.36	75.25	0.05	0.12	0.21	0.24	0.16	0.34	11.73
S2-7	Precipitate	G, Q	14.93	0.16	1.47	67.37	0.09	0.01	1.40	0.33	0.16	0.22	11.83
S24-2	Precipitate	Q, G, J	36.50	0.39	0.29	51.73	0.06	0.04	0.12	0.06	0.53	0.33	9.64
S16-3	Precipitate	J	1.01	0.05	0.14	47.37	0.02	0.01	0.09	0.51	7.02	0.08	36.33
S13-2	Precipitate	G	3.16	0.04	0.99	81.31	0.34	0.07	0.42	0.10	0.04	0.10	12.09
S12-1	Precipitate	G	2.44	0.01	0.34	82.16	0.28	0.07	0.70	0.10	0.02	0.05	12.45
Modern1	Modern		43.24	0.41	3.39	43.91	0.16	0.17	0.22	0.03	0.63	0.08	6.62
Modern2	Modern		2.80	0.03	0.67	81.73	0.31	0.07	0.56	0.10	0.03	0.07	6.22

Appendix B. Trace elemental analyses for Dakhleh ironstones reported in ppm. "Modern1" and "Modern2" are modern groundwater precipitates, whereas other values are spring mound samples. Samples labeled "SM" and "IH" come from the western basin in Dakhleh, whereas samples labeled "S" originated in the eastern basin

Sample	Type	Pb	Nb	Zr	Y	Sr	Rb	Ga	Zn	Ni	Ba	Co	V	Ce
IH1-2	Ferricrete	<9.0	7.6	130.4	<9.3	16.7	<5.1	<4.3	23.4	41.2	39.9	16.3	<5.8	9.0
IH2-1	Ferricrete	<12.5	10.3	337.0	8.3	25.9	<8.9	<9.0	23.6	24.9	61.5	<25.0	19.1	8.9
SM10-1	Ferricrete	55.1	6.0	228.1	<5.9	22.9	13.8	<6.0	38.3	66.2	1087.2	20.4	<5.8	<11.3
SM23-1	Ferricrete	89.6	6.1	425.6	<9.8	25.6	22.4	12.7	35.8	<14.5	1935.2	20.5	13.2	<13.4
SM24	Ferricrete	<9.9	8.5	124.9	6.0	13.7	7.4	<5.6	15.1	16.0	24.6	<12.8	9.4	11.0
SM47	Ferricrete	16.0	7.7	127.7	<12.3	45.6	11.2	<5.4	16.2	19.7	37.7	15.4	16.1	12.0
SM54-1	Ferricrete	<10.1	<9.8	125.6	<5.7	34.7	<6.3	<6.6	24.9	<10.9	50.0	<22.0	16.2	<13.0
SM71-1	Ferricrete	11.9	7.0	74.8	<5.2	21.4	12.6	<5.0	34.1	<13.8	241.8	<16.3	<6.0	<12.1
SM8-1	Ferricrete	15.8	11.9	589.4	16.3	8.9	11.6	<7.9	16.2	<12.3	190.4	<14.2	128.5	11.6
S35-1	Ferricrete	<14.5	<8.9	27.7	<8.6	6.4	<6.8	5.9	23.2	<11.3	45.2	<13.4	39.9	<6.4
S4-1	Ferricrete	<17.0	13.0	220.5	<7.7	58.8	22.7	<7.2	33.6	<16.4	111.4	<16.6	84.8	7.0
S8-3	Ferricrete	<17.3	<10.0	79.7	<7.2	82.2	<10.8	<6.7	<9.8	<11.9	39.6	<14.0	99.0	12.5
SM74-1	Precipitate	152.2	<14.9	69.5	<13.4	82.9	47.6	13.8	100.4	<33.0	1003.4	<25.4	81.6	<11.2
SM13-1	Precipitate	<16.1	15.5	198.5	<8.3	28.3	13.6	<11.8	192.2	<19.3	11.4	<17.0	47.3	9.5
S34-1	Precipitate	<31.5	<13.7	47.1	<18.3	12.3	<18.1	15.0	354.8	<35.1	57.6	42.5	111.1	8.8
S2-7	Precipitate	<24.5	<15.6	121.1	<12.7	103.8	<20.5	<9.7	75.7	<29.6	64.7	<23.6	29.1	8.6
S24-2	Precipitate	<23.3	<8.7	177.3	12.6	16.1	12.5	19.3	91.5	<22.9	95.8	21.8	66.1	8.5
S16-3	Precipitate	<31.9	<14.2	13.8	<9.2	70.2	59.2	7.4	<19.2	<21.8	111.2	<20.0	64.6	<7.2
S13-2	Precipitate	<41.9	<11.9	21.0	13.2	26.3	<20.4	<11.1	164.6	<35.5	84.5	170.6	33.7	<10.1
S12-1	Precipitate	29.8	<11.8	<14.3	<13.0	28.1	<19.5	<18.0	59.4	<35.4	46.0	40.3	12.7	<11.5
Modern1	Modern	63.4	10.6	298.5	16.4	51.8	25.5	8.0	51.5	<20.2	452.2	<19.2	<11.7	31.0

Paul Carpenter. We also wish to thank Johanna Kieniewicz, Maxine Kleindienst, Marcie Wiseman, Mary McDonald, and Rufus Churcher for their aid in the field and their contributions to geologic research in Dakhleh Oasis.

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